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Development and management of collective network and cloud computing infrastructures

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September, 2019

A tots els nostres presos polítics i exiliats,
en agraïment i desig de llibertat.

*To all our political prisoners and exiles,
with gratitude and desire for freedom.*

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[1]TDX: http://www.tdx.cat, CBUC: http://ccuc.cbuc.cat, CSUC: http://www.csuc.cat, NDLTD: http://www.ndltd.org

Abstract

In the search and development of more participatory models for infrastructure development and management, in this dissertation, we investigate models for the financing, deployment, and operation of network and cloud computing infrastructures. Our main concern is to overcome the inherent exclusion in participation in the processes of development and management and in the right of use in the current dominant models. Our work starts by studying in detail the model of Guifi.net, a successful bottom-up initiative for building network infrastructure, generally referred to as community networks. We pay special attention to its governance system and economic organisation because we argue that these are the key components of the success of this initiative. Then, we generalise our findings for any community network, aiming at becoming sustainable and scalable, and we explore the suitability of the Guifi.net model to the cloud computing infrastructure. As a result of both, we coin the attribute *extensible* to refer to infrastructure that is relatively easy to expand and maintain in contrast to those naturally limited or hard to expand, such as natural resources or highly complex or advanced artificial systems. We conclude proposing a generic model which, in our opinion, is suitable, at least, for managing extensible infrastructure. The Guifi.net model is deeply rooted in the commons; thus, the research in this field, in general, and Elinor Ostrom's work, in particular, have left a profound imprint in our work. Our results show that the Guifi.net model meets almost entirely the principles of long-enduring commons identified by Ostrom.

This work has been developed as an industrial doctorate. As such, it combines academic research with elements of practice and pursues an effective knowledge transfer between academia and the private sector. Given that the private sector's partner is a not-for-profit organisation, the effort to create social value has prevailed over the ambition to advance the development of a specific industrial product or particular technology.

Keywords *Collective infrastructure, Guifi.net, Community networks, Cloud commons, Shared infrastructure, Infrastructure as commons, Infrastructure deployment, Infrastructure management*

Resum

En la recerca i desenvolupament de models més participatius per al desenvolupament i gestió d'infraestructura, en aquesta tesi investiguem sobre models per al finançament, desplegament i operació d'infraestructures de xarxa i de computació al núvol. La nostra preocupació principal és fer front a l'exclusió inherent dels models dominants actualment pel que fa a la participació en els processos de desenvolupament i gestió i, també, als drets d'ús. El nostre treball comença amb un estudi detallat del model de Guifi.net, un cas d'èxit d'iniciativa ciutadana en la construcció d'infraestructura de xarxa, iniciatives que es coneixen com a xarxes comunitàries. En fer-ho, parem una atenció especial al sistema de governança i a l'organització econòmica perquè pensem que són els dos elements claus de l'èxit d'aquesta iniciativa. Tot seguit passem a analitzar d'altres xarxes comunitàries per abundar en la comprensió dels factors determinants per a la seva sostenibilitat i escalabilitat. Després ampliem el nostre estudi analitzant la capacitat i el comportament del model de Guifi.net en el camp de les infraestructures de computació al núvol. A resultes d'aquests estudis, proposem l'atribut *extensible* per a descriure aquelles infraestructures que són relativament fàcil d'ampliar i gestionar, en contraposició a les que o bé estan limitades de forma natural o bé són difícils d'ampliar, com ara els recursos naturals o els sistemes artificials avançats o complexos. Finalitzem aquest treball fent una proposta de model genèric que pensem que és d'aplicabilitat, com a mínim, a tot tipus d'infraestructura extensible. El model de Guifi.net està fortament vinculat als béns comuns. És per això que la recerca en aquest àmbit, en general, i els treballs de Elinor Ostrom en particular, han deixat una forta empremta en el nostre treball. Els resultats que hem obtingut mostren que el model Guifi.net s'ajusta molt bé als principis que segons Ostrom han de complir els béns comuns per ser sostenibles.

Aquest treball s'ha desenvolupat com a doctorat industrial. Com a tal, combina la investigació acadèmica amb elements de pràctica i persegueix una transferència efectiva de coneixement entre l'àmbit acadèmic i el sector privat. Atès que el soci del sector privat és una organització sense ànim de lucre, l'esforç per crear valor social ha prevalgut en l'ambició d'avançar en el desenvolupament d'un producte industrial específic o d'una tecnologia particular.

Paraules clau *Infrastructura col·lectiva, Guifi.net, Xarxes comunals, Núvol comunal, Infraestructura compartida, Infraestructure de comuns, Desplegament d'infraestructures, Gestió d'infraestructures*

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List of publications

Main publications

Articles in journals

[P1]   R. Baig, F. Freitag, and L. Navarro. 'Cloudy in Guifi.net: Establishing and sustaining a community cloud as open commons'. In: *Future Generation Computer Systems* 87 (Oct. 2018), pp. 868–887. ISSN: 0167-739X. DOI: 10.1016/j.future.2017.12.017. URL: http://people.ac.upc.edu/leandro/docs/cloudy.pdf (cit. on p. 9).

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[P3]   R. Baig, L. Dalmau, R. Roca, L. Navarro, F. Freitag, and A. Sathiaseelan. 'Making Community Networks Economically Sustainable, the Guifi.Net Experience'. In: *Proceedings of the 2016 Workshop on Global Access to the Internet for All (ACM SIGCOMM)*. GAIA '16. Florianopolis, Brazil: ACM, Aug. 2016, pp. 31–36. ISBN: 978-1-4503-4423-4. URL: http://dsg.ac.upc.edu/sites/default/files/dsg/acm-sigcomm-gaia-guifi-econ.pdf (cit. on pp. 9, 20, 114, 116, 138, 153).

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[O2]   D. Vega, R. Baig, L. Cerdà-Alabern, E. Medina, R. Meseguer, and L. Navarro. 'A technological overview of the Guifi.net community network'. In: *Computer Networks* 93 (Dec. 2015). Community Networks, pp. 260–278. ISSN: 1389-1286. DOI: 10.1016/j.comnet.2015.09.023 (cit. on p. 20).

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[O4]   R. Baig, R. P. Centelles, F. Freitag, and L. Navarro. 'On edge microclouds to provide local container-based services'. In: *2017 Global Information Infrastructure and Networking Symposium (GIIS)*. St. Pierre, France, Oct. 2017, pp. 31–36. DOI: 10.1109/GIIS.2017.8169801 (cit. on p. 9).

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List of acronyms

ANNGTS access networks to next-generation telecommunication services

AP access point

APC Association for Progressive Communications

API application programming interface

B4RN Broadband for Rural North

BEREC Body of European Regulators of Electronic Communications

CAPEX capital expenditure

CATNIX Catalan neutral internet exchange point

CBPP commons-based peer production

CC community cloud

CDN content delivery network

CN community network

CNMC Comisión Nacional de los Mercados y la Competencia

CPR common-pool resource

CV coefficient of variation

CXOLN Llicència de comuns per a la xarxa oberta, lliure i neutral (Free, open and neutral network commons license)

DIY do-it-yourself

DRL Demand-readiness level

DSL Digital subscriber line

EC European Commission

EU European Union

EXO Associació expansió de la xarxa oberta

FBSS file backup and synchronisation service

FONN free, open and neutral network

FTTH fibre to the home

GSM Global system for mobile

IaaS infrastructure as a service

ICT information and communications technology

ICT4D information and communications technology for development

IEEE Institute of Electrical and Electronics Engineers

IoT internet of things

IP Internet protocol

ISOC Internet Society

ISP internet service provider

ITU International Telecommunication Union

IXP internet exchange point

LTE Long-term evolution

MRE maximum relative error

NGA next generation access network

NGO non-governmental organisation

NOC network operation centre

NRA National regulatory authorities

NSP network service providers

OAN open access network

OF fibre optic

OPEX operational expenditure

P2P peer-to-peer

PaaS platform as a service

PoPIX territorial point of presence – Guifi.net specific

PPP public-private partnership

RA research activity

REST representational state transfer

RIPE-NCC Réseaux IP Européens Network Coordination Centre

ROI return of investment

RQ research question

SaaS software as a service

SDG Sustainable development goals

SLA service-level agreement

SLO service-level objective

SME small and medium-sized enterprise

TRL Technology readiness level

TV television

UDHR Universal declaration of human rights

UNESCO United Nations Educational, Scientific and Cultural Organization

UPC Universitat Politècnica de Catalunya

VoIP Voice over IP

WiFi Wireless fidelity

XAFOGAR Xarxa de fibra òptica de la Garrotxa (Fibre optic network of Garrotxa)

Introduction

1.1 Context

In this dissertation, we investigate the Guifi.net model, a new model for the financing, deployment, maintenance, and operation of telecommunications infrastructure, and explore its applicability to cloud computing infrastructure as contributions in the search for new models of infrastructure development and management that can overcome the limitations of those currently used.

1.1.1 Motivation

Our research is fit for a PhD for the following reasons:

Disruptive model This research explores a disruptive model, which is disruptive due to the following underpinning principles: (i) a unified infrastructure is collectively built and managed in a non-discriminatory manner, (ii) it is made available to everyone on equal and non-discretionary terms for any purpose, including commercial exploitation, and (iii) the participation in the construction and maintenance of the infrastructure is according to its usage.

The Guifi.net model is characterised as follows:

Bottom-up The inclusion of new participants who are free from any conflict of interest and who are not subject to the public and private sectors' inertia allows radical proposals entailing profound reforms, opening the door to the reactivation of local participation and other unforeseen scenarios.

More efficient The relocalisation of the economy and the empowerment of civil society and its implication in governance affairs put the Guifi.net model in a better position to confront many of the gaps of other currently known models without diminishing its effectiveness in the areas where these models perform satisfactorily.

Scalable No clear evidence exists of suffering from insurmountable scale limitations, either in practice or theory.

Exportable The model seems applicable to other infrastructures and facilities.

Complementary The case studies lead to the conclusion of satisfactory coexistence with other currently existing models.[1]

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[1] Non-problematic coexistence facilitates the adoption of the new model in underserved areas. Later, these deployments can be used as a reference to expand the model in areas with other infrastructure already in place.

Existence of at least one large-scale success case Guifi.net [67] is a self-sustained citizen-driven telecommunications project started in 2004 in Catalonia that currently accounts for more than 50,000 households connected using Wireless fidelity (WiFi) and fibre optic (OF) technologies that operate according to the commons model, a 'resource management principle by which a resource is shared within a community' according to [55]. Broadly, Guifi.net falls within the so-called community networks (CNs), a term used to refer to bottom-up initiatives aimed at building network infrastructure by pooling resources and collectively managing them. Guifi.net is widely recognised as the largest and the most sophisticated CN in the world.

Complexity and multidisciplinarity The research objectives involve a complex analysis that covers several disciplines, including social sciences, economics, law, and technology. According to our experience, such objectives can only be accomplished through a long-term project, such as a PhD.

Lack of literature CNs, in general, and Guifi.net, in particular, have attracted significant attention from many actors, including those in academia, for their potential in helping to reduce the digital gap and their innovative ways to address challenges in different fields, such as technology or law, among other reasons, but despite this interest, to the best of our knowledge, no one has studied a case in such detail and has explored its implications, as we present it in this work.

Alignment with the UNESCO SDGs Many of our contributions are well-aligned with the United Nations Educational, Scientific and Cultural Organization (UNESCO) Sustainable development goals (SDG) [151], in general, and are aligned to some of them very specifically. The advances towards more efficient models for infrastructure development and management through scientific research fall completely within SDG9 *Industry, Innovation, and Infrastructure*, and the promotion of social economy, ethical work, and youth employment in SDG8 *Decent Work and Economic Growth*. Ethical and efficient infrastructure development contributes to SDG11 *Sustainable Cities and Communities* and SDG12 *Responsible Consumption and Production*. Enabling effective means for civil society engagement in development and governance is among the global targets of SDG17 *Partnerships for the Goals*. Finally, the commitment to make infrastructure ubiquitous has a direct influence on SDG10 *Reducing Inequality*.

1.1.2 Industrial doctorate

This dissertation has been developed under the Industrial Doctorates Plan of the Government of Catalonia [1]. This plan promotes the development of strategic research projects within a company through private sector and research institution partnerships. Strategic research projects are expected to combine academic research with elements of practice to tackle challenges of strategic importance for the industry and must involve substantial bidirectional knowledge transfer. In the case of this dissertation, a collaboration has been established between the Universitat Politècnica de Catalunya (UPC)[2] and the non-governmental organisation (NGO) *Fundació privada per a la xarxa oberta lliure i neutral, Guifi.net* (Private foundation for the open, free and neutral network – Guifi.net[3]), the Guifi.net foundation or simply the Foundation [58]. The nature of

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[2] https://www.upc.edu/en
[3] https://fundacio.guifi.net/en_US/

the involved private-sector partner implies an expected outcome with a strong social value more than contributing to the development of a specific industrial product or a particular technology.

The research objectives, methodology, and available resources are specified in the collaboration agreement signed in September 2016. Through this industrial doctorate, the Guifi.net foundation pursued the strengthening and dissemination of the model that this NGO had been developing and using together with the Guifi.net community for more than a decade. The agreed tasks include (i) reviewing the existing literature related to the research, (ii) accurately analysing the work already done, (iii) identifying and describing possible inconsistencies or gaps, (iv) making recommendations and testing solutions, and (v) disseminating the results in the research and industry fora and in the policy-making and practitioner environments. For UPC, this was an opportunity to advance the research in the fields of CNs and the commons, an activity started in 2011 and that has entailed three European research projects (FP7-CONFINE,[4] FP7-Clommunity,[5] and H2020-netCommons[6]) and 6 PhD dissertations.

1.2 Problem statement

1.2.1 Drawbacks and limitations of current dominant models

In Western society, the current main models for infrastructure development and management are (i) the public sector model, (ii) the public-private partnership (PPP) model, and (iii) the private sector model. The public sector model, as a result of the massive liberalisations and privatisations of the past few decades, is currently limited to some particular infrastructures, all of them out of the immediate scope of this dissertation. Moreover, probably the most efficient way to influence these matters is through political action, which is also outside the scope of our work, at least as a core activity. Therefore, we do not continue this analysis.

Although no criteria are clearly defined for mapping every kind of infrastructure to a specific model, some patterns can be identified. For example, in most countries, while the justice system is run by the public sector, the telecommunications sector has been fully liberalised. Moreover, different models coexist in some types of infrastructures, for instance, there are offerings according to all three models in the education system in many countries. The coexistence of models is also possible in the same physical infrastructure. In some countries, the railway network is funded and owned by the state but is operated by one or several private companies.

These models have made an undeniable contribution to achieving the impressive level of development of Western society. Nonetheless, in our view, all of them suffer from a number of drawbacks and design limitations, which we summarise in Figure 1.1 and discuss below. First, in terms of participation, all of them take a strong top-down approach in practice, either by nature in the case of public intervention or due to the relentless business concentration in the liberalised private sector. Consequently, civil society has little chance in theory and no chance in practice to effectively engage in any of the processes of infrastructure development and management; thus, citizens are limited to being mere consumers.

The public sector model, as a result of the massive liberalisations and privatisations of the past few decades, is currently limited to some particular infrastructures, all of them out of the immediate scope of this dissertation. Moreover, probably the most efficient way to influence

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[4]EC Grant agreement number 288535, 09/2011-08/2015 (http://confine-project.eu/).
[5]EC Grant Agreement number 317879, 01/2013-06/2015 (http://clommunity-project.eu/).
[6]EC Grant Agreement number 688110, 01/2016-12/2018 (https://netcommons.eu/).
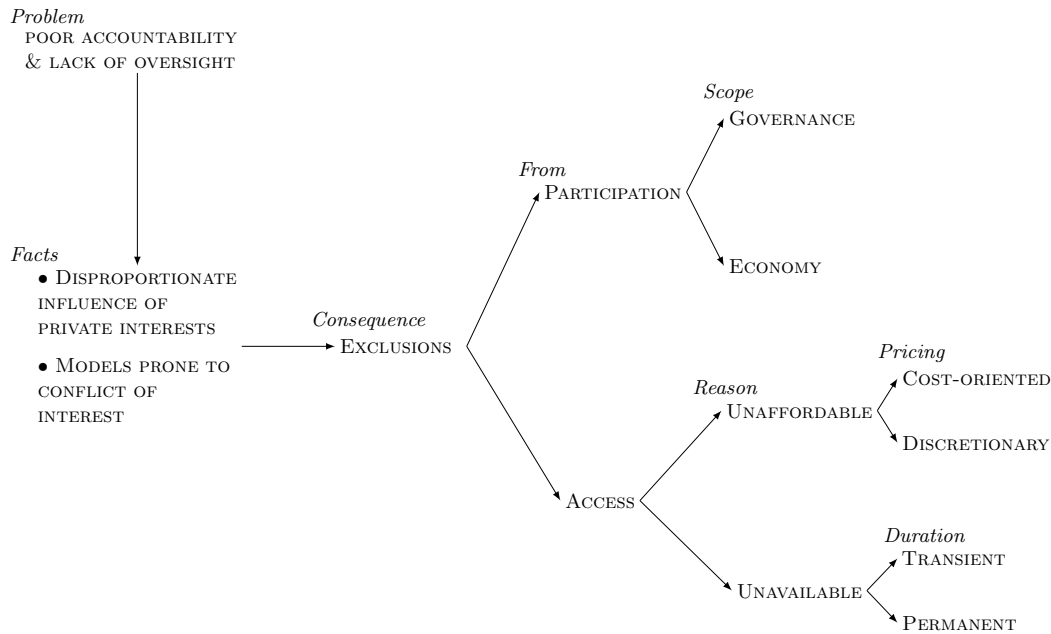
Figure 1.1: Limitations of the main current infrastructure models

these matters is through political action, which is also outside the scope of our work, at least as a core activity. Therefore, we do not continue this analysis.

As for the PPP and private-sector models, in general, the use of the PPPs is restricted either to those areas and services that the private sector would leave unattended without public backing or to those systems that are considered too critical to be left in the hands of the private sector exclusively[7]. Moreover, PPPs are used to shape the development of a service or an infrastructure in a certain way.

Examples of the use of both models in infrastructure and services that completely fall into the scope of our work abound. It is well known that the private sector has invested considerable money and effort into developing a network and cloud computing infrastructure worldwide, thanks to which, today, we have high-performance computer centres and high-speed wholesale networks. What is perhaps less known is the contribution made by the public sector, without which the overall landscape of information and communications technology (ICT) would be completely different. Given the liberalised nature of the sector, traditionally, these contributions were made through funds to private companies. However, because the direct allocation of public funds to specific private corporations jeopardises free competition, these contributions are increasingly bound to PPPs, which must make the resulting infrastructure available to all stakeholders on equal terms. Hence, we analysed both models in further detail.

In addition, PPPs have been widely criticised. In terms of efficiency, after more than 40 years of massive adoption, evidence of better performance in terms of value for money is unclear [43, 78], and thus, the diversion of public funds to the private sector has not yet been justified. In terms of social effects, some PPPs have been blamed for being *de facto* privatisations [158] and for entailing a difficult-to-revert loss of know-how of the public administration [109], both leading to social disempowerment. In terms of risk-taking and accountability, several studied PPPs

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[7]Examples include the healthcare or the education systems, although remarkable variance exists across countries in terms of which of these services are are handled through public intervention and the degree of the intervention.

have been described as riskier for the state than for the involved private companies and lacked transparency [109]. Furthermore, we can argue that, in addition to these specific problems, many of the PPPs also suffer from most of the problems inherent to the private sector model that we discuss in the following paragraphs due to poor contract arrangements.

A plausible reason behind the PPP inefficiencies could be because citizens have refrained from exercising their oversight role over the public administration due to its top-down and hermetic management. This disregard has allowed the private sector to impose a one-sided view at the legislative and executive levels. Because PPPs are no exception, they are essentially managed as private assets, meaning that they suffer from similar drawbacks. We focused our efforts in the analysis of the private sector.

Regarding the private sector, the genuine ultimate goal of any private (for-profit) initiative is to maximise the profit of the investors, and infrastructure assets are managed accordingly. Thus, when it comes to the private sector, infrastructure is highly exposed to speculative practices and speculative bubbles. Hence, the conditions under which infrastructure is made available in the market can radically change at any given time or even can become unavailable, regardless of how critical it is for society.

The shortage of private-sector funding results in transient infrastructure unavailability because the limited available funding resources are always invested in the areas with the quickest return of investment (ROI). The result is that some areas are overprovisioned, whereas others remain underserved, and the constant evolution of the available technology only exacerbates the differences. Moreover, unavailability becomes endemic under a certain population density without public intervention either through public investment or through regulatory measures.

Together with the already discussed infrastructure unavailability, pricing is the other main source of exclusion from access. The maximisation of profit criterion frequently translates into product prices and service fees that are frequently higher than they would be on a cost-oriented basis, meaning that the section of the population that could afford the latter but not the former is artificially excluded from enjoying these services or products and those who can still afford them have to pay an excessive cost. Furthermore, inefficiencies, such as infrastructure duplication or transaction costs, necessarily translate into increased costs and higher prices.Yet, not even cost-oriented pricing and inefficiency eradication alone can avoid exclusion on the grounds of affordability due to the size of the world's population living in extreme poverty and distress.

1.2.2 Expected features

The limitations and drawbacks of the current models for infrastructure development and management make it necessary to explore new alternatives. Here, we present the features that, in our view, alternative models must meet, in whole or in part. In terms of new models, they must either entail more participatory organisational systems to allow effective inclusion in governance and decision-making processes or contribute to drastically reduce the funding needs for business engagement to enable the currently excluded companies and entrepreneurs to join the economic ecosystem. Making the concept of *economy* more flexible and local to enable complementary means of business participation helps to integrate small capital that currently remains unused into the system.

Lowering the capital requirements not only makes the system healthier from the business participation perspective but also directly affects availability because more investment occurs in infrastructure, especially if the model also allows investment by citizens to promote specific

deployments, for instance, the neighbouring communities that join forces to deploy OF at their homes. The reactivation of local economies facilitates the customisation of services to better suit specific realities, offering, for instance, low-cost services for low-income families, directly diminishing exclusion by price. Another field of action to bring prices down is to reduce the total costs by increasing efficiency. Ensuring the optimal use of the existing infrastructure before deploying a new one or improving the business processes has a direct effect in this regard.

Finally, the candidate models must allow measures of last resort to ensure that no one is being excluded from access either for affordability reasons in properly served regions or due to the lack of available infrastructure because, even in the most optimal situation, some access problems are likely to persist. Essentially, these measures can be either based on public subsidies or on internal wealth redistribution mechanisms. The second option is preferable to the first because management is done organically and is more likely to be sustainable. Resources that are made artificially scarce, such as OF, are especially suitable for testing wealth redistribution mechanisms based on radically new approaches, such as the economy of abundance theory [71]. More traditionally, wealth redistribution is frequently implemented through overpricing for those who can pay, to help those who cannot. Nonetheless, these last measures must be tailored carefully to keep the total cost competitive.

1.3   Research questions

In the search of more participatory models for infrastructure development and management, the work presented in this dissertation attempts to answer the following research questions (RQs):

RQ1 Does the approach followed by Guifi.net outperform the private sector model?

RQ2 Does the Guifi.net case have enough unique and beneficial features to be considered a model on its own?

RQ3 Does the Guifi.net model apply to other infrastructures?

1.4   Methodology

In our work, as the research questions suggest, we followed an overall incremental methodology. First, we focused our efforts on the network infrastructure and the particular case of the Guifi.net CN. Then, on one side, we extended the scope to the CNs as a whole, and on the other, we studied the case of the cloud computing infrastructure. Finally, we searched for more general conclusions. For the fieldwork, we followed an action research approach [33, 149], in general, and network action research [51] and ethnographic action research [144], in particular.

Action research is a practical problem-solving methodology in which the research questions are not made beforehand as a result of a purely intellectual exercise but arise from practical experience. These questions are usually either a product of abstractions from specific problems or of aiming for the improvement or optimisation of a process of a community of practice. The solutions are tested by putting them into practice in the community and observing their effects. The overall process is iterative because successful solutions lead to higher stages of development that, in turn, bring new challenges and, thus, new questions. Hence, it is difficult to predict the final result of certain research accurately beyond general guidelines.

In line with the iterative nature and the constant critical reflection of the action research methodology, despite knowing since the beginning that we wanted to investigate Guifi.net to explore its potential to overcome the current dominant models for infrastructure development and management, we were only able to formulate the research questions presented in Section 1.3 in an explicit manner after long research work. Moreover, during the writing of this dissertation, based on our confidence in the outcomes of the RQ, we decided to add a chapter on the generalisation of the model. We believe that this chapter enriches the completeness of this work, although the model is in a propositional stage. The main reasons to choose Guifi.net as a starting point were its exceptional results already achieved by the time of starting our research and the close relationship that the research group, in general, and the advisor and the candidate, in particular, had with the Guifi.net community and the Guifi.net foundation.

The selected methodology allowed us to gather first-hand information and to conduct experiments that would have been harder to carry out otherwise while providing a high level of feedback to the communities of practice we worked with. The interactions with the practitioners included the following:

- Participation in community meetings, hacklabs, and gatherings to understand the social dynamics in the first instance and to later contribute whenever possible and to present the research results.
- Personal interviews to learn personal perceptions and understandings and to deepen our knowledge of complex or controversial aspects.
- Participation in mailing lists and social media to supplement the interaction with individuals and groups.
- Data collection and analysis to obtain supporting arguments. Quantitative data were preferred over qualitative data.
- Working meetings to discuss the research challenges and later to present and discuss the preliminary results and design the coming research iteration.

Addressing RQ1 implied the evaluation and comparison of the results in terms of availability as well as in terms of engagement. The common indicators of the telecommunication sector, namely coverage, price, and adoption, are limited to describing the performance in terms of access. Thus, to evaluate the performance in terms of opportunities for effective participation in the governance and the economic systems, the diversity of and within the stakeholder groups, the internal wealth redistribution mechanisms, and so on, the aforementioned quantitative indicators were broadened with other qualitative indicators. Our work confirmed the preliminary empirical evidence pointing towards a positive answer to RQ1.

To answer RQ2, we first deepened our research on Guifi.net, this time focusing on its organisational structure. The governance and economic systems deserved our special attention due to the critical role they play within the ecosystem and their complexity. Second, we studied the performance of other CNs (reported in [O8]) and compared the results. Our findings on the complexity and particularity of the Guifi.net initiative and its contributions to extend the social value of the infrastructure put in place led us to answer RQ2 affirmatively.

We incrementally tackled RQ3 on the applicability of the model to other infrastructures. We first investigated its scalability within the same infrastructure domain (i.e. Internet protocol (IP) networks). For this investigation, we decided to focus our efforts on CNs because, in them, not only the infrastructure is the same but the social conditions (bottom-up collaborative initiatives) are also rather similar. The comparison with less developed cases (Guifi.net is by far the most

developed and complex CN we know) allowed us to better define and understand the enabling factors of Guifi.net scalability. In the second stage, we addressed the question of the exportability of the model to other infrastructures. To this end, we decided to work on the cloud computing infrastructure in Guifi.net. Working with the Guifi.net community allowed us to benefit from all the existing synergies and allowed us to strengthen them. The main motivations for selecting the cloud infrastructure were the following: (i) the affordability of the hardware involved, (ii) the fact that the community had already made some attempts to deploy cloud infrastructure but from a rather unorganised efforts and with limited success, (iii) the fact that cloud computing and network infrastructure are frequently interdependent, and (iv) that we had the required knowledge to make the technological developments needed for the research. In terms of methodology, we kept the action research approach. First, we analysed the results and both the lack and opportunity for improving the pre-existing cloud developments. We aimed at learning about the success factors for creating a sustainable cloud computing infrastructure through making a GNU/Linux distribution available that met the needs of the Guifi.net community members. Our experimental research involved several meetings with community members for each stage of the investigation and the deployment of tens of instances of the software distribution. To stimulate the uptake, we made three rounds of partially sponsored low-cost minicomputers available to participants.

This dissertation entailed a significant amount of qualitative analysis and required a multidisciplinary approach. The solid expertise of our research group in ICT, in general, and in networking, operating systems, and programming, in particular, together with our practical experience after more than a decade of participating in Guifi.net allowed us to tackle problems raised in the areas of social sciences, economics, and laws that had been left unattended by the researchers in these disciplines, probably because the technological components were insurmountable obstacles for them.

We concentrated our research interests on practical use cases because, according to our view, (i) as researchers cannot ignore reality, we have to meet the challenge of delivering theoretical explanations to practical situations, especially for those that perform well, (ii) the interaction with communities of practice is a valuable source of knowledge and inspiring experiences and provides unique opportunities for experimenting and testing, and (iii) we believe that practical involvement is the most effective way to promote social change towards a better world.

The close collaboration our research group has had with the Guifi.net community for almost a decade and the amount of information publicly available resulting from the chosen model developed to deploy and operate the network infrastructure and services, in conjunction with detailed datasets provided to us by the Guifi.net foundation have enabled an uncommon depth of analysis. The development of this dissertation dissertation has allowed us to review and update the research results and publications of the last five years.

1.5   Contributions

The main scientific contributions of this dissertation are the following:

Collection of performance indicators of Guifi.net   Quantitative and qualitative impact indicators in terms of access include infrastructure put in place, availability conditions, and adoption. In terms of governance participation, these include opportunities for effective participation and diverse participants. Finally, in terms of economic participation, these include entry barriers and the type and distribution of participants.

Description of the differences between Guifi.net and the private sector model A review of the differences in the approach and the resulting consequences from a holistic perspective is provided, ranging from the conceptual understanding of the managed assets to the resulting conditions (attributes) of the resulting infrastructure.

Formalisation of the Guifi.net organisational model This includes the identification and classification of the stakeholder groups, the description of the interaction among them, the identification and classification of the body of developed normative elements, and the description of the governance and economic subsystem.

The work related to these three contributions is presented in Chapters 3 to 5. It was originally reported in [P2, P3, P5] and [O1, O6] and contributes to answering RQ1 and RQ2.

Identification of key factors in CNs scalability and related patterns This contribution includes a review of the main social, legal, economic, technological, and cross-disciplinary aspects in the scalability of CNs as an example of collectively developed and managed infrastructure and a collection of the most relevant good and bad practices (patterns and anti-patterns) from the CNs we studied.

The work related to this contribution is presented in Chapter 6. It was originally reported in [P4] and [O7, O8] and contributes to answering RQ3.

Analysis of the suitability of the Guifi.net model for the cloud computing infrastructure The analysis entailed the identification of the required adaptations and the initial key enablers for a successful adoption, the development of a cloud computing software stack for experimentally testing its adoption within the Guifi.net community, and a theoretical viability analysis of a business case on top of the deployed infrastructure.

The work related to this contribution is presented in Chapter 7. It was originally reported in [P1] and [O4] and contributes to answering RQ3.

1.6 Dissertation organisation

Figure 1.2 presents the general structure of the dissertation, linking the chapters, research questions, and main scientific production. The rest of this document is organised as follows:

Background (Chapter 2) collects the literature that this dissertation builds on and presents the limitations that our research contributions intend to overcome.

Guifi.net – Overview (Chapter 3) presents the context, overall structure, and the main concepts Guifi.net builds on and the results it has already achieved. It also provides evidence of its uniqueness and the potential of Guifi.net.

Guifi.net – Governance (Chapter 4) addresses the governance system of Guifi.net, a central question in any organisation and particularly in those aimed at being collaborative and inclusive.

Guifi.net – Economics (Chapter 5) analyses the key components of the Guifi.net economy and how they are related to the fundamental principles and governance system.
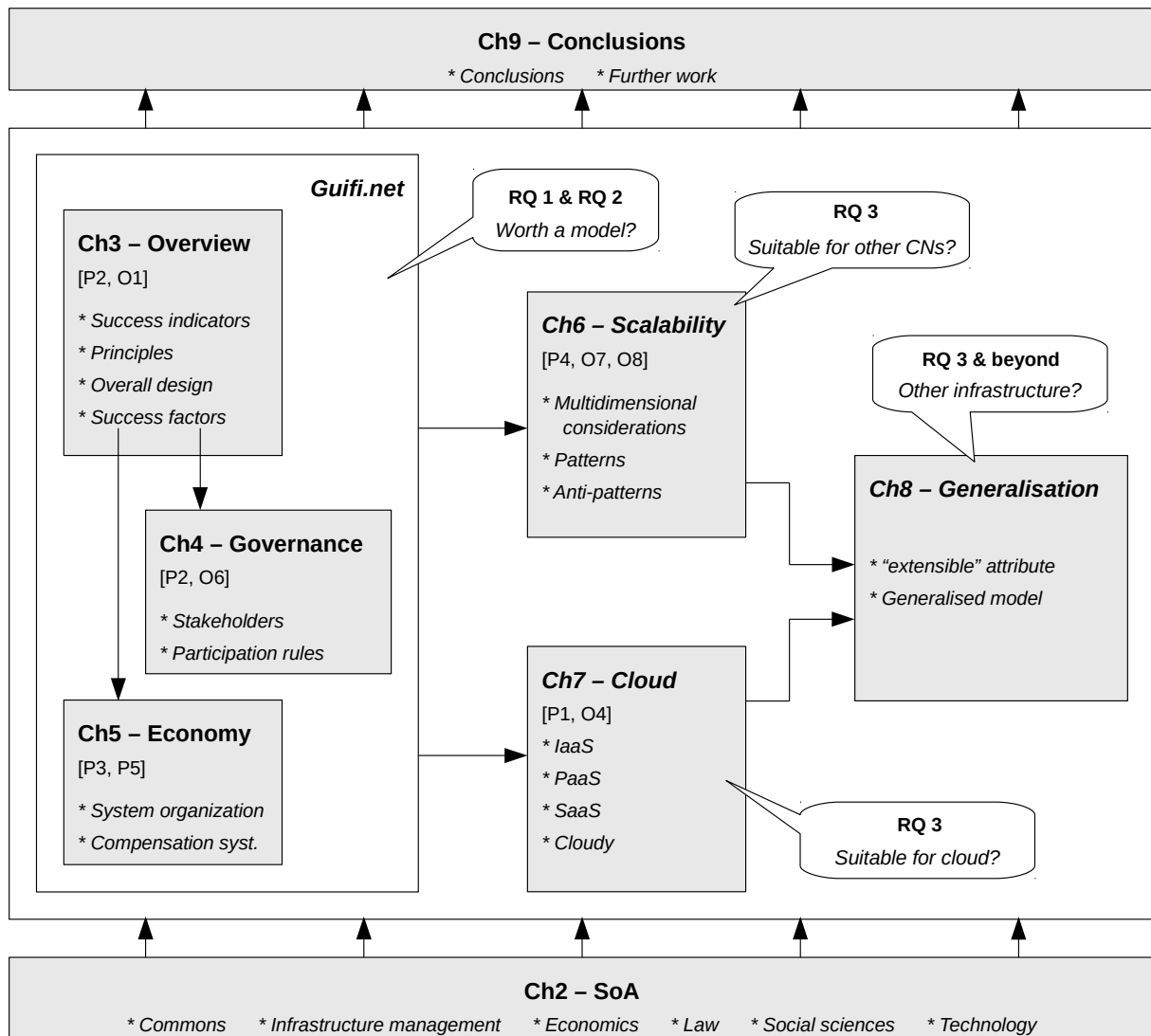
Figure 1.2: This dissertation structure.

Scalability in community networks (Chapter 6) discusses the key aspects of CNs scalability
from an holistic point of view and collects a set of patterns (the re-usable form of a solution
to a design problem) and anti-patterns (a common response to a recurring problem that is
usually ineffective and risks being highly counterproductive) extracted from the CNs that
we analysed.

Applicability to cloud computing (Chapter 7) explores the applicability of the Guifi.net
model in the domain of cloud computing in terms of feasibility (adoption) and economic
sustainability.

Potential generalisation (Chapter 8) develops the generic model we propose for collaborative
infrastructure deployment and management.

Conclusions (Chapter 9) elaborates on the overall conclusions of this dissertation and presents
future directions that deserve further work.

Each chapter starts with a short preface that presents and briefly summarises its content in the overall context. After the preface, the introduction explores the motivation of the chapter, reviews the preliminary concepts, and introduces the rest of the content. All chapters end with a section summarising the main contributions and conclusions.

Chapters 3 to 5 form a unit describing Guifi.net; thus, it is recommended to read them in conjunction and in that sequence.

Background

Preface

This chapter collects the concepts, literature, and legislative and regulatory aspects that this thesis dissertation builds on and presents the limitations that our research contributions intend to overcome. Its content is structured around the three main pillars of this work: network infrastructure, cloud computing infrastructure, and the commons. Each is addressed in a section. The network and cloud computing infrastructure sections follow a similar structure. First, they set the general context of the topic and then analyse the aspects related to governance, concluding with a review of the existing experiences of resource sharing. The network section is significantly longer than the cloud computing section because it also provides context to the ICT sector in general. The section devoted to the commons introduces the concept of common-pool resource (CPR) and how it relates to infrastructure and to CNs, in particular. A short section compiling the most relevant legislation applicable to Guifi.net follows. The chapter concludes by describing the gaps in knowledge that this dissertation intends to contribute to filling.

2.1 Introduction

The overall goal of this dissertation is to contribute to the search for new models for infrastructure development and management that overcome the limitations of those currently used. Therefore, the meaning of *infrastructure* and the scope of the term *model* must be clarified.

The *Cambridge Dictionary* defines infrastructure as 'the basic systems and services, such as transport and power supplies, that a country or organisation uses in order to work effectively'[36], and *Investopedia* defines it as 'the term for the basic physical systems of a business or nation'[37] and mentions 'transportation, communication, sewage, water, and electric systems' as examples. According to the *Wikipedia*, infrastructure 'is the fundamental facilities and systems serving a country, city, or other area, including the services and facilities necessary for its economy to function'[164] and points out 'improvements such as roads, railways, bridges, tunnels, water supply, sewers, electrical grids, and telecommunications (including Internet[1] connectivity and broadband speeds)'. Thus, for these three sources, the term infrastructure is confined to physical systems.

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[1]In this dissertation, the capitalisation of *Internet* refers to the worldwide infrastructure resulting in the interconnection of numerous networks, and *internet* refers to the generic interconnection of networks (internets or internetworks). In unclear cases, we have used *internet* because we understand the *Internet* as a case of an *internet*.

For *Lexico*, infrastructure is 'the basic physical and organisational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise' [94] and illustrates the definition as 'the social and economic infrastructure of a country'; thus, it includes organisational systems in the concept. In this dissertation, the term *infrastructure* is used in a broad sense, as it is in the definition by *Lexico*, that is, including organisational improvements.

More generally, any infrastructure involves the following main business sectors: (i) planning, (ii) design, (iii) finance, (iv) procurement, (v) deployment, (vi) operation, (vii) maintenance, (viii) commercialisation, (ix) service delivery, (x) dismantling, and (xi) waste management. In this dissertation, the term *model* is used in a broad sense, from planning to service delivery, and includes all the aspects related to governance, unless otherwise indicated. The terms *development*, *management*, and *governance* are also used in a wide sense. That is, they are not limited to a technical and narrow interpretation but encompass at least the social dimension and, usually, the economical and legal dimensions as well.

The rest of the chapter is structured as follows. Section 2.2 provides the necessary background knowledge in the field of network infrastructure, the first topic we addressed in our research. It begins with a general overview and elaborates on the gaps and limitations of the current business models. Then, it examines internet exchange points (IXPs) and CNs as existing successful experiences of network infrastructure sharing. Finally, it reviews the existing literature on cost-sharing mechanisms in network infrastructure. Section 2.3 focuses on cloud computing infrastructure. After a brief review of the typical architecture, it narrows in scope to the existing experiences of collaborative clouds. Section 2.4 is devoted to the commons. It first presents the works of Ostrom,[2] an essential milestone in the study of the commons and for this work, and the work of Frischmann, an author who has further investigated the translation of Ostrom's work into the infrastructure as a whole. After a general taxonomy of the commons, an analysis follows of CNs from the theoretical framework of the commons in general and from that of commons-based peer production, in particular. The section ends with an analysis of the coexistence of the different rights involved in common ownership. Section 2.5 compiles the most relevant applicable legislation. The chapter describes the gaps in knowledge that this dissertation intends to contribute to filling Section 2.6.

The netCommons.eu research project, aimed at studying the diversity in practices and methodologies related to network infrastructures as commons, and our contribution to its first work package in organisational models, have provided a solid base for this chapter, in particular [O8], with an analysis of the state of the art in governance models of network infrastructures as commons and other related aspects.

2.2   Network infrastructure

2.2.1   General overview

Computer networks, also referred as 'data networks', provide an artificial medium for digital communication and access to information across distance and time that complements our natural limited capacities as humans to communicate in the acoustic space, see in a narrow frequency band of visible light, and access information in the physical space around us. Traditionally,

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[2]Elinor Ostrom and Oliver E. Williamson shared the Nobel Prize in 2009 for the analysis of economic governance, the first for the commons, and the second for the boundaries of the firm.
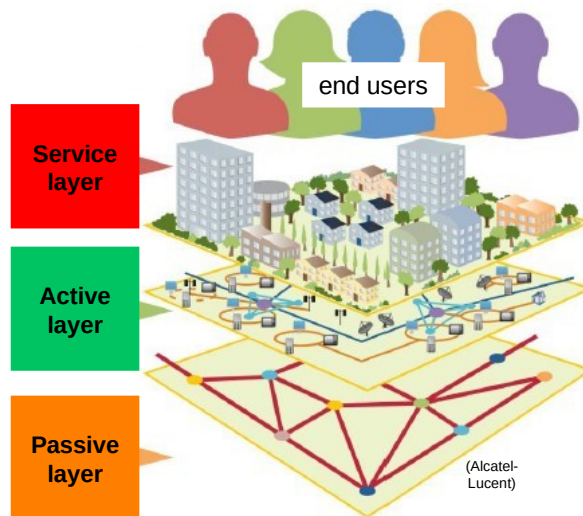
Figure 2.1: Network layers of a FTTH network.

telecom services and access to the Internet were considered an option, a luxury for corporations and for those citizens willing to pay a premium to benefit from these artificial 'superpowers'.

The infrastructure that provided these commercial services was managed by national telecom monopolies and later by telecom incumbents and other commercial (for-profit) operators. In recent times, the growing adoption of data networks as the best (and sometimes the only) option to communicate with many other people and access most information has promoted that access to an essential (sometimes called 'universal') service. This requires the involvement of governments to legislate and regulate various aspects to guarantee public universal access to these privately provided services.

Furthermore, the evolution of services, both private and governmental, from commerce and entertainment to tax-paying and education, has increasingly relied on telecommunication services in recent years, both as a means of reducing service costs and as a means to improve citizen service provision, reducing the time needed to obtain the service and allowing service provision outside normal business hours.

According to the broadband[3] investment guide of the European Commission (EC)[44] and supporting research[49], the structure of a modern network service consists of three interdependent layers: (i) passive infrastructure, (ii) active infrastructure, and (iii) delivery of service, as illustrated in Figure 2.1. In the open systems interconnection (OSI) model[80], passive infrastructure corresponds to Layer 1 (physical), active infrastructure corresponds to Layers 2 (data link) and 3 (network), and the delivery of services includes the remaining layers (from transport to application).

The most typical passive infrastructures are the traditional telephone copper wires, television (TV) coaxial cables, OF, wireless point-to-point or multi-point links, and the corresponding dedicated (licensed) or shared (unlicensed open access) spectrum. Active infrastructure typically comprises diverse data-link protocols matching the associated passive infrastructure. It converges in most cases to an IP network on top and is sometimes also combined with network virtualisation

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[3]The term *broadband* is used to refer to fast data networks, in contrast to slow and narrowband dial-up telephone lines.

techniques. These IP networks can offer a wide range of services, such as interconnection to the global Internet, telephony as Voice over IP (VoIP), and access to media content (such as television, radio, and cinema), and can be accessed by personal client devices or servers, typically through Ethernet cables or WiFi access point (AP).

The deployment and operation of these networks and services require investments that feature large economies of scale in urban areas with many citizens (customers). The concentration of customers in small areas and their grouping in buildings, make it a great business for commercial telecom providers. As the population density decreases, the distance to major cities increases or the economic capacity of customers decreases, and the margin for commercial exploitation decreases or becomes negative. However, there is growing consensus that it is important to provide these services to every citizen, in particular, in remote areas that are generally underserved when compared to more urban areas, and even public services are sometimes provided only remotely. As a result, public administrations have devised policies that promote and aim to ensure a minimum level of service for all citizens independently of their location. These policies range from subsidies to network operators in exchange for offering services in these areas, to public investment in the development of complementary network infrastructures and the definition of public (regulated) prices for key services.

However, in most cases, network infrastructures are under the control of former monopolies, now telecom incumbents. These entities control the offering and have strong lobbying mechanisms in place to influence regulation and discourage competitors. Except for the most developed urban areas, the typical situation is the lack of competition, defined as 'market failure'. The typical market structure is rather disappointing, with a very small set of large telecom providers acting as oligopolies and exercising cartel practices, which justifies public intervention [44]. This has been recognised as a critical challenge by International Telecommunication Union (ITU) in a report [87] that explores and proposes options based on the principles of separation and sharing, typically managed by governments through legislation, regulation, and subsidies. The most visible recommendations are the following:

- Extending access to fibre backbones: open access to bottleneck or essential facilities (such as fibre infrastructures), which encourages the development of multiple providers of any size and scope and promotes investment in a high-capacity infrastructure to unserved or underserved areas;

- Mobile network sharing: equivalent to the previous but applied to the mobile network, applicable to both passive and active elements of the network;

- Spectrum sharing: promotion of the spectrum 'commons', with administrative, licensing, unlicensed bands, and commercial or technical measures (such as dynamic spectrum access or cognitive radio);

- International gateway liberalisation: liberalisation of international gateways, such as access to submarine cable systems, avoiding any anti-competitive control from incumbents;

- Functional separation: also known as operational separation, creating separate business divisions for retail and wholesale that act independently from each other, where a separate wholesale division can supply network access and services to competitors, along with the incumbent, on a non-discriminatory basis;

- Structural separation: a last resort that requires an operator to separate its network infrastructure from its unit offering services using this infrastructure, also known as
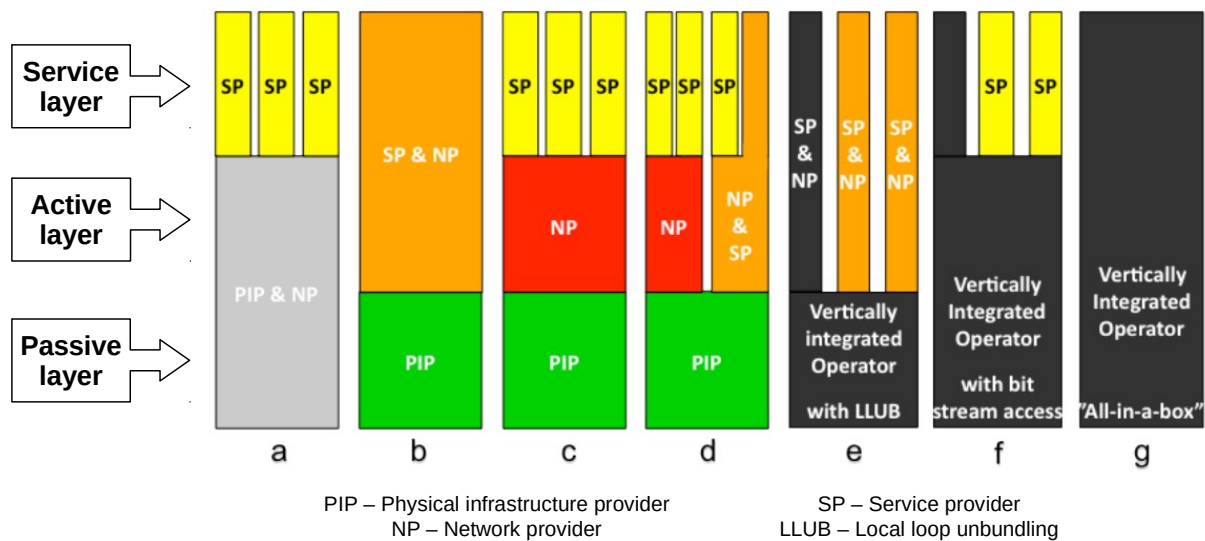
Figure 2.2: Different division and separation across service layers [49].

'ownership unbundling' or 'divestiture', and it means that all of the network elements are placed in a separate legal entity;

- Cost-sharing and user-sharing: sharing of a computer, mobile, Internet link, or content across a group of people, such as schools, libraries, public-access telecentres, or shops.

Each of these measures can help develop new business models that can make a great difference in the expansion of the coverage and usage of data networks for the socio-economic benefit of every citizen in the world [79], and community networks can benefit from changes in these directions.

In Europe, in response to these measures, the EC has introduced the cost reduction directive with measures to reduce the deployment cost of high-speed electronic communication networks (2014/61/EU) [46].

The typical business models of modern data networks follow one of the structural models depicted in Figure 2.2. Nevertheless, in some cases (and countries), functional or structural separation is in place to prevent anti-competitive, discriminatory behaviour by incumbents. The ultimate goal is to promote cooperative cost-sharing schemes to reduce the cost of deploying infrastructures of any kind (telecom-related and others, such as roads, water, and electricity that require expensive civil works) and promote competitive offerings (market) to widen choices and reduce the cost of services to customers.

Overall, the global Internet is in danger of fragmentation [40], the risk of breaking up into loosely coupled islands of connectivity driven by technological developments, government policies, and commercial practices, but is also in danger of consolidation [88], including growing forces of concentration, vertical and horizontal integration, and fewer opportunities for market entry and competition, with trends towards (i) total service environments (the 'one-stop shops'), (ii) network flattening where access networks are increasingly interconnected with less need for international transit, (iii) deep dependencies with an increasing dependency on a small number of private platforms, (iv) the risk of growing societal dependencies on a handful of powerful

economic actors in contrast to the 'no permanent favourites' principle of the Internet, and (v) a growing number of responses to the negative effects – either real or perceived – of concentration and consolidation.

2.2.2   Cases of network infrastructure sharing

2.2.2.1   Open-access networks

According to [166] an open access network (OAN) refers to 'a horizontally layered network architecture in telecommunications and a business model that separates physical access to the network from the delivery of services. In an OAN, the owner or manager of the network does not supply services for the network; separate retail service providers must supply these services. There are two different open-access network models: the two- and three-layer models. In the two-layer OAN model, there is a network owner and operator, and multiple retail service providers deliver services over the network. In the three-layer OAN model, the physical layer – the fibre or wireless infrastructure – is owned by one company. The operations and maintenance of the network and the provision of services are run by a second company, and the retail service providers provide the third layer.'

From the business model perspective 'open access' refers to 'a specialised and focused business model, in which a network infrastructure provider limits its activities to a fixed set of value layers to avoid conflicts of interest. The network infrastructure provider creates an open market and a platform for internet service providers (ISPs) to add value. The open-access provider remains neutral and independent and offers standard and transparent pricing to ISPs on its network. It never competes with the ISPs' [166]. In addition, OANs are referred to as wholesale-only networks.

In Stockholm, the public company Stokab [48] established in 1994 was one of the earliest wholesale-only initiatives. Through its OF network, it now serves more than 100 operators and has key socio-economic influence in the region [50]. In Reykjavik, *Gagnaveita Reykjavíkur* (Reykjavik Fibre Network)[4] is already offering 100% fibre to the home (FTTH) connectivity in the city of Reykjavik and in every urban home in neighbouring towns. CityFibre[5] is deploying OF in over 50 cities in the United Kingdom to reach 5 million homes. Deutsche Glasfaser[6] in Germany, and Open Fiber[7] in Italy, are other successful OF OANs in Europe.

In Mexico, Altán Redes[8] is a state PPP running *Red Compartida*, a wireless 4G Long-term evolution (LTE) broadband network with low latency and high-speed features, including indoor connectivity, offering services to mobile operators. With coverage of 32% of the population, it aims to reach 92% by 2024.

2.2.2.2   Internet exchange points

According to [165] 'An IXP is the physical infrastructure through which ISPs and content delivery networks (CDNs) exchange internet traffic between their networks. In addition, IXPs reduce the portion of traffic of an ISP that must be delivered via their upstream transit providers, thereby

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[4]http://www.reykjavikfibrenetwork.is
[5]https://www.cityfibre.com/
[6]https://www.deutsche-glasfaser.de/
[7]https://openfiber.it/en
[8]https://www.altanredes.com/

reducing the average per-bit delivery cost of their service. Furthermore, the increased number of paths available through the IXP improves routing efficiency and fault-tolerance. In addition, IXPs exhibit the characteristics of what economists call the network effect.'

For Internet Society (ISOC), IXPs are 'a key part of the Internet ecosystem and represent a vital way to increase the affordability and quality of connectivity in local communities.' According to their view, IXPs fall roughly into five categories: not-for-profit organisations, associations of ISPs, operator-neutral for-profit companies, universities or governmental agencies, or informal associations of networks.

Among the most relevant examples, the Brazil Internet Exchange (IX.br) accounts for almost 2,400 members and an average throughput of 4.4 Tbit/s and 31 IXPs. The most important are located in São Paulo with a traffic peak of over 5 Tbit/s and in Rio de Janeiro with 1 Tbit/s. The Deutscher Commercial Internet Exchange (DE-CIX), with peak traffic at a maximum throughput of more than 6.7 Tbit/s, has 870 members in 13 IXPs in 9 countries around the world. The Amsterdam Internet Exchange (AMS-IX) and the London Internet Exchange (LINX) also account for over 800 members each.[9]

2.2.2.3 Community networks

Community networks (CNs) are bottom-up initiatives aimed at building network infrastructure by pooling resources and collectively managing them. The coverage of underserved areas and the fight against the digital divide are the most frequent driving factors for their deployment, although contributors often mention doing things for experimentation or fun or to contribute to the development of a new telecommunications model *per se* as alternative motives.

The employed technologies vary significantly, ranging from very low-cost, off-the-shelf wireless WiFi) routers to expensive OF equipment [8]. The models of participation, organisation, and funding vary broadly across these networks. For example, some networks are freely accessible, whereas others are run as cooperatives or are managed by federations of microISPs. A few examples include Broadband for Rural North (B4RN) in Lancashire, United Kingdom, and the Nepal Wireless Networking Project (NWNP) in Nepal, which are networks built in response to the lack of coverage of conventional operators. B4RN deploys and operates OF in a cooperative way. NWNP [145] is a social enterprise that uses wireless technology to provide Internet access, electronic commerce, education, telemedicine, and environmental and agricultural services to a number of remote villages. The French Data Network Federation (FFDN) is a federation of French do-it-yourself ISPs comprising Digital subscriber line (DSL) resellers, wireless internet service providers (WISPs), collocation centres, and the like. HUBS is a not-for-profit transit provider whose members are the CNs that it serves. The HSLnet in the Netherlands or several members of the INCA association in the United Kingdom are examples of cooperative OF networks.[10]

Other representative examples are Guifi.net in Catalonia, Freifunk (FF) in Germany, the Athens Wireless Metropolitan Network (AWMN) in the Attica region of Greece, FunkFeuer

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[9]IX.br: https://ix.br, DE-CIX: https://www.de-cix.net/, AMS-IX: https://www.ams-ix.net/, and LINX: https://www.linx.net/.

[10]B4RN: https://b4rn.org.uk/, NWNP: http://www.nepalwireless.net/, FFDN: https://www.ffdn.org/en, HUBS[11], and HSLnet: https://www.hslnet.nl/

(0xFF) in Austria, and Ninux.org in Italy.[12] All of them include thousands of links, mostly wireless,[13] but gradually also integrating OF and optical wireless links.

In general, CNs have already been studied from several angles [O3, 99, 150, 12], and in particular, Guifi.net has been studied from the structural [30, 154, 102], technological [O2, 101, 11], and organisational [P2, 96] points of view. The results from the netCommons.eu project, including a survey of CNs in Europe and worldwide [O8], have been used in this dissertation for comparison with Guifi.net, together with [125].

2.2.3   Cost-sharing in network infrastructure

Sharing or working together leads to the problem of how to divide the joint costs and cost savings among participants. As [146] stated, no single absolutely best set of criteria exists, but diverse policies are aimed at treating every participant in equivalent terms and to be fair, impartial, and just without favouring or discriminating against any party. The policy choice depends on a number of factors, including strategic aspects of cost allocation situations and participant preferences.

The 95-percentile method [39], which is billing based on the 95th percentile of traffic volumes sampled over five-minute intervals (also known as burstable billing) [160], is the most standard measure for billing traffic in ISPs and transit providers. It is an indicator of the network usage used for dimensioning the network infrastructure. The Shapley value [139] is an established method to fairly distribute gains and costs among several actors working in coalition. [143, 108] uses the Shapley value to compute the fair contribution of each flow to the 95th percentile price of interconnected links. As noted in [142], internet transit is the highest cost for an ISP, and aggregating transit costs and group buying (*tuángòu*) decrease the cost due to the effect of economies of scale of typical sub-additive pricing and burstable billing because not all ISPs transit their peak traffic in the same period.

There are many experiences of cost-sharing in IXPs [60] and community networks, such as B4RN [6], Guifi.net [P2, P3], or RemIX [O5], to achieve quality and affordability of backhaul connectivity in remote and underserved regions, therefore ensuring the autonomy and sustainability of small ISPs. In [P3], we examined some aspects related to last-mile economics based on the monthly records of four WiFi and optical fibre deployments of the two previous years. However, beyond the case of Guifi.net, these cooperative operators have limited or incomplete traffic and economic log data, little formal and detailed cost analyses and, therefore, a lack of cost-fairness optimisation. Beyond this, commercial network providers consider the detailed traffic and pricing data to be commercially sensitive and confidential and, therefore, inaccessible for analysis.

2.3   Cloud computing infrastructure

The cloud computing field is similar in diversity and complexity to the field of computer networks. Given that we consider that the degree of complexity has already been illustrated in the previous

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[12]Guifi.net: https://guifi.net/, FF: https://freifunk.net/, AWMN: http://www.awmn.net/, and 0xFF: https://www.funkfeuer.at/

[13]The term *wireless* was broadly used to refer to this type of community network, so that many of these networks are referred to in the literature as wireless community networks (WCNs) because, originally, WiFi technologies were the only ones cheap enough and not subject to licensing to enable their use in non-commercial developments. Nevertheless, it is preferred to avoid the term in order to decouple the concept of the community network from a particular technology choice.

section and that many general concepts and approaches are shared between fields, we believe that, in this case, the following quotes suffice to introduce the necessary general background of cloud computing and why we examine community clouds. According to the *Encyclopedia of Cloud Computing*, community clouds are 'cloud systems designed to address the needs of a community.'[110] 'Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model is composed of [...] three service models'[117]: software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS). 'In the SaaS model, an application is hosted by a cloud vendor and delivered as a service to users, primarily via the Internet or a dedicated network. [...] In the PaaS model, the platform and tools for application development and middleware systems are hosted by a vendor and offered to application developers, allowing them simply to code and deploy without directly interacting with the underlying infrastructure. [...] In an IaaS cloud, raw computer infrastructure, such as servers, CPU, storage, network equipment, and datacenter facilities, are delivered as a service on demand. Rather than purchasing these resources, clients get them as a fully outsourced service for the duration that they need them.'[110]

Given the growth of Cloud computing, 'Cloud Computing is rising fast, with its data centres growing at an unprecedented rate. However, this has come with concerns over privacy, efficiency at the expense of resilience, and environmental sustainability, because of the dependence on Cloud vendors such as Google, Amazon and Microsoft.'[104] Several alternative models have been proposed in response. Many of them, 'utilising networked personal computers for liberation from the centralised vendor model', including 'Community Cloud Computing (C3).'

2.3.1 Community clouds, infrastructure sharing in cloud computing

In terms of cloud computing paradigms, fog[24] and edge computing[61] have been proposed to enable a new type of cloud service at the network edge, combining an edge cloud infrastructure with that in large data centres. Fog computing migrates cloud computing to the edge of the network, where, through edge networks, more decentralised services are expected to replace centralised cloud services[153]. Edge cloud computing is well suited to performing local data processing for the internet of things (IoT)[140]. From the peer-to-peer (P2P) cloud computing perspective[61], the users can be in the loop and participate in providing edge cloud computing services. Our approach shares the focus on decentralised infrastructure and services.

A community cloud (CC), in general, is a cloud deployment model in which a cloud infrastructure is built and provisioned for exclusive use by a specific community of consumers with shared concerns and interests, owned and managed by the community, by a third party, or a combination thereof[106]. Different examples of CCs are the ExoGENI distributed networked infrastructure for experimentation and computational tasks, the EGI federation of 350 resource providers offering computing, storage, and data infrastructure, and ELIXIR, a European intergovernmental organisation that brings together life science resources including databases, software, and computing tools for researchers.[14]

Cloud software, service, and business models abound. There are proprietary remote public cloud solutions offered by the major players[95], closed-source CC solutions, and full-stack open-source products in the market, such as OpenStack or OpenNebula, which are compared

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[14]ExoGENI: `http://www.exogeni.net/`, EGI: `https://www.egi.eu/`, and ELIXIR: `https://www.elixir-europe.org/`.

in [157], that are intended for rack or data-centre class computing clusters. These solutions are being used in several application areas, such as the financial, governmental, and health sectors, fulfilling community-specific requirements (e.g. security, performance, and local content) [167, 167]. Considering the consistency, availability, and partition tolerance (CAP) theorem [25], decentralisation means (i) local availability because the network may be unreliable, (ii) eventual consistency because the data may not propagate synchronously, and (iii) partition tolerance, such as geo-replicated systems in large networks, which tend to suffer from network partitions. Therefore, software tools come with assumptions about the centralisation of the underlying cloud computing and network infrastructure that may not apply in a community environment. To circumvent the limitations imposed by these assumptions, we developed a model for managing and aggregating cloud computing resources in decentralised networks. We envisaged that the centralised stacks will interoperate and be federated to our software stack through a public application programming interfaces (APIs) as hybrid clouds [106] do, combining the capabilities of in-house (private) and external (public) clouds, and we designed the model accordingly.

Regarding user-oriented applications, a wide range exists of free software content management systems (CMS) [118], file sharing [97, 63], and many other web tools that are useful in a CC. However each requires a specific operating system environment, installation, and configuration, so a single server host may not fit all. The need for security and resource isolation resulted in the idea of process containers [13] that, years later, translated into Linux containers, an operating-system-level virtualisation method for running multiple isolated Linux systems (containers) on a control host. This has evolved into products like Docker [107] or cluster managers, such as Kubernetes [21], that also ease application and service management and even orchestration among complementary services.

In our work, we started with containerised services. Later, we added support for Docker images and Docker Compose to automate the deployment of applications in separate containers and to benefit from the wide range of pre-packaged Docker containers available that can be included and run as applications in our CCs. We found limitations in the performance isolation required to avoid resource interference across containers to be able to ensure the quality of the provided services. We developed solutions [123, 122], but these are not yet integrated.

Feasibility, the possibility of being made, has several levels of realisation. From a Technology readiness level (TRL) [45] perspective, it relates to the results from the experimentally driven research [62] in terms of the evaluation of technical alternatives, assessment of performance and cost, and optimisation of diverse aspects of the software system. Therefore, in terms of TRL, we target the assessment of integration and validation (TRL 5), field demonstration (TRL 6), prototyping (TRL 7), and even complete system qualification (TRL 8) in some respects, if the system is adopted by a community of users. From a market pull perspective of Demand-readiness level (DRL) [159], we seek a mature understanding of local demands and governance issues to allow a matching point between technology push and demand pull. Our aim is to reach an 'adapted answer to the expressed need' (DRL 9). The results of this research can reduce start-up costs and help lower the risks for successful related initiatives. That connects with the concept of sustainability, the ability to maintain an initiative after feasibility is proven.

Sustainability for CCs refers to the deployment of infrastructure and services with long-term availability and production usage, governed and used by a community. To be sustainable, edge cloud services must be able to generate a positive socio-economic balance for their participants [69, 70]. Enabling economic activity through commercial providers within commons infrastructures, such as in Guifi.net, has been identified as a key element for enabling its transformation into a

consolidated sustainable infrastructure [P2]. Commercial providers addressing such environments need to face different risks in providing service-level agreements (SLAs) [119]. However, edge cloud services open new business opportunities to better serve citizens with tailored and local services. These services can be related to local data processing, which may attract commercial providers. Such processing of data streams by devices at the edge was suggested in [35], with privacy as an important reason for providing local services [74]. The application scenarios for such services are diverse. Some examples are image processing [121] or sensor data processing [168]. The quality of service needs of these streams will require solutions to cope, for instance, with busy streams or real-time constraints [148, 147].

2.4 The commons

A CPR or *commons* is 'a natural or human-made resource from which it is difficult to exclude or limit users once the resource is provided by nature or produced by humans.' [114] 'One person's consumption of resource units removes those units from what is available to others. Thus, the trees or fish harvested by one user are no longer available for others. The difficulty of excluding beneficiaries is a characteristic that is shared with public goods, while the subtractability of the resource units is shared with private goods.' [115]

In fact, *exclusion*, access prevention, and *rivalry* or *subtractability*, where consumption by one consumer prevents or reduces (subtracts) consumption by others ('when the benefits consumed by one subtract from those available to others' [114]), distinguishes CPRs from other forms of goods or resource systems. While excludable goods can be either non-rivalrous (toll or club goods), such as cinemas or satellite TV, or rivalrous (private goods), such as cars, food, or parking spaces, non-excludable goods can be either non-rivalrous (public goods), such as air or radio broadcasts, or rivalrous, which corresponds to goods that can be managed as CPRs. In this dissertation, a CPR is a system of (artificial) resources collectively built and managed, unless otherwise indicated.

2.4.1 Common-pool resources

The 'tragedy of the commons' problem [72] has been used since the 1970s to support the notion that shared resources must be either taken over by the state or privatised to be sustainable. However, Ostrom noted that some CPRs had lasted for centuries. After the study of some of them, in [113] Ostrom identified eight 'design principles' of stable local CPR management and in [116] outlined five basic requirements for achieving adaptive governance. After analysing 91 additional cases, Cox [34] found that Ostrom's eight principals were well supported.

According to Bevir, 'Governance refers, therefore, to all processes of governing, whether undertaken by a government, market, or network, whether over a family, tribe, formal or informal organisation, or territory, and whether through laws, norms, power or language. Governance differs from government in that it focuses less on the state and its institutions and more on social practices and activities.' [22]

Frischmann explored the applicability of *commons*, 'a resource management principle by which a resource is shared within a community on non-discriminatory terms in the *infrastructure*, a particular set of resources defined in terms of the manner in which they create value' [55] mainly from an economic point of view and focusing predominantly on demand-side issues because he argued that infrastructure policy is heavily influenced by economics and a supply-side approach. For him, 'when reduced to a public good provisioning problem, the functional

role of infrastructure is lost.' According to his view [56], infrastructures governed as commons generate positive externalities (positive effects) that benefit society by creating opportunities and facilitating many other socio-economic activities, although their benefits are sometimes hard to measure. An infrastructure that is cooperatively managed and sustained leaves a greater margin for added-value activities compared to commercial network infrastructures developed competitively. Examples of infrastructure commons are the Internet, with issues about congestion and network neutrality [55] or Internet/spectrum commons [18]. A first study of CNs as commons can be found in [P2]. Chapter 7 built upon that study, covering CCs and the value of commons in the different cloud service layers.

The commons can be fragmented into different subtypes. Ostrom developed her framework based on the analysis of case studies from local, mostly environmental, commons and extended her study with cases from knowledge commons and cultural and digital commons [75] composed by resources, communities, legal rules, interactions (commoning), outcomes, and evaluation. Scholars further extended this work in an attempt to systematise knowledge commons with another collective volume [57], including infrastructure commons with the example of internet congestion and network neutrality [55] and Internet/spectrum commons [18]. These adapted versions of Ostrom's framework examine the nature of the resource; the community; the criteria of success, failure, and vulnerability; and finally, the political purpose, such as the importance of the commons for democracy and freedom.

Finally, the study of digital commons, with the major examples of free software and Wikipedia, gave rise to commons-based peer production (CBPP) [20]. The study of CPBB develops a political economy dimension to the study of a type of commons by shedding light on the purpose and the underlying political values carried by commons as a sustainable alternative to the production by the state or the market only. The construction of such a common infrastructure requires policy action [19].

The concept of commons has been applied and extended to many domains, deviating outside the natural resource sectors. 'Before 1995, few thinkers saw the connection. It was around that time that we began to see a new usage of the concept of the *commons*. There appears to have been a spontaneous explosion of *aha* moments when multiple users on the Internet one day sat up, probably in frustration, and said, *Hey! This is a shared resource!* People started to notice behaviours and conditions on the web-congestion, free riding, conflict, overuse, and *pollution* – that had long been identified with other types of commons. They began to notice that this new conduit of distributing information was neither a private nor strictly a public resource.' [75] There are many new commons [76] sectors beyond the traditional and beyond the scope of our work, with the knowledge commons being the most relevant to our work, which includes some aspects of the Internet [77] (although others disagree [124], qualified the Internet as a club good, in particular as a set of *nested clubs*) and infrastructure commons that include the Internet infrastructure.

Commons, in the scope of our work, may be classified as follows:

Natural commons are from nature, and the emphasis is in how these commons are self-managed sustainably for the benefit of a community and its preservation.

Immaterial commons of knowledge and code follows similar principles but requires a model for its collaborative production and collective property, which Benkler [17] called *Commons-based peer production*. In this model, information and knowledge lie close to a non-rival resource, although the cost of finding it (requiring search engines) and accessing it (requiring

content servers) consumes rival resources that can be congested (energy and digital devices, such as clients or servers). Moreover, knowledge and code do not constitute an exclusion barrier in developed societies but generate exclusion in developing societies (cost of access and availability of access infrastructure, such as servers, networks, client devices, energy, etc.)

Artificial material commons are complex systems where peer production is applied to build some specific, traditionally material, resource pool (or system) that is critical for a community as infrastructure or as a means for development. There is no clear distinction between the natural commons and artificial material commons, but there is a continuous transition whereby the value of the commons is increasingly not related to the natural resource managed but to the complex engineering manipulation of it.

Traditional examples of artificial material commons are the woods and lumber production and commerce in north-eastern Italy, traditionally managed by the *'Magnifiche comunità'* (magnificent community) [98]. In modern times, a good example of artificial material commons is the pool of digital devices deliberately shared by a community that is willing to use, reuse, repair, refurbish, and recycle [53] them for the sake of a sustainable circular economy. Community network and community cloud infrastructures are also examples that are the focus of this dissertation.

2.4.2   Network infrastructures

In the past, network infrastructures were considered club goods (excludable and virtually non-rivalrous as a commercial service) that were provided by for-profit ISPs to those fortunate enough to be in coverage areas and who were willing to pay for the service fee. Thus, CNs are a social response to the wide recognition of connectivity as a basic human right and, therefore, the opportunity to connect people via network infrastructures has become non-excludable.

Modern network infrastructures are based on the packet-switching principle that provides a mode of data transmission in which a message is broken into a number of parts (packets) and is transmitted via a medium that may be shared by multiple simultaneous communication sessions (multiplexing). That results in a multiple-access scheme using switches and routers, where packets are transferred or queued, resulting in variable latency and limited throughput and is subject to network congestion if traffic gets close to its capacity. Despite being conceptually non-rivalrous, its practical implementation in a community of people, information, and network services requires careful capacity planning to cope with the demand and finite capacity to provide good quality service and to avoid network congestion that degrades the effectiveness of the network.

Under these assumptions, real (production) network infrastructures should be considered rivalrous (networks have limited capacity, and every possible packet in a network can only transfer a specific amount of data, subtracting from its capacity, and its presence in the network delays other packets). Without careful design and planning, network infrastructure can become imbalanced, congested, and exhausted as a resource system that produces connectivity as a consumable. In typical networks, this cost is subject to traffic loads and how they compare to the network capacity (over-provisioning is a desirable and common practice in all networks, but too much of it is not economically efficient due to cost). Additional traffic has a cost and an effect on the rest of the traffic.

Networks typically perform some kind of traffic engineering to operate efficiently (and manage rivalry), and network owners must monitor the characteristics and volume of traffic to plan capacity and invest in its capacity when congestion starts to degrade the quality of service perceived by its users. Many Internet links tend to saturate from time to time. As network paths involve several link hops, some degree of congestion is nearly always present. In fact, Van Jacobson in the late 1980s faced the problem of Internet congestion and, together with the research community, produced several mechanisms for congestion control [92] in the most frequent transport protocol (TCP). Network users can generate large and virtually unlimited amounts of network traffic (e.g. each home user downloading content on a 1 Gbit/s optical fibre link) typically just limited by the speed and cost of their link (and not by the cost of the data traffic). Internet peering disputes between 'eyeball' ISPs, transit ISPs, or content ISPs, are not an exception [10], and typically, capacity upgrades in network links result in elastic increases of traffic expanding and adapting very quickly to the new capacity of the link. The same principles apply to (cloud or publicly shared) computing and storage resources.

Therefore, we can consider that production network and cloud computing infrastructures are subject to congestion; thus, connectivity and computing is considered rivalrous. While commercial ISPs try to maximise benefits and minimise company risks in a competitive market (where an excludable resource is sold at the highest possible market price), a goal for CNs is to maximise social inclusion in terms of the number of participants, coverage, and cost, using a cooperative model where risks, costs, and management are shared among the participants. This results in a network infrastructure that produces connectivity as close as possible to the ideal of non-exclusion and collective property.

2.4.3   Community networks as common-pool resources

The theoretical framework of the commons and that of commons-based peer production, in particular, serve as references for the development, management, and scientific analysis of CNs. The fundamental principles of most CNs, defined from the start to be fully inclusive, revolve around the openness of access to the infrastructure (usage), and the openness of participation (planning, design, finance, construction, operation, governance, etc.) in the development of the infrastructure and its community. When these fundamental principles are applied to infrastructure, they often result in networks that are *collective goods*, *socially produced*, and built and managed as CPR.

Thus, a CN could be viewed as a *collective good* or a peer property, in which participants contribute and share their efforts and goods (routers, links, and servers) to build a computer network. The peer property emerges under the operation of different internet protocols provided that the community rules, such as community licences, are respected by all participants. The development of a CN is an instance of both *social* and peer production. The participants work cooperatively at the local scale to deploy network islands and at the global scale to share knowledge and coordinate actions to ensure the interoperability of the infrastructure that is deployed at a local scale.

According to Ostrom, CPRs typically consists of a core resource that provides a limited quantity of extractable fringe units. In the case of Guifi.net, the core resource is the network, which is nurtured by the in-kind or monetary contributions from the beneficiaries, and the fringe unit is the bandwidth they obtain. Resilient CPRs require effective governance institutions to keep a long-term direction and deal with the struggle to handle many actors and changes in a complex system. The long-term direction is defined as *sustainability* in remaining productive or

operational under the fundamental principles of the CPR, and the short-term goal is defined as *adaptability* in reacting and changing.

According to Frischmann [56], public goods and non-market goods, as network infrastructures, generate positive externalities (positive effects) that benefit society as a whole by creating opportunities and facilitating many other socio-economic activities. Therefore, open network infrastructures have great social and economic value, although their benefits are sometimes hard to measure. An infrastructure that is cooperatively managed and sustained can leave a greater margin of added-value activities than a commercial network infrastructure developed competitively, making a great difference in developing regions or communities.

2.4.4 The bundle of rights in commons

Rooted in the seminal work in [131][15] and adapted to CN in general in [111], it is essential to clearly identify the interests and specific tasks of the stakeholders and the relevant conflicts of interest with respect to a common property. As the community managing a commons can be divided into various sub-communities, depending on their role, the bundle of rights becomes a useful additional analytical grid to further break down these tasks. [131] says that the rules of each community can specify the requirements the participants must meet to exercise each right. The bundle of rights distinguishes the following:

a) Access (at the operational level[16]): The right to enter and connect to the network (contribute resources and link up).[17]

b) Withdrawal (at the operational level): The right to 'extract resources' from the system (obtain connectivity).[18]

c) Management (at the collective-choice level[19]): The right and authority to determine the rules to use the connectivity (withdrawal) and structure of a resource (e.g. zones).[20]

d) Exclusion (at the collective-choice level): The right to determine who will have access and how this right can be transferred.

e) Alienation (at the collective-choice level): The right to transfer the right to manage or exclude others (e.g. by participants transferring decision-making rights over a specific network infrastructure involved in a commons to others).[21]

The commons implies common-property resources, and 'within a single CPR situation a conglomeration of *de jure* and *de facto* property rights may exist which overlap, complement, or even conflict with one another.' [131] The property-right schema ranges from authorised user[22]

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[15]Aiming to explain outcomes achieved by joint users of a common-pool resource, particularly in-shore fisheries.

[16]Operational level: Exercising a right.

[17]The right to enter a defined physical property in [131].

[18]The right to obtain the 'products' of a resource (e.g. catch fish, appropriate water, etc.) in [131].

[19]Collective-choice level: Participating in the definition of future rights to be exercised.

[20]The right to regulate internal use patterns and transform the resource by making improvements in [131].

[21]The right to sell or lease either or both of the above collective-choice rights in [131].

[22]'Authorised users lack the authority to devise their own harvesting rules or to exclude others from gaining access to fishing grounds' in [131].

(only access *a* and withdrawal *b*), to claimant[23] (from *a* to *c*), to proprietor[24] (from *a* to *d*), and to owner[25] (all).

Related to the case of forests, but applicable to other commons, [105] defined common property as 'shared private property and should be considered alongside business partnerships, joint-stock corporations, and cooperatives' and the collective nature of a resource system: 'common-property regimes are a way of privatising the rights to something without dividing it into pieces'. Communal forests can be built from private pieces of land, managed in commons. Similarly, network infrastructure can be built from private devices, bought and installed by diverse participants, but incorporated into a network managed in commons. This arrangement can be formal (*de jure* donation or usufruct[26]) or informal (de facto), according to the rules of the community.

In the case of a CPR CN, people who accept the individual participation principles[27] and link up[28] to the network are given access rights and withdrawal rights (consumption of connectivity). The enrolment process is usually implemented and automated by a software service to register, enrol, and configure the new resource unit (link and router) and register and enrol a new participant. By implicitly or explicitly accepting the participation rules (licence), the collective governance principles according to the rules of the community, these people may have some degree of collective-choice rights: the right to participate in the governance of the infrastructure (management rights). As communities become large and complex, collective-choice rights tend to become concentrated in (informal or formal) groups of the most committed and experienced participants. As far as we know, the right of alienation (in collective-choice and, therefore, the consideration of ownership of the whole or a portion) is not transferable in the CNs we studied or in the literature. In a few cases, such as B4RN [O1], the CN issues shares are purchased by community members in exchange for an economic or volunteer effort, but the holders are not considered owners or co-owners, as these cannot be transferred to other participants.[29]

2.5   Legal basis

The European legal framework for CNs covers four main topics that are key to the activity of CNs: civil liability, data protection law, data retention law, and telecommunication law. This was the subject of study in the netCommons.eu project, and the results reported in [64]. For our case of study, the Guifi.net CN, the main legal documents (regulations, directives, laws, decrees) that relate to the deployment and operation of the network (telecommunications) infrastructure and services, as well as commons and related legal entities, at present, are as follows.

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[23]'With the right of management, claimants have the collective-choice authority to devise operational-level rights of withdrawal' in [131].

[24]'Proprietors authorise who may access resources and how resources may be used; however, they do not have the right to alienate either of these collective-choice rights' in [131].

[25]'The fishers may transfer their rights of management and exclusion over their particular spot to other fishers' in [131], but ownership refers to these rights, and can be *de jure* (given lawful recognition by formal, legal instrumentalities) or *de facto* (originate among resource users).

[26]*Usus* (use) is the right to a thing possessed, directly and without altering it, and *fructus* (fruit) is the right to derive profit from a thing possessed.

[27]In some communities, these are formalised as a community participation licence that can be legally binding.

[28]Expanding the infrastructure commons by adding network nodes (routers) and links in new locations.

[29]B4RN says that 'shares cannot be sold or given to anyone else, they can only be sold back to B4RN', nor the organisation and its commons: 'Being a "community benefit society" means that the assets are locked down and cannot be sold off to an outside interest in the way that a conventional company's could. Therefore, the time, effort, and money that the community invests to obtain high-quality broadband will be preserved for the benefit of the community and future generations, not purely to make profits for the shareholders.'

- European Union
  - General context: The liberalisation of goods and services is at the heart of the European Union (EU) legislation
    * Treaty on the Functioning of the European Union, Title VII: Common Rules on Competition, Taxation and Approximation of Laws.
  - Telecommunications
    * Telecom package Directives: 2002/21/EC (Framework), 2002/19/EC (Access), 2002/20/EC (Authorisation), and 2002/22/EC (Universal Service)
    * Further directives, such as cost reduction directive (2014/61/EC), which imposes infrastructure sharing.

- Spain
  - Telecommunications liberalisation
    * General telecommunications laws: *Ley 9/2014.*
    * Transposition of further EU regulation.
  - Common goods (*Bienes comunales* in Spanish)
    * Royal Decree 1372/1986, of 13 June, approving the Regulation on Assets of Local Entities *(Real Decreto 1372/1986, de 13 de junio, por el que se aprueba el Reglamento de Bienes de las Entidades Locales).*

- Catalonia
  - No competences in telecoms
  - Common goods (*Béns comunals* in Catalan)
    * Law 4/2008, Civil Code of Catalonia, Fifth Book, Title IV, Chapter III - partial use rights *(Llei 4/2008, Codi Civil de Catalunya, Llibre cinquè, Títol IV, Capítol III -drets d'aprofitament parcial).*
    * Decree 336/1988 of 17 October 1988 approving the Regulations on the patrimony of local authorities *(Decret 336/1988, de 17 d'octubre, pel qual s'aprova el Reglament del patrimoni dels ens locals).*
  - Foundations
    * Law 4/2008, Civil Code of Catalonia, Third Book, regarding legal persons *(Llei 4/2008, Codi civil de Catalunya, Llibre tercer, relatiu a les persones jurídiques).*
    * Law 21/2014, on the protectorate of foundations and verification of the activity of associations declared to be of public interest *(Llei 21/2014, del protectorat de les fundacions i de verificació de l'activitat de les associacions declarades d'utilitat pública).*

In the near future:

- European regulation: Electronic communications code (which will need to be transposed into national law by 21 December 2020) and the Body of European Regulators of Electronic Communications (BEREC) regulation (both entered into force 20 December 2018).[30]

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[30]https://ec.europa.eu/digital-single-market/en/telecoms

The EU admits that the market is imperfect and, thus, imposed the creation of the National regulatory authorities (NRA). The Spanish NRA is the '*Comisión Nacional de los Mercados y la Competencia (CNMC)*'.[31]

2.6   Filling gaps

In the rest of this dissertation, we will focus on shared network (Chapters 3 to 6) and cloud computing (Chapter 7) infrastructures governed (That is, planned, financed, developed, extended, managed, maintained, operated, owned, used) as commons that deliver abundant and cost-effective connectivity and cloud computing resources to the participants and on the applicability of the lessons learned to other domains.

From the scientific perspective, our results extend the production of Ostrom. The first main contribution in this regard is that we report on a CPR case – Guifi.net – that has some notable differences compared to those studied by her and the subsequent literature. Our CPR is an 'intrinsically' artificial commons, while most of the existing literature on case studies has focused on natural commons, like fisheries or timberlands, on 'moderately' artificial commons, such as irrigation systems or arable lands, or on immaterial commons, such as code or knowledge. The main challenge of the natural commons is avoiding their depletion, which is an operational problem. The same applies to moderately artificial commons, although they also entail constructional problems to some extent. Conversely, immaterial commons mostly entail constructional problems. However, any of the previous types of commons pose major operational and constructional problems simultaneously, which is the case of the intrinsically artificial commons. Moreover, most of the commons in Ostrom's studies do not exceed the tens of thousands of end users and the dozens of participants directly involved, while our case has over a 100,000 beneficiaries and hundreds of participants with very diverse roles and interests. The second relevant contribution in the field of the study of the commons is the confirmation that our case study seamlessly fits Ostrom's design principles and adaptability requirement.

Our results also extend the literature on infrastructure as commons. Although many authors have argued that the commons is a very suitable model for infrastructure development and management, to the best of our knowledge, when it comes to implementation and governance, either they omit these challenges, or the scope of the solutions are limited to public administration interventions. In this regard, we believe that these solutions are more related to remunicipalisation[32] approaches than to collectively managed CPRs. Our results document the success case of a communications network (i.e. an intrinsically artificial infrastructure), which is collectively built and managed, and show that similar arrangements should work for cloud computing, another intrinsically artificial infrastructure. Furthermore, we argue that the two previous cases have the shared attribute of extensibility, and we propose a generic model for deploying and managing infrastructure with this attribute.

In the context of open-access infrastructure, our results contribute to mitigating the main limitation of the model based on the existence of an infrastructure manager (e.g. Stokab in the case of the Stockholm municipal fibre), that is, having a single player in charge of the operation of the whole infrastructure. Based on the Guifi.net experience, in which dozens of participants effectively operate the infrastructure, we propose a model where the infrastructure is collectively operated and where specific players can be immediately replaced by others in case of failure.

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[31]https://www.cnmc.es/ambitos-de-actuacion/telecomunicaciones
[32]The recovery of previously privatised services to municipal authorities.

Finally, from the legal perspective, we show how the Guifi.net community is addressing the challenge of protecting a common good made out of a number of private property assets. The value of the solution, beyond its specific implementation of the solution that is deeply rooted in the legal framework of the project (i.e. the Catalan legislation), is in its underlying model: the combination of a licence describing the CPR and an entity obliged by its bylaws to monitor the CPR. Although, from a general perspective, this is the same model as that of many free software projects, for instance, the GNU General public licence (GPL) and the Free Software Foundation (FSF), the different nature of the protected good (i.e. an immaterial good replicable at no cost vs a usually capital expenditure (CAPEX) intensive good) has serious implications.

Guifi.net – Overview

Preface

This first chapter of the three devoted to Guifi.net provides a general vision of the project and its context. It summarises the underlying principles, the associated business model, and the benefits derived from them in comparison to the private sector model. It also reviews some of the results already achieved in terms of deployed infrastructure, the conditions under which it is made available, and the opportunities for participating in the governance and economic system. The ultimate goal of the chapter is to provide evidence that the Guifi.net case has enough unique and beneficial features to be considered a model on its own and, thus, is worth exploring in further detail.

3.1 Introduction

Guifi.net [67] (pronounced /'gɪfɪ/) is a bottom-up, citizenship-driven technological, social, and economic project aiming at creating a free, open, and neutral telecommunications network based on a commons model. The development of this common-pool infrastructure eases the access to quality, fair-priced telecommunications in general and broadband Internet connections for everybody. Moreover, it generates a model for collaborative economic activity based on proximity and sustainability.

In 2004, Guifi.net was born in Osona, a county in Catalonia, to overcome the lack of broadband Internet access in rural areas by traditional ISPs. There, citizens deployed their own network infrastructure to interconnect different locations (so-called nodes), such as houses, offices, farms, public buildings, and so on. This allowed them to self-provision telecommunications services and Internet access wherever they were needed: at home, at work, in the library, and so on. As of January 2019, Guifi.net accounts for more than 50,000 working nodes. Through an extensive production network of OF and WiFi links, thousands of people satisfy their connectivity necessities on a daily basis.

The Guifi.net project puts in practice a disruptive economic model based on the commons model and the collaborative economy by deploying a CPR network infrastructure and a fair and sustainable economic exploitation model. In September 2019, more than 30 small and medium-sized enterprises (SMEs) operate their services professionally on top of the commons network, and moreover, they do it simultaneously and in coordination with the participating individuals, volunteers, and other organisations. This is possible due to the development of governance rules that define the terms and conditions in which businesses can obtain economic profit out of the exploitation of the Guifi.net network.

In July 2008, the Guifi.net community established the *Fundació Privada per a la Xarxa Oberta, Lliure i Neutral Guifi.net* (Guifi.net foundation for the Free, Open, and Neutral Network) [58]. Its mission is to work in favour of the free, open and neutral network (FONN) by developing and applying a sustainable, collaborative, and commons-based economic model. It is responsible for the development of the required internal norms, the project's oversight, and the operation of the critical services. The Foundation is registered at the Catalan Government foundations registry; thus, it is ruled by Catalan law and, accordingly, it is officially recognised as an NGO. It is a registered telecommunications operator under Spanish regulation and is a member of the Réseaux IP Européens Network Coordination Centre (RIPE-NCC)[1] and Association for Progressive Communications (APC),[2] among other international organisations. In 2015, it received the European Broadband Award from the EC as the best project in the category of innovative models of financing, business, and investment[3].

The rest of the chapter is structured as follows. Section 3.2 lists the principles on which Guifi.net is built on, first in a natural manner, then in a formal manner. Section 3.3 presents the business model, discusses how it links with the principles presented in the previous section, and compares it with the private sector model. The overall benefits of this approach are presented and discussed in Section 3.4. Section 3.5 contextualises the project in the legal framework and discusses its alignment with the main goals of European regulation. Section 3.6 presents some qualitative and quantitative results to illustrate the achievements in terms of the diversity of participants involved in the project as a whole and in its governance and economic system, in particular, as well as the size of the investment and infrastructure put in place. Moreover, it analyses the influence the project has already had as of 2013 through official statistical data. Section 3.7 reviews the main success factors, and Section 3.8 presents the conclusions of the first chapter devoted to Guifi.net.

3.2   Principles

Guifi.net develops a comprehensive ecosystem based on the following driving principles:

- Sharing network infrastructure increases the efficiency (i.e. better performance or wider coverage for the same investment) of the network infrastructure because it stimulates cooperation, preventing duplication of efforts and facilitating economies of scale. This is particularly true in the case of OF because, once in place and operated, it can become a non-rivalrous asset (zero marginal production costs) due to its virtually unlimited bandwidth.

- Network participants have the right to satisfy their connectivity needs on their own or through the procurement of professional services in a fair competition market.

- The existence of a fully developed and healthy economic activity, rooted in good practices, such as a collaborative economy and fair trade, creates a virtuous circle of dependency and reinvestment, which has a very positive effect on the project's sustainability. Vice versa, the presence of a few 'just for profit' participants can ravage the collective production of the whole community.

- The professionals (i.e. individuals or enterprises that deliver services in return for economic remuneration) who work to operate, maintain, or extend the network deserve a fair reward

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[1]https://www.ripe.net/
[2]https://www.apc.org/
[3]https://ec.europa.eu/digital-single-market/en/news/five-projects-got-first-ever-european-broadband-award

for their work, but speculation with network assets or any other harmful practices are
forbidden.

- The network must remain open, free, and neutral.

Or more formally and summarised:

- A single infrastructure is collectively built and managed in a non-discriminatory manner.[4]

- The resulting infrastructure is made available to everyone on equal and non-discretionary
terms for any purpose, including, but not limited to commercial exploitation.

- The participation in the construction and maintenance of the infrastructure is made
according to its usage.

The spirit of sharing, social justice, and freedom is well captured by the two main mottos of
the community:

- In Catalan, '*Xarxa oberta, lliure i neutral*', which is 'neutral, free and open network'.

- In Catalan, '*Una Internet justa per a tothom*', which is 'a fair Internet for everyone'.

3.3 Business model: Infrastructure as a commons

As shown in Figure 3.1, in contrast to other existing business models, in Guifi.net, the infras-
tructure is considered a CPR in which the participants can extend the infrastructure where
necessary and actively participate in the governance system (i.e. to influence policy, actions, and
affairs) and economic system. The network infrastructure growth is through the contribution of
participants who can be fairly compensated for their contributions if other participants use them.

From the foundations, the Guifi.net business model tackles the two drawbacks of the existing
models, namely, restriction of access to infrastructure and of participation in its deployment
and operation. The private model only enables two *domains of direct action*,[5] (i.e. fields
where people take action straightforwardly). The first refers to participation in infrastructure
management, either in the decision-making area or in the economic system. As already discussed
in previous chapters, nowadays, this domain is restricted to very few people, that is, the vast
majority of the population is effectively excluded from it. The second domain is the usage of
the infrastructure provided, which, in this case, is limited by the availability of infrastructure
and by the conditions under which it is provided, deriving exclusions due to unavailability or
affordability (see Section 1.2.1). Conversely, the Guifi.net approach does the following: (i) enables
the additional domain of self-provisioning, (ii) extends the domain of participation to everyone,
(iii) eliminates uncertainty, and (iv) improves the conditions under which the infrastructure is
made available. Consequently, we find a mix of for-profit and nonprofit participants. Moreover,
in addition to the inclusion of a new type of participants, and contrary to traditional business
models, in Guifi.net, all for-profit participants collaborate in the construction and maintenance
of the single shared infrastructure.

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[4]Technically speaking Guifi.net can be seen as a distributed IXP in which peering with the rest of the members
is mandatory.

[5]We use the term *direct* in contrast to indirect procedures, such as the pursuit of legal changes through political
participation.
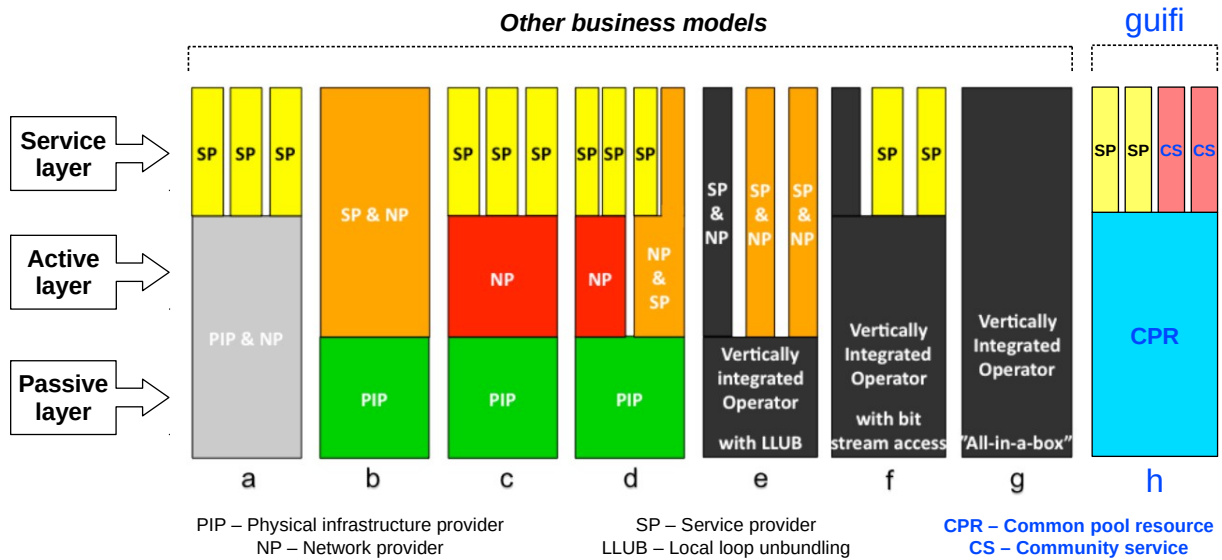
Figure 3.1: Network business model of Guifi.net. Passive and active layers as CPR (based on [49]; see Figure 2.2).

In this approach, the control over the assets is no longer a competitive factor among for-profit participants, that is, network assets cannot be traded on a discretionary basis. Thus, the resulting ecosystem becomes a true *single market*; hence, it comes close to the perfect competition conditions (i.e. the perfect market ideal) because any company in the project has exactly the same opportunities to reach any potential customers. With the removal of the control over infrastructure as a competitive factor, these become essentially limited to the increase in the quality of services or price reduction. Consequently, we can state that the Guifi.net approach not only makes the collaborative and free-market economies compatible but also brings out the best in each. The restriction of the capacity of influence of the private sector to technical and operational matters has also proven key in the sanitisation of the ecosystem as a whole.

Table 3.1 summarises the major differences between the approaches of Guifi.net and the current private sector. As the table shows, significant divergences exist in almost all fields. To begin with, while the main objective of Guifi.net is to seek a social benefit by maximising the extension and use of a shared good that is considered indispensable in the modern world, in the private sector, it can only be assumed that the underlying motivation is the maximisation of the profit of the investors, which has very little or nothing to do with the social benefit.

The conceptions of the productive assets and associated rights, strategies to achieve the goals, and investment periods are also radically different. In the first case, the assets are conceived as a long-enduring CPR. Hence, the strategy relies on the of cooperation among participants and long-term investment. In the second, the productive assets are conceived as private goods that are traded, which are bought and sold on the basis of profit opportunity, and the investment periods are becoming shorter.

The private sector requires constant external regulatory oversight because the purpose of the infrastructure and the objectives of the promoters are not bound. Conversely, in Guifi.net, the economic activity directly depends on the proper operation of the infrastructure and on the number of participants served; thus, the professionals have strong incentives to monitor the CPR. Moreover, the active implication of a number of other stakeholder groups, including the

	Guifi.net	**Private sector**
Objective	Maximisation of the size and use of the shared good (social benefit)	Maximisation of the profit of the investors
Manages	Common-pool resources	Private goods & exclusive rights
Strategy	Optimisation of cooperation	Maximisation of the market-share (become a monopoly, ideally)
Investment	Long-term, collective	Short-term, speculative
Governance	Self-governance, self-regulation	Needs external legislation and regulation
Features	Cost-oriented, inclusive, sustainable, redistributive, fair competition, single market, local economy	Directional pricing, extractive, market failures, speculative, transnational

Table 3.1: Comparison of Guifi.net and private-sector approaches.

Foundation, strengthens the internal oversight substantially, making external intervention nearly unnecessary. Such a number of divergences can only lead to different, if not incompatible, results. While Guifi.net can be described as a cost-oriented, inclusive, sustainable, redistributive, fair competition, and local ecosystem, the globalised private sector is directional in extractive and speculative pricing, and market failures are intrinsic to it.

3.4 Main benefits

Environmental impact

Reduces resource consumption The existence of a single infrastructure minimises the resources required to deliver the same level of service. The reduction is obvious in deployments where a single physical link – a pair of antennas in WiFi or a cable in OF – suffice. In these scenarios, which are the most common by far, especially in OF deployments due to the high performance of this technology, adding additional infrastructure only increases the total bandwidth surplus, which is superfluous but obviously has a negative effect on the environment. Optimisation of surpluses also occurs in network segments where a single link does not suffice. In OF, in most cases, an upgrade of the active equipment of the edges suffices. Thus, extra cable deployments are only needed occasionally. Similarly, in WiFi, in many cases, the upgrade to newer technology is enough. In any case, the management of multiple parallel links is more efficient if it is done in a coordinated fashion than if it is done independently, and these kinds of inefficiencies frequently end up in additional deployed infrastructure.

Supply side

Stimulates cooperation The retailers compete with each other for customers, but they all depend on the same infrastructure. Thus, they all share similar incentives to keep it in pristine condition.

Boosts economies of scale Joint management not only avoids the duplication of infrastructure but also allows the optimisation of human resources and enables their specialisation. Joint procurement is also more efficient and facilitates access to types and prices of offerings hardly attainable otherwise. For instance, the transition from accessing the Internet through retailers to accessing it through the wholesale market brought an extraordinary increase in the quality of service and a substantial reduction in the price.

Eliminates entry barriers In practice, the entry barriers for new professionals have been reduced to close to the capital needed to extend the network to the areas where the economic activity is intended to develop if it does not pre-exist. The backbone network and its associated services, as well as Internet access and several administrative proceedings, are already in place. Thus, in practice, a new company can immediately start trading after joining the community.

Equalises business opportunities Because infrastructure access is no longer a competitive factor, the massive production-cost reduction and access to a market with tens of thousands of potential customers are on equal terms.

Increases competition and diversifies supply As a result of the previous points, there are about 30 participants including companies, cooperatives, self-employed entrepreneurs, and associations offering a variety of options and services, such as Internet connection, tailored support, telephony services, and so on.

Demand side

Delivers a true single market The single shared infrastructure allows almost any customer to consume from any professional, regardless of the geographic location.

Increases the quality of service and reduces prices In close-to-perfect competition conditions, a reduction in production costs always translates into a reduction in the service price.

Prosumers[6]

Enables the do-it-yourself option The mere existence of the do-it-yourself (DIY) option enriches the whole ecosystem because it contributes to increasing competition – if the professionals do not fulfil the customers' expectations, the customers can always self-supply their needs or even bring new providers into the system, and its realisation raises the cultural level.

Social influence

Implements an inclusive and sustainable local economy in which the wealth generated is real and stays local.

Empowers people As any other participatory system, the implementation of Guifi.net increases general awareness, which eventually translates into more a demanding society.

Puts effective means for participation and oversight into practice This increases the chances that the built infrastructure will meet the people's needs.

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[6]A person who produces and consumes a product. Coined by Alvin Toffler in 1980, now it widely used to refer to CBPP.

Integrates internal wealth redistribution by design The economic system is accessible to the local population, reducing service prices and addressing unaffordability challenges through mutual support at the local scale.

Creates a fairer society The removal of privileges as a result of the developed real competition environment creates a fairer society.

3.5 Legal approach

There is a widespread view among the Guifi.net community that creating an environment of trust is essential because trust is key for investment, among other reasons. Consequently, the community has made a great effort to understand the legal framework, which is complex and involves several sources of law. The Guifi.net community's general will is to observe the laws, whether its members like them or not, and the rules have been breached just very occasionally. In the last case, when it has been done consciously, it has always been done as a means of protest – never to achieve anything illegally – and the actions have generally been widely published.[7] The community's positive attitudes towards the respect for the rule of law have led to participating in several consultation process and policy and regulation discussions, especially at the EU level and frequently together with other CNs and related groups.[8] At the local level, the Guifi.net community has worked hand in hand with local administrations to address several legal challenges, most of them derived from the legal impediments to these administrations to contribute to the construction of a decent telecommunications network for their citizens and the associated administrative burden.[9] [59]

Regarding the telecommunications regulatory framework, as a result of its liberal inspiration, the European regulation is very favourable towards the development of CNs because it ensures equal treatment for any telecommunications initiative. Furthermore, the contributions to extending the telecommunications infrastructure, increasing the offering, and bringing new players in the economy that CNs entail are aligned with European strategic objectives.

The alignment between CN models and the regulatory framework and its underlying principles is even more marked when compared to the EU Electronic communications code. This new regulation, which is already coming into effect, aims for further efficiency through co-investment and imposes further obligations on publicly funded infrastructure towards sharing and open access. Both co-investment and open access are common traits in CNs and are central in the Guifi.net initiative.

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[7]For instance, in some OF deployments, the poles of the incumbent have been used without explicit consent after a long waiting time.

[8]For instance, in 2017, the Guifi.net foundation took part in the campaign led by La Quadrature du Net (https://www.laquadrature.net to defend the CNs' interest during the drafting process of the Electronic communications code), which led to the release of the following public statement: https://www.laquadrature.net/en/2017/03/16/netcommons-open-letter-EU-policy-makers-on-community-networks/.

[9]For instance, since the very beginning, a system based on the use and federation of proxies connected to public DSLs was developed. It contributed to managing the scarce Internet access existing at that time, and it provided a convenient way for the mayors to share the very limited Internet access they had in town council buildings. In most rural areas, these were the only available Internet connections without dealing with unattainable legal obligations if they wanted to do it by their own means. A more recent example is the model developed as a template for a municipal ordinance by the Foundation. The purpose of this ordinance is to serve as a basis for municipalities to regulate the deployment of infrastructure that could be used for advanced networks, which is the responsibility of the city council.

In practice, the truth is rather different, however. According to the EU rules, member states must do the transposition of the directives. In Spain, transpositions frequently happen late and inefficiently. In the telecommunications sector, these failures commonly benefit big telecoms, which always push to strengthen the barriers to newcomers. As an example, they are very hostile against others investing in unreserved areas, especially if they are new players. The rationale for their belligerence is two-fold. First, new player success would provide evidence that, contrary to what they say, others can also deploy and operate network infrastructure, probably in a more efficient manner. Second, it would cut their potential market because deploying first gives a clear competitive edge, and in many areas, there is just a market for a single operator. The emergence of CNs has a positive effect because they increase the number of agents interested in the timely and effective transposition of the EU regulation.

3.6 Success indicators

This section presents some qualitative and quantitative results to illustrate achievements in terms of the diversity of participants involved in the project as a whole and in its governance and economic system, in particular. The size of the investment made, infrastructure put in place, and so on are discussed. Moreover, this section analyses the influence the project has already had as of 2013 though official statistical data.

In summary, Guifi.net is currently a strongly horizontal organisation with hundreds of people involved and is widely geographically distributed. Given its organisation and size, most of the overall indicators can only be either qualitative or quantitative estimates. However, these overall indicators can be backed with other very accurate indicators, such as the precise quantification of the investment in some significant areas, the number of participants in the economic ecosystem, and the traffic in the network operation centre (NOC).

3.6.1 Participation – Community building and governance

Scientific quantitative data of such a diverse and widespread project can only be achieved indirectly. In terms of participation, in 2014, [155] found 13,407 registered users in the Guifi.net portal and 55 mailing lists. A qualitative description of the current state of the most relevant stakeholder groups follows.

Volunteers The Guifi.net community of volunteers is healthy. Volunteers contribute to many tasks, such as bootstrapping new areas, assisting newcomers, improving software tools, performing maintenance, and so on. Due to their locality and commitment to the project, they are a key component in the task of ensuring that the rules are fulfilled, especially in areas where the presence of the Foundation is limited.

The Foundation The Foundation was established to provide a legal entity to the project and to act as the system operator. As such, it has led the process of defining and implementing the governance system. From a legal viewpoint, through the corresponding notification to the Spanish NRA, the CNMC, it is the operator of the network infrastructure by default (i.e. of those parts of the network that are not operated by anyone else), which is very convenient for participants who are not familiar with these specific legal and administrative details of the telecommunication sector, such as volunteers or public administrations.

As part of its actions to stimulate the economic activity, it promotes network projects (e.g. an optical fibre deployment in a neighbourhood), which afterwards are executed

by the professionals (project allocations are made according to pre-established rules, and the Foundation always maintains the role of project supervisor). In addition, the Foundation helps these professionals by sharing its resources, especially when they start, and accompanies them during their growth process.

Its dissemination activities include promotion in public administrations with politicians, private companies, and citizens, dialogue with the regulator and in response to any public call that may affect the commons network, and so on. Its research activities are mostly tied to collaborations with universities. The Foundation has participated in several research projects funded by the EC.

Other Guifi.net organisations Diverse nonprofit organisations complement the activity of the Guifi.net foundation. These include associations of users, co-ops, and local delegations of the Foundation. This type of organisation is a typical entry point for newcomers because they engage in many dissemination activities and provide support to beginners. Associations and informal groups are preferred by technically skilled people, while cooperatives are preferred by people who support Guifi.net 's principles and ideas but either do not have the required skills or the time to put them into practice.

Public administrations Collaboration agreements have been signed by Guifi.net with many public administrations, mostly small-to-medium municipalities (e.g. with almost all of Osona county), but also with counties (e.g. *Consell Comarcal d'Osona*). A correlation between the size of municipalities and the level of commitment with the commons network can easily be identified; the smaller and less served by conventional telcos, the stronger the commitment and the bigger the contributions. At the moment, more than one hundred councils are actively collaborating with Guifi.net, most of them through the Foundation but also through local installers and service providers.

Universities The Foundation has signed collaboration agreements with almost all Catalan universities. Collaboration activities include infrastructure deployment, research projects, student mentoring, dissemination, and so on.

Other third parties The following are examples of the many cases of successful collaborations with third parties to contribute to the network commons. These cases show that almost any entity or organisation can contribute. Since 2008, the Catalan top-level domain (.cat) has most of its hardware in the Guifi.net facilities. Their contribution was crucial to launching the first territorial exchange point. The Hospital de Vic[10] and the Hospital d'Olot[11] self-supply their connectivity needs through OF held in common.

Professionals Over 30 SMEs deliver professional services in the Guifi.net ecosystem (see the next section for further information).[12]

3.6.2 Participation – Economic system

The description of the current state key indicators of the health of the economic system follows.

Professionals As already indicated in the previous section, over 30 SMEs deliver professional services in the Guifi.net ecosystem. They range from self-employed entrepreneurs to

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[10]The capital of Osona county.
[11]The capital of Garrotxa county.
[12]https://guifi.net/en/node/3671/suppliers
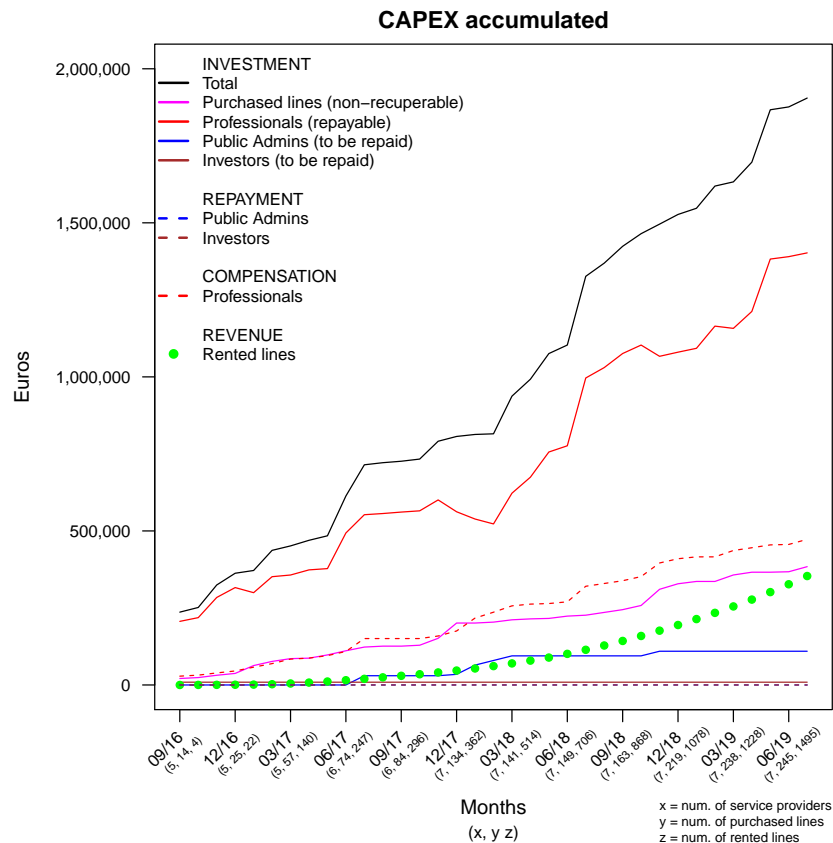
Figure 3.2: Accumulated investment in OF in XAFOGAR (Source: Guifi.net foundation).

companies accounting for over 60 employees. The key activities are deployments of new infrastructure, maintenance and operation of the existing infrastructure, and the provision of services to end-customers over the network.

End-user services Internet access is the most popular service. Nonetheless, other services, such as VoIP and remote backups, have also been offered for quite some time, and new services, such as video streaming and video on demand, are becoming popular, especially in the areas with OF.

Turnover The great economic activity in conjunction with the number of participants makes it difficult to estimate the total turnover of the whole project. However, precise data on some partial indicators exist. As an example, the total annual cost of the NOC (see Section 3.6.3) is around 400,000 € (see Table 5.2).

Investment In [P2], the total investment was estimated to be near 7.5 M€. Since then, the investment, especially in OF, has grown tremendously. As in the case of the total turnover, the total investment can only be roughly estimated. However, in this case, precise data on some partial indicators exist. For instance, the XAFOGAR project [13] is a flagship project in Garrotxa county for deploying OF across the region to every home, led by the county's *Consorci de medi ambient i salut pública (Consorci SIGMA)* (Consortium for the Environment and Public Health) and the Guifi.net foundation. Started in mid-2016, with a

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[13]http://www.xafogar.cat/ (content in Catalan).

total estimated budget of 10 M€, as Figure 3.2[14] shows, the accumulated investment by July 2019 was close to 2 M€. Although it is not possible to make a such precise quantification of the total investment because, in the rest of the regions, the accounting is not yet as systematic as in XAFOGAR, the fact that the exterior traffic of XAFOGAR is less than one-tenth of the total (see Section 3.6.3) permits us to consider that the total investment in last-mile deployments must be over 20 M€.[15]

In Figure 3.2, the evolution of the purchased lines (i.e. contributions made by the participants who want to have access to a specific deployment and avoid the line rental fees) (see *for-fee-reduction contributions* in Section 5.2.3) illustrates the potential of the system to activate direct investment by the beneficiaries, which, in this case, accounts for 25 % of the total investment. The total investment made by public administrations is less than 10 % of the total. However, the presence of public funds, with the firm commitment of SIGMA, has been key to creating a climate of confidence to activate the rest of the investment.

Revenue In July 2019, the monthly (CAPEX) revenue from rented lines (see *line rental fees* in Section 5.2.5) is close to 27,000,€, and the accumulated total represents around 25 % of the total current investment made by the professionals. This rate (i.e. without new subscribers) means an ROI period of fewer than 5.66 years, considering an annual interest rate of 5 %. The increasing trend in Figure 3.2 is also observed in almost all of the rest of Guifi.net's deployments.

Compensation among professionals As Figure 3.2 shows, the total amount compensated among the professionals operating in XAFOGAR accounts for around one-third of their total investment, which is an indicator of the high degree of infrastructure sharing among them.

3.6.3   Access – Infrastructure deployment and adoption

Figure 3.3 shows the network architecture of Guifi.net in general. Currently, almost all the traffic between Guifi.net and the rest of the Internet (the external traffic) is exchanged at the premises of Equinix [42], the main collocation centre in Barcelona, where Guifi.net has its NOC. The traffic is exchanged preferably through peering in the local IXP, the Catalan neutral internet exchange point (CATNIX) in our case, and otherwise through network service providerss (NSPs), also referred to as carriers. At the time of this writing, Guifi.net has five NSPs, two for general-purpose Internet connectivity, which accounts for over 99 % of the NSP traffic, and three for special operations, such as specific peering or operations related to mobile and fixed telephony services. The setting of two general-purpose Internet connectivity providers ensures basic redundancy. Figure 3.4 shows the traffic exchanged by the Guifi.net community with other CATNIX members

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[14]Figure 3.2 summarises the monthly evolution of the main indicators of XAFOGAR. All are accumulated values. The number of professionals, purchased lines, and rented lines are shown in the abscissa. The black curve is the total investment, which is the sum of the coloured solid curves. The red solid curve corresponds to the investment by the professionals. This curve can decrease because the investment made by the participants is refunded through the purchased lines (magenta solid) and the contributions of public administrations (blue solid) and investors (brown solid). The purchased lines are non-refundable and, along with the inflow from the rented lines (green dotted), comprise the total net income to the system (see Chapter 5). Although the contributions by public administrations and investors are refundable, as the dashed blue and brown curves show, there has not yet been any repayment because the lenders have so provided. The red dashed curve shows the total amount compensated among the professionals (see Chapter 4).

[15]This is very conservative because many deployments started using WiFi technologies, and after several upgrades and the expansion of the WiFi equipment, they have been migrated to OF.
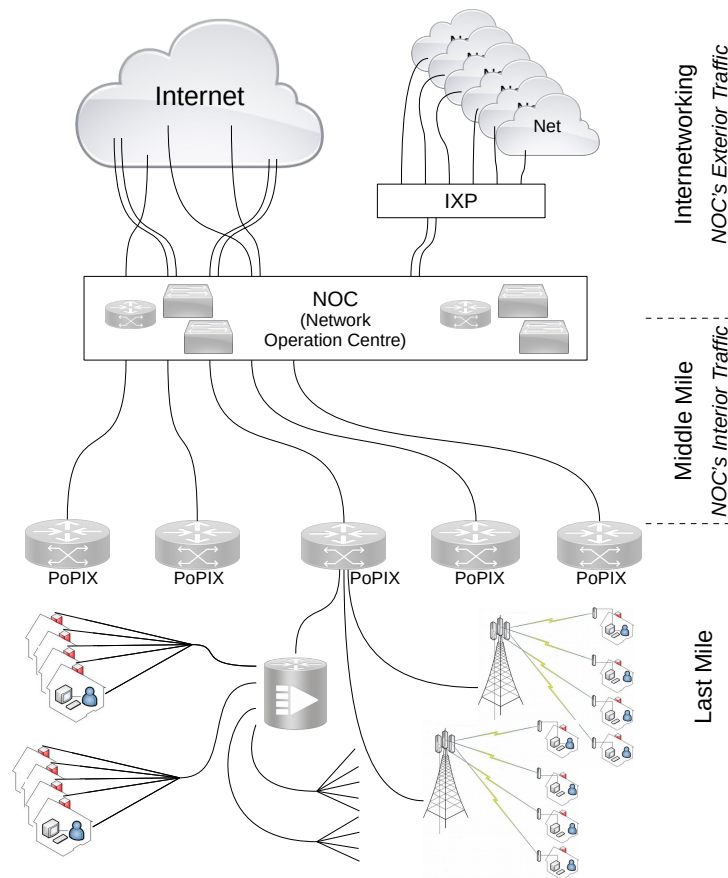
Figure 3.3: The Guifi.net network architecture.

and the two main carriers at the NOC during the second week of April 2019. Guifi.net is currently the ISP member (i.e. excluding the content providers) with the largest traffic in the CATNIX. The Foundation is the official member of CATNIX on behalf of the Guifi.net community. It has been assigned ASN 49835, IPv4 109.69.8.0/21, 5.10.200.0/21, and 185.32.16.0/22, IPv6 2a00:1508::/32 by the RIPE-NCC and operates other ASN and IPv4 and IPv6 ranges from some of the Guifi.net professionals.

The external traffic is distributed through the middle-mile network to the territorial points of presence, the territorial point of presence (PoPIX) in Guifi.net 's terminology, and from there to the end users through the last-mile networks. At the time of writing, 25 active PoPIXs exist, some of them connected through 10 Gbps OF links and the rest through 1 Gbps OF links. All the middle-mile network links are rented from third-party providers.[16]

The last mile comprises a combination of owned WiFi and OF, with the last replacing the first in existing deployments, and is dominant in new deployments. Figure 3.5 shows the WiFi network, and Figure 3.6 illustrates the number of active nodes over time. In some rural areas, the adoption is remarkably high. For instance, in Perafita, a village of 412 inhabitants, 159 main

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[16]Most of them are active Ethernet circuits traditionally rented from Xarxa Oberta de Catalunya (`https://www.xarxaoberta.cat/`), almost the only territorial connectivity provider in Catalunya until recently. However, the number of providers has increased significantly in the last years, and consequently, the supply has improved significantly. Nowadays, the links are rented from several providers.
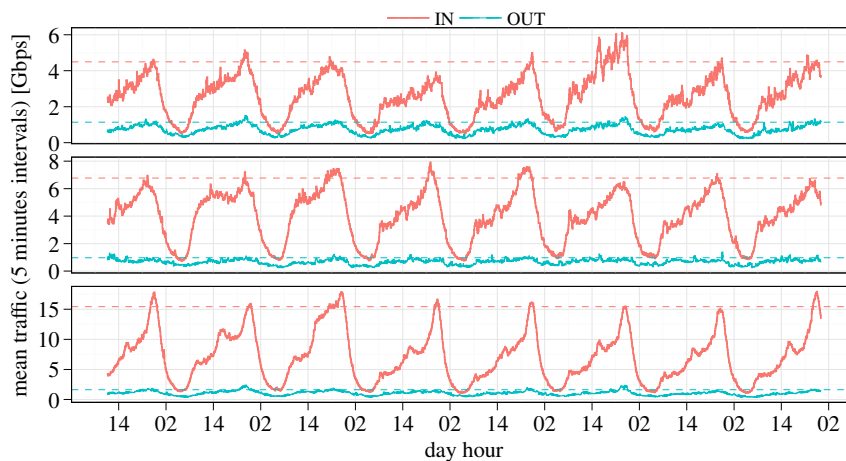
Figure 3.4: Traffic exchanged by the Guifi.net community with other CATNIX members (top) and the two main carriers (middle and bottom) at the NOC (Source: Guifi.net foundation, April 2019).
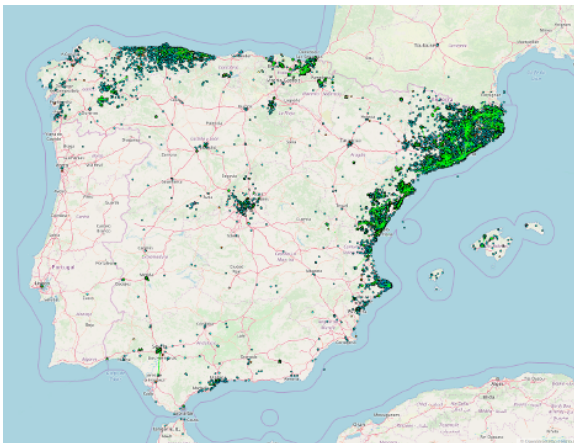
Figure 3.5: the Guifi.net WiFi network (July 2019, source: https://guifi.net/maps, ©OpenStreetMap contributors).
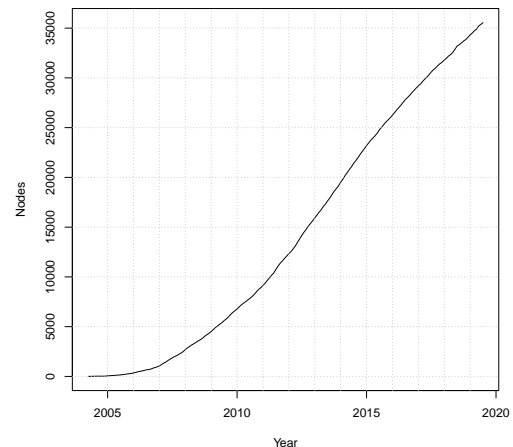
Figure 3.6: Guifi.net active WiFi nodes (source: https://guifi.net/guifi/menu/stats/nodes).

family dwellings, and 76 secondary family dwellings (235 in total) [86],[17] accounts for 91 active WiFi nodes, that is, a penetration of about 40 % in a village with good coverage of LTE and DSL.

Figure 3.7 shows the OF backbone of XAFOGAR. Garrotxa county has 55,579 inhabitants [83] and 23,560 non-empty family dwellings [85]. Olot, the capital, has 34,486 inhabitants and 13,439 [85]. The other 21,093 inhabitants are distributed among 20 municipalities, ranging from 200 to 3,000 each in 10,121 non-empty buildings. Before the launch of XAFOGAR, Olot was the only municipality with OF available. Shortly after the project was publicly announced, the incumbent started deploying outside Olot.[18] Nonetheless, XAFOGAR is progressing satisfactorily. In July 2019, there were 256 purchased lines and 1572 rented lines (245 and 1495 in June 2019, as shown in Figure 3.2), covering 18 % of the total non-empty dwellings. It must be considered that OF roll-outs are made per neighbourhood, at least and that it is an on-going project. The

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[17]According to the local government, the garbage collection service in August 2019 issued 277 bills in total for 253 family dwellings and 22 enterprises.

[18]This pattern has been observed in many other OF deployments.
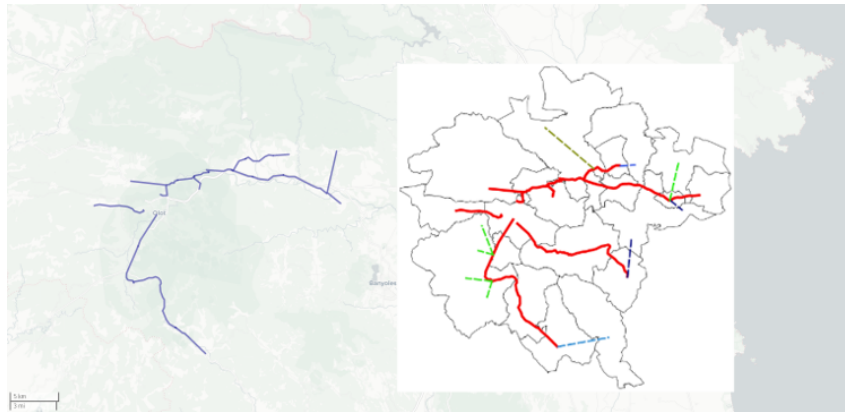
Figure 3.7: Planned (background) and executed (inner square) OF backbone network of XAFOGAR (July 2019, Source: Consorci SIGMA, ©OpenStreetMap contributors).

penetration rate in covered municipalities is up to 90 % (e.g. Tortellà). It is also worth noting that, Olot, which did not join the project at the beginning, also joined recently, and the initial OF deployments are expected by the last quarter of 2019.

3.6.4   Access – Affordability

The main offerings (prices per month) by the four largest service providers in September 2019 are the following (in alphabetical order)[19]:

Delinternet

   OF up to 800 Mbps 27.71 €; up to 800 Mbps with a fixed-line (metering) 31.34 €; up to 800 Mbps with one mobile (3 GB, unlimited) with one fixed-line (metering) 43.09 €.

   WiFi 19.01 €; with a fixed-line 22.64 €; with one mobile (3 GB, unlimited) with one fixed-line (metering) 34.39 €.

Goufone

   OF 300 Mbps 36.20 €; 1 Gbps 39.95 €; 1 Gbps with one mobile (4 GB, unlimited) with one fixed-line (unlimited) 47.95 €; 1 Gbps with TV 49.95 €.

   WiFi 8 Mbps 36.20 €; 8 Mbps with one mobile (4 GB, unlimited) with one fixed-line (unlimited) 44.95 €.

Iguana

   OF 1 Gbps/300 Mbps 46.00 €; 1 Gbps/300 Mbps with one mobile (7 GB, unlimited) with one fixed-line (unlimited) 58.00 €.

   WiFi 3 Mbps/3 Mbps 25.50 €; 4 Mbps/4 Mbps 29.50 €; 6 Mbps/6 Mbps 37.50 €; 10 Mbps/10 Mbps 54.50 €.

XTA

   OF 50 Mbps/50 Mbps 29.00 €; 300 Mbps/30 Mbps 39.00 €; 300 Mbps/30 Mbps with one mobile (3 GB, unlimited) with one fixed-line (500 minutes) 49.00 €.

   WiFi 3 Mbps/0.5 Mbps 18.00 €; 6 Mbps/1 Mbps 23.99 €

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[19]Delinternet: https://delinternet.com/, Goufone: https://goufone.com/, Iguana: https://www.iguana.cat/, and XTA: https://www.xta.cat/.
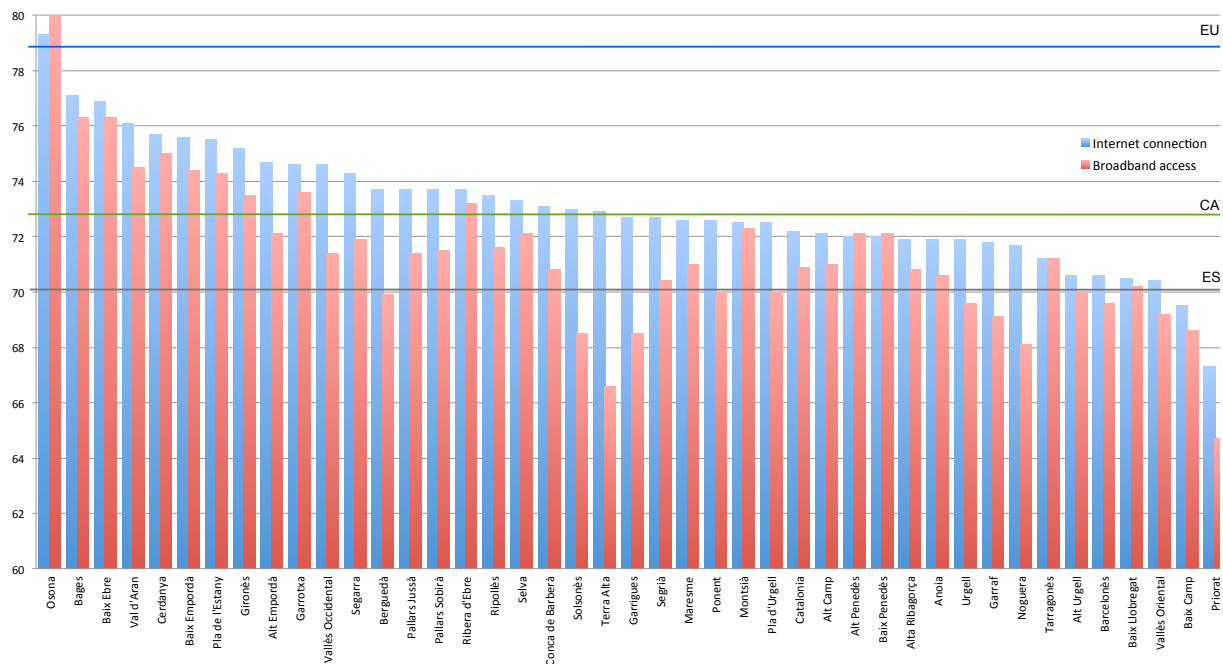
Figure 3.8: Household bandwidth and Internet access in Catalonia per county (2013, source: IDESCAT [84]).

All of the above offerings are free of acquisition cost; for-free-reduction contributions have a 17 € monthly discount.

The Associació expansió de la xarxa oberta (EXO) association of users has a monthly membership fee of 10 € plus 2 € for WiFi Internet access. Users must contribute their own links.

3.6.5 Impact

Methodologically, we believe that impact must be supported by data from third parties, where possible. Based on this assumption, in 2015, in [P2], we assessed the Guifi.net project impact based on information from 2013 by the public Catalan Statistics Institute (*Institut Català d'Estadística* (IDESCAT)[20]). Unfortunately, to the best of our knowledge, those statistics have never been updated,[21] which has prevented us from being able to update our research. Thus, the quantitative information of this section is more than six years old and is outdated, considering the significant changes in the telecommunications industry in the last years. Nonetheless, we have opted to include the work we presented in 2015 because we believe that it is still valid to provide evidence about the capacity of CNs to produce real impact.

Figure 3.8 presents the data about the penetration of the bandwidth and Internet access in the households of Catalonia in 2013, released by IDESCAT per county [84]. It also contains the average rate of Internet access in the European Union, Spain, and Catalonia. The first item to notice is that, despite the fact that Catalonia is about three points above the Spanish average, it is still seven points below the European average. Second, and the most relevant point regarding the influence of Guifi.net, the Catalan county with the best results and the only one above the

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[20]http://www.idescat.cat

[21]IDESCAT has been updating every two years, but in the following iteration of the questionnaire, the questions of our interest were eliminated and were never reintroduced.

EU average is Osona, where Guifi.net was born. Moreover, it is the only county where broadband access is above Internet access. The indicators of other counties where the presence of Guifi.net is significant, such as Bages and Baix Ebre, are also larger when compared to similar counties where the presence of Guifi.net is irrelevant.

At that time, Osona had about 9,000 nodes.[22] Combining this number with others coming from IDESCAT,[23] we conclude that about 22.4 % of the Osona inhabitants had Guifi.net access: around 30,500 people.

3.7   Success factors

This section discusses, in our understanding, the key success factors of Guifi.net based on our active participation and research on Guifi.net and in comparison to other CNs.

Clear and simple principles and scope, and a firm commitment to them In conjunction with the firm commitment to simplicity and clarity and avoiding distractions, simplicity and clarity in the fundamental questions ease the consensus and set the basis for focusing the efforts, which are key for effectiveness. In the particular case of Guifi.net, the principles are openness and non-discrimination, and the scope is the network. Any other issues, such as commitment to free software or dislike towards profiting are left outside of the project.

Development and early adoption of a network licence The licence is an instrument to formally establish the principles and scope, which are the basis to deliver legal certainty. Thus, it must be drafted to be enforceable by law. To be so, the terms and conditions must be very well defined, severely restricting them in scope and range of interpretation. The more precise the definitions and the narrower the ranges of interpretation, the less likely it is to reach consensus. Thus, from a pragmatic perspective, the fewer people involved increases the likelihood of the process to be successful. In Guifi.net, at the time of drafting the licence, there were no more than a few dozen participants involved. Inspired by the example and good results of Guifi.net, other CN have tried to draft a licence, but most of them have failed due to the excessive number of participants already involved.

The infrastructure as a CPR The CPR model has proved to be a very suitable and effective resource management principle and is probably the only one that is really compatible with the project's fundamental principles.

Adequate legal architecture and law compliance The developed legal tools, starting from the ground rules – the licence and the Foundation's bylaws – have proved to successfully withstand exogenous and endogenous attacks without relinquishing the private property right. Any breach of law puts the project at risk.

Activation of a flourishing economic ecosystem The incorporation of professional activity as an organic component of the system has contributed to drastically reducing the dependency on volunteering work and has enabled unprecedented growth.

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[22]http://guifi.net/ca/Catalunya, The number was 8,958, adding Osona and Lluçnęs, not counting Santa Maria de Marlès and Sant Feliu Sasserra, as they belong to other counties (*comarques*).

[23]In 2013, Osona had 71,597 households, and Catalunya had 2,944,944 [82]. In Osona, 38,029 buildings have at least a household, and 75.6 % of the households are single-family houses [81]. The Osona population in 2013 was 153,563 [83]; thus, there were 4.08 inhabitants/building. The rate of supernodes to nodes is 0.1. Estimates are that half of them are not installed in homes.

Early identification and sound management of conflicts of interest The Guifi.net community has combined starting a new project (thus not to bear the burden of inherited dynamics) with knowledge extracted from the traditional telecom industry and from its own experience to detect those practices that lead to bad practices and a vicious circle early and act accordingly. As a result, Guifi.net has defined and put into practice a complete governance system, including a well-defined stakeholder group system and the clear attribution of roles and incompatibilities. These arrangements effectively protect the community against bad practices and stimulate competition.

Diverse and well-balanced participation As a result of the governance system, which has been developed incrementally based on new challenges and lessons learnt, the system is very diverse.

Effective tools for participation and coordination The tools developed around open data, procedures, automation, and coordination tools help to lower the barrier to access the infrastructure and to participate in its social production. They reduce the cost of decision making and action and are imperative for transparency and accountability.

Leadership and stewardship The entire process is very innovative; therefore, due to its open nature, it is susceptible to deviation. Clear ideas and strong leadership have been keys to stopping useless discussions and isolating disturbing attitudes. At the same time, the stewardship is reasonable, inclusive, and accountable enough to maintain the community's engagement.

Balanced effort between the development of support tools and network deployment The main goal and the way to keep the project alive is to deploy infrastructure and maintain it operationally. Obviously, to accomplish it, a full set of tools, many of them discussed in this dissertation, must be in place. In Guifi.net, the efforts spent in building this enabling set of tools and those spent in the fieldwork are well balanced. Unfortunately, we have witnessed many projects that have failed due to excessive efforts in one of the two aspects, leaving the other unattended.

Society engagement Reasons to start a CN project vary. The most frequent ones are experimentation and research by a group of highly skilled technical enthusiasts. However, the CNs of this type that we are familiar with have not been able to engage society because these motivations are not appealing to the public; thus, these networks have remained marginal projects. In contrast, Guifi.net has been envisaged as a production network since the beginning; thus, it has attracted the attention of many people who have found in it an opportunity to solve their connectivity problems. Once they understood the social value of the proposition, some have become very active contributors.

3.8 Conclusions

In this chapter, we have provided a general overview of Guifi.net by analysing its traits and benefits and presenting a collection of impact and performance indicators. The review of the fundamental principles, ultimate objectives, and business models already reveals remarkable differences. The innovative conception of the passive and active layers as a participatory CPR shaped the development of the project in a singular and inclusive manner. This conception does not preclude the development of economic activities and commercial offerings but enables a number of additional alternatives, such as coops or DIY. Furthermore, in terms of business

opportunities, the virtual elimination of entry barriers with the equalisation of opportunities
in terms of use in the existing infrastructure translates into a thriving and competitive local
economy, as a number of the quantitative and qualitative indicators presented demonstrate.
Part of this economic success is due to the capability of the system to activate and aggregate
small financial and funding players, and the lack of significant public funds prove that, from
the economic perspective, the system is healthy and self-sustainable. The commercial offerings
are generally similar to the average [41, 152], but, contrary to the traditional ISPs, the service
providers within Guifi.net offer the 1 Gbps (OF) to the domestic market at domestic prices
($\sim 40\,€$). Several self-sustainable mechanisms allow the inclusion of socio-economic groups that
cannot afford the standard prices.

In terms of social involvement, the results are also noteworthy. To the best of our knowledge,
an unprecedented amount of information is publicly available on this scale (tens of thousands
of households connected). The opportunities and the number and diversity of participants in
the governance affairs is also unique. Regarding the infrastructure put into place, there are
irrefutable facts: next generation access network (NGA) technologies (essentially OF) are being
deployed on a daily basis in areas traditionally deemed to be unprofitable.

Based on the aforementioned results and the evident singularity and potential of the Guifi.net
approach, we conclude that it deserves a deeper analysis. Hence, in Chapter 4, we investigate
the governance and economic systems, which, in our opinion, are the two main components of
Guifi.net. Due to their complexity, we address them in two separate chapters. In our analysis, we
paid special attention to understanding the way conflicts of interest and sustainability challenges
are addressed because, in our opinion, these are the two most relevant traits with the highest
potential effects.

Guifi.net – Governance

Preface

This second chapter devoted to Guifi.net is the first aimed at providing a systematised description and analysis. Specifically, it focuses on the study of its governance system and how the project is protected from the legal perspective. It starts with a classification of the different stakeholder groups. Then, it presents a structured analysis and description of the internal governance regulation principles, agreements, and instruments. The cost-compensation concept and how it is implemented are carefully analysed because these are central components in the coordination of transactions among participants. The chapters also address the source of legitimacy of the project and the standard three branches of power (legislative, executive and judicial) and how they relate to each other and to the overall context in which the project is developed. After that, it examines the legal construction aimed at the preservation of its core resource (the network infrastructure) and the associated activities. A short overview of the historical evolution seeks to provide a minimum understanding of the incremental process followed and the relevance that the combination of practical experience and theoretical approach has had in it. This is a continuous process, as the next chapter illustrates with an analysis of the discussions that are now taking place. The chapter concludes with a comparative analysis of the design principles and requirements proposed by Elinor Ostrom of the long-enduring CPR institutions with Guifi.net. As described in greater detail, ensuring proper management of the conflicts of interest by design has a primary role in the whole governance architecture.

4.1 Introduction

As introduced in the previous chapter, the Guifi.net network infrastructure is considered a commons and therefore is managed as an open CPR with the network infrastructure as the core resource. Treating the infrastructure as an open CPR has some immediate positive effects, such as the avoidance of redundant infrastructure because all participants operate on the same infrastructure and the increase in efficiency of the infrastructure in terms of cost savings and ease of participation. The CPR grows through the contributions of participants to expand or improve the network. In exchange, the contributors gain network connectivity [P2]. Participants can benefit from pooling with lower individual investments because the resources are shared. The knowledge on the network is open, and the network is neutral. No barriers artificially limit the extent of contributions, such as expansion, content, or service creations. For commercial services, Guifi.net as a CPR translates into a reduced entry barrier.

Nonetheless, Guifi.net, like any other CPR, is fragile. More precisely, because it is (intentionally) non-excludable and the fringe unit (the connectivity)[1] is subtractable (rivalrous),[2] it is prone to congestion and exhaustion. In this chapter, we present the governance tools developed and put into practice by the Guifi.net community to protect the core resource – the network infrastructure – from depletion and ensure the maximisation of the production and its fair distribution.

The rest of the chapter is structured as follows. Section 4.2 identifies and classifies the existing stakeholder groups. Section 4.3 describes the stack of internal regulations that has been developed and put into practice, which ranges from ground rules to a number of sectorial rules and practices. Section 4.4 introduces the cost-compensation system, a central component in the realisation of the Guifi.net principles that links its governance to its economic system. Once the key governance building blocks have been introduced, Section 4.5 elaborates on how the source of legitimisation of the system and the separation of powers are implemented. Section 4.6 analyses the legal architecture of the project with a special focus on the mechanisms used to shield the shared resources from privatisation attempts. Section 4.7 briefly outlines the project history. Section 4.8 discusses the relationship between Guifi.net and the main works by Ostrom, the academic reference in the study of CPR institutions. Finally, the conclusions of the chapter are presented in Section 4.9.

4.2   Stakeholders

The Guifi.net ecosystem accounts for thousands of participants. Accordingly, the motivations for engaging in it and the degree of involvement of the participants vary widely. As an example, some people contribute occasionally on a purely volunteer basis, while others fully develop their professional careers in it. Moreover, quite frequently, the participants have several motivations to participate and diverse kinds of participation. For instance, many professionals make nonprofit contributions in addition to their paid jobs. As a result, the interactions within the community are complex, and their underlying reasons – the interests – may be classified according to different criteria.

We identify three primary motivations for participation and, based on this, we define the three sets of stakeholder groups below and depict them in Figure 4.1. We define the elements of each set (i.e. the stakeholder groups) by the roles they play and the goals they pursue.

In-return This set is formed by the stakeholder groups whose members expect some return from their participation. In some of the stakeholder groups, the members are bound by SLAs.

    CPR professionals They are the professionals whose activities fall under the scope of the CPR.

        Installers They expand or upgrade the network by adding new hardware.

        Maintainers Maintainers keep the infrastructure in good condition.

        Network operators They operate the network infrastructure.

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[1] As explained in Section 2.4.3, CPRs typically consist of a core resource that provides a limited quantity of extractable fringe units. In the case of Guifi.net, the core resource is the network, which is nurtured by the in-kind or monetary contributions from the beneficiaries, and the fringe unit is the bandwidth they obtain.

[2] In practice, OF is non-rivalrous, but the implications of this fact have not yet been translated into different procedures in the community of practice. For our analysis, it is convenient to preserve the rivalry condition because a governance system able to deal with a resource with this constraint is likely to also work for a resource without it, but the reverse is not true.
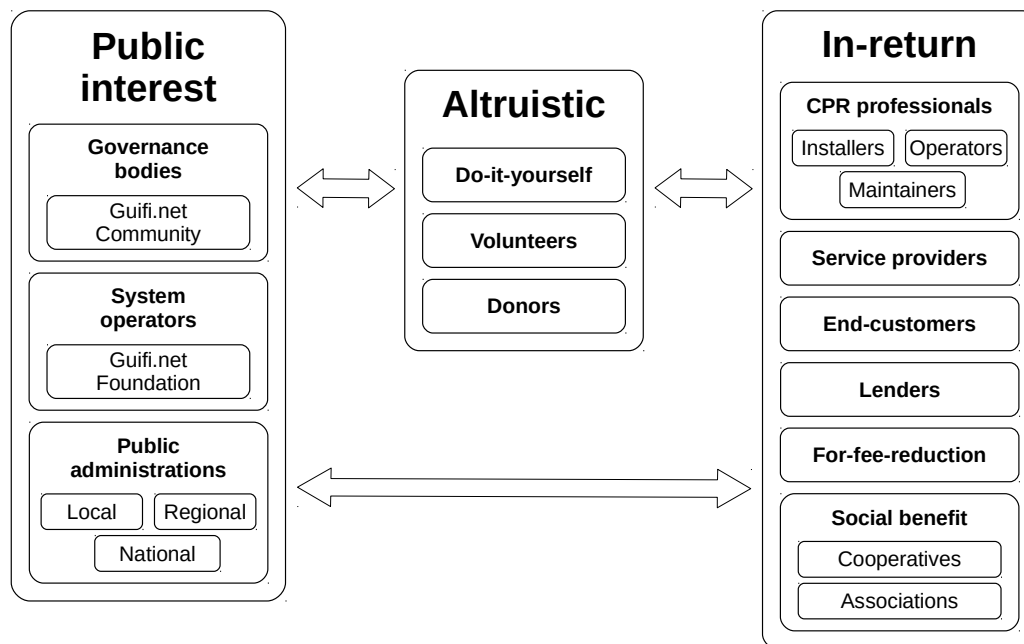
Figure 4.1: Stakeholders.

Service providers The service providers market services on top of the existing infrastructure.[3]

End-customers The customers buy services from the service providers and professionals.

Lenders Lenders lend money that must be repaid, optionally with interest.

For-fee-reduction contributors They make contributions in exchange for a reduction of their service bill once the infrastructure they contributed to funding is put into production.

Social benefit Organisations, despite being nonprofit, have some sort of service obligation (social benefit) towards their members.

    Cooperatives These are cooperatives of consumers.

    Associations These are associations of participants.

The professional and end-customer stakeholders as well as coops and associations, although they are fewer in number, are well-established groups. The for-fee-reduction contributors and lenders are stakeholder groups that are now actively promoted by the Guifi.net foundation as part of its current efforts to harmonise the CAPEX investment because, for the time being, most of these sources of investment are handled by the professionals without any record or oversight and, thus, without the guarantee that they respect the Guifi.net spirit and rules.

Contrary to what one may expect, there is no *borrower* stakeholder group as such to counterbalance the for-interest lenders or the for-fee-reduction contributors because, in the Foundation's borrowing model, loans are taken by the Foundation on behalf of the

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[3]In Guifi.net, the term *operator* is frequently used to refer to CPR professionals and service providers, which play different roles as explained in this section. As discussed in Chapter 5, the activities of the former is regulated, while that of the latter is unrestricted. In this dissertation, we refrain from using the term as much as possible to avoid misleading the reader.

whole community and not individually by the beneficiaries or installers of each specific loan. Thus, the Foundation is in charge of counterbalancing the for-interest lenders. Furthermore, frequently, the Foundation must defend the interests of these two stakeholder groups against other stakeholder groups, such as the installers or operators.

Altruistic This set comprises the individuals and organisations whose motivation for participating is furthering the project without pursuing any specific material reward.

> **Volunteers** The volunteers contribute time and knowledge to set up infrastructure and services, help other people to join, and so on.
>
> **DIY** The DIY group contributes time and the hardware needed to satisfy their own connectivity needs.[4]
>
> **Donors** The donors make economic or in-kind contributions beyond what is strictly required to satisfy their connectivity needs, or the contributions are even completely independent from these needs.

The cooperatives and associations of participants that do not require SLAs with their members can be included in this set of stakeholder groups.

In the nonprofit set of stakeholder groups, labour and knowledge are always contributed on a volunteer basis; hence, they cannot be remunerated. Material costs, such as hardware or accommodation costs, can be economically compensated. The non-remunerated labour policy does not apply to the staff of the ruling bodies or the staff of the system operators because these costs are considered operational costs. In these cases, the employees are paid fair salaries, in line with the guiding principles of a collaborative economy and fair trade. The professionalisation of these tasks, which increases as the project grows, has been shown to be indispensable to meet the needs of the development of the project as a whole, both in terms of the services offered and their quality. The best effort groups play a critical role in counterbalancing the for-profit stakeholders. The cooperatives and associations of users have traditionally joined this counterbalancing role regardless of whether or not they entail SLAs.

Public interest The motivation for participation is to contribute to the social welfare.

> **Ruling bodies** The ruling bodies are responsible for policy-making and strategic decision making. Guifi.net is a direct democracy system; thus, the ruling body is the whole community. The rule-making process is conducted through participatory meetings, always seeking the greatest possible consensus
>
> **System operators** The system operators are responsible for running the critical services of the system. Unlike the usual practice in Western countries, in Guifi.net, to prevent collusion or conflict of interest by design (thus, to avoid having constantly to resort to ad hoc policies and regulations), the tasks of the system operators cannot be performed by for-profit participants. The Foundation is the system operator of Guifi.net. As

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[4]Although it can be argued that the stakeholder group of pure DIYs participants (i.e. the group of participants that only contribute what is strictly necessary to join the network) can also be included in the for-profit stakeholder groups set, we have chosen to keep it the nonprofit set for the following reasons. The first is to limit the for-profit set to contributions based on economic exchanges. Second, we argue that a DIY contribution implies a substantially higher degree of commitment with the project than the simple economic contribution of the for-fee-reduction contributors. Finally, in practice, the number of pure DIYs participants is currently negligible because nearly all former pure DIY individuals became customers as operators became ubiquitous and because the vast majority of those who are currently in the DIY group are also making other nonprofit contributions as donors or volunteers.

such, it performs most of the system operation tasks, although there are some interesting experiences in which other nonprofit participants actively participate in the implementation of some of these tasks[5] (see Section 3.6.1 for additional information on tasks of the Foundation).

Public administrations Public administrations are responsible for regulating interactions between network deployment and *public interest*, such as public domain occupation. Thus, they must at least treat Guifi.net as any other participant in the telecommunications sector. Beyond their legal obligations, they can take action either by satisfying their telecommunications needs in the Guifi.net marketplace or by subordinating their funds and subsidies to the contribution of the corresponding infrastructure in the CPR.

Participants are defined as natural and legal persons. Nowadays, there are around 40 SMEs doing business within the Guifi.net ecosystem, with at least four of them accounting for over 20 employees, serving tens of thousands of customers.[6] Despite the emergence of professional activity and for-fee-reduction investors, the DIY contributions are still a substantial amount of the overall investment. The DIY approach is still a usual approach to start deploying in new areas, especially those that are far away from areas with intense economic activity, and is still in good shape in many of these last areas. The experience shows that many of the SMEs and more active volunteers in other matters, such as governance, capacity building, project acquisitions, and so on, started as DIY volunteers. There are half a dozen of self-provisioning associations and cooperatives, some of which are also remarkably involved in the overall governance. The Guifi.net foundation has five members on the board of directors and six full-time employees in addition to some volunteers. There are over 200 local public administrations directly involved in the project.

It is important to note that the stakeholder groups belonging to the same set does not imply that they must necessarily share the same goals. Quite the contrary, frequently they have conflicting goals. Pricing is an obvious example in the case of the professional and customer stakeholder groups, although both belong to the for-profit set. Nonetheless, the grouping of the stakeholders based on the primary motivations for participation has proved to be very useful in identifying and handling potential conflicts of interest, especially in an intricate collaborative environment such as Guifi.net, in which it is not uncommon that the same participant could have several roles. For instance, operators also often invest in new infrastructure to reach new markets. In this case, contrary to their common wishes to bundle infrastructure and services, the investment must be treated according to the procedures of investment acceptance and repayment, which essentially stipulates a repayment period and financial interest and services provided through the network utilisation procedures (i.e. to participate in the cost-compensation system).

If a participant plays more than one role, in the case of conflicts of interest among them, the most restrictive exclusion prevails. For instance, a professional who also does voluntary contributions can participate as a professional in the deliberative processes affecting the relations between volunteers and professionals but not as a volunteer.

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[5]For example, in XAFOGAR, a county's agency is actively contributing to the implementation of the cost-compensation system in the area.

[6]The number of enterprises doing harmonised activity can be obtained from the registry of economic activity of the Foundation. The number of customers can only be estimated because the reports that the professionals deliver to the Foundation are still very incomplete, although the Foundation is struggling to obtain better records because it would like to integrate the number of customers served as a metric for the cost-sharing mechanism.
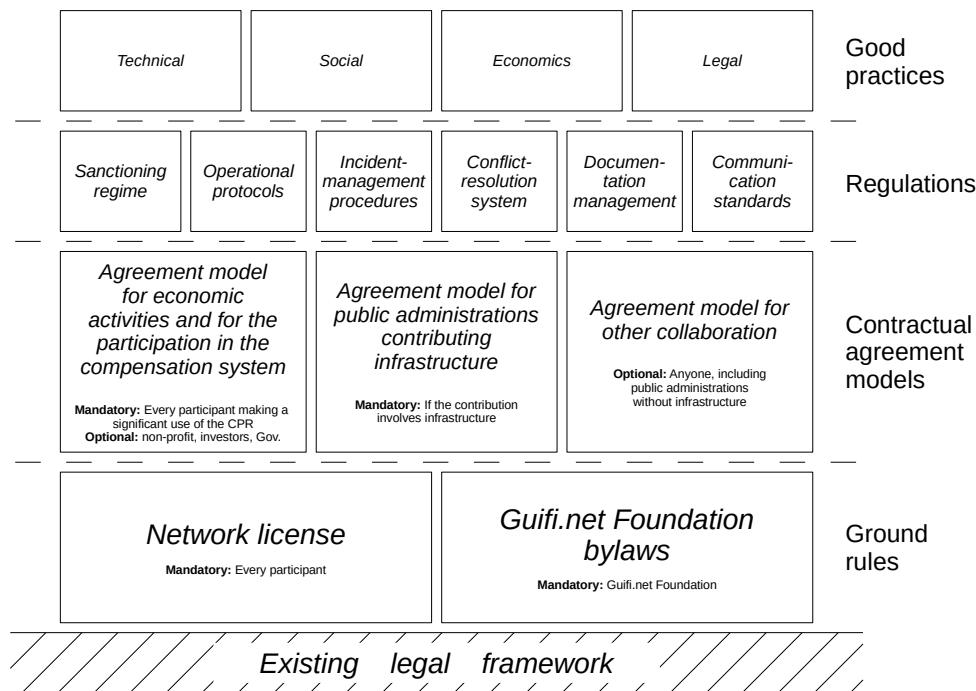
Figure 4.2: Internal regulations.

4.3   Internal regulations

Figure 4.2 presents the internal regulations developed by the Guifi.net community. It is intended to be enforceable by law; thus, all the components and, in particular, those of the lower layers, have been carefully written and are kept under constant review to guarantee their compliance with the existing legal framework.

Ground rules These include the role of every participant (licence) and the role of the governing body (bylaws).

    Network licence[7] It is called '*Llicència de comuns per a la xarxa oberta, lliure i neutral (CXOLN)*' in Catalan, a 'free, open and neutral network commons licence'. It is the basic standard on which the rest of the internal regulations are built. The preamble establishes the founding principles.[8]

    The articles establish, among others, (i) the scope of the project (i.e. the network infrastructure and necessary services to build and maintain it) and nothing else – software or content licensing is out of the scope of the project; thus, nothing is imposed

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[7]https://guifi.net/ca/CXOLN (content in Catalan). [68] is an English translation that has not been proofread.
[8]The founding principles are the following:

1. You have the freedom to use the network for any purpose as long as you do not harm the operation of the network itself, the rights of other users, or the principles of neutrality that allow content and services to flow without deliberate interference.

2. You have the right to understand the network and its components and to share knowledge of its mechanisms and principles.

3. You have the right to offer services and content to the network on your own terms.

4. You have the right to join the network and the obligation to extend this set of rights to anyone according to these same terms.

on the participants in this regard, (ii) who the participants are and their rights and duties – for instance, the duty to contribute to the development and maintenance of the infrastructure, (iii) the Foundation and its mission, (iv) the management of the ownership of the assets contributed – essentially, the participants keep the ownership rights on the infrastructure assets in proportion to their contribution to building and maintaining them, and (v) the procedures for making changes to it. The acceptance of the licence is compulsory to join Guifi.net. Any activity done in the network implies the acceptance of the licence by the participant responsible for the activity.

Guifi.net bylaws[9] The bylaws develop the competences of the Foundation as the governing body and operator of the system critical resources and establish the incompatibilities of the board members and employees. They define the Foundation as a nonprofit non-partisan organisation and mandate it to promote the FONN and to monitor it, conferring on it the legal capacity to represent the community and to rule over it. They specify the procedure for changing their content.

Contractual agreement models With the network licence and the Foundation's bylaws in place, on behalf of the Guifi.net community, the Foundation signs legally binding agreements with participants who need additional specifications to create trust to enable further development of the infrastructure and associated activities.

Agreement model for economic activities and participation in the compensation system[10] This agreement model designates which participants are obliged to participate in the construction and maintenance of the infrastructure and how they must do so. It is mandatory for professionals and those who 'make significant use of the network, such as to be convenient to compensate or to ensure the proper operation of the network or its sustainability'. The clause is wide enough to avoid having to deal with thresholds and particularities, which is left for more specific tools but, at the same time, is precise enough to not leave room for free-riders to put the system at stake. It is optional for investors and donors who want to track their contributions. It is the key document of the cost-compensation system.

Agreement model for public administrations contributing infrastructure[11] This specific agreement model is meant for public administrations that contribute to the network infrastructure of the project. It is a technical template that deals with the particularities that the legal framework imposes to public administrations to be allowed to participate in the telecommunications market. Although it is not mandatory, the Guifi.net foundation strongly recommends it because it has been accurately developed with legal experts. It is of special interest to small local administrations who otherwise only have the option to follow the guidance of big telecoms because they have insufficient means to deal with the legal and administrative burdens.

Agreement model for other collaborations[12] This is a generic collaboration agreement model for any third party interested in developing any activity that requires further specification.

Regulations These specific regulations develop specific areas that deserve special attention. Some play a dissuasive role and rarely are put in practice, such as the sectioning regime,

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[9]https://fundacio.guifi.net/page/estatuts (content in Catalan).

[10]https://fundacio.guifi.net/conveniactivitats (content in Catalan).

[11]https://fundacio.guifi.net/conveniapp (content in Catalan).

[12]https://fundacio.guifi.net/convenialtres (content in Catalan).

while others aim at making the whole project more efficient and are used on a daily basis, like the operational protocols or communication standards. The regulations are built on the ground rules, especially on the network licence; thus, the participants are obliged to observe them.

Sanctioning regime It establishes a graduated sanctioning system aimed at stopping misbehaviour in the first place, secondly, at demonstrating that the misconduct of participants does not go unpunished, and finally, at redressing the damage where possible. The sanctioning regime is maintained and operated by the Foundation; hence, it is responsible for imposing and enforcing the penalties.[13]

Operational protocols This group of regulations involves a wide variety of protocols of different fields. They establish common ways of addressing recurring situations or tasks to reduce uncertainty and make operational activities more efficient, especially in terms of time and cost savings.

Incident-management procedures These are similar in nature to the operational protocols, but their scope is constrained to unforeseen circumstances in which downtime is critical. The management of incidents may involve the modification of operational protocols, either to reduce the probability of further similar incidents or to be better prepared to address them. Most of the operational protocols, as well as the incident-management procedures, are developed and implemented almost autonomously by the interested parties; thus, the Foundation usually only plays a moderator role at most.

Conflict-resolution system[14] It is a systematic and clear procedure for resolution of conflicts in a quick and standard way. It consists of three stages, conciliation, mediation, and arbitration. The conciliation and mediation consist mostly of voluntary rounds of meetings among conflicting parties, with the intervention of a mediator in the last case. The arbitration is mandatory and driven by a lawyer chosen from a set of volunteers whose arbitral award is binding. The cost of the procedures is charged to the responsible party or to both parties in the case of a tie. It was developed with the sanctioning regime at a time when flame wars between a few participants threatened the entire project. In this case, the Foundation is only in charge of the maintenance of the ruling system and the set of volunteer lawyers. Charging the cost to the responsible parties had an immediate effect on stimulating direct settlements between the conflicting parties.

Documentation management Effective data and documentation management is critical for sharing resources. The current state of development of the Guifi.net project involves a wide range of data sources, repositories, and so on. One of the key factors of the initial massive adoption were the tools available on the website. For a long period, the extensive use of the website allowed records of relevant data of that time – a registry of the participants and a database with technical information on the network, including the position of the nodes, assigned IPs, links, and so on– in remarkably good shape. However, the current situation is less satisfying due to several factors, most of them linked to the increasing reluctance of professionals to share data. First, many stopped reporting technical data on the website systematically a long time ago, claiming business confidentiality. Despite the changes introduced to make sensible data publicly inaccessible and the efforts by the Foundation, the restoration is still incomplete.

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[13]Currently, it is being extended to make it also applicable to the Foundation (i.e. to sanction the Foundation in the case of default).

[14]https://fundacio.guifi.net/resolucioconflictes

In addition, the technical reporting tools were not updated in a timely manner to integrate the emergence of OF deployments. The professionals took advantage of this absence to start using their own closed solutions. The Foundation is also expending a great deal of effort to reverse this situation, including the development of a software solution for OF management, the reactivation of the sanctioning procedures, etc.), but it is not yet clear if it is too late to do so.[15] This reluctance to share information also extends to economic matters, which has become a critical part of the information system because these data are critical for the cost-compensation system.

Communication standards These establish the methods and channels for communication among participants. General and specific mailing lists used to be the standard, but with the advent of social networks and instant communication tools, they have declined.

Good practices They cover a heterogeneous set of specific norms and conduct codes developed through the experience in which compliance is desirable but not obligatory.

4.4   Cost-compensation system

The cost-compensation concept and its generalisation and formalisation through the cost-compensation system, which orchestrates transactions among participants, have been key to overcoming serious threats throughout Guifi.net 's history and typify the paradigm shift that the whole project embodies. As in the private model, in Guifi.net, the contributors not only have the right to have their contributions recognised (i.e. to keep the ownership of their contributions) but also have the right to be compensated for their contributions if they are used by other participants. However, contrary to the private model, cost-compensation is made according to objective and non-exclusionary rules and always implies the proportional transfer of the ownership of the assets involved.[16]

As discussed in Section 4.3, the main document that lays down the operation of the cost-compensation system and establishes for whom it is mandatory and for whom it is optional is the agreement model for economic activities and for the participation in the compensation system. Figure 4.3 shows the functional block diagram of the system. The objective of the system is to periodically and systematically correct imbalances between investment in (top left) and usage of the commons infrastructure (top right) among participants. As shown in the figure, the system is strongly dependent on information systems and up-to-date data because the functional blocks communicate with each other through databases. Overall, the system works as follows.

On one hand, to claim any cost-compensation, after having effectively made the contribution, which can be either CAPEX or operational expenditure (OPEX) (i.e. integrating new infrastructure or carrying out any operation on the existing assets, such as maintenance, operation, or upgrade), the applicant must declare the contribution, and express the willingness to be compensated, and provide evidence of its execution. The system operator reviews all declarations. On the other hand, the consumption of resources of each participant is measured through appropriate metrics. At this point, although the system operator is responsible for this task, its implementation is likely to rely on information that can only be provided by third parties, such

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[15]As a consequence of this lack of information, the exact number of current households served is unknown.

[16]The debate within the community regarding to whom the ownership is transferred is still open. The two main options are proportionally to those who have participated in the compensation or to the Guifi.net foundation. What is clear is that the participant who receives the compensation loses the exclusivity of rights.
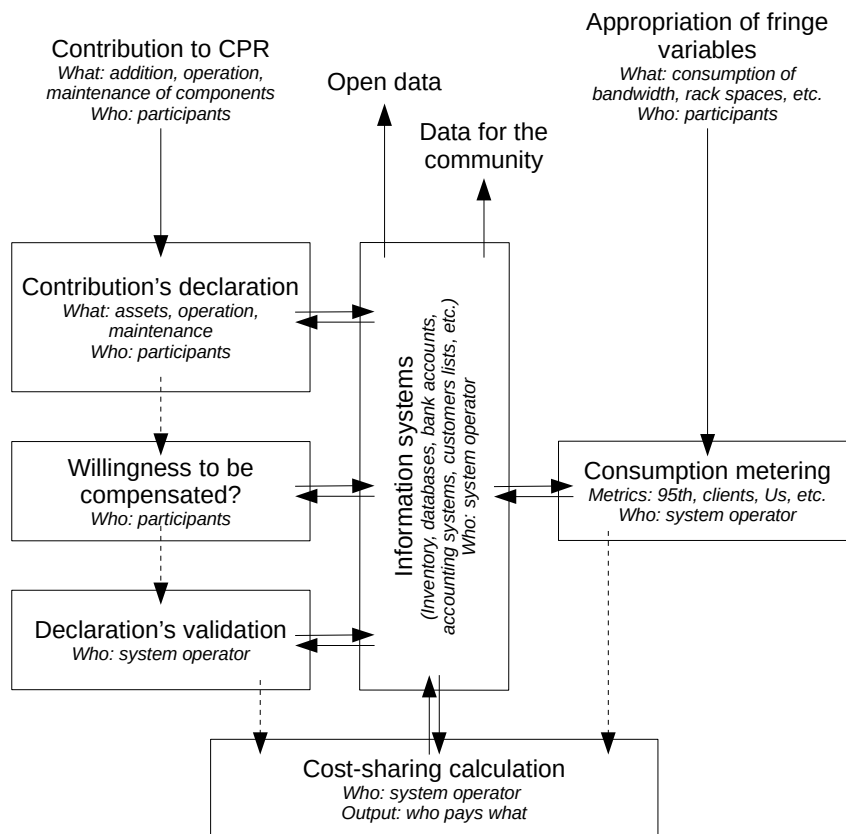
Figure 4.3: Generalised architecture for a cost-compensation system for CPRs.

as the number of customers of an ISP. This information dependency also happens in other areas, such as the inventory of contributions.

Nonetheless, in this case, those who have the information may have a strong temptation not to deliver the information to avoid having to compensate for the usage of the resources they have made. Thus, measures to enforce the delivery of the needed information and avoid fraud are likely to be required. Finally, cost assignments are calculated by collating the registries of contributions and consumption.

The declaration of contributions and claims for compensation is done through the website in a single form. To avoid obsolete claims and to encourage participants to keep the information systems up to date, cut-off dates have been set. All system operations (i.e. validation of declarations, maintenance of information systems, consumption measurements, and cost-sharing calculations) are performed by the Guifi.net foundation.

4.4.1 Cost classification

Any cost to be compensated is assigned to a *clearing house*[17] or split into two or more of them. A clearing house is a functional aggregation of network components or services. At present, there are two categories of clearing houses in Guifi.net: the NOC, which includes all the services and infrastructure from the exterior traffic to the links connecting the NOC to the territorial exchange points (see Section 3.6.3), and the territorial, which encompasses the last-mile services

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[17] *Taula de compensació* in Catalan.

and infrastructure, that is, the infrastructure and its related services from the PoPIX to the final points of consumption. The costs of a cabinet (hardware, electricity bills, etc.) to distribute the fibre in a district is an example of a cost to be allocated to a single clearing house, the corresponding territorial clearing house in this case. In contrast, some of the human resource costs of the Guifi.net foundation are distributed among several clearing houses because the workers perform tasks in them.

The cost-compensation system is implemented through a set of clearing houses. Hence, each clearing house has its own cost-compensation instance and its own compensation cycles. In the clearing houses, the costs are assigned to *cost centres*. The cost centres are defined based on finance and accounting criteria. A typical criterion is the CAPEX and OPEX distinction. In practical terms, the crucial difference is that, whereas the settlement of costs classified as CAPEX can be distributed among several compensation periods, those classified as OPEX must be cleared entirely in the next compensation settlement. Recurrent costs, such as utility bills, are always OPEX. On the contrary, capital intensive investments for hardware renewal or infrastructure deployment are CAPEX costs for which repayment is usually distributed over time.[18] Single payment fees, like registration fees, can also be repaid over several compensation cycles.

The redistributions of CAPEX and OPEX are calculated separately due to their different natures. In the territorial clearing houses, both CAPEX and OPEX costs are usually significant. Thus, two cost-compensation calculations exist for each of them. Conversely, in the NOC, given that, OPEX costs are generally much higher than CAPEX costs, the CAPEX is subsumed as OPEX through periodic charges for a given number of months. Furthermore, the NOC has different kinds of cost centres defined, and some costs are split between two or three cost centres (see Section 5.3).

In terms of implementation, costs are classified through two main processes. The first is for the costs incurred by the participants, which are typically the costs of new deployments, maintenance, and upgrades; thus, they are usually assigned to a single clearing house. In this case, the selection of the clearing house is made by each participant through the web form for declaring the contributions and is checked and amended where necessary by the Foundation as part of the process of contribution validation. The second is for the costs incurred by the Foundation. The bulk of these costs is for staff, hardware, and services. These costs are assigned to the clearing houses by the Foundation. As already discussed, staff costs are usually split among several clearing houses and cost centres.

4.4.2 Cost-compensation meetings

As already explained, the cost-compensation system is implemented through cycles and through clearing houses. Each of these cycles always comprises a meeting open to all the participants of the given clearing house. These meetings are aimed at discussing and approving the cost-sharing assignments in the previous cycle, which are presented in advance by the Foundation, and at discussing any operational issue affecting the scope of the clearing house, such as doubtful cost classifications, new deployments or updates, or rules affecting the development of the cost-compensation instance itself. This is why, for instance, cost-compensation periods may vary from one clearing house to another.

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[18]The amortisation period must always be shorter than the lifetime of the asset.

4.4.3 Cost-sharing fundamentals

The total cost borne by a participant of a clearing house is the result of a fixed charge that is equal for each participant, the *membership fee*, plus a charge for consumption for each cost centre from which the participant uses resources, the *consumption fees*. Consumption fees are usually calculated by proportionally allocating the costs of the cost centres among the resource usage of the participants.

The rationale behind this cost-sharing mechanism is two-fold. On one hand, the membership fees, which are equivalent to equally weighted parts of the costs, act as a filter against opportunistic participants to keep the costs related to the number of participants under control by establishing an entry barrier. On the other hand, proportionally assigning most of the costs to each participant's usage not only avoids negative externalisations from big consumers towards smaller consumers but also has a wealth redistributive role because it makes technologies available that smaller consumers could not afford separately or though coalitions without big consumers.

4.5 Separation of powers

The source of legitimisation is the Guifi.net community,[19] which drafted the first version of the network licence through two acts of legitimisation, in January 2005,[20] and the establishment of the Guifi.net foundation in July 2008 set the ground rules of two branches of power within the project, the legislative held by the community and the executive held by the Foundation.

By default, the policy-making process (i.e. the legislative branch in the internal organisation of a state) is open to all the community and is made by consensus. Occasionally, the deliberations are kept confidential or restricted in participation for confidentiality reasons.[21] If consensus is not reached, decisions are made by taking a vote – sometimes by weighted vote. The natural places for the discussion of operational issues are the cost-compensation meetings and working groups, whereas the discussion of proposals affecting the ground rules takes place in specific public meetings open to the community. In addition, questions of common interest can also be addressed during the general meeting held by the community once a year.

The Foundation, as the head of the executive branch, has the duty to veto any decision made by the legislative power contravening the fundamental principles of Guifi.net expressed in the network licence. In addition to this inescapable duty, it may provide guidance and steer the deliberation process but does not have the right to intervene in decision making. As the executive power, it is also responsible for implementing enacted regulations, including system operation tasks. The *duty to veto only* solution has proven to be a very practical solution to create a common ground for the active collaboration among the stakeholder groups and professionals.

In terms of law interpretation, which is in the field of the competence of the judicial branch, the developed internal tools are limited to the conflict-resolution system, which is aimed at dealing with conflicts among participants, which are the most likely to happen. In the pursuit of

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[19]Before the drafting of the first network licence, anyone who wished to be was a member of the community, which implied embracing the principles of sharing and mutual support. With a network licence in place, anyone who accepts its terms belongs to the community.

[20]It was called *Comuns sensefils* in Catalan (https://guifi.net/ca/ComunsSensefils), wireless commons licence (https://guifi.net/en/WCL_EN). In December 2009, it was replaced by the present CXOLN.

[21]Mostly because either some of the information involved is confidential by law or for strategic reasons (e.g. to avoid providing commercially sensitive information to competitors outside of the ecosystem, such as infrastructure deployment plans).

effective power separation, the rest of the conflicts, especially those involving the Foundation, are intentionally left to be settled through external legal mechanisms.

4.6 Legal armour

The maximisation of the growth of the project and the assurance of its endurance over time are the key design criteria of almost any tool in Guifi.net. The overall legal structure of the project and of its bases, in particular, play an especially critical role in the achievement of these goals. Any mistake in their design or implementation can jeopardise the whole project at any time. The legal framework was analysed under these premises. As a result, a structure entailing the definition of a good (an IP network with a specific legal form), the commons, described by a legally valid instrument (a licence), and a legal entity obliged to protect the good (a private foundation) was chosen.

Hence, the legal bases of Guifi.net are composed of pairing the licence and private foundation, in which the licence determines the legal good of the project, making its scope and conditions of existence explicit, and the Guifi.net foundation, through its mission, obliges itself to ensure compliance with the licence. The endurance of the mission of the Foundation over time is guaranteed by the private foundation Catalan law, which prevents private foundations from changing their mission under any circumstances. In the case of Guifi.net, due to the link between the licence and the Foundation, this legal impediment translates into the impossibility of changing the operation or exploitation conditions of the existing or future assets.

The assets of the Guifi.net CPR are owned either by the Foundation or by the participants. The Catalan legislation allows the dissolution of the private foundations. However, under no circumstances should the dissolution of the Guifi.net foundation affect the CPR because, according to this legislation, in the case of the dissolution of a private foundation, all the remaining assets are placed under guardianship of the Catalan Government, which must preserve them according to the purpose for which they had been donated or bought by the Foundation.

Regarding the assets owned by the participants, although the contribution does not alter the ownership rights, the assets can still be freely traded. However, it does entail a servitude that obliges maintaining the operation and exploitation conditions, that is, the existing assets must remain in the CPR regardless of whether they change hands.

In relation to the concept of common property and the bundle of rights outlined in Section 2.4.4, the Foundation is the *de jure* institution in charge of representing and effectively protecting the common property as shared private property from abuse at the collective-choice level of management and from exclusion or alienation (such as privatisation). As such, the members of its governing bodies – the board, in normal operation, or the Foundations' protectorate of the Catalan Government, in case of dissolution of the Foundation – must be independent, free from any conflicts of interest regarding the telecommunications sector, and unquestionably committed to serving the public interest and the Guifi.net CPR, in particular.

4.7 Historical development

Generally, the improvements in the governance system have been introduced in response to specific challenges as they appeared. Thus, the development of the governance system is inseparable from the technical, economic, and social evolution of the project. From the design criteria perspective, a clear success factor of Guifi.net has been to find a well-balanced compromise

in scaling introduced changes – not so small as to make the changes simple but non-reusable patches, and not so large as to make them effectively unimplementable. Informally, we can put the intended scaling factor of the sought solution between one and two orders of magnitude higher than the problem addressed. Systematisation, automation, and autonomy have been the guiding principles. It has also been key to keeping an appropriate balance between hands-on and conceptual work.

Figure 4.4 presents the most relevant threats and needs that are faced over time, their context, and the governance tools developed in response to them. The initial meetings among the inhabitants of neighbouring villages of the county of Osona took place in the first quarter of 2004. The initial wireless links were set up in mid-May by the villagers and, in a few months, several villages were already connected to the backbone. Although the initiative was very well received by the local authorities because it offered an affordable and immediate solution to the generalised problem of lack of Internet access in a familiar way to them (the collaborative approach), most them looked forward to further legal development; thus, very few dared to invest in such an incipient and innovative project. The development of the concept of a federated proxies network not only contributed to making the use of the very few existing and limited-bandwidth DSL connections more efficient and resilient but also contributed to circumventing the legal challenges of Internet access liability because the service required personal credentials. The democratisation of the access to these few DSL connections, mostly from the few local administrations that had already joined the network, exponentially increased the attention and interest of the inhabitants in the surrounding villages. This explosion of interest, in turn, caused more councils to join the project and caused the appearance of the initial for-profit participants, the installers. The installers made an invaluable contribution to the democratisation of access to the network because they eliminated the need to have technical expertise to join the network and the dependency on volunteer contributors. The development and integration on the web of a set of tools aimed at easing the participation and reducing the required technical knowledge, such as the maps and the *unsolclic*,[22] also proved very useful in the democratisation of participation.

The release of the first network licence marked a real turning point in terms of certainty both conceptually and legally because it clarified the scope of the project, which was to develop a telecommunications network, and the implementation conditions, which should be open and remain open to everybody for any (legal) purpose. The drafting process of the network licence settled most of the controversies, such as the legitimacy of economic activity, and its approval enabled the integration of many other councils, the consolidation of the installer stakeholder group, and the significant increase in the investment in network assets.

Nonetheless, the development of a for-profit activity also involved the appearance of bad practices that have put the whole project at stake several times and have triggered, at least partially, some of the major improvements in the governance system, including the establishment of the Guifi.net foundation and the development of most of the governance tools, such as the cost-compensation and conflict-resolution systems, the sanctioning regime, the second version of the network licence, the professional agreements, and so on.

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[22]A software solution that automatically generates the configuration setup of the devices to be connected to the network.

YEAR | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019

FACTS

PROJECT INCEPTION
- Volunteers
- Community empowerment
- WiFi technology

WEBSITE
- Initial version

FIRST PUBLIC ADMs
- Village councils to fight lack of Internet
- Local public funds for supernodes
- Internet via proxy connected to precarious DSLs

ISPs: INITIAL ECONOMIC ACTIVITY
- Local SMEs to carry out Councils' projects and to connect end-users
- Initial Internet access delivered by ISPs as a service (using DSLs)

- Thousands of nodes, tens of Councils and SMEs, etc.

WEBSITE
- Maps
- Unsolclic (HW auto-conf)

WEBSITE
- Crowdfunding

BAD PRACTICES
- Some SMEs working below expectations
- Bad reputation for the whole project

PROFESSIONAL AGREEMENTS
- Formalisation of duties to pursue a professional activity

- NRA registration
- Initial optical fibre deployment

- RIPE-NCC

- Catalan IX CATNIX

INTERNET CONNECTION
- Carrier house, wholesale Internet
- gLIR working group

REGIONAL BACKHAUL
- Fibre optic rental
- PoPIX

ISPs: LACK OF COOPERATION
- Not pooling services due to lack of collaborative tools and habits

COST-COMPENSATION SYSTEM
- At carrier house
- Cost oriented
- Costs shared according to resource usage

COMPENSAT. SYS.
- Two more zones added
- Dissemination to other zones

COMPENSAT. SYS.
- System activation
- Two initial zones

ISPs: TRADE WAR, CARTELS, ETC.
- Poor reporting
- Lack of tranparency
- Private deployments

CONFLICT-RESOLUTION SYS.
- Development
- Activation

SANCTIONING REGIME
- Development
- Activation

- Fibre massive adoption
- XAFOGAR: 1M€
- deployments in other areas

XAFOGAR kick-off
- Fibre optic flagship project
- Goal: connect every household of Garrotxa county
  Traits: 1) strong commitment of the county public agency, 2) systematic reporting, 3) 4 competing ISPs since the beginning

DISINVESTMENT
- Because CAPEX is not yet taken into account.

COST-COMPEN. SYS.
- CAPEX
- Compensation buckets

ISPs: JOINT LOBBY
- Complaint about the cost-compensation syst. efficiency
- Attempt to impose radical changes under threats of massive abandonment of the system

COMMUNITY
- Identification as a major challenge
- Reactivation of non-profit participants
- Joint (for-profit, non-profit, Foundation, pub. adms.) long & fruitful discussions
- On-going work

COST-COMPEN. SYS. & OTHERS
- Joint review started
- On-going work

THREATS/NEEDS

- Difficulties for rising investment due to uncertainty
- Fragmentation of efforts due to the lack of a shared vision

- Legal requirements (registration at the NRA, etc.)
- Impossibility to access public/private institutions, professional resources, etc.

DISINVESTMENT
- Due to lack of reinvestment. Strong competition in prices does allow ISPs to maintain the existing network mostly deployed by volunteers and public funds

ISPs: BREACH OF DUTY AGAIN
- Old + new bad practices

RESPONSES

LICENSE
- First release
- Specification of rights and duties
- Mandatory for all participants

FOUNDATION
- Establishment
- NGO, non-partisan, without conflicts of interest

LICENSE
- Modification to fulfil legal requirements

LICENSE
- Second version release

COST-COMPEN. SYS.
- OPEX
- Per PoPIX

ECONOMIC ACTIVITY AGREEMENT
- Mandatory for all professionals
- Enforcing participation in the cost-compensation sys.
- Commitment based commons

SANCTIONING REGIME
- Tweaks
- Reactivation
- Systematic application

Figure 4.4: Historical development. Purple text indicates facts, red threads or needs, and green the responses to threads or needs.

4.8 Relation to Ostrom's research

As discussed in Section 2.4.1, CPRs were studied in depth by Ostrom. In [113], Ostrom presented eight *design principles* of the long-enduring CPR institutions held in common and in [116], proposed five *basic protocol requirements* for achieving adaptive governance. According to Ostrom, local adaptability is indispensable for the sustainability of CPRs because their management is highly dependent upon the type of resource involved and the local conditions, meaning that an effective strategy at one location or of one particular resource may not be necessarily suitable for another.

Ostrom focused on natural resource management. Nevertheless, her design principles and basic requirements fit admirably with such an artificial resource as a computer network, as we discuss below. To the best of our knowledge, Ostrom's work remained unknown by the Guifi.net community until 2011. By that time, although the Guifi.net community was pretty well established and had developed the vast majority of its governance tools, the discovery of her work contributed decisively to strengthening the community's confidence because, interestingly, the tools already developed fit very well with her findings and with consolidating the theoretical framework and provided invaluable guidance in identifying and developing the remaining tools.

4.8.1 Design principles of long-enduring CPR institutions

In this section we discuss the degree of applicability of each of the eight design principles of [113] for stable local CPR management to Guifi.net.[23]

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[23]Ostrom's quotations, in italics, are extracted from Table 3.1 of [113].

'**1. Clearly defined boundaries:** *Individuals or households who have rights to withdraw resource units from the CPR must be dearly defined, as must the boundaries of the CPR itself.*'

- The term *participant* is used instead of '*individuals or households*' to better accommodate the diversity of stakeholder groups.

- There is a clear criterion to establish the participants '*who have rights to withdraw resource units from the CPR*': the acceptance of the network licence, which is mandatory to use any CPR resource. The fact that, in this case, the CPR is mostly artificial and that the current legislation allows the deployment of telecommunications infrastructure in private domains virtually nullifies the risk of legitimate rights of individuals who have not subscribed to the network licence.

- '*The boundaries of the CPR*' are '*clearly defined*' by the licence and the professional agreements, and the existing resources only are those that are listed in the inventory of the information systems.[24]

'**2. Congruence between appropriation and provision rules and local conditions:** *Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local conditions and to provisioning rules requiring labour, material, and/or money.*'

- '*Appropriation rules [...] are related to provisioning rules requiring labour, material, and/or money*': The obligation to contribute the CPR based on the appropriation, mostly proportionally, is one of the fundamental principles of Guifi.net as a whole and of the cost-compensation system, in particular.

- '*Appropriation rules [...] are related to local conditions*': The cost-compensation system is implemented through local autonomous instances – the *clearing houses*. In each of them, the participants are able to tailor the implementation particularities that better suit their needs as long as they are not contrary to the network licence, in which case they would automatically be vetoed by the Foundation.

'**3. Collective-choice arrangements:** *Most individuals affected by the operational rules can participate in modifying the operational rules.*'

- Inclusion in governance affairs is another of the fundamental principles of Guifi.net. More precisely, the decision-making and policy-making processes are, by default, open to every participant and are only kept confidential or restricted in participation for confidentiality reasons. However, in the case confidentiality arguments can be used as arguments to exclude from the deliberations or vote any of the participants directly affected by the rules under discussion are exceptions. Any exclusion of this kind would be considered arbitrary; thus, it would automatically activate the Foundation's veto power

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[24]To have an up-to-date inventory of the CPR assets is a must for the implementation of a truly participatory institution, according to Ostrom. To highlight the strategic importance of the inventory, in Guifi.net, there is a saying that 'what is not listed in the inventory does not exist'.

'*4. Monitoring: Monitors, who actively audit CPR conditions and appropriators' behaviour, are accountable to the appropriators or are the appropriators.*'

- '*Appropriators' behaviour*' is monitored by the participants, who report to the Foundation but also by the Foundation to prevent, *inter alia*, cartel behaviour.
- The '*audit CPR conditions*' mainly include the monitoring of the network and the appropriation metering. The Foundation monitors the core network components as a task of the operation of these resources. The participants, especially the operators and maintainers, monitor the edge components. The Foundation appropriates the metering where possible. The rest of the information required must be delivered by the affected participants. The breach of this duty activates automatic sanctions.
- The Guifi.net foundation is accountable to all Guifi.net participants and, by law, also to the Catalan Government.

'*5. Graduated sanctions: Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of the offence) by other appropriators, by officials accountable to these appropriators, or by both.*'

- This is implemented through the ('*graduated*') sanctioning regime. Like most of the system operation tasks, it is applied by the Guifi.net foundation. It is one of the tools that, although it had already been considered, was not yet developed when the Ostrom's work was discovered by the Guifi.net community.
- The extension of the sanctioning regime to make it also applicable to the officials is being considered.

'*6. Conflict-resolution mechanisms: Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.*'

- It is implemented through the conflict-resolution system, which consists of three stages, all of them seeking and encouraging dialogue. The last includes the drafting of a binding resolution.
- Any conflict involving the Guifi.net foundation is intentionally excluded from the conflict-resolution system as a power distribution measure. Any participant, at any time, can submit a case to an external competent authority, although agreement on the sought solutions is always preferred.

'*7. Minimal recognition of rights to organise: The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.*'

- All the activity within the project is intended to be compatible with the legal framework. Thus, the project should not be '*challenged by external governmental authorities*' for legal reasons unless there is unintended unlawfulness, in which case, a collaborative attitude of the authorities is expected, as has generally been the case.
- In the European Union, the telecommunications sector is liberalised; thus, any public administration should not discriminate CNs. Moreover, given the social value of the project, an even more proactive attitude of the public authorities is desirable. This has been the case for many municipalities. Nonetheless, very hostile – and even illegal – attitudes from larger administrations have also been observed.

'For *CPRs that are parts of larger systems:*

8. Nested enterprises: *Appropriation, provision, monitoring, enforcement, conflict-resolution, and governance activities are organised in multiple layers of nested enterprises.*'

- Decentralisation and local autonomy have been key for scaling-up, and it is generally accepted that current and future strategies must proceed further along this path.

4.8.2   Adaptive governance

In this section, we discuss the suitability to Guifi.net of each of the basic protocol requirements for achieving adaptive governance [116]. [25]

'**1. Achieving accurate and relevant information** *by focusing on the creation and use of timely scientific knowledge on the part of both the managers and users of the resource.*'

- There is a strong interaction of the Foundation and of the participants with universities and research centres. The Foundation has over a dozen research agreements signed and has participated as a partner in five European research projects. The result main of these collaborations is a remarkable work of conceptualisation and optimisation of diverse governance tools.

- The literature review has been very inspirational. The fact of learning about other initiatives working around the commons has contributed to creating confidence in the project.

- The Foundation's endeavour is to convince the participants – especially professionals – to base their decisions on objective data, not on mere beliefs.

'**2. Dealing with conflict**, *acknowledging the fact that conflicts will occur, and having systems in place to discover and resolve them as quickly as possible.*'

- Conflict is part of the Guifi.net history and has triggered major changes, which have made the system more resilient. This includes the development of a number of channels to deal with conflict.

'**3.   Enhancing rule compliance** *by creating responsibility for the users of a resource to monitor usage.*'

- Although responsibility for the users is always welcome, the conviction is that resiliency cannot depend on the participants' will, which may change over time. The strategy adopted revolves around establishing protocols, automation, and enforcement.

'**4.   Providing infrastructure** *that is flexible over time, both to aid internal operations and create links to other regimes.*'

- The Guifi.net community has maintained an infrastructure to support the internal operation that has evolved continuously and incrementally to address its growing complexity, scale, and needs, and to facilitate participation while keeping it effective

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[25]Italics and bold typesetting denote quotations from Ostrom [116]. Italics denote quotations from Wikipedia [163].

for all. The community maintains links with external organisations and other regimes in other locations and other topic areas.[26]

'***5. Encouraging adaption and change*** *to address errors and cope with new developments.*'

- Adaption to change is also part of Guifi.net history. From the techno-economic point of view, some of the major changes faced include the integration of OF and the evolution from retail Internet access to wholesale. In social terms, the way people communicate is constantly changing due to technological innovation. The community has also to deal with radical changes in the legal framework provoked by technological and social progress.

4.9   Conclusions

In this chapter, we have described in detail the design of a governance model for Guifi.net. The model implements its principles under a governance framework and allows structured participation and cost sharing. The system has developed organically to address the evolution, expansion and professionalisation of the community. Our investigations deepen knowledge and understanding of the critical role the proper management of the conflicts of interest plays in the whole Guifi.net project. They also shed light on the legal architecture aimed at the preservation of the network and the associated activities, which is deeply shaped by the concern for deterring conflicts of interest. Our understanding of these legal and organisational structures, to which we refer as the governance system, have been the basis for the successful development of the economic system, studied in Chapter 5.

In the field of the study of the commons, we can state that, the Guifi.net is a case that extends the CBPP model to capital intense resources, a (material) network infrastructure in this case. The analysis of the governance model from the perspective of the Ostrom's design principles and requirements shows that the model complies as a CPR. It is not necessary that all governance systems have the same elements, but we do believe that it is important that these fit well because, as shown in Chapter 5 and Chapter 6, misalignments lead to conflict. The development of bottom-up projects entail complexity and uncertainty due to changing requirements and growing scale. Therefore, an issue-based or reactive design and development approach works better than *a priori* top-down design, which more adequate for scenarios with well-predefined requirements, uniform structures and no changes expected. Our observations show that Guifi.net has followed evolutionary development. In addition, as Ostrom states in her principles and requirements, the complexity of mechanisms has to be proportional and adaptive to the difficulty of the problem at hand, otherwise we will be under or over regulating, with potentially catastrophic effects.

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[26]The eReuse.org initiative was inspired by the Guifi.net model [53, 52].

5

Guifi.net – Economics

Preface

This second chapter, which is aimed at providing a systematised description and analysis of Guifi.net, focuses on economic matters. It is structured in two main parts. The first addresses the topic from the general perspective. It analyses the financial flows as a whole and then discusses the sizing of the territorial clearing houses and examinees the CAPEX and OPEX financial instruments. Next, it presents and discusses how the sustainability of CAPEX and OPEX is ensured. The first part concludes with an analysis of the current open issues and how they are being currently addressed by the community in general and by the Foundation in particular. The second part elaborates in detail on the cost-sharing mechanism that Guifi.net has developed as part of its cost-compensation system through the accurate analysis of its implementation in the specific case of the distribution of the interconnection costs of the NOC. In addition to providing detailed information on the implementation aspects, it investigates the sensitivity of the system to alterations in the set of participants, comparing the results to a widely known cost-sharing mechanism (the Shapley value). This chapter is the last of the three devoted to the study of Guifi.net.

5.1 Introduction

Guifi.net started in 2004 as a grass-roots movement with the objective to provide Internet access to rural areas using WiFi. However, over time, Guifi.net experienced enormous growth, offering novel models of participation and new business opportunities. This environment has stimulated the development of a number of companies and entities that offer professional services inside the network and make investments to improve and extend the infrastructure and services. At the time of writing, the investment in WiFi deployments has been clearly exceeded by the investment in OF, which is much more capital intensive, and it is expected that the OF roll-outs in the middle term will replace almost all WiFi deployments.

The capacity to enable economic local and regional ecosystems with professionals offering services has proved to be one of the essential factors for making Guifi.net sustainable and scalable beyond voluntary efforts and non-refundable contributions. Another essential factor has been the ability to create a context of sufficient trust to enable the size of the investment that conservative estimates put at over 10 million €. Underlying this environment of confident economic success are both the governance system as a whole, which is analysed in Section 5.3, and the economic subsystem, which is discussed in this chapter.

The rest of the chapter is structured into two main sections, Section 5.2, which examines the economic system of Guifi.net in general, and Section 5.3, which elaborates on a case study

of cost-sharing in detail. Section 5.2 presents and discusses the main financial flows within the Guifi.net ecosystem, putting special emphasis on two particular facts. The first is the distinction between professional activity in the CPR itself, which is regulated, and professional activity developed on top of the CPR, which is liberalised. The second is that all CAPEX investments and OPEX costs must always be compensated for, regardless of the source of funding. Section 5.2.1 discusses the key considered aspects in the investment strategy, identifying three main zones based on the ROI period, and Section 5.2.2 elaborates on the influence these zones on the sizing of the clearing houses. Sections 5.2.3 and 5.2.4 analyses the main sources of funding of CAPEX and OPEX, respectively. The template for billing the subscribers of the service providers, which the Guifi.net foundation is promoting as a tool for improving the collection of CAPEX and OPEX fees, is presented in Section 5.2.5. Finally, Sections 5.2.6 and 5.2.7 concludes with a discussion of the open issues that remain open and how they are being currently addressed by the community and by the Foundation.

In Section 5.3, we discuss the cost-sharing calculation through studying the specific case of the cost-distribution of the interconnection between Guifi.net and the rest of the Internet, which is the network service with the largest number of participants. We analyse this case in sufficient depth to show the traits and operational details of a real working example. Sections 5.3.1 to 5.3.3 provide a detailed description of the use case of the cost-compensation system developed by the Guifi.net community of practice. Section 5.3.4 presents and elaborates on the datasets used. Section 5.3.5 elaborates on a mathematical model of the characteristic cost function, and Section 5.3.6 explains the cost-sharing mechanism. Section 5.3.7 analyses the sensitivity of the mechanism to participants with high usage. The results are compared with the Shapley value in Section 5.3.8, and Section 5.3.9 presents a proposal for improving the system currently used. The section concludes with an analysis against ceasing cooperation in Section 5.3.10. The conclusions of the chapter are presented in Section 5.4.

5.2   General approach

From the economic operation perspective, the Guifi.net project seeks the creation of virtuous circles of sustainability and expansion of network infrastructure based on the efficient use of the funds available and the connection of as many users as possible. Figure 5.1 shows the current state of the general economic organisation that the community is developing and implementing.

However, before proceeding to the analysis of the economic organisation in further detail, it must be made clear that its proper implementation is highly dependent on the governance system because neither the objectives nor the strategies of the project as a whole necessarily match the objectives and strategies of the participants or professionals, in particular. Thus, regarding the economic operation, the objectives of the Guifi.net governance system[1] are to ensure the following: (i) The available funds are effectively used for building network infrastructure. (ii) The infrastructure is effectively available to all the population. (iii) The infrastructure is built, operated, and remains according to the Guifi.net fundamental principles. Before any further analysis, it is also worth remembering that the scope of the CPR is limited to the network construction and its operation. Thus, it is outside of the scope of the project to rule over the profit of the professionals that use the network to deliver their services,[2] but speculative

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[1]The typical forms of fraud in the telecommunications sector include the diversion of funds to other purposes, the change of the conditions under which the infrastructure is built or maintained, and the lack of interest in connecting end users because doing so reduces the overall profit.

[2]As already discussed in Chapter 3 the construction and maintenance of a single common infrastructure used by all competitors under the same conditions delivers a true single market with close-to-perfect competition. As a
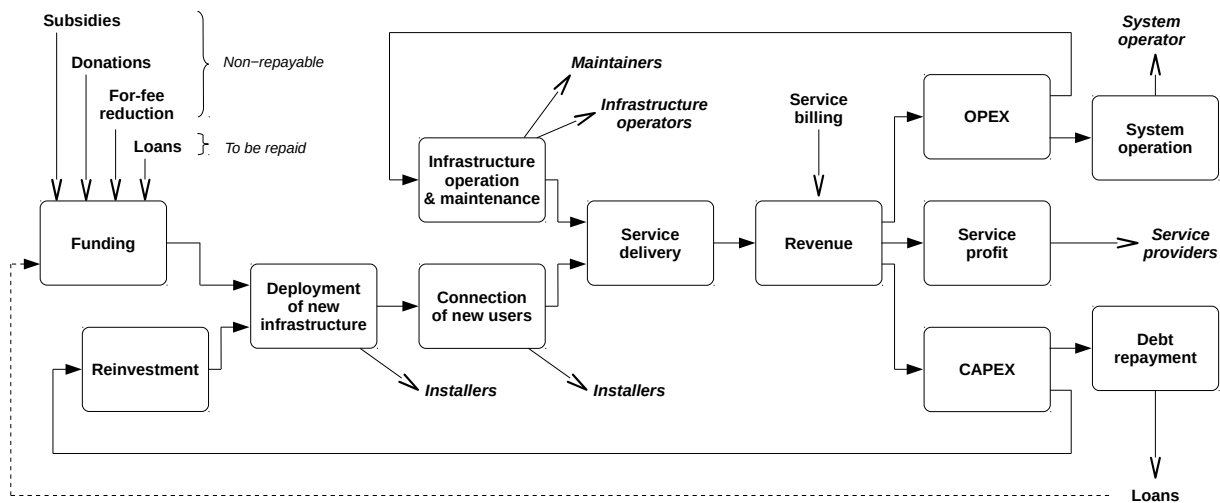
Figure 5.1: Global financial flowchart.

and extractive practices are not allowed in the construction, operation, or access to the CPR. Accordingly, the only two sources of profit within the CPR are labour remuneration and interest on loans. All of them are collectively established. The labour remuneration is set on the basis of fair salaries.[3] The interest on loans is set by compromising between being sufficiently high to be competitive with similar investment opportunities outside the Guifi.net system and providing excessive benefit, which also prevents abuse of the lending facilities.

As Figure 5.1 shows, the cycle starts with the presence of one or more external funding sources. The funds, which may be subject to a repayment obligation, are used to put some initial infrastructure in place by the installers and connect the initial users to it. Once the infrastructure is in place and is operated, the service providers start acquiring customers, delivering services, and generating revenue through the corresponding service fees. This revenue is used to cover the OPEX, to repay any debt, and to fund new infrastructure where possible, closing the virtuous circle in this way. In addition to this first reinvestment loop, which entirely depends on internal management, a second loop is possible on the basis of debt repayment. The realisation of this second loop does not depend exclusively on internal factors but also on external circumstances, including the investors' will, investment alternatives, and so on. Nonetheless, the timely repayment and attractive interest rates certainly have a positive effect on the investors' decision to keep their capital within the system.

5.2.1   Investment strategy

The investment plans are defined considering the ROI periods and influence of competitors. Three main types of areas can be defined based on these two factors. The *unprofitable areas* are areas with ROI periods longer than the infrastructure amortisation periods. The *single deployment areas* are areas with a market that is able to stand a single deployment. The *multiple deployment areas* are the areas capable of standing more than one infrastructure deployment. Very remote areas, rural areas, and cities are common examples of each of them. The classification

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result, as the free-market theory predicts, the commercial offers within Guifi.net have cheaper prices and better services than external competitors.

[3]Standardised labour prices are necessary to avoid conflicts in the cost-compensation system (introduced later in this chapter and further analysed in the next one).

is traditionally related to the population density and its purchasing power, that is, non-business parameters. However, business-related parameters, such as lower business costs and the capacity to activate alternate or complementary sources of funding, such as contributions coming from the beneficiaries, can make a difference in converting an unprofitable area to profitability.

In practice, most of the existing Guifi.net deployments have started taking advantage of the window of opportunity left by the traditional operators. In WiFi, given its low CAPEX, the deployments have usually been developed through a number of small investment cycles, deploying them first in the most profitable areas and extending to the rest later on, according to the available funds. A significant part of the funds for the iterations come from the neighbours of the uncovered areas who, following the example of their fellow citizens, want to extend the infrastructure to their homes. In OF, the scale of investment rounds has increased to accommodate the CAPEX needs and the specialisation of the sector.[4]

Contrary to the sharing spirit of the community and what was done in the past, nowadays, the deployment plans and associate marketing campaigns to gather investment from the beneficiaries are handled discreetly to counterbalance overbuilding and other bad practices noted by traditional operators. As a result of these bad practices, many very promising projects have been derailed.[5]

5.2.2   Clearing houses sizing

The sizing of the clearing houses (defined in Section 4.4.1) must seek a balanced compromise between operability – too large clearing houses become inefficient in the fulfilment of wealth redistribution objectives. Deployments in unprofitable areas are only viable by compensating for losses with gains from profitable areas.[6] Given that the territorial clearing houses are the natural place for local wealth redistribution, they are the ideal place for levelling the differences between neighbouring profitable and unprofitable areas. Thus, their geographical scope must seek a balance between these types of areas and never be limited to unprofitable areas unless a mechanism for wealth distribution between them is put in place, which is not yet the case in Guifi.net, although it is planned for the future.

5.2.3   CAPEX

The two sources to finance new infrastructure are external resources and reinvestment. The main sources of external funding are the following.

Non-recoverable They are irreversible contributions (in most of the cases). The most common are the following:

    Donations They are contributions made without return consideration. The contributions can be in-kind, monetary, labour, knowledge, and others, including DIY contributions. They can be made to the community, in which case, they are essentially protected by

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[4]The specialisation index of the WiFi installers is very low, meaning that a single installer is able to perform most of the tasks involved in deployment if not all of them. However, in OF, this index has increased to the point that there are installers specialised in a single job, such as cable deployment, fibre splicing, and so on.

[5]There are well-founded suspicions that confidential administrative information has been leaked by public administrations to the competitors.

[6]The viability of these deployments outside Guifi.net is frequently based on subsidies; thus, it always depends on the continuity of the subsidies. In Guifi.net, these types of solutions are unacceptable due to their dependency on third parties and because they are unsustainable. So far, the occasional subsidies received have been integrated into the financial flows as another source of funding.

the network licence, or to the Foundation, in which case they are also protected by the law applicable to foundations and the Guifi.net foundation bylaws. Although the notion of irrevocability is implicit in the donation concept, according to the network licence, the in-kind contributions to the community could be reverted. In contrast, the donations to the Foundation are legally irreversible. In addition, the donations to the Guifi.net foundation are tax-deductible. The motivations for donating range from supporting the community and the project in general to promoting very specific actions, including the initial deployments of an area, the test of new technologies, and so on. Some of the funding instruments explained below are donations to the Foundation, in some cases.

For-fee-reduction contributions These are contributions made by the participants who want to have access to a specific deployment and avoid the line rental fees. Thus, they are contributions made expecting a specific return. The donations are made in exchange for a reduction of the service fee once the infrastructure is put in production. It is a stipulated amount corresponding to the estimated average CAPEX per connected household. This funding instrument is not common in WiFi deployments. Currently, the amount for OF deployments is 1,500.00 €. The resulting lines are referred to as *purchased lines* Formally, these are donations to the Foundation, which has the task of guaranteeing the proper execution of the projects.[7] This is a very convenient funding instrument because it provides up-front non-repayable capital in a highly replicable fashion. Despite the obstacles from service providers (see Section 5.2.6), it is very successful in some areas, and the Foundation is highly promoting it.

Subsidies They are non-repayable contributions by public administrations. Although small in amount because they basically come from small local administrations, they have contributed to the expansion of the WiFi network in the past. However, beyond these local contributions, Guifi.net has been traditionally excluded from the major sources of this type of funding.

To be repaid These are capital contributions that must be repaid, frequently in addition to interest. They are typically five- to seven-year loans (i.e. medium-term loans). The fact that the borrowed capital must be repaid brings additional certainty to their efficient use. The most common types of loans are the following.

From public administrations Commonly, they are used for strategic deployments aimed at sparking further investment from other agents by showing commitment and financing the first pieces of infrastructure to show the potential. They are usually interest-free. Although the total contribution in the overall financial capital is currently rather low, this type of funding has been key to activate very successful deployments.

From private lenders They are private loans frequently with financial interest. To attract lenders, the interest rate is usually higher than the interest rates offered by banks. Usually the lender does not bind the loan to any specific deployment.

From investment banks These loans have started being explored as an alternative to the loans from retail and commercial banks.

Repayable Are contributions that at some point might be repaid by the end beneficiaries of a deployment.

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[7]This kind of contributor can also be referred to as a crowdfunder because they receive a reward – the fee reduction – in exchange for having paid some money up front.

From end-users These are contributions to specific deployments made by users. Although this option is nominally open to everybody, so far, in most of the existing cases, the lender has been a for-fee-reduction contributor who has contributed additional capital to accelerate the execution of the project. A typical case is an industry that incurs the total cost of the deployment in its industrial park to ensure rapid execution. The immediate repayment [8] in addition to the corresponding interest were agreed upon for these cases, where possible. However, for the time being, almost none of these lenders has expressed the desire to receive the capital or interest back.[9]

From professionals These are contributions to specific deployments made by professionals who incur the cost of a deployment to sell a rental service to a customer. in contrast to the *rented lines* or *financed lines*, which are financed by a third-party investor. The resulting lines are referred as *rented lines* (see *line rental fees* in Section 5.2.5 for the monthly fees). The customer has the right to pay the for-fee-reduction contribution at any time, hence, stop paying the rental fee.

According to the Guifi.net principles, any user of the network must participate in the recovery of CAPEX and OPEX of the network regardless of the source of funding. Conceptually, this rule prevents dumping practices (see Section 6.4.19) in addition to recapitalising the system. At the implementation level, the redistribution of these costs is made within the scope of the clearing houses through objective prefixed amounts per compensation period and per participant in the clearing house or per service provider customer.These amounts are referred to as fees. The only participants that are exempt from CAPEX fees are those who have made the for-fee-reduction contribution or have incurred the total cost of deployment. The for-fee-reduction contribution can be made at any time, but, in any case, the recurrent fees that may have been incurred before can be recovered or deducted.

Currently, the only reinvestment has come from the CAPEX recovery of deployments funded through donations and non-refundable subsidies because all of the projects funded through loans are still in the stage of investment recovery (i.e. the break-even point has not yet been reached in any of them). It is in the power of each clearing house to decide on the reinvestment strategies, but in any case, they must always be reinvested in network infrastructure and cannot be used for any other purpose.

The CAPEX contributions of the Guifi.net foundation to the CPR are assigned to the corresponding clearing house and are settled like any cost of any other participant.

5.2.4   OPEX

Like in CAPEX, in OPEX there cannot be a profit because the operational activities are part of the CPR. The cost of the interventions of the installers, maintainers, and operators (labour, hardware, travelling costs, etc.) are pre-established through objective estimations. The standard operations are also predetermined in terms of duration and, thus, their total cost, too. All these costs are reported to the respective clearing houses for their settlement.

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[8]For instance when, with the necessary budget already in place, additional for-fee-reduction contributions are made.

[9]However, it is also true that very few of them have formalised their contributions as donations. In some cases, the contributors have explicitly stated that the reasons to do so are that they prefer to keep the capital invested in exchange for having the right to track the development of the project.

The recurrent costs of the activity of the Guifi.net foundation, as the system operator, are also CPR OPEX costs and are distributed among the different clearing houses.[10]

5.2.5 Revenue streams and service-detailed billing

The two main sources of net income in the project are the non-repayable contributions – project revenue – and the service billing from the service providers to their subscribers – service revenue. The non-repayable contributions are essentially devoted to infrastructure deployment, and they only cover a fraction of the total CAPEX costs. Therefore, the rest of CAPEX and the entire OPEX costs must be obtained from the service bills that the service provider issues to their customers. From a business as usual (BAU) perspective, the service providers have a business-to-customer (B2C) relationship with end-customers and a business-to-business (B2B) with the CPR professionals. Of the CPR professionals, only the installers have a B2C relationship with end-customers and only when the end-customers contract the installations directly from them and not through a service provider, which is the most common case.[11]

To harmonise and secure the fee collection and increase the transparency to the customers, the Foundation developed a template to be used by the operators for invoicing their service subscribers, which is presented in Figure 5.2. As the figure shows, the invoices must include the following items.

Line rental fees These are the total standardised CPR CAPEX amounts. The current amounts are 17 € for OF and 4 € for WiFi per month per customer. It is only charged to the customers who have not made the for-fee-reduction contribution.

Network operation fees These are the total standardised CPR OPEX amounts. The current amounts are 6 € for OF and 4 € for WiFi per month per customer.

Service fees These are the additional charges set by each service provider. The fee must include the service provider's CAPEX and OPEX amounts that are not part of the CPR and, optionally, the desired profit.

The proper implementation of this billing system also requires the service providers to provide updated data to the corresponding clearing houses through the Foundation. Currently, the billing template has not yet been adopted by any of the service providers. However, in the active clearing houses, the fees are already accounted to the greatest possible extent (see Figure 3.2).

5.2.6 Open issues

At the time of writing, some companies operating within Guifi.net, especially the largest ones, are exerting a great deal of pressure to gain control over the infrastructure to manage it at their will, using the pretext that the current setting is not viable. They have openly expressed their intention to leave the project unless the community accepts a set of changes they propose. Many other participants, including volunteers, co-ops, associations, and other companies, as well as the Foundation, have expressed serious doubts about the compatibility of these changes with the spirit of the project.

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[10]To reduce costs, the Foundation prioritises the collaborations based on exchange and other win-win agreements.
[11]The BAU is not suited for describing the complexity of Guifi.net as a whole, but it is adequate to highlight the most relevant traits of the relations between end-customers, service providers, and CPR professionals.
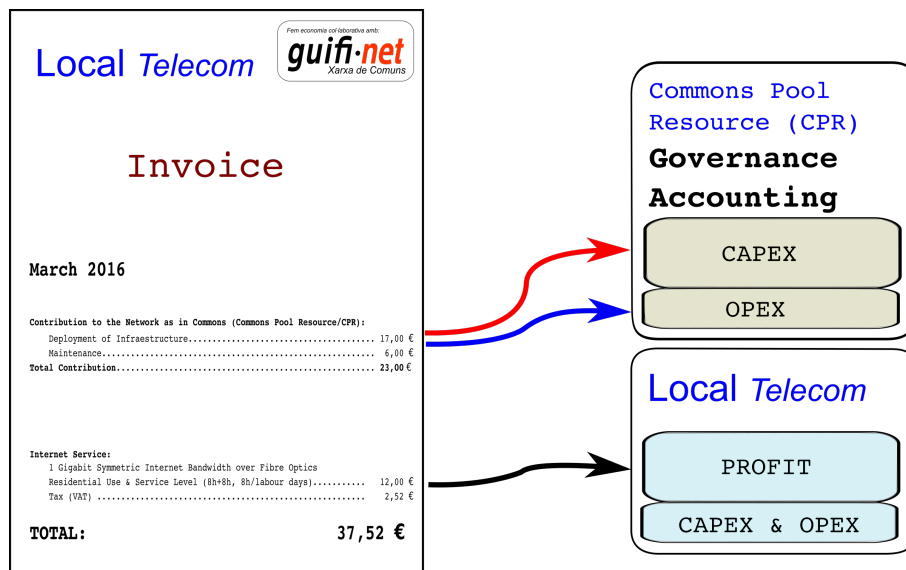
Figure 5.2: The template to be used by the operators for invoicing their service subscribers and the destination of the items.

The professionals' strategy is to claim ownership rights over the infrastructure because they have funded the vast majority of it. The controversy, which has a profound legal background, especially in terms of a bundle of rights (see Section 2.4.4), must be addressed by the community at some point. But the suddenness and intensity of the professionals, claims may also shed light on the real motivations for their actions, which are contrary to the general interest. These include declaring as little expense as possible to the compensation system, discounting the contributions made by others, and their preference to deploy in new areas instead of extending the coverage that exists now.

The changes proposed by the professionals have triggered an intense discussion, which is still going on at the time of writing this dissertation. Because most of the central points must still be clarified, and because of differences of opinion (including who must be considered the debtor and who owns the resulting infrastructure of the funding instruments presented earlier), these two questions have been intentionally withheld from previous sections. However, they are addressed as part of this discussion.

For the professionals, a central question is the delimitation of the assets that can be classified as *funded* by them. For the Foundation, this is not such a critical question. However, the views about which assets can be classified as funded by the professionals differ radically. First, the professionals tend to consider as funded by them all the projects they have executed, regardless of the sources of capital involved. In this regard, the Foundation maintains that donations, the for-fee-reduction donations, and contributions by public administrations and other participants belong to the commons by default. Or, at least, each contributor must be asked individually if they want to transfer their rights to the professionals.

Second, there is also a controversy over the infrastructure funded through bank loans. For although the professionals are the debtors, it is equally true that, beyond the opportunities that the Guifi.net project gave them to learn and grow, their current creditworthiness is directly bound by the size of Guifi.net. Moreover, their collateral also is likely to be bound to the network,

meaning that they have put at stake other participants' interests. From this point of view, ownership rights cannot go entirely to the professionals.

A more important question for the Foundation is to clarify the impact on the infrastructure if a professional withdraws. The Foundation argues that, according to the network licence and the agreements for developing economic activity signed by the professionals, under any circumstance the professional could not retrieve any infrastructure if it has been co-financed by others. This includes any received cost-compensation. Thus, determining the scope *an infrastructure* becomes crucial. In the Foundation's view, the term is to be interpreted widely, that is to say, any physical infrastructure reachable without the need to cross assets outside Guifi.net forms a single infrastructure. Thus, the lack of co-investment can happen, at most, in isolated deployments and only if the party that wants to retrieve infrastructure proves that it has made the entire investment.

Another key point is the definition of the rights of the service providers' customers, especially those who have not made a for-fee-reduction contribution. The Foundation assumes that all the participants, including the service providers' customers, have CPR rights unless explicitly waived by them. Thus, even assuming a lack of investment, changing the conditions under which the infrastructure is exploited would require the explicit, informed consent of each customer.

Finally, there are opposing points of view on the destination of the CAPEX fraction of the customers' bill after a debt is repaid. For reasons similar to the ownership dispute, the professionals argue that they have the right to decide what to do with this money, including using it as a profit. On the contrary, the Foundation and the volunteers claim that the funds can only be reinvested in the CPR.

5.2.7 Mitigation measures promoted by the Guifi.net foundation

According to the Guifi.net foundation rationale, it is not possible to provide all the quantitative information because the professionals have not provided enough information to the Foundation. However, there is strong evidence that both the infrastructure and the professionals using it have not only lasted over a long period but experienced substantial growth. This means that the overall approach is wise. Therefore, contrary to some professional claims in favour of internal deregulation and weakening of the commons, the Guifi.net foundation deliberately opts to keep developing and putting into practice methodologies to strengthen collaboration among the participants and resource-sharing through the CPR model. To this end, it is fostering the following measures.

Holding multilateral meetings and organising working groups The Foundation is coordinating a round of participatory meetings to discuss the proposal made by the professionals and other solutions and improvements. The round is not yet finished but for the time being the meetings have helped to defuse tensions and restore confidence. Some working groups have been created to address specific issues.

Reinforcing systematic data reporting Updated data is essential for many tasks, such as calculating cost-compensation and refining cost estimates. On the one hand, the professionals complain about the poor performance of the governance tools, including the cost-compensation and the conflict-resolution systems. On the other hand, they usually report their data late, and it is frequently incomplete.

Clarifying professional roles The professionals systematically oppose any measure which implies revealing any information about them. There is a widespread sense that this is a strategy to hide their profits, which are suspected to be higher than what they actually state and more than the community would accept. Therefore, it is a central issue to clarify which part of their activity is for the CPR (regulated) and which is related to service provisioning (liberalised). Thus, their activity must be transparently reported and regulated by community rules.

Revising cost estimates There is also the impression that current costs are too conservative, which is favourable for the professionals. This is another incentive for them not to report to the clearing houses.

Adopting a detailed billing template Although the template has been available since 2016, very few participants have adopted it and, to the best of our knowledge, no professional has done so.

Establishing new clearing houses and strengthening the existing ones In the Foundation's view, the clearing houses play a key role in the governance system, as they are the most direct way for mutual supervision and coordination. Thus, it not only opposes the reduction of activity in the existing ones; it wants to foster their full implementation and activate newer ones in other areas.[12]

Restoring the communication through shared channels The professionals have not used the community's communication channels for some time, and they are communicating with each other only through parallel channels. Again, there is a widespread perception that this is part of a strategy to exclude the other participants. However, because the professionals have a point about the need to update existing channels to meet their needs, the Foundation is updating the communication systems.

Ensuring transparency in loan management Participants should inform each other about these initiatives and recognise that periodic and occasional repayments are part of the cost-compensation cycles of the clearing houses.

Developing lines of credit The Foundation is working with investment banks to design funding instruments that are under the technical supervision of the Foundation. The investment banks would standardise these lines of credit. Such financial instruments would help to harmonise procedures, guarantee that administrative burdens and financial risk are reduced, and ensure that the infrastructure is developed and remains in the commons.

Conducting an information campaign The Foundation is leading an information campaign to inform participants who would be directly affected by the professionals' intentions but who might not be aware of them, and to invite them to have a say.

5.3 Analysis of a case of cost-sharing

Cost sharing allows the development and operation of a few common resources among multiple parties instead of building and maintaining multiple separate facilities. The potential for

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[12] The professionals argued that the clearing houses should stop running and any imbalance should be settled through private negotiations among them. The general opinion is that accepting this proposal would entail *de facto* the death of the overall project.

efficiency and sustainability in sharing comes with the overhead of coordinating the participation, contribution, and output allocation among multiple participants with widely different possible capacities and needs. Thus, efficient cost allocation methods are required.

In this section, we address the challenge of advancing the development of such methods in the particular case of network services and infrastructure because the potential for savings due to cooperation in this field has been well described in [142]. Nonetheless, the lack of case studies seems to be a major barrier for the uptake of resources and service-sharing practices beyond IXPs or some community networks. To contribute to filling this gap, we analyse in detail the mechanisms developed and put in practice by the community of practice of Guifi.net [P2] to jointly enable the provisioning of a critical service, such as the transit service, and to share its costs.

5.3.1 Carriers setup

The general configuration of the NOC is discussed in Section 3.6.3. Hereafter we focus our attention on the two main carriers, which we refer to as C_1 and C_2. To ensure a certain quality of service in the case of failure, the hired capacities of C_1 and C_2 are required to be always the same.

The pricing scheme of C_1 is a strict flat rate for its entire capacity, and the pricing for C_2 is a flat rate for the traffic below 10 % of its capacity plus a per traffic fee for the traffic exceeding this. The flat rate part of C_2 is around two-thirds the cost of C_1. The routing policy is to maximise the use of the capacity of C_1 within a safety margin, and the rest of the traffic is diverted to C_2. The hired capacities are extended when the cost of the per traffic fee of C_2 becomes greater than the cost of the capacity expansion of C_1. On average, the contracts are being renegotiated every year or year and a half to accommodate the growth in demand. In May 2019, C_1 and C_2 have been upgraded from 2×10 Gbps to 3× 10Gbps, and the IXP connection is 1× 10Gbps, but it will be soon upgraded to 2× 10Gbps. The costs of the additional NSPs for specific operations is less than 4 % of the total external connectivity costs.

5.3.2 Cost classification

As explained in Section 4.4.1, in the clearing houses, the costs are grouped according to the CAPEX and OPEX criterion except for the NOC, in which case the grouping is made by *cost centres*. The current cost centres are *exterior traffic*, *interior traffic*, and *rack spaces*. The exterior traffic costs include the NSPs and IXP, and the interior traffic includes the middle-mile links. Rack space costs are those that refer to the housing facilities. Table 5.1 shows the NOC's most significant costs, how these are distributed among cost centres, and the maximum amortisation period (MAP) in months, if any.

5.3.3 Available resources

Two resources (flow variables or *finge units*) can be consumed at the NOC: network bandwidth and rack space. The metric used to measure the usage of network assets is the sum of the 95th percentile of five-minute time averages of the inbound and outbound traffic of the given link per participant. Rack space is measured through the standard *rack unit*, which is half the minimum size. To ensure liquidity, the cost-sharing calculations, the *compensations* in Guifi.net's terms, are done periodically. In the case of the NOC, they are done on a monthly basis.

Item	Cost centre			MAP [months]
	Exterior t.	Interior t.	Rack s.	
Hardware (routers, switches, etc.)	✓	✓	−	36
Insurance (annual fees)	✓	✓	✓	12
Administration	✓	✓	✓	−
Management	✓	✓	−	−
Technical support	✓	✓	−	−
Legal support (outsourced – monthly fee)	✓	✓	✓	−
Housing – acquisition cost	−	−	✓	36
Housing – monthly fee (including electricity)	−	−	✓	−
Housing – shared hardware slots	✓	✓	−	−
IXP – monthly fee	✓	−	−	−
carriers – monthly fee	✓	−	−	−
Middle-mile circuit – acquisition cost	−	−	✓	36
Middle-mile circuit – interconnection costs	−	−	✓	36
Middle-mile circuit – monthly fee	−	−	✓	−

Table 5.1: Most significant network operation centre costs, cost centre assignment (✓: assignment applies, −: assignment does not apply) and maximum amortisation period.

5.3.4 Datasets

The Guifi.net foundation has given us access to a traffic dataset and to some of the spreadsheets generated on a monthly basis to calculate the cost sharing and has provided some additional information on carrier offerings. To maintain confidentiality, the names of the participants and carriers have been kept anonymous.

5.3.4.1 Traffic

The traffic dataset contains(i) the inbound and outbound aggregated traffic of each participant (i.e. the traffic exchanged by each participant in both directions with the IXP and the carriers and the other participants all together), and (ii) the inbound and outbound traffic of each carrier and the IXP. The dataset we have evaluated in this section consists of the mean traffic of five-minute samples, recorded during the second week of April 2019, from Saturday the 6th to Friday the 12th. The data files are in comma-separated value (CSV) format and can be found in the public repository [29]. As an example of this data, Figure 5.3 shows the *inbound* and *outbound* traffic of three participants. The dashed lines correspond to their 95th percentiles. Throughout the section, we sorted the participants in ascending order by the addition of the *inbound* and *outbound* 95th percentiles. Accordingly, the graph on the top corresponds to the participant with the least usage (26 Mbps), the one in the middle to medium usage (49 Mbps), and the one on the bottom to the highest usage (7.9 Gbps). As Figure 5.3 shows, the traffic patterns become more evident as the traffic of the participants increase.

During the recorded period, 26 participants had traffic activity in the NOC. Figure 5.4 shows their mean traffic and 95th percentiles in the log scale sorted according to the aforementioned criterion. It is interesting to note that nearly a constant distance exists between the mean and 95th percentiles in the log scale, especially for participants with higher traffic. For instance, let q_p^{in} and m_p^{in} be the *in* traffic at the 95th percentile and the mean, respectively, of participant p. There are 13 participants using $m_p^{in} > 0.1$ Gpbs. For these participants, the mean of q_p^{in}/m_p^{in} is 1.93 with a standard deviation of only 0.11. Thus, if only the mean traffic is known, a rule of thumb for the five-minute sampling at the 95th percentile is taking twice the mean.
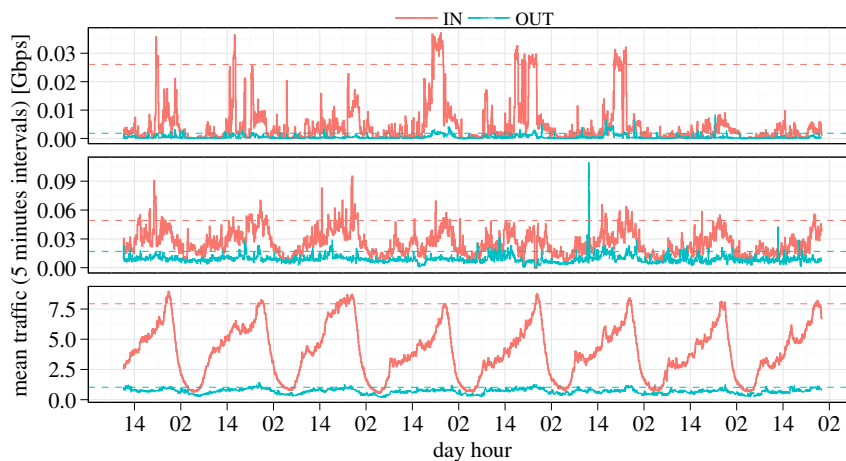
Figure 5.3: Exterior traffic of three participants. The dashed lines correspond to the 95th percentiles.
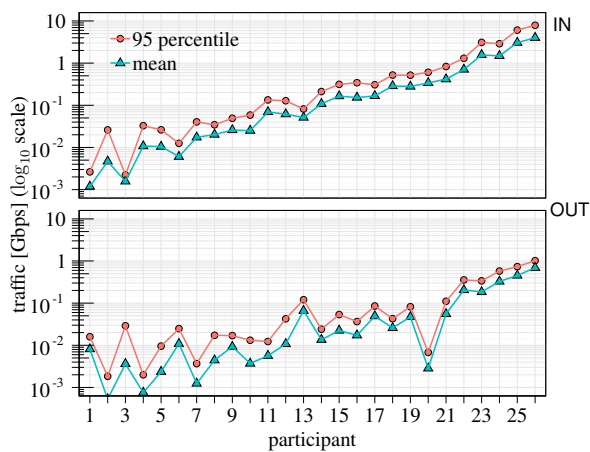

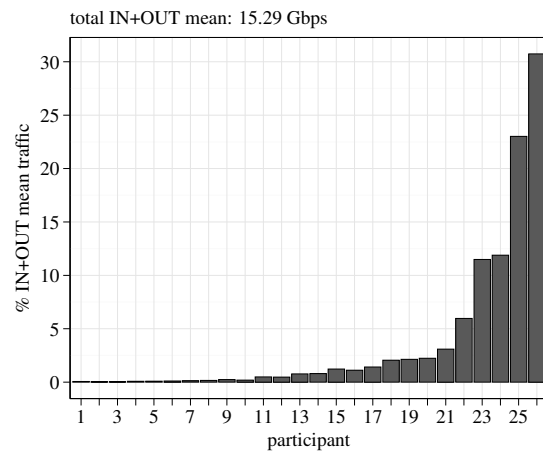Figure 5.4: In and out traffic: mean and 95th percentile.

Figure 5.5: Percentage of mean of inbound and outbound traffic.

Outbound traffic that is higher than the inbound traffic corresponds to content providers, whereas the opposite indicates that the participant is either an end user or an access network provider. To appreciate the large difference between participants in terms of traffic exchanged, Figure 5.5 shows the percentage of mean inbound and outbound traffic exchanged by each participant. The participant with the highest usage exchanges 30.74 % of all traffic, and the four participants with the highest usage account for the 77.12 %. Indeed, all of them are service providers, and together, they have over 25,000 subscribers. Conversely, the 10 participants with the least usage together exchange only 1.10 % of the traffic. Among these participants, there are associations, self-provisioning participants, micro-service providers, and so on, that account for less than a thousand end users each.

5.3.4.2 Costs

The NOC's cost-compensation spreadsheet has numerous data and formulae because it is used to calculate the dues of all participants for the exterior traffic and the middle mile and racks. As already explained, for simplicity, we focus on the distribution of the costs associated with external traffic. To this end, we recalculated the cost assignments because, for historical reasons,

	Cost centre			
	Exterior t. [€]	Interior t. [€]	Rack s. [€]	Total [€]
Exclusive	6,362.00	14,501.00	2,558.00	23,421.00
Shared	2,963.00	6,754.00	339.00	10,056.00
Total	9,325.00	21,255.00	2,897.00	33,477.00

Table 5.2: Considered costs per cost centre (April 2019).

Item	Cost [€]	Cost function category	
		NSPs & IXP	Other
C_1 (2×10 Gbps)	2,800.00	✓	−
C_2 flat rate (2×10 Gbps)	1,500.00	✓	−
C_2 excess	317.00	−	−
Additional NSPs	356.00	−	*equally split*
IXP (1×10 Gbps)	650.00	✓	−
RIPE-NCC	87.00	✓	*constant*
Cabling	652.00	−	*participants*
total	6,263.00		

Table 5.3: Exterior traffic cost breakdown (April 2019) and assignment to cost function categories (✓: assignment applies, −: assignment does not apply).

in Guifi.net's spreadsheets, the labour and other costs are entirely charged to the exterior traffic cost centre, whereas, as shown in Table 5.1, they should also be partially incurred by the internal traffic and, in some cases, by the rack spaces as well. To address this anomaly, we proportionally distributed the costs that should be incurred by more than one cost centre to the total amount of exclusive costs of each cost centre of the previous month. We used the data of the previous iteration because some of the exclusive costs, such as the cost per slot of housing, depend on the proportionality factors. Hence, they cannot be obtained from the data of the current iteration due to indeterminate problems.

Table 5.2 shows the exclusive costs per each cost centre and our redistribution of the costs to be incurred by more than one cost centre and the corresponding totals. Table 5.3 shows the costs of the external traffic cost centre. Given that the deals with the carriers are private and subject to non-disclosure agreements, in this table and hereafter, we use approximations for the actual costs by rounding the values with deviations below 1 %. The membership fee is 154.00 €.

5.3.5 Cost estimation model

In this section, we derive a function to estimate the total cost of the external traffic on Guifi.net for an arbitrary coalition (i.e. a subset of participants) and traffic consumption. This will be the baseline cost function that we use in the cost-sharing analysis we perform later in Section 5.3.6. For ease of reference, Table 5.4 summarises the parameters and values defined in our model cost, and Table 5.5 displays the main variables of this section.

In line with the classification in Table 5.3, we propose a cost function with components that can be grouped into two main categories: the *NSP and IXP costs*, which exclusively depend on the port capacities contracted to the NSPs and the IXP, and the *other costs*, such as housing,

Parameter	Value	Unit	Description
P	26	part.	Number of participants
A_P	$\{1, 2, \cdots P\}$	part.	Grand coalition
α_{C_1}	0.58	–	Proportion of traffic exchanged at C_1
α_{C_2}	0.17	–	Proportion of traffic exchanged at C_2
α_{IXP}	0.25	–	Proportion of traffic exchanged at IXP
K_{C_1}	1.25	–	C_1 overprovisioning factor
K_{C_2}	1.25	–	C_2 overprovisioning factor
K_{IXP}	1.50	–	IXP overprovisioning factor
$q(A_P)$	25.06	Gbps	95th-perc. of traffic exchanged by A_P, Eq. (5.3)
$m(A_P)$	15.29	Gbps	Mean traffic exchanged by A_P, Eq. (5.7)
c_T	8, 575.00	€	Total cost of A_P
H_f	1, 193.33	€	Other costs parameter, Eq. (5.6)
H_d	$\dfrac{1, 423.33}{m(A_P)}$	€/Gbps	Other cost parameters, Eq. (5.6)
H_p	$\dfrac{1, 758.33}{P}$	€/part.	Other cost parameters, Eq. (5.6)

Table 5.4: Parameters of the cost model.

Variable	Description
i	External connectivity provider, $i \in \{C_1, C_2, \mathrm{IXP}\}$
p	Participant, $p \in \{1, 2, \cdots P\}$
A	Coalition of participants, $A \subseteq \{1, 2, \cdots P\}$
q_i^{in}, q_i^{out}	95th percentile of *in* and *out* traffic of provider i
q_p^{in}, q_p^{out}	95th percentile of *in* and *out* traffic of participant p
m_p^{in}, m_p^{out}	Mean of *in* and *out* traffic of participant p
$q_{in}(A), q_{out}(A)$	95th percentile of *in* and *out* aggregated external traffic exchanged by A
$m_{in}(A), m_{out}(A)$	Mean of *in* and *out* aggregated external traffic exchanged by A
g_p	Guifi.net cost assigned to participant p
s_p	Shapley value cost assigned to participant p

Table 5.5: Main variables used in this section.

electricity, exceeding traffic, insurance, manpower, amortisations, and so on, that is, costs that depend on several factors, with the number of participants and traffic volume being the most significant. Roughly, each of them represents one-half of the total cost. These categories must not be confused with the exclusive and shared cost classification criterion from Section 5.3.4.

5.3.5.1   NSPs and IXP costs

The total cost of this category is the sum of the cheapest combinations of links offered by the NSPs and the IXP that are able to satisfy the respective capacity demands. Since the links are symmetric, each provider demand is established based on the maximum of its inbound and outbound traffic of the previous iteration, that is, of the traffic consumption of the previous month. For dimensioning purposes, the traffic to be considered is given by the following:

$$q_i = \max(q_i^{in}, q_i^{out}), \quad i \in \{C_1, C_2, \mathrm{IXP}\}, \tag{5.1}$$

where q_i^{in} and q_i^{out} are respectively the 95th percentile of the *in* and *out* traffic of provider i.

	Monthly fees [€]		
Capacity	C_1	C_2	IXP
1 Gbps	*430.77	*276.92	200.00
10 Gbps	*1,400.00	*750.00	650.00
20 Gbps	2,800.00	1500.00	–
30 Gbps	4,200.00	1800.00	–
100 Gbps	*20,000.00	–	3,900.00

Table 5.6: Monthly fees of the NSPs and the IXP (May 2019; * estimated values; − indicates no data available for that configuration and estimation is not needed).

Using Equation (5.1), we can compute q_i of the coalition containing all participants, the grand coalition of all participants. However, for smaller groups of participants (coalitions), we assume that the NSPs and IXP traffic proportions remain the same because the dataset only encompasses aggregate traffic records but not which proportion of the traffic of each participant is exchanged at NSPs and the IXP. That is, we let P be the number of participants, and $A \subseteq \{1, 2, \cdots, P\}$ be any coalition and let α_i, $i \in \{C_1, C_2, \text{IXP}\}$, be the proportion of traffic exchanged by all participants at C_1, C_2, and the IXP, respectively. Then, we obtain the following:

$$\alpha_i = \frac{q_i}{\sum q_i}, \quad i \in \{C_1, C_2, \text{IXP}\}, \tag{5.2}$$

and given aggregated external traffic exchanged by coalition A:

$$q(A) = \max(q_{in}(A), q_{out}(A)), \tag{5.3}$$

where $q_{in}(A)$ and $q_{out}(A)$ are respectively the 95th percentile of *in* and *out* aggregated external traffic exchanged by A, we assume that the traffic exchanged by A at NSPs and the IXP is $\alpha_i q(A)$, $i \in \{C_1, C_2, \text{IXP}\}$.

Establishing an overprovisioning factor K_i for each provider, we conclude that, for dimensioning purposes, the demands are the following:

$$d_i(A) = K_i \alpha_i q(A), \quad i \in \{C_1, C_2, \text{IXP}\}. \tag{5.4}$$

Table 5.6 shows the prices we considered. As already explained, NSPs prices are subject to private negotiations and non-disclosure agreements. Thus, our precise information on the offers is limited to the current services contracted. The rest of the NSPs values are estimations, as indicated. In contrast, the IXP fees are publicly available on its website [28].

Assuming cost additivity in the case of capacity aggregations, the minimum cost to allocate the traffic demand for each $i \in \{C_1, C_2, \text{IXP}\}$ is obtained by the solution of the integer linear program (ILP):

$$c_i(A) = \min \ \sum a_{ij} n_{ij}, \tag{5.5}$$
$$\text{s.t.} \ \sum b_{ij} n_{ij} \geq d_i(A)$$
$$n_{ij} \geq 0, \ n_{ij} \in \mathbb{Z}$$

where n_{ij} is the number of links of type j, with cost a_{ij} for a bandwidth of b_{ij} Gbps (rows in Table 5.6), and $d_i(A)$ is the demand given by Equation (5.4).
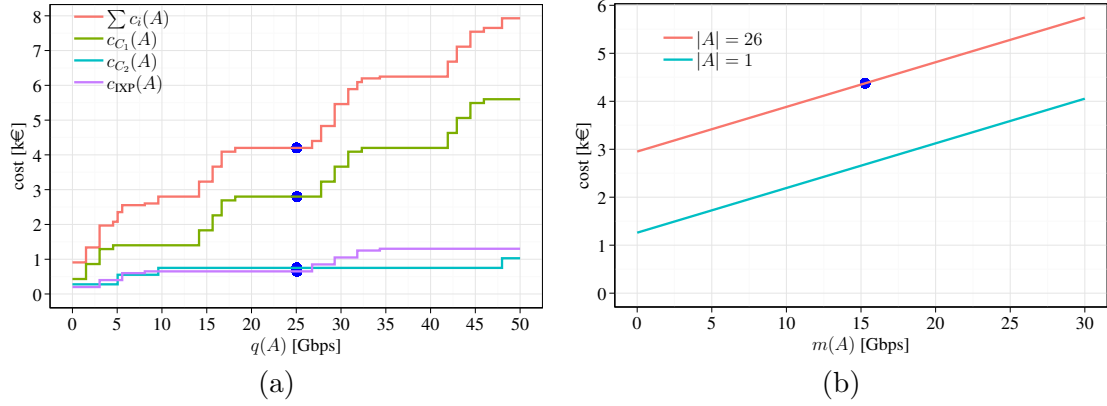
Figure 5.6: (a) NSPs and IXP costs (Eq. (5.5)), and (b) other costs (Eq. (5.6)). The dots show the costs for the grand coalition.

5.3.5.2 Other costs

We model these other costs as a three-term function. The first term gathers the fixed costs; thus, we model it as a constant. The second relates to the costs associated with the exchanged traffic, in this case, taking the addition of the means of inbound and outbound traffic, as shown in Equation (5.7). The third reflects the costs primarily influenced by the number of participants.

We estimate the other costs as follows:

$$c_h(A) = H_f + H_d\, m(A) + H_p\, |A|\,, \tag{5.6}$$

where $|A|$ is the number of participants in coalition A (i.e. the cardinality of A) and $m(A)$ is given by:

$$m(A) = m_{in}(A) + m_{out}(A), \tag{5.7}$$

where $m_{in}(A)$ and $m_{out}(A)$ are respectively the mean of *in* and *out* aggregated external traffic exchanged by A.

To assess the constants in Equation (5.6), we used the values in Table 5.2 and Table 5.3. We split the sum of the shared costs and the additional NSPs into three terms, and we added the RIPE-NCC fee to the constant, the C_2 excess to the traffic, and the cabling to the participant terms, respectively. This results in the values reported in Table 5.4.

5.3.5.3 Total cost of a coalition

Summarising, we estimate the overall monthly cost of the external traffic exchanged by any coalition $A \subseteq \{1, 2, \cdots P\}$ using the following equation:

$$c(A) = \sum_{i \in \{C_1, C_2, \text{IXP}\}} c_i(A) + c_h(A), \tag{5.8}$$

where $c_i(A)$ are the NSPs and IXP costs given by Equation (5.5), and $c_h(A)$ includes the other cost given by Equation (5.6).

Figure 5.6 shows the NSPs and IXP costs (a) and the other costs (b) using the model given by Equations (5.5) and (5.6), respectively. In Figure 5.6 (b), we show the resulting cost for

a single participant, $|A| = 1$, and the cost for the total number of participants present in the current dataset, $|A| = 26$. The NSPs and IXP costs account for 4,200.00 €, the other costs for 4,325.00 € and the total for 8,575.00 €. The difference between the calculated total and the total in Table 5.2 (9,325.00 €) is because, for the calculation, we did not impose d_{C_2} to be equal to or greater than d_{C_1} as done in Guifi.net, as explained in Section 5.3.1. If $d_{C_2} = d_{C_1}$ were set to compute $c_{C_2}(A)$, Equation (5.8) would also give 9,325.00 €.

5.3.6   Cost-sharing

In this section, we formalise the cost-sharing mechanism used by Guifi.net, and we compare it with the Shapley value. Let P be the total number of participants, $P = 26$, and A_P the set of all participants. Using Equation (5.8), the total cost assigned to the set of all participants is as follows:

$$c_T = c(A_P). \tag{5.9}$$

5.3.6.1   Guifi.net's cost-sharing mechanism

As explained in Section 4.4.3, a portion of the costs are equally weighted among the participants, and the rest are allocated according to their resource consumption. We refer to these parts as the *fixed*, F, and *shared*, S, costs:

$$
\begin{aligned}
F &= \gamma \, c_T && \text{fixed cost} \\
S &= (1 - \gamma) \, c_T && \text{shared cost,}
\end{aligned}
\tag{5.10}
$$

where $0 \leq \gamma \leq 1$. The fixed cost, F, is equally divided among all participants. For simplicity, the shared cost, S, is proportionally divided according to each participant's usage. Thus, the cost g_p assigned to a participant p is given by the convex combination:

$$g_p = \frac{F}{P} + S \frac{u_p}{\sum u_p} = \frac{\gamma \, c_T}{P} + (1 - \gamma) \, c_T \frac{u_p}{\sum u_p}, \quad p \in \{1, 2, \cdots P\}, \tag{5.11}$$

where u_p is the bandwidth usage of each participant, defined as the addition of the 95th percentiles of its inbound and outbound traffic:

$$u_p = q_p^{in} + q_p^{out}, \quad p \in \{1, 2, \cdots P\}. \tag{5.12}$$

In the rest of the section, *traffic* and *usage* of a participant will be used interchangeably to refer to u_p given by Equation (5.12). Note that the fixed cost in Equation (5.11), the first summand, is the same for all participants (i.e. it corresponds to the membership fee). The allocation in Equation (5.11) is *budget-balanced* (i.e. $\sum g_p = F + S = c_T$) and possesses the *anonymity property* (i.e. the labelling of the participants does not play a role in the assignment).

5.3.6.2   Shapley value

The Shapley value is a solution concept in cooperative game theory that fairly and uniquely solves the problem of the distribution of surplus (or joint-cost allocation) among players when considering the worth (or cost) of each coalition [138]. Today, the Shapley value is perhaps the most commonly used method to allocate the costs in cost-sharing games [120] because it is budget-balanced and guarantees equilibrium in any game, regardless of its parameters [66]. We compute the Shapley value (see Appendix 5.A) using Equation (5.8) as a characteristic function.

5.3.6.3 Optimal γ

Let s_p be the cost assigned to participant p by the Shapley value. We call γ^* the value of γ in Equation (5.11) that minimises the mean square error with Shapley values (i.e. $\min_\gamma \sum (g_p - s_p)^2$). Computing $\partial \sum (g_p - s_p)^2 / \partial \gamma = 0$, it can be easily found that a unique critical point exists and has a positive second derivative; thus, it is a global minimum. The value is given by the following:

$$\gamma^* = \frac{\sum_{p=1}^{P} (s_p/c_T - \eta_p)(1/P - \eta_p)}{\sum_{p=1}^{P} (1/P - \eta_p)^2}, \tag{5.13}$$

where $\eta_p = u_p / \sum u_p$, $p \in \{1, 2, \cdots P\}$, $0 \leq \eta_p \leq 1$, $\sum \eta_p = 1$. Thus, η_p represents the relative system usage of participant p. Note that, for an arbitrary mapping between relative usage η_p and Shapley values s_p, γ^*, given by Equation (5.13), is not bounded (i.e. $\gamma^* \in (-\infty, \infty)$). However, it would not be reasonable to take γ in Equation (5.11) outside the interval $[0, 1]$. What this result shows is that having $\gamma^* \in [0, 1]$, Shapley values might be approximated well by Equation (5.11), taking $\gamma = \gamma^*$, while Equation (5.11) might not approximate Shapley values well when $\gamma^* \notin [0, 1]$. We see that the condition $\gamma^* \in [0, 1]$ holds for our dataset, and we believe that this happens in most practical cases. Furthermore, when $\gamma^* \in [0, 1]$, its value can be used as an indicator of how balanced the system is. If the system is very unbalanced, for example such that a single participant $\hat{p}$ consumes all resources (i.e. $\eta_{\hat{p}} \to 1$, $\eta_{p \neq \hat{p}} \to 0$, and thus, $s_{\hat{p}} \to c_T$, $s_{p \neq \hat{p}} \to 0$), then from Equation (5.13) we have the following:

$$\lim_{\substack{\eta_{\hat{p}} \to 1, \, \eta_{p \neq \hat{p}} \to 0 \\ s_{\hat{p}} \to c_T, \, s_{p \neq \hat{p}} \to 0}} \gamma^* \to 0. \tag{5.14}$$

Alternatively, if the system is balanced, such that $\eta_p \to 1/P \; \forall p$ (i.e. all participants consume the same and, thus, $s_p \to c_T/P \; \forall p$), then from Equation (5.13), we have the following:

$$\lim_{\substack{\eta_p \to 1/P \\ s_p \to c_T/P}} \gamma^* \to 1. \tag{5.15}$$

Therefore, we conclude that $\gamma^* \to 1$ for a system where participants equally consume the resources, while $\gamma^* \to 0$ for a system where most resources are consumed by a reduced number of participants. For our dataset, we obtain $\gamma^* = 0.43$. Thus, we can expect that Shapley values can be approximated well by Equation (5.11), taking $\gamma = \gamma^*$. We will confirm this with the numerical results explained in the following. Moreover, $\gamma^* = 0.43$ is far from 1, showing a rather unbalanced system, as we have seen in Section 5.3.4.1 (the four participants with the highest usage account for 77.12 % of the traffic).

Figure 5.7 (a) shows the cost assignments according to the two previous cost-sharing mechanisms, the Shapley value and Guifi.net, with several values of γ in the last case. All of the distributions are *individually rational* because, in any case, a participant pays more when not cooperating with anyone else (*standalone* curve). Figure 5.7 (b) shows the normalised values of Figure 5.7 (a) resulting from dividing the assigned costs by the means of the inbound and outbound traffic, giving the cost in €/Gbps. The €/Gbps is a metric commonly used by service providers to assess alternatives. The curves of this figure are not strictly monotonically decreasing due to the differences between the metric used in the cost-sharing calculations, u_p, and the metric used for the normalisation, $m(p)$. Figure 5.7 (c) shows the cost gain, defined as the standalone cost over the cost incurred inside Guifi.net (i.e. the cost depicted in Figure 5.7 (a)).
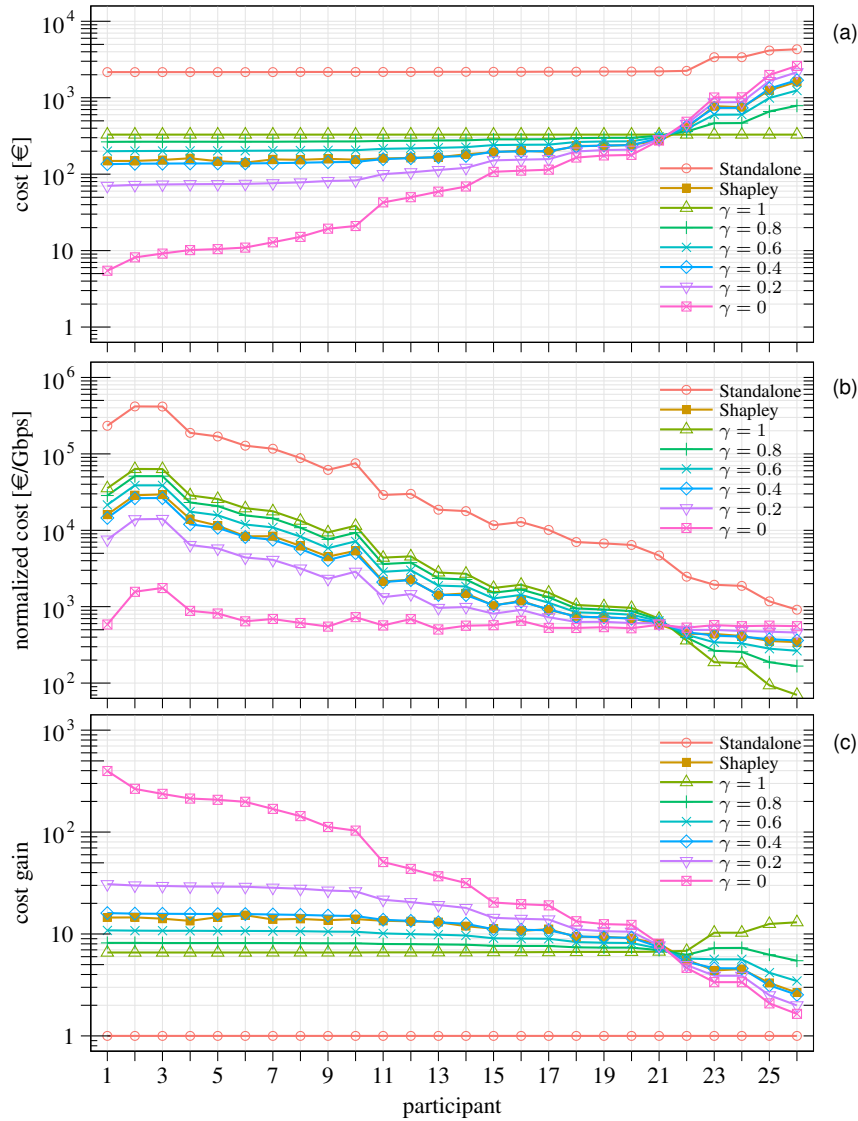
Figure 5.7: Cost sharing: (a) absolute value, (b) normalised to the traffic mean, and (c) cost gain.

Interestingly, Figure 5.7 reveals that for $\gamma = 0.4$ a striking coincidence exists between costs computed using the Guifi.net method and the Shapley value. Indeed, recall that $\gamma^* = 0.43$. The fixed cost per participant resulting from Equation (5.11), $\gamma\, c_T/P$, is $142.37\,€$ for γ^*. This is rather close to the membership fee of $154.00\,€$ used in Guifi.net, which corresponds to $\gamma = 0.47$. In other words, without being aware of it, Guifi.net participants are contributing an assigned cost that is very close to the Shapley value.

5.3.6.4   Meaning of γ

Note that, from Equation (5.10), in one extreme, by setting $\gamma = 0$, we assign the whole cost to the shared part, thus proportionally dividing the cost according to each participant's traffic. At the other extreme, by setting $\gamma = 1$, we assign the whole cost to the fixed part, thus equally weighting the total cost among all participants. As shown in Figure 5.7 (a), the assignment line varies from a curve with the highest positive slope when $\gamma = 0$ to a flat line when $\gamma = 1$. Therefore, for the participants on the left (with low traffic) the lower the γ is, the lower the cost

they pay. While the opposite holds for the participants on the right, with high traffic, the lower the γ is, the higher the cost they pay. The boundary between these regions is given by the point where the cost does not change with γ. Therefore, this point can be computed by $\partial g_p / \partial \gamma = 0$. Using Equation (5.11), we find that the boundary is given by the following mean usage:

$$\langle u \rangle = \frac{1}{P} \sum_{i=1}^{P} u_p. \tag{5.16}$$

This is a logical result because users with a lower usage than the mean, $u_p < \langle u \rangle$, prefer $\gamma = 0$; thus, every participant is paying for his or her usage. On the other hand, users with higher usage than the mean, $u_p > \langle u \rangle$, prefer $\gamma = 1$, thus dividing their cost among all participants. The optimal γ computed before using the Shapley value is a good compromise between these opposite interests.

5.3.7 Sensitivity to participants with high usage

The participants with the highest bandwidth consumption, those that contribute the most in absolute terms, might be tempted to leave Guifi.net and build their own coalition, or at least to threaten to form one to impose cost-sharing rules that are more favourable to their interests, for instance, a higher γ. To elucidate whether this reasoning is well-founded, in this section, we investigate the increase in costs that participants would incur upon the largest contributors leaving the current coalition.

Let S be the set of participants leaving Guifi.net and $\bar{S}$ be the remaining set, $\bar{S} \cup S = \{1, 2, \cdots P\}$. Recall that we assume the participants are ordered from the least (participant 1) to the most (participant 26) bandwidth usage (see Equation (5.12)). Figure 5.8 shows the Shapley value assigned to a selected group of participants, including the participants having the least and most usage, s_1 and s_{26}, respectively. The figure also shows the total cost assigned to the participants in S and $\bar{S}$, $c(S) = \sum_{p \in S} s_p$ and $c(\bar{S}) = \sum_{p \in \bar{S}} s_p$, respectively (see Equation(5.8)), and its sum $c(S) + c(\bar{S})$. The abscissa corresponds to the cardinality of the subset S, $|S|$. For instance, for $|S| = 0$, all participants are inside $\bar{S}$, and for $|S| = 1$, participant 26 has already left the Guifi.net coalition (i.e. $S = \{26\}$). For $|S| = 2$, $S = \{25, 26\}$, and so on. Note that for $|S| = 1$, s_{26} corresponds to the standalone cost of 26, already depicted in Figure 5.7 (a). The figure shows that between s_{15} and s_{10}, a threshold exists beyond which joining the new coalition is more beneficial than staying in Guifi.net. The figure also shows the local minimums in the staying curves (thin segments) and local maximums in the leaving curves (thick segments). These are because the NSPs and IXP cost components of the cost function are step functions. Hence, the unit price functions are not strictly decreasing, which is the condition for economies of scale to take place. This creates intervals with local optima that discourage traffic growth and, thus, cooperation. For instance, when participant 25 leaves, the costs incurred by most of the rest who stay decrease, and the same happens for participant 9. Nevertheless, from a general perspective, these local reductions of savings are, by far, compensated for by the region of savings that the greater order of magnitude of products entails (e.g. when moving from combinations of 1 Gbps links to a 10 Gbps setting).

Figure 5.9 shows the minimum and maximum increments in log scale of the Shapley value for both the participants staying in Guifi.net (top) and those leaving Guifi.net (bottom) with respect to the Shapley value before splitting into the staying and leaving sets. That is, let $r_p(k)$ be the relative cost increment of participant $p \in k$, $k \in \{S, \bar{S}\}$, and $s_p(k)$, $k \in \{S, \bar{S}, A_P\}$ be the
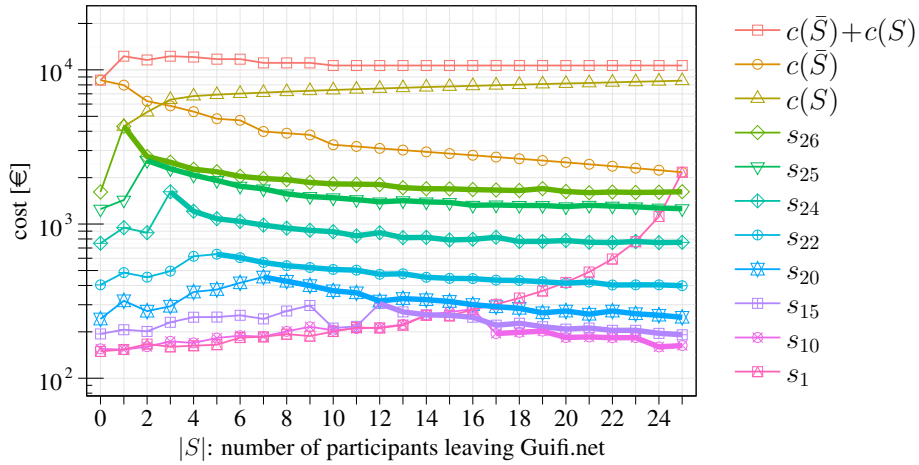
Figure 5.8: Shapley value of a selected group of participants (1 and 26 are the participants exchanging the least and most external traffic, respectively) upon a subset S of the highest-usage participants leaving Guifi.net, and $\bar{S}$ staying. Segments are thicker after the participant has left Guifi.net.
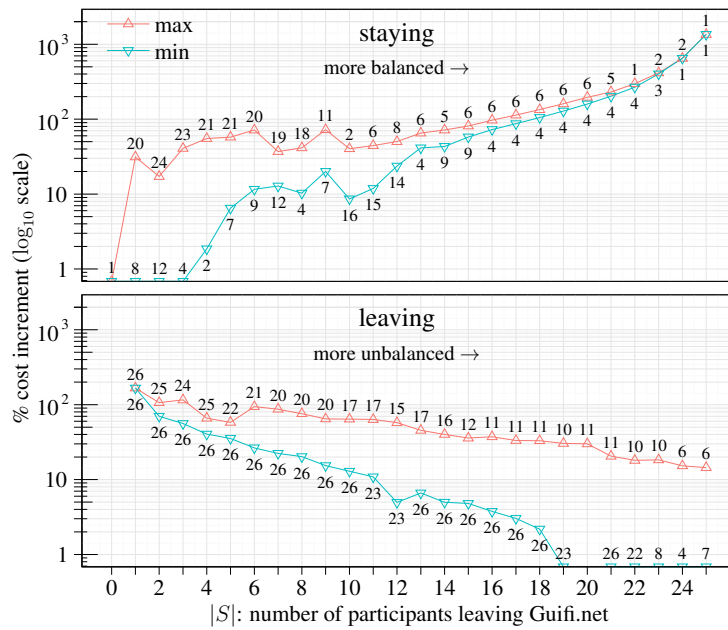
Figure 5.9: Maximum and minimum percentage cost increment over all participants in $\bar{S}$ (staying in Guifi.net) and S (leaving Guifi.net) corresponding to Figure 5.8 in log scale.

Shapley value assigned to participant $p \in k$, where $A_P = \{1, 2, \cdots P\}$ is the set before splitting. Then, we obtain the following:

$$\max_{p \in k}(r_p(k)) = \max_{p \in k}\left(\frac{s_p(A_P) - s_p(k)}{s_p(A_P)}\right), \quad k \in \{S, \bar{S}\}, \tag{5.17}$$

and likewise for the minimum. The labels next to the points indicate which participants reach the max and min cost increments.

Figure 5.9 shows that the Shapley value increments are very different among the participants. For instance, when $S = \{26\}$ and $|S| = 1$, we find that $\max(r_p(\bar{S})) = 31.26\,\%$ (reached by

Figure 5.10: CV of the participants' bandwidth usage, u_p, in each staying $\bar{S}$ and leaving S sets. The lower the CV is, the more *balanced* the sets are.

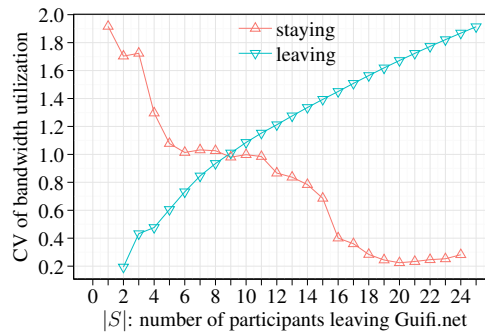participant 20), and $\min(r_p(\bar{S})) = -4.33\%$ (reached by participant 8). Therefore, participant 8 is slightly favoured by the departure of participant 26, while participant 20 has a significant increment in the assigned cost. When more participants with higher usage leave Guifi.net, the set of staying participants are more balanced, and the ratio between the maximum and minimum is lower (top of Figure 5.9). Recall that the ordinates are in log scale, and we observe that $\log(\max) - \log(\min) = \log(\max/\min)$ diminishes up to 0 at $|S| = 25$, when there is a single participant in $\bar{S}$. At this point, Figure 5.9 shows that the cost increment for the single participant in $\bar{S}$ increases more than $1,000\%$. It becomes apparent that the cost would not be affordable for a single participant, nor even for a small group of participants with low usage.

The opposite occurs for the set of leaving participants (bottom of Figure 5.9). When more participants join the set, the $\max/\min$ ratio is more unbalanced and higher. To assess how balanced these sets are, Figure 5.10 shows the CV of the participants' bandwidth usage, measured using Equation (5.12). Figure 5.10 confirms that the CV of the staying set tends to 0 (more balanced) as participants leave the set. Alternatively, the CV of the leaving set increases (more unbalanced) as new participants join. Thus, we conclude that, in general, the more unbalanced the set becomes when a new participant joins the set, the greater the ratio will be between the maximum and minimum cost increments that the participants of the perturbed set will have. We can guess that the same occurs when participants leave the set.

If we assume that the participants leave Guifi.net from the lowest usage (participant 1) to the highest usage (participant 26), we would obtain Figure 5.9 moving from right to left and with the staying and leaving sets being those at the bottom and top, respectively. For instance, if participant 1 leaves Guifi.net, Figure 5.9 at the bottom shows that participant 6, a participant with low usage, would have an assigned cost increment of 14.44%. This is a remarkable increment, given that the participant leaving is the one with the least usage, and, thus, with a low assigned cost. Furthermore, participant 6 would have a cost increment of -1.15% if participant 26 left instead of 1. We thus conclude that some participants are more sensitive to departures of low-usage participants rather than high-usage participants.

It is also interesting that, in set $\bar{S}$ (staying), the participants with a higher usage are those with higher cost increments, while the opposite occurs in set S (leaving). This is a logical result because, when a participant with high usage leaves Guifi.net, the other participants with high usage must afford the cost that their need for greater resources requires, which had been shared with the participant who left. The opposite occurs for the set S, where the leaving participant joins. Thus, we conclude that, when a participant with high usage joins the set, the participants in the perturbed set that will have the least assigned cost increment will be those of the same

type (high usage). Alternatively, if a participant with high usage leaves the set, the participants of the same type will have the highest cost increment.

Yet again, because the unit price functions of some cost components are not strictly decreasing, on some occasions, the traffic reduction through the reduction of the number of participants is beneficial for some of those who stay, reaching up to $10\,\%$ in savings between s_9 and s_{10}. Nonetheless, Figure 5.9 as a whole confirms that the dominant strategy is to be part of the grand coalition.

5.3.8   Approximation of the Shapley value using Guifi.net's cost sharing

In Section 5.3.6, we found that Guifi.net's cost sharing is close to the cost assignments obtained using the Shapley value. This is a significant result because the Shapley value is difficult to compute for numerous participants. In this section, we analyse how well the Shapley value is approximated using Guifi.net's cost-sharing mechanism given by Equation (5.11). We investigate the approximation for all sets S (participants leaving Guifi.net) and $\bar{S}$ (participants staying in Guifi.net) analysed before. Note that these sets form coalitions of participants with very different characteristics, as shown by the high variation of the usage CV in Figure 5.10 (ranging approximately from 0 to 2). Thus, our analysis will compare the approximation for a wide range of situations.

For each S and $\bar{S}$ sets of participants, we consider two cases: (i) when Guifi.net's cost sharing uses γ^* given by Equation (5.13), and (ii) when Guifi.net's cost sharing uses a fixed membership fee. We denote these cases by γ_k^* and $\hat{\gamma}_k$, $k \in \{S, \bar{S}\}$, respectively. Case (i) gives us the best approximation of the Shapley value (with the minimum mean square error) that can be obtained using Guifi.net's cost sharing. Case (ii) is more practical. Note that computing γ_k^* requires knowing the Shapley values of the participants in the set $k \in \{S, \bar{S}\}$. In practice, it is likely that Guifi.net's cost sharing is used, fixing a reasonable membership fee. The fee can be fixed with different criteria, for instance, such that participants with a low budget can join Guifi.net. In our analysis, we will consider the membership fee currently used in Guifi.net (i.e. $154\,€$).

Figure 5.11 shows the value of γ_k^*, $k \in \{S, \bar{S}\}$ given by Equation (5.13). The curves labelled with $\hat{\gamma}_k$ show the value of γ_k, $k \in \{S, \bar{S}\}$ corresponding to the fixed fee of $154\,€$, that is:

$$\hat{\gamma}_k = \frac{154\,|k|}{c(k)}, \quad k \in \{S, \bar{S}\}, \tag{5.18}$$

where $|k|$ and $c(k)$ are the number of participants and total cost (Equation (5.8)), respectively, of the sets $k \in \{S, \bar{S}\}$.

To assess the approximation, Figure 5.12 shows the maximum relative error (MRE) in percentage between Guifi.net's cost sharing and the Shapley value assigned to any participant using γ_k^* and $\hat{\gamma}_k$:

$$\text{MRE}(\gamma) = \max_{\forall p} \left(\frac{|g_{p,k}(\gamma) - s_{p,k}|}{s_{p,k}} \right), \quad \gamma \in \{\gamma_k^*, \hat{\gamma}_k\},\ k \in \{S, \bar{S}\},\ p \in k, \tag{5.19}$$

where $g_{p,k}$ and $s_{p,k}$ are the Guifi.net's cost sharing (Equation (5.11)) and Shapley value, respectively, for each set $k \in \{S, \bar{S}\}$ and for each participant $p \in k$.
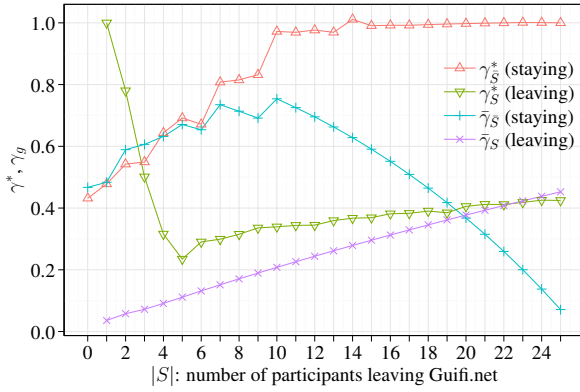
We observe the following:

Figure 5.11: γ_k^* and $\hat{\gamma}_k$ for each set k: S (leaving Guifi.net) and $\bar{S}$ (staying in Guifi.net).
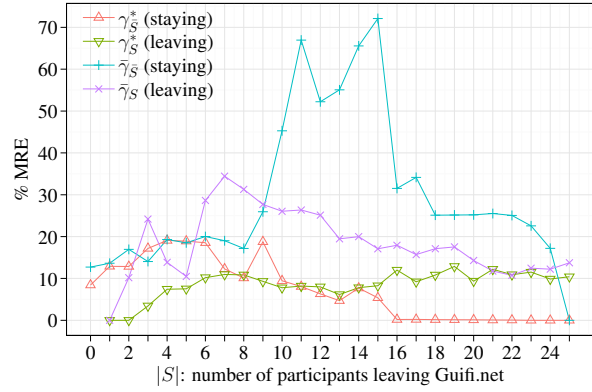

Figure 5.12: MRE between Guifi.net's cost sharing and the Shapley value.

- Figure 5.11 shows that, in most cases, we obtain $\gamma_k^* \in [0, 1]$, $k \in \{S, \bar{S}\}$. Thus, at least for the cost model derived in this section, Shapley values might be approximated using Guifi.net's cost sharing using γ^*.

- Figure 5.12 shows that, in all cases, the MRE corresponding to γ^*, $k \in \{S, \bar{S}\}$ is lower than 20 %. Thus, confirming that Shapley values are reasonably well approximated by Guifi.net's cost sharing using γ^*. Furthermore, because γ^* minimises the mean square error, the relative error is expected to be much lower for participants with higher costs. Indeed, we found that the participant with the highest assigned cost, participant 26, has a lower relative error than 4.14 % in all scenarios. This is important because participants with the highest cost assignments are those that bother the most about the fairness of the assigned cost.

- In Section 5.3.6.3, we derived that, if the system is balanced, $\gamma^* \to 1$. The *staying* subset becomes more balanced each time as participants with higher traffic leave (see Figure 5.10). Figure 5.11 shows that $\gamma_{\bar{S}}^* \to 1$, as expected.

- In Section 5.3.6.3, we found that, if the system is unbalanced, $\gamma^* \to 0$. The *leaving* subset rapidly becomes unbalanced as participants with lower traffic join the group (see Figure 5.10). Accordingly, Figure 5.11 shows that γ_S^* decreases and remains low (less than 0.5) as expected.

- Figure 5.12 shows that the MRE corresponding to $\hat{\gamma}_k$, $k \in \{S, \bar{S}\}$ is below 20 % in most cases. For instance, for $|S| = 0$ (when all participants are within Guifi.net), the maximum error is only 12.72 %. Figure 5.12 shows that the MRE corresponding to $\hat{\gamma}_{\bar{S}}$ increases beyond 50 % when a considerable number of participants with higher traffic leave Guifi.net, and the group still has more than 10 participants. This is motivated by the fact that when all participants have lower traffic usage, the *other cost* dominates the *shared cost* in Equation (5.11). Consequently, the Shapley value equally divides costs among all participants. That is, the membership fee should cover the overall cost, hence the higher MRE($\hat{\gamma}_{\bar{S}}$). In all other cases, even if γ_k^* and $\hat{\gamma}_k$, $k \in \{S, \bar{S}\}$ are significantly different, the MRE corresponding to $\hat{\gamma}_k$ is lower than 40 %. We conclude that, for a reasonable value of the membership fee, Guifi.net's cost sharing is not expected to be significantly different from the Shapley value (MRE less than 40 %).

5.3.9   Tuning Guifi.net's cost sharing

Although the Shapley value can be considered a sensible fair scheme from an economic point of view, it has some drawbacks when used directly as a cost assignment mechanism in Guifi.net or other similar scenarios. Possibly the most important drawback is that the Shapley value is difficult to compute because it needs to formulate the characteristic function and use numerical methods, such as Monte Carlo simulations. Thus, many participants would possibly not be able to compute or estimate the assigned cost and validate whether it agrees with the Shapley value.

On the contrary, the simple Guifi.net cost sharing is easy to understand and easy to estimate. Participants know that they are assigned a membership fee and a variable cost that is proportional to their bandwidth usage. Thus, participants with low usage can estimate that the assigned cost will be close to the membership fee. Possibly, these participants do not care if the cost they are assigned has a relative error of 20 % with the Shapley value, as long it is not far from the membership fee they knew beforehand. Furthermore, Guifi.net's cost sharing is easily computed using the average traffic, which is a measure available to all participants. Thus, they can easily validate the cost they are assigned.

As seen in Section 5.3.6, participants with higher usage in Guifi.net afford costs that are orders of magnitude higher than those of the participants with low bandwidth usage. Such participants are concerned about the cost they are assigned and the fairness of the amount of the membership fee. One convincing justification to them can be the Shapley value. That is, if the cost they are assigned is close to the Shapley value, it is a sound argument to convince them that the cost assignment is fair.

We have seen in Section 5.3.8 that, when using γ^* in Guifi.net's cost sharing, the MRE with the Shapley value is expected to be less than 20 %. Because γ^* minimises the mean square error, for participants with high assigned costs, the relative error with the Shapley value is even lower than 20 %. Indeed, we found that the participant with the highest assigned cost, participant 26, has a relative error that is lower than 4.14 % in all analysed scenarios in Section 5.3.8. Therefore, considering that traffic patterns are not much different in consecutive months, we propose the following modification to Guifi.net's cost-sharing approach. Every time the membership fee is to be updated, the following should be performed:

1. Compute γ^* using Equation (5.13) and the dataset of the previous month. We assume that we obtain $\gamma^* \in [0, 1]$.

2. Compute the membership fee M corresponding to γ^*:

$$M = \frac{\gamma^* c_T}{P}. \tag{5.20}$$

Thus, Guifi.net cost sharing will be used with the membership fee of M. Participants with high usage who are worried about the fairness of the cost assignment could compute the Shapley value and validate that it has a small deviation from the assigned cost.

5.3.10   Arguments against ceasing cooperation

Cooperation is an inherent part of Guifi.net history. It is only through collaboration and aggregation of demand that small players can access competitive solutions, such as the architecture presented in Section 5.3.1 and the associated services. All participants started from scratch; thus,

they directly benefited from the joint efforts to overcome the telecommunications' sector entry barriers. The forms of cooperation have evolved over time from the initial informal agreements around small and rather isolated projects to the current well-structured and legally binding body of normative agreements to meet new external challenges and the changes in interests, expectations, and objectives of the participants. This transformation process, which involved long discussions, agreements, and concessions among the participants, has had to cope with internal tensions recurrently jeopardising the cooperation. The threat of ceasing cooperation by one or more members has frequently been one of the causes of this tension or has at least been used as a means of enforcing internal rule changes.

In this regard, our findings not only provide arguments in favour of staying within the Guifi.net coalition but also to focus the efforts towards integrating new participants and increasing the resource usage. As Figure 5.8 shows, leaving would entail the broadly accepted fact that considerable extra costs would result for the remaining participants and for those who leave, which is something much less well known or at least less publicly acknowledged by those promoting the schism. Figure 5.9 illustrates that the losses greatly exceed the meagre benefits of the few participants when others leave. Conversely, both figures together, read from right to left, underline the benefits of the increasing number of participants and amount of usage consumption. Lastly, to obtain an approximation of the order of magnitude of the losses due to the cease of cooperation, we must consider that the external traffic case we analyse in this section is just a minor fraction of the total activity volume in Guifi.net for these service providers.

5.4 Conclusions

TThis chapter has been structured in two main sections, Section 5.2, which is on the economic system of Guifi.net in general, and Section 5.3, which elaborates a case study of cost-sharing.

Concerning the economic system as a whole, our main conclusion is that it seems sound and coherent with the fundamental principles of the project. The financial sustainability approach is backed with a remarkable practical level of investment recovery, especially taking into account that the most successful deployments are in areas that had been unattended by the traditional telecoms due to their long-term ROI.

The success of the Guifi.net economic system is deeply rooted in the governance system developed and implemented by the community in general, and in one of its components in particular, the cost-compensation system and the clearing houses through which it is implemented. The implementation details of these two instruments are established in the template of the agreements that the professionals must sign with the Foundation in order to develop any remunerated activity in the system. Therefore, what we presented in Section 5.2 is, essentially, the results of the application of these agreements.

The distinction between professional activity in the CPR and professional activity developed on top of the CPR, which is liberalised, has helped to clarify which of the professional tasks are regulated (installation, maintenance, and operation) and which are liberalised (service provisioning). This clarification has, in turn, contributed greatly to sanitise the system.

Making mandatory the recuperation of all CAPEX and OPEX regardless of the source of funding also is an innovative contribution. In addition to recapitalising the system, this rule has proven to be effective against dumping practices, which put the whole system at risk at some point in time.

The activation of this flourishing economic ecosystem by incorporating professional activity as an organic component of the system has drastically reduced the dependency on volunteer work, and it has enabled an unprecedented growth. However, the good ROIs achieved is the basis of some tensions that currently exist between the professionals and the rest of the community. The question has a strong legal background and depending on how it is eventually solved, it can have catastrophic consequences for the CPR. However, the interim results already achieved through the dialogue combined with the successful resolution of previous conflicts, and the long experience in conflict management already achieved, leaves room for optimism. The conflict is part of the Guifi.net history and has triggered major changes, which have made the system more resilient.

In Section 5.3, we analysed the cost-sharing mechanism that the Guifi.net community network has developed and put in practice to split the transit costs among their more than 20 beneficiaries for almost a decade. The way costs are distributed among the participants is a key question in the management and viability of shared resources. Although all cost-sharing mechanisms are subjective and thus, it is eventually up to the participants to accept one or another, some general criteria seem desirable, such as being budget-balanced and that, in any case it results more costly for a participant to cooperate than not to cooperate.

We started our analysis by introducing the general context and present the particularities of our case study, for which we elaborated a mathematical model including the characteristic cost function and cost-sharing mechanism. Then, we evaluated the model for a specific dataset, and we compared the results with the Shapley value, a reference cost-sharing mechanism in many areas. We followed with an investigation on the sensitivity of the system to reductions in the number of participants and demand. Drawing on our work, we suggested to the communities of practice that they seem to be facing recurrent periods of internal tension in which cooperation is endangered either because some participants cast doubt on the cost-sharing criteria or because they think they would get a better payoff outside the coalition.

The Guifi.net's cost-sharing mechanism of external connectivity, which follows the Guifi.net approach, comprises an equal membership fee for each participant in addition to a proportional distribution of the remaining costs according to the resource consumption. Our results yield a cost assignment similar to the Shapley value. Furthermore, we found that the simple sharing approach of Guifi.net can approximate the Shapley value in a wide range of cases. We believe that this is a significant contribution because the Shapley value for such a large number of participants is difficult to compute.

Our analysis also shows that any alternative to the coalition of all participants entails significant total cost increases and detrimental widespread cost allocation. For instance, that the four highest-usage participants account for 77.12% of the traffic. We estimate that, upon these participants leaving Guifi.net, the staying and leaving groups of participants would have increased overall external traffic costs by 28.11% and 54.01%, respectively.

The quality of the data that we have had access to has allowed us to reach an uncommon depth of analysis. In order to ease the validation of our results and to enable further investigation, we have made much of this information publicly available.

This chapter concludes the block devoted to the Guifi.net CN study. Given the interest raised by the project in general, and by its governance tools in particular, as it has been agreed that are the key to the success of the project, we hope that the work we have presented will meet the expectations of those who were interested in understanding the particularities of this innovative

but complex system for the participatory construction and management of network infrastructure as a CPR.

Appendix 5.A   Shapley value

The Shapley value is a well-known concept in coalitional game theory. For the sake of completeness in this appendix, we provide a brief review of the Shapley value adapted to our problem, using the notation defined in previous sections. The selected literature about the Shapley value can be found in [129].

Our coalitional game consists of the pair (A_P, c), where

- $A_P = \{1, 2, \cdots P\}$ is the set of participants (the *grand coalition*), and

- $c : 2^P \to \mathbb{R}$ associates with each coalition $A \subseteq \{1, 2 \cdots P\}$, a real-valued cost, $c(A)$, given by Equation (5.8). We assume $c(\emptyset) = 0$.

The Shapley value assigns the cost to each participant:

$$s_p = \frac{1}{P} \sum_{A \subseteq A_P \setminus \{p\}} \frac{c(A \cup \{p\}) - c(A)}{\binom{P-1}{|A|}}, \quad p \in \{1, 2, \cdots P\}, \tag{5.21}$$

where the summation extends all subsets of A_P not containing participant p (with one of the subsets being the empty set), thus resulting in 2^P summands. Note that the idea behind Equation (5.21) is assigning the average marginal cost to each participant, that is, the average increment of the cost that each participant adds to every possible coalition where he or she is included.

The Shapley value is the unique assignment that satisfies the following desirable properties:

1. *Budget-balanced*: $\sum_{p=1}^{P} s_p = c(A_P)$.

2. *Symmetry*: If $\forall A \subset A_P : c(A \cup \{p_1\}) = c(A \cup \{p_2\})$, then $s_{p_1} = s_{p_2}$.

3. *Dummy player*: If $\forall A \subset A_P, p \notin A : c(A \cup \{p\}) - c(A) = c(\{p\})$, then $s_p = c(\{p\})$.

4. *Additivity*: If we combine two coalitional games (A_P, c_1) and (A_P, c_2), in $(A_P, c_1 + c_2)$, then $s_p(c_1 + c_2) = s_p(c_1) + s_p(c_2)$.

Due to the exponential growth of the summands, computing the Shapley value using Equation (5.21) is impracticable for large P. In our research, we used the R package [130] to compute Equation (5.21) up to $P = 10$. For larger values of P, we used a Monte Carlo simulation (see for instance [103]). We provide our source code in the public repository [31]. The Shapley value is the unique assignment that satisfies the following desirable properties:

1. *Budged-balanced*: $\sum_{p=1}^{P} s_p = c(A_P)$.

2. *Symmetry*: if $\forall A \subset A_P : c(A \cup \{p_1\}) = c(A \cup \{p_2\})$, then $s_{p_1} = s_{p_2}$.

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CHAPTER **6**

Scalability in community networks

Preface

This chapter analyses the scalability of CNs once many of these initiatives have shown the feasibility to build bottom-up network infrastructures around the world. Scalability in the design of CNs makes a difference between an infrastructure for limited membership clubs and a general-purpose production network for an entire population. Following the perceptive introduction of the topic and an analysis of the reasons for scaling up, the rest of the chapter is structured in two main parts. On the basis and comparison of our studies of Guifi.net and other CNs, in the first part, we elaborate on the overall strategies from what we consider the four main dimensions of CNs: social, legal, economic, and technological , along with an analysis of cross-disciplinary factors. The second part presents a selection of patterns and anti-patterns that cover the vast majority of the generalisation components of the Guifi.net's internal organisation architecture.

6.1 Introduction

Once an initiative has proven its initial feasibility and delivered results (see Chapter 3), developed a solid governance in response at the challenges faced or anticipated (see Chapter 4), and developed a sustainable economic model that allows investment, deployment, maintenance, revenue streams, and cost-sharing (see Chapter 5), the next challenge is its scalability.

Scalability is a property related to the ability or sensitivity of a system to accommodate a change in a relevant dimension. Scaling up relates to *an increasing number of elements or objects, to process growing volumes of work gracefully, and/or to be susceptible to enlargement* [23], but finding the right size and determining how the it affects a system is challenging.

The aforementioned terms are widely used in the fields of computer science, telecommunications, and economics. In the field of computer science, the capability of physical systems and theoretical designs to handle a growing amount of work is commonly analysed in terms of resource consumption (time, CPU, RAM, and storage). The potential to be enlarged falls into two broad categories: horizontal scaling, which refers to the addition of nodes, and vertical scaling, which refers to the enhancement of existing nodes [161]. In field of economics , the term is usually applied to companies or business models to denote their capacity *to maintain or even increase its level of performance or efficiency even as it is tested by larger and larger operational demands* [89].

In this chapter, we elaborate on the scalability of CNs understood as the potential of these initiatives to deliver connectivity to their current members and to extend it to larger populations.

Particularly, we look at scalability in the design of CNs, arguing that, despite starting out small, pioneers should be aware of and plan for the size and characteristics of the potential group of participants and beneficiaries. That makes the difference between clubs (see Section 2.4) (organisations restricted to a few) from institutions for the common good (extensible network commons able to accommodate, serve, and benefit all members of a given community or area). [1] We base our analysis on our personal experience in Guifi.net combined with our knowledge of other CNs with the sole ambition of sharing our thoughts and vision.

It should be borne in mind that the aim of this study is to provide a general overview of CNcapability of scaling and to identify possible major blocking factors in this regard. Thus, it was not our purpose to carry out a comprehensive analysis of the factors that may influence the scalability of the initiatives regarded as a CN nor how these factors should be addressed.

The rest of the chapter is structured as follows. In Section 6.2 we discuss the reasons why CNs should scale and the general strategies to achieve it. In Section 6.3 we analyse the reasons and strategies to tackle scalability in more depth. In Sections 6.3.1 to 6.3.4 we do it from the perspective of what we consider the four main dimensions of CNs: social, legal, economic, and technological[2] dimensions. In Section 6.3.5 we make a cross-cutting analysis to address the relevant aspects that do not fit well in the previous thematic approach or that required further discussion from another point of view. The arguments are illustrated with experiences and lessons learnt by Guifi.net and other CNs and each of them concludes with a footnote with a proposed set of activities to be completed by the reader. We conclude our analysis in Section 6.3.6 with a review of the main actions that global external organisations can take to boost the uptake and development of CNs. In Section 6.4 we present a set of the most frequent and relevant organisational patterns that apply to any CN, or even artificial material commons, and present it in a structured way. These emerge from specific experience in Guifi.net or close CNs and, after generalisation, can be applied in re-engineering CN practices to promote the benefits of patterns or prevent the drawbacks of anti-patterns. Finally, we present our conclusions in Section 6.5.

6.2   Reasons for scaling up

There are four main reasons for scaling up. The first is the willingness to share a satisfactory experience with new people. Indeed, the keenness to share is one of incentives most commonly invoked by many contributors for participation [O1]. By getting involved in a CN, the participants not only have the opportunity to help their peers but also help extend the Internet, which has fostered sharing and collaboration in an unprecedented manner. In addition, the larger the CN, the more opportunities to share one's experience and to learn from others. In the specific case of Guifi.net, sharing knowledge and resources and helping neighbours were the fundamental conditions set by the mayor of the village where the CN was born (Gurb, Catalonia) to give access to the council's DSL, the only existing Internet access in the village at that time. These conditions aligned with the spirit of the promoters of the project.

The second reason relates to reaching economic sustainability. To persist over time, any project must grow at least to the point where the contribution of beneficiaries meets the resources

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[1]*In the past, networking infrastructures were considered a club good (excludable and virtually non-rival as a commercial service) provided by for-profit ISPs to those fortunate to be in covered areas and willing to pay the service fee. CNs are a social response to the wide recognition of connectivity as a basic human right, and therefore the network infrastructure connecting people becomes non-excludable.[O8]*

[2]In fact, from the technological perspective, CN are not so different from any other network deployment. Even though, technological aspects too often mistakenly attract the attention of the debate.

required to maintain the activity, the so-called break-even point in economics. In the case of the CNs, the costs to be covered include at least the hardware (routers, antennas, cables, etc.), but from a given time, manpower costs should also start being included, as the projects that are purely based on voluntary work do not scale well and tend to decay.

To attract enough users to reach the break-even point, CNs must offer value, that is, competitive services that maximise the satisfaction of the user needs in comparison to competitors. In turn, competitive services can only be offered after a minimum outlay, meaning that only projects over a certain budget are viable in the long term. In addition, scaling up also helps reach the critical mass to counteract the demotivating effect that the stabilisation of the infrastructure and the access to good quality Internet access may have over those initial members who were looking for technical challenges.

The third reason is that growth strengthens self-protection. The larger the community, the larger the community knowledge is and the higher the chances to provide mutual support are. Moreover, the stronger the dependencies on a given resource, the more difficult is to be obstructed by potential adversaries. Social pressure is a recourse to warn against situations of injustice, like unfair and discriminatory treatment by public bodies or private companies. For instance, Guifi.net has used its presence in the territory and its social support to denounce malpractice cases by public administrations and by the incumbents.[3] As a result, many public administrations had to backtrack on policies that were manifestly abusive and discriminatory, like levying a tax only on new operators after the established operators deployed their networks and the incumbents had to review their initial positions.

Finally, yet importantly, larger scales increase efficiency and are conducive to economies of scale. Some cost savings, such as in procurement, are quite predictable. Others, though, are not so obvious beforehand. As an example, wholesale Internet access is generally significantly cheaper and of much better quality than domestic connections; thus, a CN makes a qualitative leap when it is able to switch from retail connections to wholesale and, at the same time, it reduces costs. Similarly, quantity discounts are common among hardware providers. In addition, less obvious savings appear with the increase of the activity within the CN ecosystem. For instance, in Guifi.net, we have observed that, as economic activity increases, the professionals tend to specialise, fostering their expertise and improving their productivity. The repetition of tasks leads to optimised procedures and good practices that can be collected, documented, and some even automated. In turn, these optimisations enable further growth.

Furthermore, the spirit of sharing that characterises CNs amplifies the ordinary positive effects of growth, as any progress (in software, methodology, etc.) is immediately available to all practitioners –also from other CNs– and the adoption rates are usually very high. Sometimes, the spirit of sharing is so deeply rooted that practitioners are not even aware of the benefits that come along with it. In Guifi.net, for instance, the contributors are so used to automatically getting the configuration parameters of their devices through the website that is highly likely that many of them are not even able to estimate the resources needed to do so manually, which is probably no longer possible given the size of the network.

However, growth has some drawbacks as well. As the community becomes larger, information exchange and personal interaction across the community may become costlier and require

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[3]For instance, the first connection between Guifi.net's fibre deployment and the public fibre network of the Catalan Government was only achieved after pressuring the authorities with roadblocks in Sunday afternoons to show the visitors that despite the two infrastructures were side-by-side the Catalan Government was rejecting to connect them.

additional coordination to avoid overload. A larger community may increasingly need to stipulate and formalise procedures to reduce the burden of otherwise unstructured interactions across a larger set of participants without increasing complexity. Larger constituencies may benefit from distributing functions and responsibilities and more clearly defining the organisational structures. Thus, the challenge is how to accommodate growth with coordination mechanisms that keep the community equally or more effective in delivering benefits to its participants without disempowering them by centralising decision making or overloading them.

6.3   Multidimensional approach

There are many approaches and factors to be considered when it comes to quantifying the size of a network. Our viewpoint is from the socio-economic value of the infrastructure; thus, the most representative indicator is the number of beneficiaries. The maximisation of this indicator with respect to the size of its constituency, that is, the potential beneficiaries, should be the target of any non-speculative infrastructure[4] of any kind. Importantly, the strategies leading to this type of maximisation must always be subordinated to the principle of social fairness, which includes respect for the environment, fair wages and working conditions, inclusion and non-discrimination of minorities and the vulnerable, and so on.

To maximise the number of beneficiaries, the ultimate goal of any action, direct or indirect, must be either the expansion of the network (acquisition of new beneficiaries) or the improvement of the services delivered (loyalty of beneficiaries). These actions must be prioritised by the principle of opportunity and repayment maximisation, again, carefully combined with social fairness goals. Direct actions include the deployment of new nodes (horizontal scaling), enhancement of the existing infrastructure through technology upgrades or migration (vertical scaling), and the improvement of services offered to the participants. Indirect actions include improvements in the governance system (licensing, agreements, procedures, etc.), development of software tools, dissemination activities, stakeholder engagement, and influencing public policies and regulations, among others. As discussed in the following section, the realisation of CNs generally leads to disruptive innovation. As such, it can create relevant resistance on the part of well-established interests, which see any innovation that they cannot control as a threat. Countering the strong influence of these interests demands cleverness and perseverance. In this respect, the basic literature on strategies and tactics offers appropriate tools. For instance, in Guifi.net, the frequently used tactics of distributed action, rapid action, and exploitation of apparently minor opportunities to provoke significant changes are very reminiscent of the lessons from Sun Tzu [162].

In the following sections, we deepen the analysis on the factors influencing scalability. We structure our study around the four main areas that, in our opinion, every CN should consider, followed by a section analysing the cross-disciplinary requirements. We elaborate on external and internal threats and on internal mistakes and make recommendations based on our experience and research on Guifi.net and other CNs.

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[4]Speculation has its own logic which is out of the scope of this chapter, but certainly does not have social good as its ultimate goal.

6.3.1 Social considerations

The social objectives are the main shaping factors of any project. Computer networks, aiming at an experimental network for hackers,[5] have very different implications at all levels than aiming at a general-purpose production network for an entire population. In the same manner, the implications of aiming at a network for dozens of users are not the same as aiming at one for every one of the hundreds, thousands, or millions nearby. The social objectives do not need to be necessarily prescribed since the beginning and might evolve over time,[6] but an early tentative definition[7] facilitates initial progress because many of the critical decisions needed to move forward depend on them.

Moreover, explicit definitions and clear positioning on fundamental relevant topics (e.g. support of the right of participation in the decision-making process) are needed to ensure that there is common ground among the participants on these topics for an effective progress. Nevertheless, it is important to note that the requirement of consensus must be strictly restricted to the truly relevant matters to avoid unnecessary and undesirable exclusion.[8] One of the first decisions to be explicitly made with a determinant influence on the nature and potential of our project is the choice of the socio-economic model for the infrastructure: the network.

To this end, we propose to learn about the predominant ones considering their (real) social objectives[9] and understand their (unwanted) implications[10] and to raise a number of questions, such as whether we envision the network to be self-sufficient by allowing economic activity and, if so, under what conditions (e.g. do we allow profit making? Do we allow competition?). Our social objectives do not match those underlying the traditional network models. Thus, finding a suitable socio-economic model requires us to be innovative. For instance, it is clearly incompatible to pursue a user-centric network and to choose a model prone to speculation. The topic to address in this decision-making chain relying on social objectives is to select the governance model.

We again propose to review the existing solutions and address some questions, such as who may participate in the CN governance, how decisions should be taken, what the usual practices emerging at the local level are in similar initiatives, and so on. As in the previous case, given the divergence between social objectives, most likely we will have to be innovative because, arguably, the top-down traditional governance practices will not satisfy our needs.[11] Such divergence in aims and fundamental approaches leads to the emergence of disruptive models and practices.

In Guifi.net, for instance, the social objective is stated as "a fair Internet for everyone."[12] At first sight, it may resemble the motto of any of the existing large telecom companies, but

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[5]It is not our intention to establish a classification schema for CNs, but for us such restrictive initiative does not meet the minimum requirements to be labelled as CNs.

[6]See the discussion on the iterative development process in Section 6.3.5.

[7]We can start being conservative and then become more ambitious.

[8]The example of open content is illustrative. A sympathy for open materials and services can be presumed among most of the participants. Nonetheless, in a participatory project the rule on openness must and can only be imposed on the content and services that are strictly necessary to run the project but not on others contributed by the members.

[9]For instance, maximization of the dividend to shareholders.

[10]For instance, that the network resources and customers are mere speculative assets.

[11]Strategies of organisational maturity: debate (learning), construction (testing, implementation): scaffolding and consolidation, replication (in new areas, communities). Related to Ostrom's principles for sustainability (every time, short term) and adaptability (to changes, medium or long term) [112].

[12]"*Una Internet justa per a tothom*" in Catalan.

the terms fair and for everyone have implications that few of them would ever fully implement. Regarding fair, one could argue that the concept may hold different meanings for different people, but certainly it is quite apart from the real underlying principle of the business models of the current dominant telecom operators, which is the profit maximisation of the investors.[13] In any case, the other Guifi.net motto "neutral, open and free network"[14] makes the implications of the term clear on the properties of the network to be implemented. The use of *for everyone* leaves no room for interpretation: it means exactly for everyone regardless of one's individual capability to afford it or not.

From the socio-economic model viewpoint, in Guifi.net, the infrastructure is conceived as an open CPR, and it is basically governed following Elinor Ostrom's (1990) principles. The Guifi.net community has followed a long process to establish its theoretical basis. The concept of CPR and Ostrom's principles had to be adapted to suit the specificities of an artificial resource (the network) because the previous experiences –and the academic studies– were restricted to natural resources.[15] In conjunction with the governance system, the stakeholder groups and their rights and duties must be defined. Special care should be dedicated to the definition of the non-transferable roles of each stakeholder to ensure that there are no intrinsic incompatibilities or uncovered tasks.

The solution should strike a clear distinction between for-profit and not-for-profit contributors, as there are tasks that cannot be transferred from one to another. For instance, we argue that core governance activities must be under the responsibility of not-for-profit participants (to avoid conflicts of interest), while delivery of services to customers should be done by for-profit actors (to prevent market distortion).

Lastly, it is clear that, to create value, any network infrastructure must be connected to the Internet. Even more, it is not a matter for the active participants to decide whether the users may have access to the Internet or not. Their duty is to ensure proper Internet connectivity and let the users decide for themselves.

6.3.2   Legal considerations

The telecommunications sector is a highly regulated area, and CNs cannot afford disrespecting established rules, as the lack of compliance to the legal framework would only jeopardise their development. Although CNs are local initiatives and thus develop their activity under diverse legislative and regulatory frameworks, some practical guidance is applicable to nearly all contexts, regardless of the specific domestic legislation. The first is to acquire knowledge on the legal system as a whole: how the legal system is structured where the CN will be developed, what the fundamental components are, such as the authorities that can regulate and bodies that can legislate, and how they relate to each other. The internalisation of this knowledge is crucial given the existing strong economic interests of the telecommunications sector and the influence that their lobbies usually enjoy.

The telecommunications sector is very dynamic with a global trend towards liberalisation. As a result, the legislation is constantly evolving, making compliance even more complex. This changing scenario is harnessed by a wide range of lobbies aiming at shaping the new rules towards

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[13]This explains overbuilding (deploying excessive capacity) while there are underserved areas at the same time, the business concentration, and so on.

[14]"*Xarxa oberta, lliure i neutral*" in Catalan.

[15]These adaptations the most important contribution of Guifi.net at the theoretical level; at practical level, it is the size achieved.

their interests (influencing policy) and influencing the public perception of these rules when they are not satisfied with the existing provisions (manipulation, FUD[16]). Importantly, CNs organisers willing to lobby for legislation and regulation facilitating CNs should consider that legislative and regulatory competences are often distributed between several public administrations, and this situation increases the difficulty even more for the general population to participate in public affairs, while favouring the activities of those interests enjoying well-funded lobbying organisations. In addition, CN organisers should be prepared for the frustrating reality that critical decisions may be left undecided or in the hands of less than expeditious bureaucratic processes.

Under these circumstances, CNs have no other choice but to be smart and creative. A good knowledge on legal matters will facilitate a clear understanding of the limits posed by our legislative frameworks, that is, what is allowed and what is not. It is important to reiterate that the public understanding on these matters is typically confused and may even reveal contradictions between what it is generally assumed to be legally possible and what the law really says. Furthermore, in several occasions, we have realised that just a fraction of the true potential of the legislative framework is put into practice. The rest remains unexplored and unrealized.[17]

This generalised lack of knowledge and the unexplored possibilities of existing legislation bring us to the first line of action, which is to make creative proposals, working hand in hand with public servants whenever possible, and pursuing win-win situations through proactive actions. This must always be the first choice for CN members because positive attitudes are undoubtedly much more effective than any confrontation.

These win-win tactics, which should not be restricted to legal matters but should be extended to the other areas, have been very satisfactory for Guifi.net. As an example, the Guifi.net

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[16]FUD: Fear, uncertainty, and doubt. A clear example that illustrates the bad practices by public authorities and the private sector is the case of the Torelló council against Guifi.net. The first key point is that it should have been Guifi.net against the Torelló council because it was Guifi.net who complained about an abusive tax for ducts usage, but the Torelló council took advantage of its longer experience to open a case first at the regulator with a question that was not the substance of the matter. Instead of asking about the prices, they asked about the right to levy taxes on public infrastructure usage. This right was something that Guifi.net never discussed and it was not until the allegations made by Guifi.net that the prices were considered as well, which was the question really disputed. To this, the council alleged that there had been an error in the calculation of a parameter and proposed a newer one which resulted in a fair amount. Unfortunately, the regulators resolution (available at https://www.cnmc.es/sites/default/files/1538376_7.pdf only in Spanish) is written in a way that makes the reader think that it says that the council is right because it answers the initial question: yes, councils have the right to levy taxes on public infrastructure usage, which, again, is something that Guifi.net never discussed and it is just later in the text body that addresses the tax quantities issue, and just stating that thought the process of the dispute resolution a technical error for its calculation was fixed.

Despite it is a clear case lost by the council (they had to change the prices) it is being presented by the council as well as by the competitors as a case lost by Guifi.net because they still claim that Guifi.net wanted to use the public ducts without paying.

[17]For instance, one of the keys to success of the XAFOGAR (see Section 3.6.2) project has been a new finance scheme for the municipalities. This perfectly legal instrument ensures the capacity of the municipalities to make sure that the public money is allocated to build commons network infrastructure, that is, for what it is intended for, and it is not captured by traditional telecoms that build private infrastructure. In summary, the innovation is to allocate the money to an NGO instead to a private company directly through a public contracting process because these processes are completely dominated by the big telecoms. Nevertheless, the public procurement law direct allocation to NGOs. Through this novel procedure the Guifi.net foundation, which is only allowed to deploy network in commons, receives certain amounts of money from the municipalities under the commitment to deliver connectivity to the municipal buildings. This money represents just a fraction of the total project budget, but it is helpful to start and at the same time proves commitment of the local authorities to third-party participants such as beneficiaries or investors.

foundation, in collaboration with some small city councils, developed an ordinance to make the coexistence of the public, propriety, and commons usage of fibre ducts compatible. [59][18] Nevertheless, it is important to be on guard against malicious collaborations, and CN members should always consider that public administrations and regulators may be constrained by special interests.[19] In this respect, we have observed delaying tactics aimed at harming the project, for instance, by giving time to the competitors to deploy first.

The second line of action is to lodge complaints using all the resources available (ordinary courts, higher courts, national regulatory agency, etc.), thus exploiting reactive actions. These legal actions must be used very selectively because they might be costly in both time overruns and money. Nonetheless, they are worth doing because they can have a strong effect on the success of the case. They establish legal precedents and demonstrate maturity, strength, and capacity for action on the side of CNs.

The third line of action, influencing policy-making processes, is also very demanding but must not be left unattended because, to a large extent, the success or failure of our project depends on the laws to be passed. A single modification can kill an initiative or can drastically boost it. For instance, in the regulation of access to the backhaul, the introduction of a discriminatory fee on a resource, such as one based on distance, directly makes remote rural projects unfeasible, while a fixed price taxation with low prices fosters the rise of connections not only in rural areas but also in urban areas, as they become denser.

The number of policymaking bodies and the diversity of their competences demands distributed and coordinated action among the CNs. To be efficient, the international and regional activities must be led by international specialised organisations (like La quadrature du net in Europe, APC, and ISOC globally) to better cope with the requirements of this field, which is full of subtle details unknown to the layman. Furthermore, CN members must be ready to provide support and become involved in specific actions when needed. Conversely, national and local policy influence must be conducted by the affected CNs, possibly being endorsed by international organisations.

The power of apparently small successes should not be underestimated. Even small victories should not be kept unpublicised but should rather presented to other legislators and regulators for their consideration. For instance, the 2G spectrum-licensing scheme for indigenous communities developed by the Mexican government together with Rhizomatica[20] is currently being adopted by other Latin American states[21] with the help of the respective CNs.

Civil disobedience or disrespecting rules is something that we can only understand for very specific cases, where rules or their application are patently illegitimate or unjust and should never be considered a means to consolidate an illicit situation. Nonetheless, it is indispensable to distinguish between truly illicit actions and those that are deliberately presented as such by some stakeholders but, in reality, are perfectly legal. A clear example is the position of the Spanish incumbent against the usage of the telephone poles by Guifi.net to deploy fibre cable. As long as

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[18] Unfortunately the ordinance could not have been passed by any municipality despite many of them are interested in doing so due to the (deliberate) lack of a clear response of the upper public authorities. In this case the administrations involved are the Ministry of Industry and the regulator. They always respond at the limit of the legal period of time allotted, with irrelevant observations or further requests, and so on, but never entering into the substantive debate. This is terribly harmful because in the meanwhile the traditional telecoms are deploying in the same areas, in most of which there is market for just one deployment.

[19]For an analysis of the regulatory capture phenomenon, see for instance [27].

[20]https://www.rhizomatica.org/

[21]At least in the case of Colnodo, with the government and Telecom regulator in Colombia.

the technology used by Guifi.net was limited to WiFi, the position of the incumbent towards the initiative was mainly that of disregard, probably with the objective to make the CN look irrelevant. However, its position completely changed when Guifi.net started deploying fibre cable in 2009.[22] Since then, the incumbent has been hostile and the denial of Guifi.net's rights to use the existing telephone poles has been one of the most-used weapons by the incumbent.

On the one hand, this combative attitude clearly demonstrates that established telecommunications operators feel threatened by the emergence of CNs. On the other hand, the fact that operators, who certainly do not lack legal advice and funds, have never initiated a lawsuit in court shows that they are very aware that the utilisation of the poles by Guifi.net is completely legal.[23] The certainty set by a judgement would be fateful for the operators' interests; thus, the tactics of coercion and misinformation seem more profitable, as established operators usually enjoy relevance and influence. The Guifi.net example demonstrates that, when dominant operators applied these tactics, only the most motivated supporters stayed with Guifi.net, while the rest were frightened.

On another front, the conception of the network as a CPR has proven to be a very powerful legal shield against speculation. The network is a crowdsourced CPR from which the contributors can withdraw and have the right to be compensated for their contributions, but those who stay have the right to retain the infrastructure. So, as long as a participant is staying, the infrastructure remains in commons. In Guifi.net, the whole system is secured through the Foundation, which has the ineluctable mission[24] to protect the network commons.

6.3.3 Economic considerations

The development of an economic system with revenue streams and economic exchanges is fundamental to achieve sustainability and thus to expand the CN at a later stage. Even in resource-limited environments where external funds are needed to initiate the project or to contribute and maintain it over time, the development of a local economy is the most effective way to ensure the healthy survival of the network and its successful evolution, that is, to expand in the quality of services and the number of users served.

Any strict and self-imposed limitation of the scope of the project in terms of the area or the type of population to be served must be avoided. A project restricted to unprofitable regions or certain excluded segments of the population will rarely be self-sustainable, and it will most probably depend on external help; thus, its self-determination will never be achieved[25] [15, 16]. Limitations can be induced by third-party agents (external threat) but are also sometimes self-imposed (internal mistake) due to misconceptions.[26] Some of the external attempts to limit the scope of CNs are also due to more misconceptions,[27] but others may be intentionally

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[22]Obstructive strategies such as letters, minor litigation, and so on, to create doubt, lengthen processes to delay and discourage deployments, while avoiding any clear public decision that would clarify competition.

[23]Reinforced by the adoption of the The Broadband Cost Reduction Directive (Directive 2014/61/EU) of the European Parliament and of the Council on 15 May 2014.

[24]The Catalan legislation establishes that a Foundation cannot change its mission and in case of dissolution of a foundation its assets are kept under guard by the Catalan Government until they can be reallocated to another entity that respects the conditions under which the assets were donated to the initial organisation.

[25]Self-determination in combination with the disruption capacity is the most frightening for the well-established business.

[26]Fortunately, the term wireless is not used any more to refer to CNs as it clearly was an unfortunate self-limitation towards a specific technology, which –paradoxically– also implied the violation of the network neutrality.

[27]There are still too many well-intentioned international organisations that circumscribe CNs to unprofitable spheres.

instigated by adversary lobbies. Restrictions due to misconceptions can be prevented by raising awareness, for instance, by raising the question regarding why we should limit the potential of something positive. On the contrary, intentional attempts to limit scope must be countered by other means, such as judicial disputes, policy advocacy, and so on. It is also important to note that access to profitable segments are not only needed to ensure sustainability but also to be able to implement redistributive policies because it will be the users of these segments that will generate the surpluses to sustain these policies.

In addition, to have access to profitable markets and to enable economic activity and thus investment, trust is needed. Initial investment by pioneers has several positive effects on building trust and increasing predictability. First, they allow covering the initial costs of the initial installations. These initial installations, in turn, allow the start of delivering services, which make repaying the investment possible, and they can be used as working examples in the dissemination activities aimed at expanding the network. Another positive effect of the increased trust resulting from the initial investments is that they are considered proof of commitment by new investors, thus facilitating new funding rounds.[28] It must be noticed that, currently in Guifi.net, the term investor usually refers to anyone putting money in the network, regardless of whether he or she does it to obtain connectivity (final users) or as an economic benefit either directly through an interest (money lender) or indirectly through creating business opportunities (service providers).

Transparency is a key component to create trust. In Guifi.net, transparency about what is done and predictability about what can be done are achieved through clear interdependent rules of (i) governance, (ii) recognition of investments, (iii) inventory of network assets, (iv) costs sharing, (v) monitoring of network resources consumed, and (vi) dissemination of good social, economic, technical, and legal practices.[29] Predictability is related to accountability (auditable statements for transparency that include investment, consumption, expected return of investment, depreciation, and margin) and the ability to plan and forecast social and economic impact and growth based on whatever goals and metrics are critical. For instance, cost accounting allows determining an estimate of the unit cost to expand the network to a new location or maintain a unit of network infrastructure, which determines the investment required and the critical mass for feasibility as a CN expands. Predictability and planning relate to risk mitigation, which becomes more critical as CNs grow.

Furthermore, organisational resilience is a concern, particularly for a commons infrastructure. In a cost-oriented ecosystem, reserve funds in the form of monetary deposits from participants are a key instrument to face and mitigate financial risks. Risk mitigation plans and the corresponding reserve funds must include the response to the technological evolution and hardware obsolescence. As a reference, the depreciation period of electronic components (WiFi, Ethernet, and optical fibre) should be no longer that four years, and the cabling (copper and optical fibre) from 10 to 15 years.[30]

In Guifi.net, the conception of the network as CPR has enabled a flourishing non-speculative economic system based on services in which over 30 Internet service providers (ISPs) are offering

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[28]The full-cycle of a funding round was described in Guifi.net in 2007: (i) dissemination, (ii) techno-economic proposal, (iii) crowdfunding, (iv) execution, and (v) re-start the cycle (https://guifi.net/node/7934 available only in Catalan and Spanish)

[29]See [P2] for a diagram and further explanations regarding these elements.

[30]These are pretty conservative estimations, especially for copper and optical fiber (electronics and cabling). The conservative estimations enable sound financial housekeeping and hardware reallocation policies. Cheaper deployment costs may increase maintenance costs (e.g. shallower or less protected fiber deployments accelerate deployment but increase the risk of cuts).

their services on equal terms to tens of thousands of customers and coexist with many other stakeholders, such as volunteers, public institutions, and so on. From the economic perspective, the CPR is a crowdfunded infrastructure because it is paid by its users.

6.3.4 Technological considerations

Technological matters must be addressed in accordance to social objectives. From this perspective, technological decisions must also be driven by the opportunity criterion to optimise the extension of the network and the quality of services offered. Furthermore, these decisions must be taken in line with the economic capability and legal possibilities.

Therefore, it is important to elucidate technology challenges from a neutral perspective. A given solution might be the right choice at a specific time but inappropriate at another time. For instance, fibre-optic technology has unrivalled performance characteristics. Nonetheless, it is so demanding in terms of CAPEX and deployment time that it is the suitable technology for starting CNs only in very special occasions. In most cases, WiFi is the right option to initiate a CN due to its good value for the money and the legal and administrative facilities, as there are radio-frequency unlicensed bands in most states. Nevertheless, a WiFi-only network cannot grow infinitely due to the OPEX costs and capacity constraints of these technologies. Thus, in the long term, the adoption of fibre is cost effective even for most of the small WiFi deployments and is necessary and indispensable for a network that is growing.

The potential congestion of a resource (routers, links, etc.) is not a threat to combat with restrictions but an opportunity to improve the network. For instance, in Guifi.net, the rule is to double capacity when the usage exceeds 50 % of the capacity. The additional capacity enables better services for the current users, attracts new users, and makes the infrastructure more resilient because the spare capacity can be used to mitigate the effects of planned or unplanned outages in other segments of the network.[31] The challenge is to turn the demand for these assets into resources to enhance them. To this end, we need procedures to know who is using them and in which proportion and how to contact the users, gather the contributions, and track their usage, and so on.

Technologists must provide effective tools –mostly software– to develop and implement not only the aforementioned procedures but also many others that are crucial for the healthy development of CNs, like those mentioned in the section of this chapter dedicated to economic matters. Most likely, the fulfilment of the social objectives will entail the publication of the source code (free software) and the data (open data), obviously in compliance with the law.

From the network architecture perspective, it must be understood that all components (last mile, backhaul, backbone, and interconnection) play a critical role in delivering connectivity to the users. Thus, they must be maintained in good condition and must be harmoniously engineered. Initial Internet gateways might be built by pooling consumer-grade Internet connections, but the sooner to access the wholesale market the better, not only for the reasons of economy of scale already discussed but also because, from the technological and management viewpoints, it implies major upgrades. Emergency and technology upgrade interventions must be scheduled to maximise the benefit of users served, but in the long run, the benefits must be extended to all users.

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[31]Alternative paths allow to keep the network operational despite planned or unplanned outages. Monitoring, routing and load balancing mechanisms can automatically reconfigure the network to mask any effect.

Community networks must exchange traffic with third parties in IXPs whenever possible, as peering (swap)[32] is better aligned with CNs principles[33] and network neutrality in general than transit (paid). From the management perspective, the community must ensure control over all critical resources (software and hardware), as loss of control of any critical resource might be misused to favour particular interests (internal attack) and jeopardise the collective interests of the CN community. For instance, in Guifi.net, we have observed that technical control over access routers from a given professional (see Section 4.2 and Section 5.2) has been used to harm the interests of competitors. In terms of content, CNs must promote the development and hosting of local content accessible locally and from the Internet. This way, not only does the content remain under the control of the community but it also increases the symmetry of traffic, which results in reduced interconnection costs.

6.3.5   Cross-disciplinary considerations

Community networks are likely to start out tiny, but their contributors must develop the strategic planning according to the target size of participants and beneficiaries. The strategic planning must have a holistic vision, the strategy to develop it, and the priorities and action plan to implement it (the so-called VMOSA).[34] Given that the composition of the initial group of *pioneers* has a determining effect on the initial choices, the character of the CN, and how it is perceived by the surrounding environment, special care must be taken to include representatives from different perspectives with different skills to reach a balance in terms of multiple dimensions that can represent a large community (e.g. gender, cultural, economic, and geographic dimensions). While some members may be more active than others, the involvement of all of them will help make the organisation more representative of the target community and therefore more suitable to serve their needs as it scales up.

Moreover, CNs develop their activity in such a demanding environment that, to be able to succeed, they need to take a holistic view, adopting a multidisciplinary approach without preconceived ideas beyond the driving principles that define the essence of the initiative.[35] That is, once the driving principles[36] are accepted, a rational attitude is the most effective to address the emerging challenges. Furthermore, from the risk management perspective, a multidisciplinary approach is optimal, as all areas or viewpoints previously discussed are equally important since any major failure in any of them would seriously undermine the whole project. Even more importantly, it would be difficult to find tasks or decisions to be made that would fit exclusively in one of the fields. For instance, the maturity level of a technological solution determines the amount of people able to actively contribute to implement it and thus the degree of dependency of skilled contributors, which is a social issue.

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[32]The interconnection fees in IXP usually depend on the symmetry of the traffic exchanged (cheaper or even free with a balanced mix of content to provide and readers, while more expensive for only readers: also called eyeball networks)

[33]Technically speaking, internally Guifi.net is a fully distributed IX because its licence makes compulsory to peer with the rest of participants.

[34]VMOSA: Vision (what aim), Mission (what and why), Objectives (what to accomplish by when), Strategies (how), and Action Plans (what change will happen). See https://ctb.ku.edu/en/developing-strategic-plan-and-organizational-structure

[35]In Guifi.net, for instance, decisions are taken by voting and not by consensus because in the past, the consensus process had been used to block the decision-making process because the blocked situation benefited the blockers.

[36]In this document we have discussed the driving principles as part of the social axis, but given their importance (they are the basis of the project) and their nature (they are indisputable – either one accepts them or not) they could have been analysed in a specific section.

Decisions must be taken giving the highest priority to the less restricting options while trying to foresee the future consequences. Nonetheless, given that not all the consequences can be predicted beforehand and that decisions must be made to move forward, a compromise between design and planning tasks and actions on the ground must be found. Moreover, on the ground activities provide valuable knowledge –difficult to achieve otherwise– that helps to make better choices in the subsequent decision-making rounds.

An iterative and incremental approach with short iteration cycles enables finding a good balance between the need for design and planning and the need for action in a harmonious manner. It also allows us to rectify issues when needed without much loss of effort and to quickly integrate learning lessons from experience. The decisions of the subsequent iterations must be based on the objective assessment of the results of the previous ones (quality metrics). Thus, a continuous monitoring system is needed, and with such a system in place, quality assurance and quality assessment can be implemented. In addition, such formality and rigour also increases trust, which, as already commented, is essential to attract new investors and beneficiaries. Another reason in favour of short iteration cycles is that it allows the gradual introduction of changes in isolation, which is necessary to be able to well understand their effects. Lastly, changes must have specific and assessable objectives.

6.3.6 External support

The case of Guifi.net shows that a single CN can scale at least up to more than 100,000 beneficiaries with the latest networking technology[37] in a self-sustained manner. So far, we have analysed what practitioners can do to enlarge and strengthen their CNs. To conclude, we briefly discuss what are, in our opinion, the main external actions that can be implemented to support the development of CNs and ensure that they can develop all their potential to expand the Internet worldwide. External support is crucial to accelerate the development of CNs and make the efforts of their contributors more productive because, although many CNs are working to improve their procedures and methodologies, their margins are too narrow –if any at all– to make any significant progress at a world scale.

In our opinion, the most important thing is that these organisations also fully comprehend that CNs can be large-scale fully competitive networks and thus do not confine themselves to marginalised corner cases. From the legal perspective, the legislators and regulators must ensure at least the equality of treatment with the rest of the ISPs. Ideally, they should give preference to CNs given their openness and unequivocal social value and the wide range of positive externalities they trigger [15], but in any case, they should combat malpractice by commercial providers, such as predatory overbuilding or misinformation about their deployments.

In economic terms, external funds should be allocated to develop a comprehensive platform (methodologies, databases, and software as well as training and seed funds) with global reach for supporting and assessing the creation and growth of CNs with regard to network design, monitoring, and management, project management, conflict resolution, and so on. The development should follow an approach able to deliver operational products as fast as possible to make them available to existing CNs and to use them in all the deployments funded by international organisations, such as ISOC, Institute of Electrical and Electronics Engineers (IEEE), development agencies, and so on.

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[37]Other indicators for the health of the Guifi.net project: doubling inter-networking capacity (transit and peering) every 18 months, +30 microISPs, +20,000 customers for professional services, and so on.

Ideally, the development of the aforementioned platform could be led by an international organisation[38] commissioned to keep track of all CN initiatives around the world and to provide them technical assistance and assessment, while offering financial support. This international organisation could be funded with national universal access funds because their objectives are totally aligned and because the effect would certainly be more visible than any of the actions funded –and frequently failed– so far. Furthermore, universal access funds could also fund the deployment projects promoted by this organisation.

Lastly, international organisations must work to ensure that CNs have appropriate access to wholesale and backbone networks and to local IXPs, as these resources are critical for the healthy development of CNs. Nonetheless, they must also ensure that their actions do not (unintentionally) contribute to perpetuating the dominant position of the owners of these resources, as it could happen, for instance, if the access is achieved through a co-funding model or directly subsidising the connections. The right way to do so is to ensure that the owners of the infrastructure charge fair, reasonable, and non-discriminatory prices for their services.

6.4   Organisational patterns and anti-patterns

The idea of defining *organisational patterns* for CNs originates from the idea of a *design pattern*, the re-usable form of a solution to a *design problem* [2]. Patterns can be expressed in a *pattern language*, a method of describing good design or organisation practices or patterns of useful organisation within a field of expertise. Organisational patterns [132] and pattern languages can help people think about, design, develop, manage and use information and communication systems that more fully meet human needs. Conversely, anti-patterns are common responses to recurring problems that are usually ineffective and risks being highly counterproductive. We integrate this concept, which is well known and frequently used in software design, to supplement the effectiveness of the organisational patterns method.

Below, we present a selection of patterns and anti-patterns that, as a whole, cover the vast majority of the components of the generalisation of the Guifi.net's internal organisation architecture, which we take as a reference. Figure 6.1 shows this generalisation and how each of the patterns and anti-patterns relates to it.

6.4.1   Crowdsourcing/sponsorships (Pattern)

Problem Solving an identified bottleneck in a network infrastructure that affects one group of
   participants.

Context Community networks as they grow in an unplanned manner face bottlenecks that may
   be easily solved but depend on collective solutions that require contributions from several
   parties, particularly for solutions that benefit multiple participants (e.g. a village, region).

Discussion Before crowdfunding became popular, many CNs implemented crowdsourcing efforts
   to expand networks. This is particularly relevant for backbone nodes, that are more complex
   and expensive to deploy, requiring more economic contributions but also expertise from
   different people. These network segments can bring benefits to a wider range of people
   that may be interested in contributing to the funding and deployment of improved nodes
   and links.

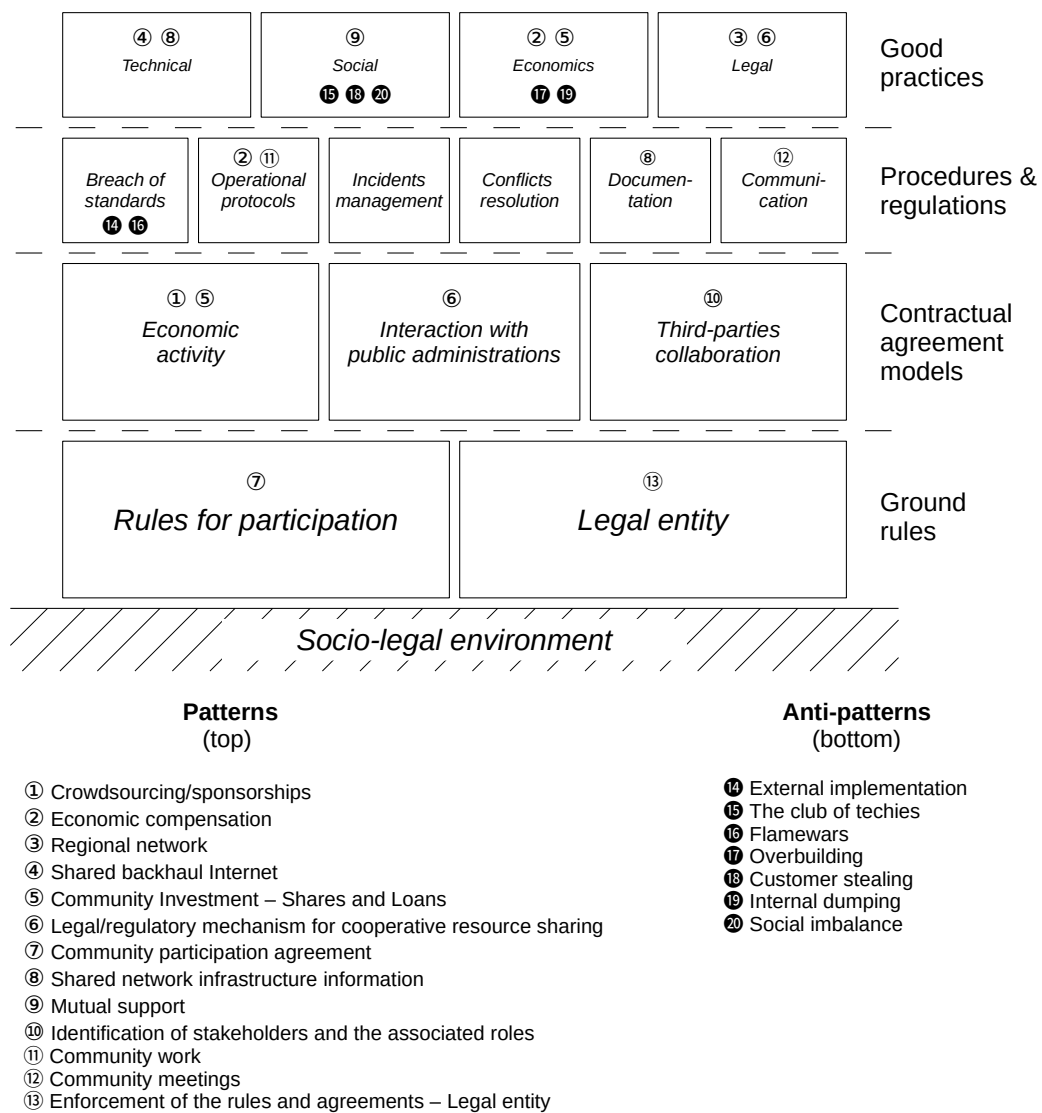[38]It could be newly founded or operate as a section of an existing one.

Figure 6.1: The mapping of patterns and anti-patterns to a generalisation of Guifi.net's internal organisation.

Solution Once the bottleneck is identified and a solution agreed, a campaign is launched to collect contributions of economic, human and hardware resources with a soft or hard deadline. Once the objective is met, the contributions are collected and the solution implemented, and celebrated.

Example Guifi.net *apadrinaments* in Catalan (sponsorships) in date, status, priority, contact, description, items, payment instructions (January, 2006). See Figure 6.2.

References [P2].

6.4.2 Economic compensation (Pattern)

Problem Cost sharing, coordination of contribution and consumption, to achieve overall sustainability.

3618 Posar Santa Eugènia de Berga "guifi" amb Supertrastos i Supernodes
created: Mon, 09/01/2006 - 22:41 — rroca - updated: 09/08/2006 - 8:02am

Closed - n/d (no ticket) - Crowdfunding - until 10/08/2006 - - Zone: Osona, 9 items   **3,295.00€**

93% (3.080,0 of 3.295,0€)

Anem a fer un desplegament sistemàtic al municipi de Santa Eugènia de Berga.Ens hem reunit l'Ajuntament, gent del poble i més gent de guifi.net de la comarca i aixi ho hem acordat. Tots en tenim moltes ganes i hi ha il·lusió en tirar-ho endavant i que surti bé. L'objectiu és unir bé Santa Eugènia amb la resta de xarxa troncal de guifi.net a la comarca d'Osona, connectar el Telecentre i donar cobertura al poble, incloent fer també connexió amb la Llar d'infants i el casal d'avis.

Aprofitarem aquest impuls per fer-ho ja servir de banc de proves per a la nova generació de supertrastos i la construcció d'infraestructures a 5Ghz pensades per arribar a 10-15 Mbps reals amb distàncies llargues per no haver de dependre del que es faci a Vic. És a dir, aquest plà encaixa plenament en la previsió que es va fer pel plà de desplegament 2005-06 per Osona Sud.

Figure 6.2: Web summary of one of the oldest calls for crowdfunding in Guifi.net for supernodes to cover key nodes in a village of the Osona county.

Context In remote or less populated areas, the demand and its growth may not be enough for small communities and ISPs to have access to long distance links, and therefore be competitive with larger operators.

Discussion Long distance links, particularly optical, have a high cost and may not be economically competitive for small or slowly growing demands. Pooling and compensation by sharing costs and expenditures across many participants may allow to bootstrap and promote the investment and consumption of network infrastructure among a larger number of participants. However transparency and auditability is required in the declaration and stipulation of costs, investments, consumption, and an authority to settle the required compensations oriented to cost, not to profit, considering return of investment, and quickly resolve conflicts.

The overall aim is to ensure the sustainability of the commons infrastructure, as all critical costs, investments and consumptions are declared, auditable and balanced.

Solution Declaration of investments and consumptions with periodic settlement (compensation tables).

Example The Guifi.net foundation compensation tables.

References [P3].

6.4.3 Regional network (Pattern)

Problem Regional backbone network connectivity across several islands of CN connectivity, avoiding higher costs of open Internet transit.

Context Remote, rural, under-serviced regions can benefit from larger and more resilient connectivity when islands of connectivity are interconnected. This is a critical attribute for long-term sustainability.

Discussion The concept of the IXP, an Ethernet fabric central to the structure of the global Internet, is largely absent from the development of community-driven collaborative network infrastructure. The reasons for this are two-fold. IXPs exist in central, typically urban, environments where strong network infrastructure ensures high levels of connectivity. Between rural and remote regions, where networks are separated by distance and terrain,
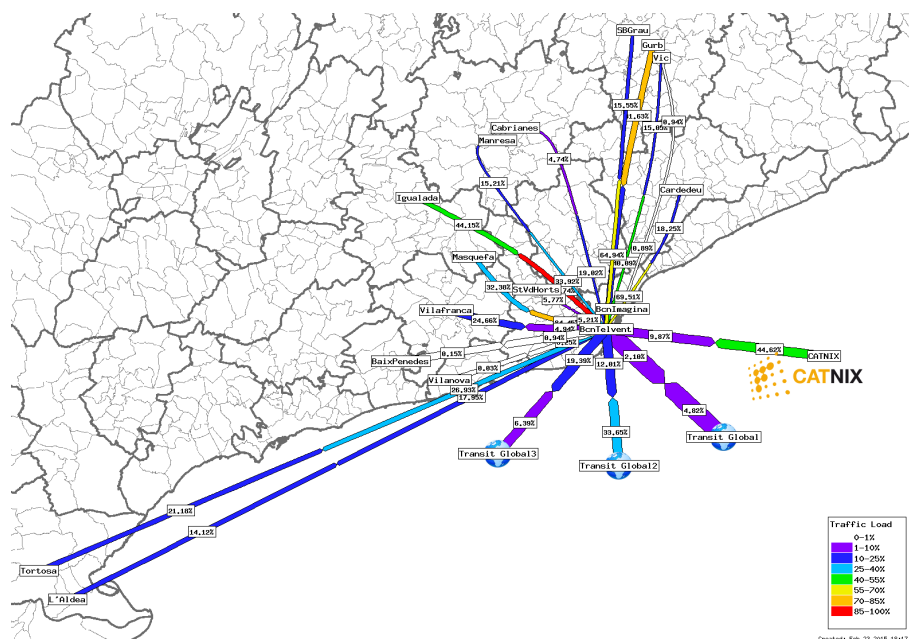
Figure 6.3: The Guifi.net PoPIX regional backbone, interconnecting several islands of connectivity.

no such infrastructure exists. A distributed IXPs architecture designed for the community network environment can help to scale up, and benefit from economies of scale and economies of larger population (the Metcalfe effect). This regional network can be used to bring the benefits of good interconnection across several separate densely connected areas. The interconnection can reduce the network diameter, increase the average performance and the reliability of the overall network. For the case of Guifi.net shown in Figure 6.3, it has brought huge improvements in performance, reliability, latency, as before the optical interconnection traffic had to go through many wireless links to get to distant nodes. Aside pure regional traffic, a typical use of a regional network backbone is sharing a backhaul Internet access, which is the next pattern. That regional interconnection can be obtained in different ways, ranging from wired or wireless long distance community links, or using public fibres in roads, or renting a leased optical link from a telecom provider or an open-access network provider.

Solution Sharing the costs of backhaul connectivity in a regional network to remote and underserved locations. This is an organisational vehicle that combines networks to generate economies of scale and a supporting network infrastructure. For example, a remote port into RemIX [O5] could be housed in a small cabinet atop a hill, or in space that is donated by a property owner for this purpose. Equipment is therefore restricted to the small and power-efficient. RemIX has four main components, consisting of a switching fabric, member autonomous systems (ASes), exchange transit and auxiliary services.

Example the Remix (HUBS) regional network, PoPIX in Guifi.net.

References [O5, P2].

6.4.4 Shared backhaul Internet (Pattern)

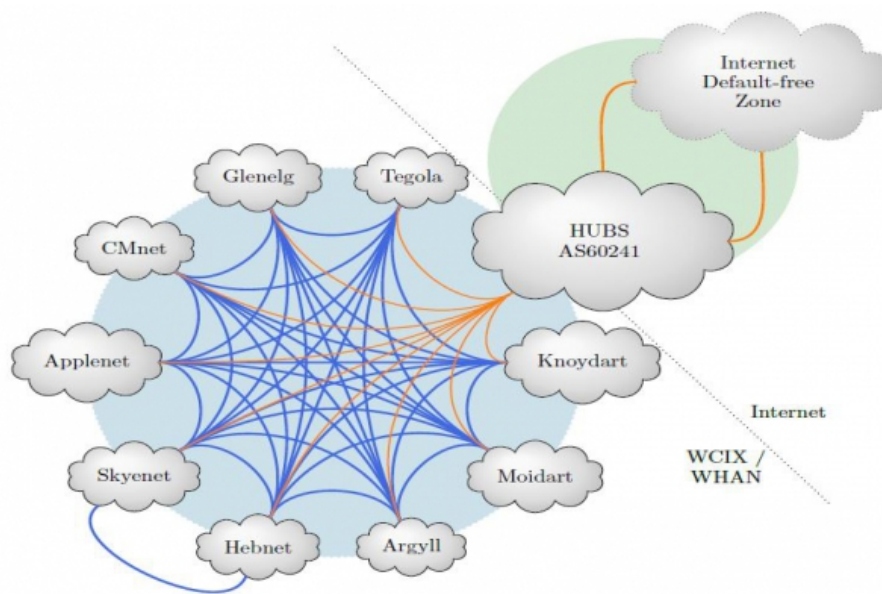**Problem** Internet backhaul connectivity for a group of several islands of CN connectivity.

Figure 6.4: The Remix HUBS implementation

Context Remote, rural, under-serviced regions, can share the cost of good Internet connectivity across a regional network interconnecting small communities. This is a necessary attribute for long-term sustainability.

Discussion RemIX by the HUBS organisation and the Guifi.net foundation use the regional interconnection to share the cost of Internet access. In both cases several small CNs can share the cost and benefit from the economies of scale in contracting Internet carriers to reach the global Internet. For instance, in the case of Guifi.net, this arrangement allows to share among many Guifi.net participants 22 Gbps across four optical connections with at least three separate Internet carriers. This pattern depends on the previous two patterns: economic compensation, and regional network.

Solution Sharing the costs of Internet access, relying on a regional network that allows to efficiently share the cost and the benefits of good Internet connectivity and benefit from economies of scale in Internet carriers, both in terms of higher speed at lower cost, and the possibility to have several separate connections that increase the reliability of the Internet connectivity.

Example Remix reference implementation in HUBS in Figure 6.4, Guifi.net carrier house cost sharing.

References [O5, 38, P3].

6.4.5   Community Investment – Shares and Loans (Pattern)

Problem Investment in a CN infrastructure.

Context Planning, initial deployment, expansion of networking infrastructure.

Discussion Funding sufficiently a network infrastructure allows its deployment to advance quickly and provide connectivity asap. A quick deployment not only benefits citizens but

also leaves less room for overcapacity provisioning by competitors, typically incumbents that play strategies to deter competitors or reduce the coverage or feasibility of alternative operators when they emerge. Furthermore, a local networking infrastructure is a good way for citizens to invest in a resource that can provide good financial returns (interest) and contribute to add value to their houses and the region. Investments can also have good tax returns. At least for the case of B4RN in the United Kingdom and Guifi.net in Spain, investment in infrastructures or organisations (such as foundations) of public interest, has important tax incentives, with deductions of up to 30 % of the investment in B4RN. In the case of donations to the Guifi.net commons network under Law 49/2002 (rev.2015) for patronage, with the limit of 10 % of the total incomes every year, individuals can recover up to 35-75% and organisations can recover up to 40 % of their investment in CAPEX.

Solution Community shares, as a contribution/investment by citizens to fund the deployment of a network infrastructure. Returns in quicker access to connectivity, financial (interest) return, and tax return.

Community loans, subscribed by communities (collectively) from a common fund to be invested in the deployment of a network infrastructure in exchange of a return.

Example Broadband for the Rural North Limited was registered as a Community Benefit Society. It was formed to raise funds from the sale of shares to own and operate the network. However, much of the labour to dig trenches was supplied by local volunteers, who were rewarded with the chance to get a connection for their families or businesses, and some work is also rewarded in shares. Farmers and other landowners allowed free access for duct and the fibre within to cross their land.

Because B4RN is not-for-profit they only extend the network into communities where they are wanted. Each new area that invites B4RN in needs to raise the investment to cover the work and materials required for their area's installation.

Shares Every community's core investment is made up of shares, the value of which can be ring-fenced for supporting the build-out in their area. The shares are an investment, not only do they support the project in that community, but they have tax advantages and will pay a good return.

In a nutshell (See Figure 6.5 and Figure 6.6 and a sample share request form[39]):

- Minimum shareholding £100 / maximum £100,000.
- All shareholders are members of B4RN. One member one vote.
- Shares must be held for a minimum of 3 years.
- Individual investors can claim 30 % tax relief (HMRC Enterprise Investment Scheme).
- After year 3, interest of 5 % can be paid out or reinvested.
- Some shareholders choose to invest £1,500 and claim free connection worth £150.
- Shares can only ever be sold back to B4RN at £1 each.

Loans B4RN also currently accept a limited number of 5 year loans from the community, paying 4 % interest. The minimum shareholding will be £100 and anyone purchasing this will become a member of B4RN and entitled to vote at meetings and become involved in the strategy of the society. The B4RN Investment Policy Statement rules investors may hold

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[39]http://www.b4ys.org.uk/how-do-i-get-it/invest-shares/

Figure 6.5: The B4RN summary of community shares.

Figure 6.6: Extract from a B4RN community share request form.

a maximum of £100,000 worth of shares in the B4RN. As a community benefit society a member is entitled to one vote irrespective of the number of shares they own. All shares are "withdrawable shares" and can only be sold back to B4RN. They have no potential for capital gains and will only be redeemed at face value. For the first three years the investment cannot be withdrawn nor will any interest be paid. From year 4 and onward annual interest will be paid at a rate which will be determined by the board after taking into account the financial position of the society and Financial Conduct Authority rules. At present our target rate is 5% which will be paid in the form of additional shares credited to the investor's account. From year 4 onward investors may apply to withdraw their investment. We intend to put aside an amount each year to fund these withdrawals. However the amount available will be subject to the company's trading position and will be at the discretion of the board so there is no guarantee that it will be sufficient to meet all demands.

The shares issue is designed to be compatible with the tax office Enterprise Initiative Scheme which gives a 30% tax relief against the value of the shares purchased.

References B4RN Resources for investors[40] and videos explaining the project and investment plans[41].

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[40]https://b4rn.org.uk/resources/
[41]https://b4rn.org.uk/b4rn-launch-video-courtesy-of-lunar-creative-video/

6.4.6 Legal/regulatory mechanism for cooperative resource sharing (Pattern)

Problem A reliable way to access and share critical resources for communication under a cooperative scheme, which includes cost sharing and infrastructure sharing schemes.

Context Community networks need ways to establish communication links. That implies right of pass to access to public space (like streets, roads, pipes, poles, towers, water channels, other cables) for the deployment of cables, or the right to use electromagnetic spectrum for wireless communication (unlicensed spectrum such as WiFi frequencies, or licensed spectrum such as Global system for mobile (GSM) or TV frequencies). That access can be used for long distance links (backhaul) or access to end-users (also know as "the last" or "first mile").

Discussion Rights to setup communication links, either as passing through public space with cable, or using wireless spectrum is a critical resource for communications. Governments can privatise the public space (either underground, or over ground used for different types of infrastructures) or the electromagnetic spectrum, in exchange of huge amounts of money in licensing fees. However once privatised, it can be exploited to provide cost effective services covering most of the population (in terms of geographic coverage and price), or only a few (for different reasons) but at the same preventing others to try. The Universal declaration of human rights (UDHR) declares the right to information and communication, to implement that right citizens should have a way to access public space to communicate digitally as well as it can be done over other means. That implies defining ways to ensure access to public spectrum and public space. Different regulations and works look at that, but there are different solutions in different contexts, but all look at different degrees and forms of sharing, as ITU described in its report [87], and global organisations for a free and open network have promoted [7].

According to [141] Mexico in 2015, *the Mexican communications regulator, Instituto Federal de Telecomunicaciones (IFETEL), published its new frequency plan (IFETEL 2015). IFETEL has set aside mobile spectrum in the 800MHz band to serve social good. The criteria for using this spectrum is that the population of communities being served must be less than 2,500 or the community must be designated as an indigenous region or priority zone.* Rhizomatica is a not-for-profit organization that has been providing GSM services to indigenous communities around Oaxaca since 2012. Until 2015, it operated under a special dispensation from IFETEL, but the allocation of spectrum to this purpose is now official and any organization may apply for access to this spectrum under the conditions specified. This access gap is identified by studies from ITU in [90] and there is ongoing work with ITU to promote that type of regulation for spectrum sharing with underserved communities. The specific instrument is Recommendation D.19 (approved in March 2010) [91], that provides guidance on a number of issues concerning ICTs in rural and remote areas considering *that provision of ICT services and applications by small entrepreneurs in rural and remote areas have the potential of creating employment. These ventures can be supported by financial institutions and receive support from various government schemes* and *that the accumulation of experiences world-wide on community access institutions (telekiosks, multipurpose community telecentres, multi-media centres), points to the need for pro-active and supportive government policies to simulate demand of the services available.* Examples of support instruments are *These facilities, where necessary, should also be supported by Universal Service Funds as an essential component of rural communications.*

According to the model of universal deployment for access networks to next-generation telecommunication services (ANNGTS) by the Guifi.net foundation [59]: *Since the authorities already manage spaces and public domains in order to host various services and, to the extent possible, plan for these infrastructures to support the deployment of ANNGTS not only in a private manner but also on a shared basis, providing any type of service in any mode of operation or business model is not mutually exclusive. It is an opportunity to improve efficiency and diversity and consequently develop the existing regulatory framework at the municipal level in a consistent and orderly manner.*

Consequences of not adopting it:

Perpetuation of old practices and conflicting interpretations of the law *It is important to note that, prior to the regulatory changes, the framework was very different; therefore, procedures that are appropriate for a state monopoly for the use of the infrastructures that are currently capable of supporting ANNGTS were set. For example, in the previous situation, when a public operator occupied an infrastructure, it occupied the domain in its entirety. Currently operators are private. In those cases where sharing is technically feasible, if they have a chance, they could aim for occupations to be interpreted according to the existing practices to hinder the presence of new competitors. New entrants would then be forced to attend an exception proceeding, such as having to appeal through the regulator, so that they are forced to share or to present a conflict, when this obviously proves much less effective from the perspective of compliance of the law than having a well-established form of sharing from an applicable rule. All this results in a slowdown and discourages new deployments.*

Increased costs and the digital divide *The necessary infrastructures to effectively provide these new generation services have a significant cost. If not shared effectively, this entails several dangers: that the availability of the infrastructure will result in a lack of real diversity in supply, that the deployment will become uneven or slow following strict speculative or economic efficiency-based criteria, that some operators will try to hinder the entry of others, over-investment, or that the performance of the administration will affect certain business models, excluding or hindering new ones.*

All these dangers can ultimately materialise, cause discrimination when it comes to access, and unnecessarily increase the cost of services.

This practice is linked with the different initiatives around the world to promote sharing, that can be defined in terms of facilitating sharing the cost of building infrastructures (e.g. including fibre when building roads), but that typically do not define the details of the sharing, either at cost (cooperatively) or at market prices (competitively), or the obligations to use the resources effectively, prevention of obstacles, and so on. Different studies worldwide support this[14, 7, 141].

Solution Regulation and policy measures that promote infrastructure sharing, both for construction and usage, both for wired and wireless scenarios. Given the social role of CN, and the strength of the competitors, particularly in underserved or "market-failure" areas, additional support is needed, such as default mechanisms to allow communities to operate under clear terms that do not create uncertainty, that facilitate deployment, both for the "first mile" deployments and for regional connectivity. This is related to the patterns of regional network and the anti-pattern of overbuilding.

Example Community GSM Spectrum Allocation for communities in the Mexican regulation, the Universal Deployment model promoted by the Guifi.net foundation for high-speed network infrastructures, the APC Infrastructure sharing recommendations, the ITU sharing recommendations, the European cost savings directive.

References [14, 141, 7, 59, 87], Recommendation D.19 [91].

6.4.7   Community participation agreement (Pattern)

Problem Definition of clear rules for participation that are create a well defined boundaries and unambiguous framework for collaboration.

Context Community Networks can involve many diverse participants. In a crowdsourced infrastructure, the principles must ensure i) the openness of access to the infrastructure (usage), and ii) the openness of participation (construction, operation, governance) in the development of the infrastructure and its community [O8].

Discussion Different CN have defined their own community licences. This formal or informal document is the basis for community participation. Without it conflicts can arise and destroy the community without remedy given that the boundaries of participation are not defined. This is related to the flamewars anti-pattern.

Solution A document, typically know as participation licence or community licence, that defines an agreement between the participants in a CN. It defines the permissions, and therefore clearly defines the boundaries of participation. Typical clauses promote neutrality (no discrimination) and transitivity (share links alike, to allow expanding the network from any existing node).

Example the Picopeering agreement, and the FONN.

References [54, 68].

6.4.8   Shared network infrastructure information (Pattern)

Problem Having a common repository of information that represents a network infrastructure.

Context A structured repository of that represents the state of a network infrastructure provides transparency, an unambiguous common status information, and facilitates all community network related processes to build and operate the network infrastructure.

Discussion Community Networks typically have a database that describe the relevant resources (e.g. routers, links, locations, address assignments, configuration, status) must be kept up to date to reflect the addition of nodes, their removal and changes to their configuration. It is desirable that the process requires minimal manual intervention and, if possible, that changes are reflected rapidly.

Solution A centralized database with an exhaustive representation of the network infrastructure.

Example LibreMap, NetJSON, Freifunk map, Guifi.net, QMPSU Map, Wind database.[42]

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[42]LibreMap: http://libremap.org/, NetJSON: http://netjson.org/, Freifunk map: https://www.freifunk-karte.de/, Guifi.net map: https://guifi.net/maps, QMPSU Map: http://dsg.ac.upc.edu/qmpsu/, Wind database: https://wind.awmn.net/

References [32, 9].

6.4.9　Mutual support (Pattern)

Problem Finding and combining complementary capacities to achieve a goal.

Context Community networks are open for participation by any interested citizen, however interventions (such adding new nodes, creating new links) may require a set of concrete competences to be successful.

Discussion Since CN are open for participation, and tasks may be complex, there must be a way to find out participants willing to contribute the necessary and complementary competences to perform certain tasks.

Solution This is typically achieved through stipulated mechanisms to discover, attract or encourage the contribution of complementary capacities to make sure a goal can be achieved.

Example Calls for participation, sometimes linked to the crowdsourcing pattern. Incentive mechanisms to promote and recognise voluntary contributions, as planned in Ninux.

References [5].

6.4.10　Identification of stakeholders and the associated roles (Pattern)

Problem Diversity of ways and incentives to participate in CN and contribute to sustainability of the commons infrastructure and the benefits to each and all the participants.

Context As CNs grow, the divergence in motivations, expectations, needs, incentives and interests become more diverse. In this context, if the roles are not well established, conflict must be expected to increase.

Discussion The clear differentiation of interests, thus the stakeholder groups, and the delimitation of the associated roles is a necessary step towards the implementation of an effective governance system aimed at making possible the coexistence of such diversity.

Solution In the Guifi.net community, as shown in Figure 4.1, we have identified up to 17 stakeholders groups, which we have grouped in three sets based on the primary motivations for participation, that is to say, *altruistic*, which make not-for-profit contributions, the *in return*, which expect some return either economic or as a service from their participation, and the *public interest*, which are responsible for the social welfare. We believe that the three main sets is applicable to any CN which aims at scaling, and that the rest of the classification can be used as a guideline for the other communities.

Example The stakeholder groups of each set in Guifi.net are: *altruistic* (*DIY, volunteers, donors*), *In return* (*CPR professionals –installer, operators, maintainers–, service providers, end-customers, lenders, for-fee reduction, and social interest –coops and associations–*), and *public interest* (*governance bodies, system operators, public administrations*).

References [O8].

6.4.11   Community work (Pattern)

Problem Doing something collectively that cannot be achieved by a single participant.

Context While many aspects of a CN can be done in isolation (the DIY attitude), there are key tasks for a community that require complementary profiles to succeed.

Discussion Several key tasks in a community may require diverse contributions from several participants. This may involve sharing and combining diverse knowledge (such as setting an optical or wireless long-distance link, or developing an open-source firmware or a central node database).

Solution Setting up a team from a set of volunteers in a (mailing) list, defining a near-term goal, assigning responsibilities and commitments, with a date to deliver, and ensuring that at the end there is a reward, like a group celebration such as a group lunch or party such as in.

Example Many deployments in Guifi.net or Ninux end with a group lunch to celebrate the collaboration and the collective achievement, and recognise the contributions.

6.4.12   Community meetings (Pattern)

Problem Coordination requires a sense of being part of a team, and sharing opportunities for easy spontaneous, opportunistic, informal and formal communication.

Context Communities need to build a sense of group, which implies trust, shared values, since that creates opportunities for informal interaction, that can result in more focused activities such as knowledge sharing, coordination, community building, and so on.

Discussion Although discussions in the communities are primarily carried in mailing lists or other social media, periodic (weekly, by-weekly, monthly) face-to-face meetings facilitate many types of informal and formal interactions, interactive discussions, and decision making typically with a consensus-based method.

Solution Periodic meetings create an opportunity for interaction, sharing information, exchanging devices and materials, building social bonds, decision making, conflict resolution, and having positive feedback (fun). These meetings can be unstructured (in the spirit of "what is discussed/decided is what it had to be") or structured, with an agenda, moderator, minutes, decision making policy. These meetings can be done remotely with conferencing tools, or in a given place. Each way has its own limitations and strengths.

Example The weekly meetings in several of local groups in CNs like ninux and Guifi.net.

References [100].

6.4.13   Enforcement of the rules and agreements – Legal entity (Pattern)

Problem A mechanism is needed to ensure the fulfilment of the rules and agreements.

Context Several CNs have developed internal regulation to coordinate the collective action and to protect the shared resources. However, the regulation alone does not suffice to protect

the community against possible breach of rules, because an active actor is needed to this end, including going to court, where necessary.

Discussion Although occasionally the required actions to ensure respect of rules can be taken by specific individuals, a legal entity established to this end is more appropriate in the long term, as it reduces dependencies on specific individuals, who might become unavailable or change their minds. Furthermore, rule enforcement through collegiate body reduced the risk of biased decisions, and doing so through a legal entity increases the sense of legal certainty.

Solution Different CNs have developed different solutions, from informal decision-making bodies to formal legal bodies, but in any case it is recommended to get legal aid to clearly understand the benefits and risks of each option because the applicable legislation vary a lot geographically, and the protection measures change in a great extent depending on decision made. For instance, in the case of the establishment of a legal entity, many legal frameworks allow to change the mission of the legal associations (usually with a simple majority in the general assembly) while changes in the mission of foundations are significantly more limited.

Example The Guifi.net community established a Foundation in 2008 with the mission to protect the community's network assets and ease the governance of the community. Redes por la Diversidad, Equidad y Sustentabilidad A.C. is a civil association in Mexico that helps indigenous communities to set up community GSM infrastructure and help the communities to come up with the convenient organisational structure to protect the resulting infrastructure. Similar solutions exist in the free software community (e.g. the Free Software Foundation).

References [P2].

6.4.14   External implementation (Anti-pattern)

Problem Addressing needs in a community through the deployment of an external implementation.

Context Typically in calls from a community, emergencies, campaigns, with an international component.

Discussion This a typical discussion in the are of information and communications technology for development (ICT4D) with a distinction between emergencies relief and cooperation for development. The urgency to bring a solution prevails over the process required to understand the need, the environmental conditions, empower the local community, work with them or just support them to find a local solution. In simple terms, the durability of an infrastructure is proportional to the amount of time in the preparation and the level of local involvement, sense of ownership and entitlement.

(Anti-)Solution Juast after a call, bring a pile of devices and experts that deploy an operational network and leave them connected but ignorant of the operation and troubleshooting of the network, or the financial aspects of it. Did I mention the locals? No, because they don't speak English.

Improvements Training, preparation with target communities and follow-up in key areas: technology operation and maintenance; planning, business models and economic sustainability training and advice; digital literacy.

Example Wireless deployments in emergencies that are left in place but the locals ignore all details except its usage. After any minor problem the network becomes useless and the infrastructure is abandoned due to lack of local knowledge.

References [126], local ownership [128], active entitlement [127].

6.4.15 The club of techies (Anti-patttern)

Problem CNs are by techies for techies (only).

Context Many CNs are bootstrapped by a group of tech savvy people that enjoy testing connectivity solutions. It starts because that group has the skills to start the network.

Discussion The infrastructure may grow quickly among other similar technologists, but it may be unable to go beyond that group given the technology and complexity barrier. Normal citizens may find it not accessible not due to the economic cost, but due to its complexity and the lack of training or the need to invest too much time to benefit from it. The core techie group may not appreciate "externals" that do not share their passion and language, or that want to connect without being able to contribute technically.

(Anti-)Solution CN for those that really understand the technology, share a nerd language, and can invest a lot of time in it.

Improvements Development of training material and activities, pairing techies with "normal" citizens, twinning, developing tools to simplify the deployment, usage and maintenance of the network.

Diversification of the activities including and highlighting non-technical contributions to the network.

Organize courses for externals led by techies. They have a lot of experience and information to share, and with guidance from non-techies, they can help the non tech savvy to be introduced in the movement. Plus, if these courses are done with the help of some external association it can be a way of enlarging the audience of the community.

Example Unfortunately any CN is part of the problem. All suffer from different degrees of club behavior. A positive example of this anti-pattern is the Battlemesh[43].

6.4.16 Flame wars (Anti-pattern)

Problem Different participants get into emotional discussions as a result of a real or apparent conflict.

Context Communities need to take collective decisions that affect differently the membership. This involves very diverse people, with different values, objectives. Sometimes discussions lead to an amplified conflict.

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[43]Image from the excellent Wireless Battle Mesh (Battlemesh: http://battlemesh.org/) event, a great techie forum, Maribor 2015

Discussion Interaction in network-based communication tools, particularly text-based, can create situations where a conflict cannot be solved by argumentation, but amplified. Flame wars might involve many people and generate hostility. In the Usenet community it was common to say that some discussions became unproductive, generating "more heat than light" (Hamlet).

(Anti-)Solution Sending more messages to clarify and continue the discussion, hoping to guide it to a solution.

Improvements A conflict-resolution system that can stop the discussion (even blocking the mailing list or other communication mean, and follow a structured process to close the discussion).

Example The conflict-resolution system is a systematic and clear procedure for resolution of conflicts with a scale of graduated sanctions. It consists of three stages –conciliation, mediation, and arbitration– all of them driven by a lawyer chosen from a set of volunteers. The cost of the procedures is charged to the responsible party or to both parties in case of a tie. This system was developed based on experience and has defined in a precise manner to help in addressing these conflicts in a quick and standard way, with help from lawyers, and scalable for a growing community. It was developed at a time when the flame wars between a few participants threatened the entire project. The Guifi.net foundation had to take a leading role in its development and implementation.

References [P2].

6.4.17   Overbuilding (Anti-pattern)

Problem External network providers, such as incumbents or providers deployment proprietary network infrastructures, may use competitive tactics to prevent a commons to develop.

Context In many countries we have seen that dominant telecom providers may be doing quick overbuilding actions to prevent any other provider to expand in a region by making strategic investments to block alternatives.

Discussion For instance, when a CN decides or starts to deploy in an area, a dominant telecom provider might decide to quickly deploy and start serving in a few key locations to make any other investment not economically feasible. They don't intend to really address the needs of the community, but just prevent or block others to do it with the minimal investment and coverage that makes alternative deployments unfeasible. The proverbial dog in the manger, which neither eats nor allows others to do so.

(Anti-)Solution Communities plan full deployments (covering all households, including the more and the less financially feasible), and use community shares or loans to perform the deployment as quickly as possible to reduce the temporal window where overbuilding can produce a effect. Once 100 % of homes are covered by the CN, overbuilding becomes futile.

Improvements Deterrent effects in deployments: planning deployments covering 100 % of a given area, no publicity before the deployment is done, initial commitment of citizens like with community shares, which contribute to disincentive reactive deployments by incumbents or privative operators.

Example Most of the times a community announces a plan to deploy a community or municipal network in an underserved area, the incumbent quickly deploys the minimal infrastructure to make the local deployment unfeasible. There are examples all over the world of this behaviour, not very productive since the overbuilding is not an alternative but just a deterrent: it does not try to satisfy the needs of all the underserved population or locations, but just connect the minimum to prevent the viability of alternatives. The B4RN model of 100 % coverage and community shares has succeeded in many areas in preventing overbuilding, since when the news are out, everyone in the community is connected or committed through investment, and overbuilding there will be a clear waste: no one will choose to leave the local community for a slower and more expensive service.

6.4.18 Customer stealing (Anti-pattern)

Problem Participants, particularly professionals, act strategically to steal customers from other professionals, typically in the same area, instead of looking to new customers.

Context It is easier to steal a customer from another professional rather than expanding to new customers or new regions. Stealing customers may appear to work in the short term, but brings instability to the community and since it creates uncertainty to the professionals and the value of their services, it affects negatively the sustainability of the commons and the community in general.

Discussion The expansion of the user base and the area covered is the best strategy in the medium and long term for the sustainability of the commons and its professional participants. In fact, the faster, wider and better the network infrastructure commons is, the more business opportunities for professionals. The real competition is with external operators and service providers that have proprietary/privative infrastructures, particularly incumbents given its economies of scale and influence. The population that has bad, expensive or no service are a great opportunity for the expansion of the commons to new people and new areas.

(Anti-)Solution Competition to steal customers from other local professionals involved in the commons. Connected to the next "internal dumping" anti-pattern.

Improvements Focus on creating new markets: new customers, new areas, new services.

Example Several cases among professionals in Guifi.net of competition, differentiation, and specialisation to benefit from complementary offers from other providers.

6.4.19 Internal dumping – Downward spiral of prices below cost (Anti-pat.)

Problem Participants forget that beyond the initial cost of purchase and installation of a network device and link, there is a need to contribute to the development and maintenance of the network infrastructure. Participants do not want to pay any fee to maintain the network infrastructure beyond its own node and link. Professionals and service providers using a CN infrastructure compete in price and features compromising the sustainability of the infrastructure.

Context Humans have bounded rationality, and may not have a clear distinction between the commons and their own interests or beliefs; or between its own link and the whole

network. A volunteer or professional participant (individual or SME) can be confused by the openness of a commons infrastructure, and assume things are free and magically sustainable. Participants forget that beyond the initial cost of purchase and installation of a network device and link, there is a need to contribute to the development and maintenance of the network infrastructure.

Discussion Freedom to join the network does not preclude contributing to the cost of the commons (not free of charge). There is sometimes the assumption that community initiatives may be "magically" free, just as opposition to expensive private resources and services. Open access (freedom) to a commons does not mean it is free of any cost. The two main sources of confusion are that the commons infrastructure is free of cost once deployed (for maintenance or usage particularly), and that lowering prices is the best strategy (related to the previous "work stealing" pattern). Ignoring these costs may appear as a good way to get more customers (for a professional participant) or more participants (for a volunteer), but it is unsustainable for all: for the newcomers that do not get what they expected, for the intermediary that is in a conflict and at loss, and for the commons infrastructure that is subject to an unsustainable usage. The lack of nurturing of the commons leads to a scenario of "tragedy of the commons".

(Anti-)Solution Trivialisation the network is just a sum of nodes contributed by participants, not more, and it would magically work for anyone and forever with no maintenance costs.

    Omission a participant does not plan for recurrent contributions to maintenance, it just reacts to crisis (congestion, repairs).

    Internal dumping Professional operators using the commons may reduce the prices for services below the cost (not collecting contributions to maintain the infrastructure commons) or deliver more features than competitors (below their internal costs).

    Cannibalisation Professional operators using the commons focus their efforts in competing against each other instead of putting the efforts in acquiring new customers from outside of the ecosystem.

Improvements For activists: create not-for-profit user association that collects periodic contributions to maintenance cost.For professional service providers: separate the fixed per-client contribution to the infrastructure costs from the added value services costs provided by the service provider.

Example Guifi.net in Barcelona and in the county of Bages have created user associations (EXO, Guifibages) that collect network maintenance fees to ensure the sustainability of the infrastructure.

The Guifi.net foundation model of service invoices for professionals using the commons infrastructure, that details in two separate subsections the service fees, and the required contribution to the commons. See Figure 5.2.

6.4.20 Social imbalance (Anti-pattern)

Problem Participants in an open group may not be balanced across all dimensions. Typically there's a strong gender imbalance to men, a interest imbalance to technically focused people. How to compensate these imbalances with an inclusive spirit?

Context Communities tend to be more welcoming to people that match the profiles of the majority. Many CNs have a strong imbalance in terms of gender and interests.

Discussion A decision making protocol is needed when the community enlarges. Communities start with local, small-scale groups and auto-coordinate. Then when the community enlarges, people will still want to use the informal way of decision taking they used in the past, while it is not usable anymore.

(Anti-)Solution Not doing anything because *"the community is open to anyone"*.

Improvements The choice of reference models, examples, speakers to external audiences, specific support to new members from existing members with a close profile, help to address these imbalances. People representing a community become role models, and deliberately or not, embed their own values and language in their interactions. Therefore, they create proximity and facilitate understanding with potential members with similar profiles.

Example The gender and techie imbalance in probably all CNs.

6.5 Conclusions

The sustainability of a project, its ability to persist over time, requires a minimum critical mass of beneficiaries to raise the required resources in order to repay the initial investment and continue the operations, thus reaching the so-called break-even point. Once reached, CNs may consider expanding their activity beyond that, that is, to scale up. Based on the results of our comparative research between several European CNs and from the rest of the world, we claim that they must do so not only because it helps realise their fundamental values of social justice but also because they become more resilient. By becoming larger, CNs enable dynamic local economies which, in turn, reduces the dependency on volunteers and increases their freedom. As a result, volunteers can focus their efforts on more specific tasks that cannot be professionalised, like those related to governing the project. Growth also brings savings through economies of scale and strengthened self-protection against external and internal attacks and against internal mistakes, as there are more people involved and overseeing the project.

At an internal level, our experience recommends that, to achieve healthy and sustainable development, these communities must adopt an inclusive multidisciplinary approach to cover the needs of the social, legal, economic, and technical dimensions in a balanced manner, that is to say, without leaving any of them excessively unattended. In line with the most relevant works on the study of collective action, we also maintain that adaptation to local conditions is as critical as having a multidisciplinary view. Thus, successful solutions from one community of practice might not deliver similar results in another. However, our results show that both general guidelines and specific illustrative examples can be extracted from successful experiences.

Successful cases show the potential of these communities to become a driving force for the expansion of the Internet by developing tools to make the existing initiatives more effective and to incubate new ones. However, especially in developing regions, it is hard for CNs to develop. In this regard, there are positive experiences of external organisations contributing to the strengthening of existing CNs and to the establishment of new ones. On this basis, we believe that this external support should increase and have a special priority in the development of sustainable and replicable (and scalable where possible) solutions. To this end, we propose the creation of an international organisation to be funded with funds already oriented towards

universal access, such as the universal service funds in several countries. Such an organisation could lead to the development of standardised methodologies, databases, and software, besides providing technical assistance and coordinating funding and financial support to CNs.

From our research and formalisation of the experience in Guifi.net and other CN, we have identified a set of the most common and relevant organisational patterns and anti-patterns in CNs that are presented in a structured way. In that form, these patterns are more generic and, while working with diverse local communities in Guifi.net or other CNs interested, can apply some organisational patterns or mitigate certain anti-patterns, always adapted to the specificities of the local communities.

In this dissertation, the comparative work among CNs we conducted helped us to identify key aspects that have enabled Guifi.net to reach its current size and complexity as well as the coming obstacles (see Section 5.2.6). Based on all the knowledge we gathered, our main conclusion regarding the capacity to scale Guifi.net is that it does not have any major known impediment beyond its current scale. Thus, although we are not in the position to establish any quantitative limit, our conjecture is that the model can scale, at least, several orders of magnitude from its current size, especially taking into account its replicability, federation, and nesting potentials.

Applicability to cloud computing

Preface

This chapter investigates the exportability of the proposed model to other types of infrastructure by analysing the case of cloud computing infrastructure. Inspired by the Guifi.net case and its governance and economic systems, we explore the feasibility and sustainability of community clouds as participatory commons. We propose organising the IaaS and PaaS cloud service layers as CPR to enable a sustainable cloud service. On this basis, we outlined a governance framework for community clouds, and we developed Cloudy, a cloud software stack that comprises a set of tools and components to build and operate a community cloud services. In a mix of action research and experimentally driven methodologies, Cloudy was designed to meet the needs of the Guifi.net CN. However, we believe it can be adopted by other communities with minor changes. We validated the feasibility of our concept of community clouds by deploying in Guifi.net of some 60 devices running Cloudy for over two years. To gain insight into the capacity of end-user services to generate enough value and utility to sustain the whole cloud ecosystem, we developed a file storage application and tested it with a group of 10 Guifi.net users. The experimental results and the experience from the action research confirm the feasibility and potential sustainability of the community cloud as participatory commons. Based on this particular result, the lessons learnt during our experiments with Cloudy, and our previous studies on CNs, we believe that other types of infrastructure can also be organised as participatory CPR.

7.1 Introduction

The generic term CCs refers to cloud systems designed to address the needs of a community [110]. The CCs have the potential to solve unattended needs of CN members and improve the efficiency of some existing services (especially latency, performance, cost, and availability of services such as web, video, and data content) through the benefits of the cloud paradigm. These come mainly from the flexibility and savings that elasticity, pooling, and on-demand self-service bring in terms of performance, cost, and availability from the use of multiple alternative nearby servers in the same community or access network. The technical knowledge of the participants and their openness to research and innovation are other positive factors. The CCs deployed locally can bring benefits to communities and can address unattended needs, such as latency-critical applications; critical local sensing and control services that cannot rely on non-existent, fragile, or expensive Internet connectivity; local storage services with customised access control policies for content; applications for emergency and disaster scenarios; and privacy and data-security sensitive uses, where remote services may not be trusted or they gather, expose, or exploit sensitive data.

The CCs describe a model that can be organised in diverse ways, such as a competitive free market, a firm, a hierarchy, or a cooperative. In this chapter, we explore CCs as *participatory commons*: open, user-driven (self-provided) clouds formed by community-managed computing resources, where the IaaS and PaaS cloud components are organised as CPR, on top of which users deploy SaaS to consume resources and platform services or provide application services for free or for a fee. We claim that the Guifi.net offers a suitable model for this type of CCs to emerge. According to our findings, the local management of CCs creates more opportunities for access to cloud infrastructure adapted to the local socio-economic conditions, in terms of both production and consumption of resources and services. Thus, they have the potential to involve further participants and leverage new relationships, bringing new opportunities for entrepreneurship and innovation for more people. In the context of CNs, the capability of CCs to generate local value translates into incentives to strengthen the existing networks and to bootstrap new ones, especially in developing countries.

The two key interrelated concepts and related research questions are:

1. *Feasibility*, as the possibility of being easily or conveniently done, which is related to reaching technology and demand readiness. This leads to the first question: *Which social and technological artefacts and what factors are required to bootstrap CCs, organised as open commons?*

2. If feasible, then we look at *sustainability*, as the ability to be maintained at a certain rate or level, which is related to organisational, governance, and economic aspects. This leads to the second question: *Which artefacts and factors are important for sustaining CCs, and how do these affect the value of CCs for their participants?*

We argue that this kind of cloud can emerge through a suitable cloud software stack (the artefact we identified as the cornerstone of the initial phase) and an enabling networking infrastructure (not necessarily a CN). They can grow and become sustainable when appropriate governance tools are in place and when they can generate value for the community. This value comes from the usefulness and economic utility of the specific services the CC provides to their participants. Underthese conditions, feasibility translates into sustainability.

To prove our claims and answer our research questions we:

a) analysed a success case of digital infrastructure managed as an open commons, inspired by the Guifi.net experience;

b) proposed a framework for the structure of a CC;

c) designed a CC software stack and implemented it in a Linux-based environment;

d) co-designed and promoted our cloud software stack in a community and assessed its initial uptake to confirm the feasibility of this kind of cloud; and

e) made a techno-economic analysis of the viability of a cloud storage service in this environment as a proof of concept of the sustainability of CC services.

In terms of research methodology, we supplemented the participatory action research with a significant amount of iterative experimentally driven research [62]. We worked closely with the

Guifi.net community and specifically with a subgroup of volunteers to elaborate on our proposals, conduct our experiments, and discuss our results and implications. After the initial analysis, research, co-design, and prototyping during part of 2013 and 2014, we worked with the Guifi.net community in two main iterations of the research over two more years starting in June 2015, integrated in a community of practice with around 60 participants. After the intensive iterative development phase, the Cloudy system is still maintained and extended with new features jointly developed by the community of users and the research group.

The interactions with the community took place in two mailings for discussion and mutual support and in focus groups organised in the framework of weekly community meetings. The group discussions concerned the planning, co-design, transformation, and result phases of the action research, with a focus on the cloud deployment and the use of the software system, services, and applications. We used a combination of larger meetings to collect diverse opinions and small group meetings for analysis and decision making. These interactions were useful for understanding needs and preferences, getting feedback about new features and changes as the software evolved, and refining the community cloud model and its governance instruments.

The rest of this chapter is organised as follows. In Section 7.2, we propose a framework for managing CCs as open commons. In Section 7.3, we discuss the design and implementation of our CC software stack, and in Section 7.4, we evaluate the feasibility of its deployment. Section 7.5 explores the economic sustainability of a production storage service as a case for professional activity in the CC. Section 7.6 discusses and further elaborates on the results as they relate to the main research objectives. Finally, in Section 7.7, we summarise our findings and make suggestions for future work.

7.2 Framework for community clouds as open commons

As with CN resources, cloud resources can be developed as open CPRs, and for that we have build on the analysis in the previous section. In the case of a CC, the core resource is nurtured by the diverse contributions of networking, computing, storage, and service elements that the participants deploy to expand or improve the CPR, and the fringe unit is the services they obtain. An architectural comparison of clouds to networks in the context of CPRs, detailed in [156],[1] leads to the following main differences:

Diversity of building elements For a CC, the building elements are more diverse than in the underlying network. In addition to the physical level where host devices (servers) provide computing and storage capacity and the network provides connectivity, the cloud software stack components (IaaS, PaaS, and SaaS) are also building elements that provide diverse additional services (e.g., resource allocation and user authentication). This higher complexity has a direct effect on the CPR model, architecture, and implementation, as described in the following sections.

Inter-dependency among resources At the network level, the CPR is a primary infrastructure, that is, it has no inherent dependencies on other infrastructures. This is not the case for the cloud, which inherently depends on network connectivity for the interaction among building elements and users. In addition, there are inter-dependencies among physical resources with services and across different services (e.g., a PaaS depending on IaaS). Moreover, some resources or services are more critical or demanded than others.

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[1]The comparison of models, conceptual and system architectures, and identification of requirements was part of Clommunity (EC FP7-317879).

Thus, the consequences of the deployment of an infrastructure with such dependencies must be studied not only from the viewpoint of usage/demand/traffic of a specific class of resources but also from a holistic approach. This will allow us to answer questions concerning the following: the complexity of interaction and balance across classes of cloud resources, resource bundles required in services, congestion management and fairness across services, and the influence of related infrastructures, such as the underlying network, the power grid, the environment, or the socio-economic aspects of the community of users and organisations. The answers to these questions have a direct effect on the design of the CC software architecture and particularly in the mechanisms for service allocation and discovery used to select service instances, described in Section 7.3.

Boundaries of the CPR The rule applied for the network infrastructure level, *the Guifi.net community takes care of the infrastructure as a CPR, the content is left up to the users* (considering content to be pure usage and therefore external to the CPR), can also be applied to a cloud. However, the criteria to determine what must be considered external (as content) and what is considered infrastructure are flexible at the design level (see Figure 7.1 of Section 7.2.1) and might not be so obvious at the implementation level. In hybrid clouds, where in-house (private) infrastructure is complemented with external (public) infrastructure, that boundary is clear; external owned vs external rented and therefore metered. In our context, the main distinction depends on the nature of the exchanges that can be done cooperatively (to cover the costs declared) in a CPR, or competitively (at profit, with market prices ignoring the costs) in a commercial market, and even for free for some amount of exceeding resources. The different nature of the exchanges has a direct effect on the application of the CPR model to the governance of the different cloud layers, described in Section 7.2.1.

As for any other open CPR, the implementation and sustainability of a cloud requires effective rules and tools for the governance, maintenance, expansion, and so on. In the following sections, we discuss our proposals to meet these challenges according to the same structure as in Chapter 4 and in Chapter 5, and compare to the network infrastructure case, paying special attention to the differences just outlined.

7.2.1   Community clouds as open common-pool resources

The fundamental principles of Guifi.net also apply to a CC. It must be fully inclusive, that is, it must ensure the openness of access (usage) to the infrastructure, and the openness of participation (construction, operation, and governance) in the development of such an infrastructure and its community. The application of these fundamental principles results in a CC resource and service infrastructure that is a *socially produced collective good* governed as a *CPR*. Likewise, the high-level design requirements (e.g., standardisation of resource management, interoperability of individually contributed resources, and ease of participation) are equally valid.

With a set of essential IaaS and optional PaaS cloud services given as a CPR, enhanced and aggregated SaaS services can be built upon them and be offered on a cost-sharing or for-profit model. Similar to how the network CPR reduces the entry barrier (through transparency, network neutrality, and cost sharing, resulting in reduced CAPEX and OPEX costs) and enables the market niche of proximity services, a cloud infrastructure held as a CPR appears to contribute to making cloud computing even more accessible for entrepreneurs or SMEs as described next in general, and specifically in the comparison with commercial cloud providers in Section 7.5.4.
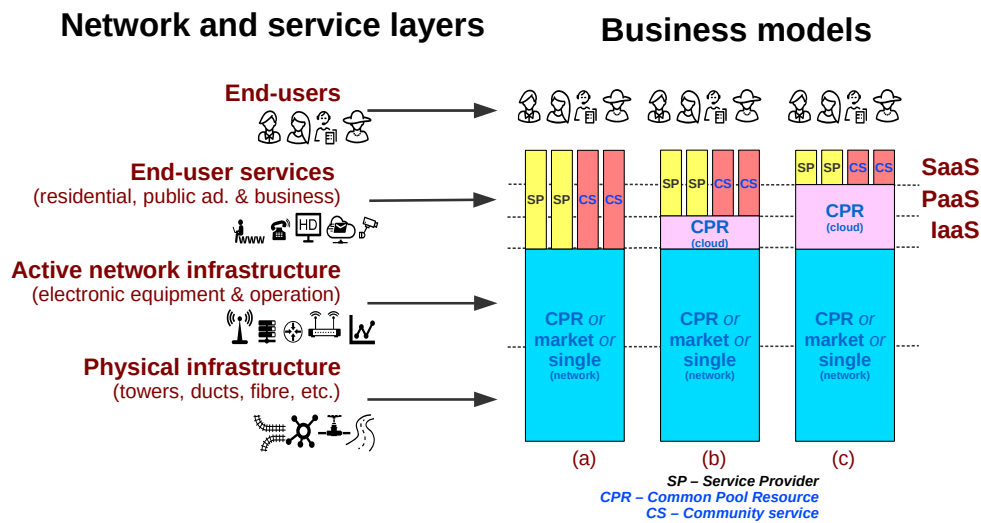
Network and service layers   **Business models**

Figure 7.1: Alternatives in the layering of community cloud service provision over any kind of network service.

7.2.2 Scenarios for community clouds

Figure 7.1 illustrates different scenarios for CCs. In CNs like Guifi.net, although the network infrastructure is a CPR, the network can be provided according to different models by single or multiple commercial providers in a market [49]. Over the network layer, for the cloud service layers (i.e., IaaS, PaaS, and SaaS), different combinations of service provider solutions and community solutions are possible to satisfy the users' needs.

The scenario on the left of Figure 7.1 (a) corresponds to the *vertical integration* approach, the most widespread implementation, with no cloud CPR. In this scenario, a dedicated hardware deployment and software stack must be developed and maintained without the possibility of benefiting from any cooperative resource federation among different providers. Examples of that are the well-known commercial cloud providers, or private clouds, the combinations (hybrid) without horizontal integration at the IaaS or PaaS layers.

Scenario (b), the *infrastructure commons*, addresses a novel cloud scenario where the resources for the IaaS, such as virtualised or bare-metal computing, storage, or networking resources in community locations like cabinets, warehouses, or mini data centres, are provided by the participants and pooled cooperatively. One of the benefits for such a case is inherited from the characteristics of the cloud resources on which the IaaS is built. For instance, a geographically distributed heterogeneous IaaS enables new types of services that cannot be provided by centralised data centres. The proximity to its users translates into lower latency, lower network partition sensitivity, and higher trust, among others. Examples with various levels of cooperation are the ExoGENI or EGI, mentioned in the related work, and the Brighton Digital Exchange,[2] a cooperatively-owned and run data centre, where member businesses can peer and co-locate equipment and provide services to Brighton businesses and the world.

In scenario (c), the *platform commons*, commercial or community organisations provide end-user services through cooperative community-based IaaS and PaaS. In this case, the community-owned PaaS can provide valuable platform services of local interest, with tighter

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[2]BDX: http://bdx.coop/

integration with the local environment. This setup, built on community-managed platforms can, for example, deliver activity logs that enable higher levels of transparency and auditability of cloud applications. A practical application is in the IoT domain, where a publish-subscribe platform service can be audited in terms of data input and output, thus providing more local control about personal data flows (such as running cloud applications in community or home locations, firewalled from the open Internet, and monitoring or auditing data transfers for trust and privacy reasons). An example of a platform commons is ELIXIR, mentioned in the related work. The experimental Guifi.net CC is another case detailed in Section 7.3.

7.2.3   Stakeholders

Our experience over two years working with the Guifi.net community and its community cloud deployment confirms a similar stakeholder structure of the Guifi.net network commons. The coexistence of volunteers and for-profit participants, already happening at the network level, has started to expand to all cloud layers, with initiatives, experiments, or offers at all cloud levels, but not to a significant scale yet. In a comparable way, the presence of a minimum number of customers (and the corresponding service providers) is crucial to ensure the required income to sustain the system. The participation of public administrations is also desirable but is not there yet. Nevertheless, the *proactive* motivations (*we participate because we want to, either to self-satisfy our cloud needs or to contribute to the initiative*) must be explicitly promoted because, at the cloud level, public administrations have much less legal obligations to intervene than at the network infrastructure level. Ideas such as the digital exchanges mentioned above, create opportunities and incentives for local partnerships among all stakeholders in creating local data centres to host computing and service infrastructure and to promote local public and private services, socio-economic development, and digital inclusion.

One topic in the discussion between the research team and members of the community involved in the pilot was about the inter-dependency between the different cloud components that can lead to a separation between volunteer and professional initiatives given the quality of service expectations, unless the software can provide effective quality control (e.g., isolation, prioritisation, interference, and congestion control), and a socio-economic mechanism exists to quantify and compensate the contribution and consumption of resources and services among all participants. However, this is still under research, regarding examining virtualisation [47], incentives [4], activity logs, and payments ledgers using blockchains or digital currencies [5].

During the pilot, the central role of software development was clear to all. The CCs require an international community of open-source software developers (voluntary or professional but not necessarily local) that develop and maintain a set of core tools, APIs, and compatible applications that can be shared by many CCs. The software, far from trivial, requires not only initial developments but also adaptation of cloud software intended for other scenarios (e.g., data centre), integration, and maintenance.

Finally, working with the community of users, the need for a reference authority was clear, similar to Guifi.net foundation in the case of the network, as proposed by the Guifi.net community. This role was assumed experimentally by the Guifi.net foundation. This allows us to bypass the overheads of creating a new organisation, but in the future, if the project consolidates into a stable CC, a dedicated organisation is imperative to preserve the independence of the two ecosystems.[3]

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[3]Guifi.net foundation has actively participated in the whole conceptualisation process as well as the development of the software stack and in the implementation of the experiments.

7.2.4   Participation framework

As a result of the pilot, and the discussion with the Guifi.net community, we propose a separation of the body of normative structure into layers with a general mandatory licence and a set of complementary dedicated agreements. The details of the structure can vary for other CC, but the principles will be equivalent.

Licence A cloud computing licence, which harmonises the contribution and usage of the cloud resources, eases the take-up process of the CC model in a similar way as the network licence has had on the network infrastructure. The discussions about cloud computing licence were started, but the licence has not been established yet. Similar to the network licence (FONN) process [68], the steps to draft the cloud computing licence go through deliberation with the community and evolve as the commons develops and transforms. The discussion with the community, with a rights-based approach [65], has resulted in the following proposals. The licence must consider aspects like the relationships between users and service providers and between the cloud layer and network layer. We propose that the licence must cover at least the following aspects:

  Neutrality The requirement of public access without discrimination, that is, providing the same treatment (service) unless there is some compelling reason.

  Fair use Rules of conduct and means of control to avoid abuse of the resources in commons.

  Transparency and accountability As discussed, access to information and accountability is essential in any CPR and is an enabler for participation in the operation and governance of the commons.

  Privacy In an architecture where sensitive data are distributed across the network, privacy respect and protection must start from the licence. This implies precautions to handle private data, which may be collected deliberately or not, with proportional care, according to data protection laws.

Collaboration agreements As with the network infrastructure, the level of commitment of the operators with the commons is expressed through a supplementary agreement detailing the specific implications of the licence, considering service-level objectives (SLOs). The set of collaboration agreements for the cloud contributes to enhancing confidence among operators offering cloud services, comparable to our experience with the network infrastructure commons.

7.2.5   Socio-economic tools

As in other communities, the governance involves all actors to drive a CC infrastructure through challenges and changes to keep it operational and balanced, which is key to resilient and adaptive CPRs. From the discussion with the Guifi.net community, the following tools were proposed as necessary, although they must be adapted to local conditions:

Conflict-resolution system In the case of Guifi.net, the already existing system for the resolution of conflicts can be applied 'as is' to CC related issues.

Sanctioning system The general structure as well as the administrative provisions of the Guifi.net sanctioning system is a good starting point. The technical provisions must be tailored to the specific requirements of CC.

Economic compensation system It must clarify the terms of participation to promote investment and reduce the number of disputes. The already existing network compensation system (see Section 4.4, Section 5.3, and [P3]) can be adapted to fit the cloud requirements and can be used to balance expenditure at the cloud layer. In addition, the effect that the usage of the cloud services can have on the network infrastructure and its consequences on the economic compensation system of the network must be investigated to determine whether the current calculation system, which is based on the total amount of network traffic at the points of presence of the infrastructure, suffices or needs to be adjusted. This system must balance the exchanges of disparate resources (IaaS, PaaS, and SaaS) between the different participants (volunteers, coops, and for-profit enterprises).

7.2.6   Communication and coordination tools

As with the network infrastructure, the diversity in the requirements for the coordination of the collaboration can only be covered through the combination of several tools. The discussion with the Guifi.net community raised the need for the following tools:

Software tools for cloud management and provisioning The Guifi.net website success shows that efficient and easy-to-use solutions for participant needs are key for the project uptake and harmonisation of the participation. As for the CC, most of the needs can be grouped per cloud layer as follows: for IaaS, contribution and request for computing and storage capacity; for PaaS, deployment and discovery of services, user authentication, and access policy management; and for SaaS, an initial set of appealing applications.

Communication tools From the experience during the pilot, tools (mailing lists, web fora, etc.) and strategies (face-to-face meetings, presentations, etc.) were indispensable. In an equivalent way, the provisioning and management of the infrastructure and services can benefit from specific solutions and separate communication channels.

7.2.7   Initial key enablers

Our experience shows that the start-up phase of any community initiative is critical, including our action and experimentally driven research. From the initial discussion with the group of volunteers to prepare the launch of the pilot and from the ongoing discussions and experience with the Guifi.net community during the pilot, these are our collective findings on the key conditions (feasibility factors) that must be met to ensure a successful bootstrap of a CC:

Demand As a result of an increasing global awareness on data privacy, security concerns, and so on, there is a growing demand worldwide for user-driven (self-provided) cloud services. We confirmed during the pilot that this demand also exists within that community. We collected requirements and suggestions from the participants, which determined the priorities in the implementation of the service offering.

Early adopters The start-up phase is critical for any cooperative project. Among the Guifi.net members, there is a respectable number of technology enthusiasts interested in experimenting with innovations. Moreover, the authors have been involved in Guifi.net for more than a decade, which facilitates the introduction of the product. The involvement of a few key active and recognised adopters in the start-up phase accelerated the involvement of the rest of the community in the pilot.

Third-party technology availability The two main requirements are network connectivity and computing and storage capacity. Affordable off-the-shelf devices powerful enough to run our cloud software stack have been available in the market for more than half a decade. Thus, a CC can be bootstrapped anywhere with local or Internet connectivity. In terms of software, the existence of many open-source base components (e.g., GNU/Linux, services, and applications) were enablers for the start-up phase.

Cloud licence In view of the positive effects of the Guifi.net network lincense (e.g., CPR protection, encouragement of investment, and dispute avoidance) and given that the introduction of major changes becomes more difficult in larger communities, the precise definition and approval of the cloud computing licence is the main next step to ensure the sustainability of a larger community beyond the pilot.

7.3 Cloudy: a community cloud software stack

As part of our participatory action research, we have worked with the Guifi.net community to understand the needs, and design, develop, test, and evaluate the solution over at least two cycles. Several iterations were made with many formal and informal meetings with groups of community members across all phases of the research, with key plenary meetings in two of the annual Guifi.net conventions.

We envisioned the CC in the scenario (c) of Figure 7.1 (infrastructure and platform commons), realised through the combination of two main types of devices on top of the Guifi.net network commons. The first consists of low-power consumption mini-computers contributed by the end users and installed in their homes and offices. The second are more powerful dedicated servers located in more centralised points, like local data centres, warehouses, or street cabinets, usually contributed as a result of a coordinated action of end users or by organisations, such as companies, universities, cooperatives, or public administrations.

Regarding software development and re-utilisation, we prioritised the open-software solutions for our own convenience (licences, access to the code source, and ethics) but also because this model is the best aligned with our target audience (e.g., activists, SMEs, and educational institutions). We have also prioritised the utilisation of existing solutions over our own developments, restricting the last to the minimum strictly necessary. In accordance to this open spirit, we made all the code and related documentation publicly available.

In the remainder of this section, we describe how the cloud software stack presented in Section 7.2 has been implemented as an operational Linux distribution that we named Cloudy[4] that runs a combination of IaaS, PaaS, and SaaS on end-user oriented cloud nodes (user devices), presented in Section 7.3.1, and includes the Community-Lab[5] software that can run multiple service IaaS instances on server nodes (resource devices), presented in Section 7.3.2. Sections 7.3.3 to 7.3.5 discuss the specific aspects related to IaaS, PaaS, and SaaS, respectively.

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[4]Cloudy was started as part of the Clommunity research project (EC FP7-317879).
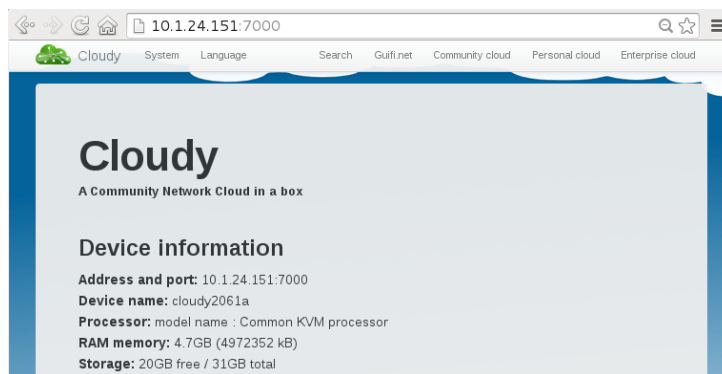[5]https://community-lab.net/

Figure 7.2: Main menu bar of the Cloudy's web user interface.

7.3.1   Cloudy software for user devices

Cloudy[6] is a Debian GNU/Linux-based software distribution aimed at participants of a CC that we have developed as part of our research.[7] Conceived as an open-software platform to bootstrap and manage decentralised CCs and services in them, it includes a set of cloud services and applications that are managed through a common web front-end interface. As an open platform, it integrates a set of pre-installed applications, which the user can activate through the web interface, and allows users to install additional services (see Section 7.3.5). As a cloud software stack, it offers IaaS and PaaS services (see Sections 7.3.3 and 7.3.4). These include common services needed by every participant to join and participate in the CC as well as most common network services used in Guifi.net. In addition, users can extend Cloudy with their own services. This flexibility allows the service offerings (for free or for a fee) to grow and adapt to specific needs of the community. The source code as well as the binaries are freely available in public repositories.[8]

Given the wide range of essential and optional software and services (IaaS, PaaS, and SaaS) for a decentralised CC, Cloudy can have a similar role in terms of standardisation and unification at the cloud infrastructure and service level as the Guifi.net website has had at the network infrastructure level. Two mailing lists have been set up, one for the standard users[9] and another for coordination of the development.[10]

7.3.2   Community-Lab software for resource devices

Resource devices are network-attached low-power computers (desktop, mini, or rack) deployed in several locations in the Guifi.net CN. The resource devices provide computing and storage resources in the form of virtual machines implemented as Linux containers with access control, some degree of resource isolation, and management capabilities to grant a trusted remote user full access to the processing, storage, and network resources allocated to a given container. The

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[6]Documentation for users: http://cloudy.community/ and for developers: http://en.wiki.guifi.net/wiki/What_is_Cloudy/.

[7]In the Clommunity and netCommons (EC H2020-688768) projects.

[8]The source code is available as a GitHub project https://github.com/Clommunity/ or http://dev.cloudy.community. The binaries are available as ISO images and as Linux containers http://cloudy.community/download/.

[9]https://llistes.guifi.net/sympa/info/cloudy-users.

[10]https://llistes.guifi.net/sympa/info/cloudy-dev.

software[11] for resource devices is based on the OpenWRT GNU/Linux distribution[12] extended with a remote control (representational state transfer (REST) API) resource manager service that can manage the life-cycle of multiple containers running concurrently in the same host. We call each of these containers a *sliver*, and the set of slivers on diverse resource devices belonging to the same service is called a *slice*.

A collection of resource devices delegates its resources to a (single) resource controller service, as seen in Figure 7.3. The resource controller[13] is a software package and a service that provides a web interface as well as a REST API to a resource registry. It allows users to create and manage slices in all associated resource devices as well as register and offer new resource devices, among other tasks. The resource controller allows service owners to select and request several computing resources from a collection of associated resource devices. The resource devices periodically poll the controller and launch the jobs requested, thereby downloading an operating system template and launching a container where a service can be installed: a sliver of a given slice.

7.3.3 Community cloud infrastructure

The infrastructure layer (IaaS, scenarios (b) and (c) in Figure 7.1) includes the infrastructural resources of the Guifi.net CC. These are i) user-oriented cloud devices, acting as local interfaces or proxies between users and the cloud, so that participants can interact with these devices and the rest of the cloud through a web user interface, ii) dedicated computing and storage devices, devoted to running service instances and storing pieces of data, iii) the underlying network infrastructure, and iv) the locations where these devices are housed. All these resources can be sliced (virtualised) to be shared and provide isolation across multiple users (containers for computing and storage, VLAN or SDN for networking, and rack space in shared locations).

Cloud user devices Home devices running Cloudy as described in Section 7.3.1. The hardware used is either desktop PCs (e.g., Dell Optiplex 7010SF), mini PCs with Atom CPUs (e.g., Jetway, Minix NEO Z64, Jetway JBC372F36W-2600-B), or single-board computers (e.g., Beaglebone Black, Intel Galileo, or Raspberry Pi).[14]

Cloud resource devices Pure server devices run the Community-Lab resource manager, as described in Section 7.3.2. The hardware corresponds to network-attached low-power computing devices (desktop, mini, or rack computers) deployed in diverse community locations. In the peak of the deployment, during the CONFINE project (2011-2015), there were 80 resource devices. All these devices are managed through a single resource controller where a set of containers (a slice) can be deployed on several resource devices in multiple locations.

Underlying network infrastructure All server devices are connected to the Guifi.net network, most of them in the Barcelona mesh network. The rest are spread across other rural or urban areas. We also have a few servers in the campus network and connected to other

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[11]The software was developed in the CONFINE (EC FP7-288535) research project, as the Community-Lab.net testbed, with a set of research devices in multiple locations of several CNs. Initially intended to run research experiments, it is integrated in the Cloudy software stack to run experimental services distributed across several resource devices.

[12]

[13]Also known as CONFINE controller or Community-Lab controller: https://wiki.confine-project.eu/soft:server

[14]More details on the hardware installation procedures with performance and typical workloads in http://cloudy.community/es/hardware/.
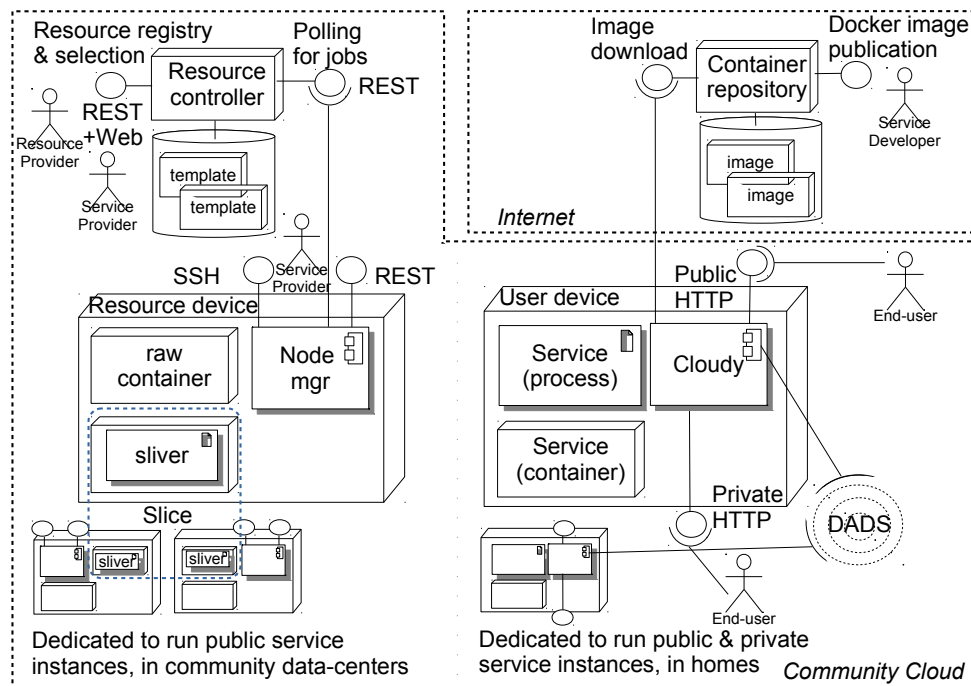
Figure 7.3: Structure and components of a community cloud deployment.

ISPs. A tinc overlay can be used to create a distributed overlay network with tunnelling and encryption across multiple ISPs, even bridging over NATs. Therefore, the model, software, and deployment can run on any IP network, including the open Internet.

Locations The devices are typically deployed at homes together and connected to the network router as well as in-service rooms, offices, or our research laboratory. Without restrictive environmental requirements, the devices just need power and network (wired or wireless), without any I/O connected device, as management is done remotely over the web or ssh interface. Most other Guifi.net locations for routers qualify (e.g., homes, service rooms in buildings, street cabinets, warehouses, and public data centres). Only the resource controller server is a rack server hosted in the university data centre.

7.3.4   Community cloud platform

The Cloudy platform layer (PaaS) offers services oriented to develop and support CC applications in a decentralised setting. The current platform includes three essential generic services, and three specific Guifi.net services are also part of the platform. The generic services are:

Distributed announcement and discovery of services (DADS) This is responsible for automatically discovering the services available in the network and to present them in a meaningful manner. This is a critical service in a decentralised community context because the services are made available in an uncoordinated fashion. Moreover, DADS is based on Serf, a tool for cluster membership, failure detection, and orchestration that is decentralised, fault-tolerant, and highly available [73], which uses a gossip protocol based on SWIM.[15] The Cloudy web interface presents the discovered services grouped by category

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[15] SWIM: Scalable Weakly-consistent Infection-style Process Group Membership Protocol.

(see Section 7.3.1) and allows sorting the services according to several metrics including locality (based on latency) and availability.

User authentication service This service provides user authentication through a recognised independent third party that manages a registry of users. The concept results from the evolution of the solution to the authentication needs of the Guifi.net federated proxy system. Currently, it is implemented using the LDAP protocol in a redundant master-slave architecture hosted and operated by Guifi.net foundation.

Service activation and deployment Pre-configured applications or generic application containers can be started as Docker containers. These applications can be private or public (shared) in the CC (not in the open Internet).

The three main Guifi.net specific services that have been integrated in the Cloudy platform layer are:

DNS service To participate in the Guifi.net DNS system for the resolution of internal addresses (RFC1918). It is based on BIND.

Network monitoring To contribute data to the network monitoring system. It is implemented using SNMP feeding RRDtool ring buffers.

Web proxy To be part of the hundreds of Internet gateways contributed by volunteers that allow other Guifi.net members to have free best-effort Internet access. Any validated user can access any of the federated web proxies. The service is based on the Squid proxy software.

7.3.5 Community cloud application services

To identify the most demanded SaaS components, we did a survey of the application-oriented services offered in several European CNs, including Guifi.net. Given that our work was primarily intended for this CN, we complemented our work with interviews with Guifi.net participants in several face-to-face workshops. Our analysis [156] showed, on one hand, that remote file storage (backup, replication, and remote access) and video streaming of community events were almost common factors in all the cases, and on the other hand, that a solution to the diversity of other applications was mandatory to ensure the success of our development. The second finding motivated the *activation and deployment* service presented in Section 7.3.4. In response to our first, the following third-party applications have been integrated (pre-installed) in the current Cloudy software stack:

Syncthing A decentralised cloud storage system with cryptographic features for privacy, which gives full control to the users over where their data are replicated and shared with a group.

Tahoe-LAFS A fault-tolerant encrypted decentralised cloud storage system, which distributes user data across multiple servers in replicated data chunks. Even if some of the servers fail or are taken over, the entire file store continues to function correctly while preserving the users' privacy and security.

WebDAV server A set of extensions to the HTTP protocol, which allows users to collaboratively edit and manage files on remote web servers. Implemented with the Apache Web server DAV module.

PeerStreamer A peer-to-peer media streaming framework with a streaming engine for the efficient distribution of media streams, a source application for the creation of channels, and a player application to visualise the streams.

To ensure a satisfactory user experience, each application was carefully tested and some were tweaked (e.g., PeerStreamer) before becoming part of the pre-installed applications of the Cloudy software stack [137]. Assessments were done for Tahoe-LAFS [136], PeerStreamer [134], and the search service [133]. The evaluations included the deployment of the applications under realistic conditions on several nodes in the CN, considering the relevant metrics affecting the user experience in each case (e.g., read times in the case of Tahoe-LAFS, video chunk losses in the case of PeerStreamer, and service discovery effectiveness in the case of the search service).

7.4   Feasibility analysis of community clouds

The feasibility of our concepts and developments were tested in Guifi.net. For this purpose, we bootstrapped a CC inside this CN. The first Cloudy instances were deployed in March 2015 and are still active (September 2017). The main objectives were:

a) Confirm the feasibility of the deployment (hardware and software) with a group of volunteers, and evaluate its performance and overhead in a realistic environment, starting from the first release of the software. Section 7.4.1 summarises the features of our experimental deployment, and Section 7.4.2 presents quantitative results.

b) Work with a group of volunteers from Guifi.net to co-design, fine-tune, and evaluate the benefits and limitations of the software system. Section 7.4.3 presents the main qualitative results from that experience.

c) Discuss and develop the governance model with the participants and their experience as participants in the Guifi.net CC. The results were the basis for Section 7.2.

d) Discuss and assess the interest, feasibility, and sustainability of specific community services of interest. Section 7.5 describes our analysis and experience for the case of file storage.

The main findings of the feasibility analysis of the software system, which provide an answer to our first research question, are presented in Section 7.4.4.

7.4.1   Experimental deployment

To test the software system under realistic conditions of number, distribution and heterogeneity of users, devices, locations, and connectivity, we prepared an experimental deployment in the Guifi.net network. In June 2015, as part of our research in the Clommunity project, we made a call in the Guifi.net mailing lists for volunteers to host MINIX NEO Z64 Android TV devices (150 € each) with Cloudy installed to be connected to active network nodes. The initial plans were to donate 25 units, the number funded by the project. Nevertheless, given the positive response, we finally donated 28 in the first call, and we made an additional call in July in which we donated another 16. In the second call, half of the costs were sponsored by Guifi.net foundation and the other half by the end users. Beyond the sponsored devices, we know that, until the end of the year, around 15 additional devices were contributed by community members, making a total of 59 user devices involved. In addition, during that period, we maintained around five cloud

community instances of our Community-Lab cluster online. There is a public Cloudy instance available online[16] for demonstration purposes.

7.4.2 Quantitative evaluation

With the aim to assess the ability of the Cloudy-based CC to operate in the experimental deployment, we performed experiments to qualify its operation. We evaluated the performance and availability of several services and applications, reported in [137]. However, the performance results reflect the performance and variability of the underlying Guifi.net network across Cloudy devices and the network influence on each specific application, but does not help to judge Cloudy itself. The most representative metric we found about the value of Cloudy comes from the number of nodes and service instances reachable from a typical Cloudy node. As the discovery service presents to users the list of discovered service instances for a given service, in order of growing latency, the number of accessible nodes and services represents the level of choice that a Cloudy instance offers to its users. Beyond that, the choice and usage belongs to each CC service instance, and the resulting performance will depend on the specific devices and networks used.

Figure 7.4 shows the number of Serf network nodes and the accessible services seen by one of the Cloudy nodes in a typical week during the pilot study (end of November 2015). The figure is representative of what was observed over the duration of the pilot. The variations over time are due to the changes in the network conditions (load and network partitions) and the number of cloud nodes and services made available by the participants. The 'Serf' (top) line corresponds to the number of nodes of the Serf network seen by that Serf node. It is interesting to note that, despite all nodes having DADS activated by default, the 'DADS' line is usually below the 'Serf' line. This is due either to a manual deactivation of the DADS, which is very unlikely because there is no objective reason for that, or probably due to a timeout in the discovery of the DADS service. This parameter, set to 5 seconds by default, determines the maximum time allowed for responses to the search service queries. Thus, the most plausible explanation for the differences is that some of the nodes of the Serf network are too far away in terms of latency to be able to respond to a search query on time. The rest of services presented in Figure 7.4 are self-explanatory, except for the 'OpenVZ', the initial solution for computing virtualisation, which was later replaced by Docker. Current values can be seen at any time at publicly available Cloudy instances.

We know that at least two of the sponsored devices were not properly installed. Thereby, the rate between the total number of Cloudy instances deployed during the second half of 2015 that we are aware of (62), and the average number of online cloud nodes at the end of that year (50) was around 80 %.

7.4.3 Qualitative evaluation

Our main source to get qualitative feedback was informal interaction with the community, which we already started during the design process, and it involved at least 64 members. These interactions took place in two plenary meetings with a year of difference, several smaller meetings in different locations (Guifi-labs), short and small weekly follow-up meetings between a few members of the community and the research team, and the continuous interaction in two mailing lists. According the discussions with the users, Cloudy was considered a useful instrument that effectively addressed some of the practitioners' needs and has a lot of potential. The most frequent

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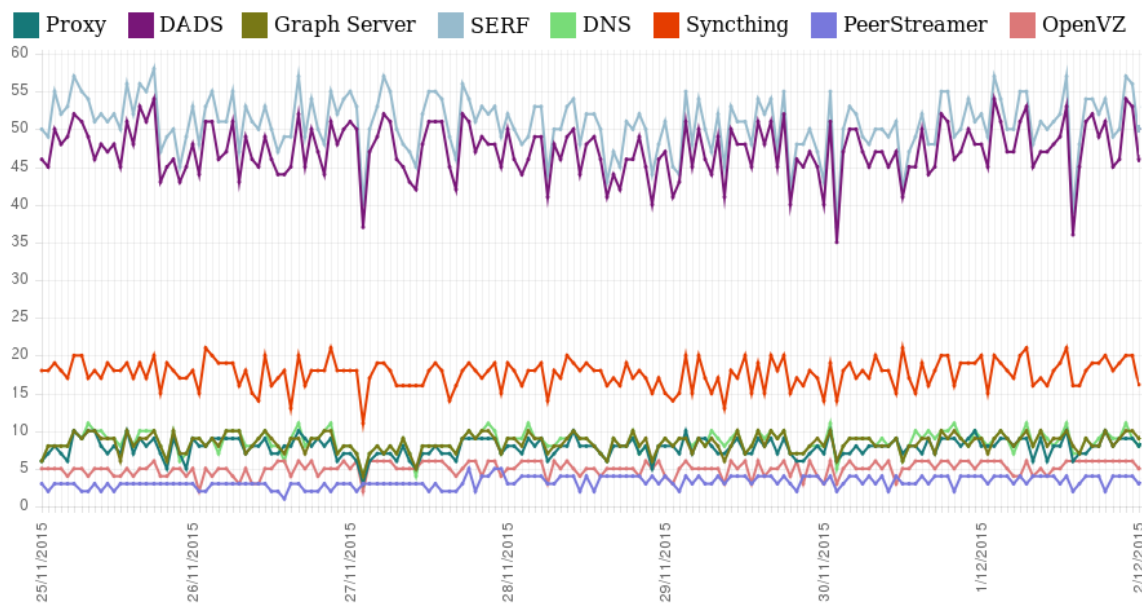[16]http://demo.cloudy.community User: *guest*, Password: *guest*

Figure 7.4: Number of Cloudy instances and services in the community cloud during a typical week (sampling period: 1 hour).

motivations for adopting Cloudy are the easiness to install and activate services, particularly the Guifi.net specific services that are otherwise difficult to set up (see Section 7.3.4), and the flexibility to decouple services from servers. The users have acknowledged the ease of installation of the distribution as a key aspect for a successful uptake, and the search service as a satisfactory alternative to the current publishing services system (a static web page). The unification of management tasks through a meaningful website has also been well received. The main drawbacks were the need to go through an installation process, the limited set of applications, and the difficulty to expand the system with new features or customise the software.

7.4.4   Findings and implications

The positive qualitative feedback matches the quantitative results. The high rate of online nodes (around 50 on average) and the estimated successful adoption rate (around 80 %) are well aligned with the positive comments received. This is also supported by the number of nodes contributed by the community members during the first half year: 15 fully paid by them plus another 16 partially paid (50 % contribution).

  The experience with the design of a CC, implemented through the Cloudy software stack as a key element, combined with the co-design and adoption of the CC governance model and the quantitative and qualitative evaluation of adoption by the Guifi.net community validates the feasibility of CC as open commons. Feasibility is not only achieved at the level of 'system prototype demonstration in operational environment' (TRL7) [45] but, as being adopted by the Guifi.net community, it can be considered 'actual system proven in operational environment' (TRL9). The identification of key social and technological artefacts and factors that result in showing feasibility at certain levels is the answer to our first research question, further discussed in Section 7.6.

The difficulties found are mainly intrinsic to any experimental software system with a small developer community and were helpful to drive the development towards including more applications, particularly an extension that allows running third-party services, such as Docker containers, to increase the range of applications available. The fact that the system has a web interface was considered another limitation. In fact, while the majority found the system very useful to offer specific Guifi.net services, a few users expressed decreasing interest given the software was less polished than other free commercial offerings. Regardless, these negative results were expected from such a pilot with limited resources, and this was not our ambition in the research.

The range and quality of the applications have an effect on the interest and value of a CC. The next section provides a detailed analysis of the technical feasibility and the economic sustainability of an application of wide interest among the participants in the pilot.

7.5 Sustainability analysis through SaaS: the case of file storage

The analysis of long-enduring CPR depends on two key factors: (i) the design of a comprehensive governance system, which implies the existence of convenient tools to implement it [113] and adapt to change [116], and (ii) the overall goal to ensure the preservation and maintenance. As far as CCs is concerned, we have already discussed the first in Sections 7.2 to 7.4, and in this one, we explore the second.

A system can reach economic sustainability after its total cost is below or equal to its total revenue. In our scenario, the total revenue is the sum of donations, in-kind contributions, direct contributions (active participation), and sales. As discussed in Chapters 3 to 5, the emergence of professional activity, which is mostly based on sales, permits overcoming the limitations of the dependency on amateur contributions and increases the growth rate. Therefore, it is essential to elucidate whether such professional activity can emerge on CCs, that is, whether CCs can offer business opportunities. We focused our research efforts on the SaaS layer because we believe that there are few chances to find business opportunities either in the IaaS or PaaS, at least in the initial stages. We were interested in a service to meet the break-even point (the point at which cost or expenses and revenue are equal) as quickly as possible. Thus, we were interested in a service with a good balance between the potential to attract users and the costs to put it in place and operate it.

We eventually analysed a low-cost file backup and synchronisation service (FBSS), a service we developed over Syncthing, which was already part of the Cloudy distribution. The rest of the section is structured as follows. First, in Section 7.5.1, we explore the software design, and then, in Section 7.5.2, we review the technical implementation assessment of a pilot deployment with real end users. In Section 7.5.3, we analyse the economic viability and sustainability of the file storage service, which is compared to the existing cloud commercial offers in Section 7.5.4. Finally, we present our findings and their implications in Section 7.5.5.

7.5.1 Application design

The FBSS we developed is called SwebFS. SwebFS is essentially a web interface for Syncthing,[17] an open-source software that enables file synchronisation between devices that already was part of Cloudy (see Section 7.3.5). Syncthing provides users with control over where the data are

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[17]Syncthing: http://www.syncthing.net.

stored and how often they are updated. It addresses several features relevant to end users: communication is encrypted, nodes are authenticated, the user can choose where the data are stored, and data can be shared with a group if desired. The Backup Syncthing (BST)[18] is a web application that manages the provision of remote, private Syncthing instances for end users through Docker containers. SwebFS, BST, and Syncthing are part of Cloudy, and combined they implement the FBSS.

There are other FBSS-like cloud services offered by large commercial providers,[19] like Dropbox, Google Drive, SpiderOak, Box, SugarSync. Most of them offer a *freemium* service, with a limited amount of free storage space available to engage customers into one of the paid subscription plans offering more space. These services are based on closed-source proprietary solutions (e.g., the Dropbox client) with data lock-in in the hands of a foreign private company. Privacy handling of these services is a concern if the data of the users are hosted in countries with different data protection laws or the users do not trust the provider.

As an alternative, a few open-source software solutions,[20] provide file synchronisation between devices. To our knowledge, Syncthing is the only open-source application that provides easy multi-device file synchronisation without the need for a central server.

7.5.2 Technical implementation assessment

Even though typical storage services are intended to be decentralised, we prepared a simple single-server experiment to evaluate the technical feasibility of the service. This is an experimental SwebFS server for the FBSS. The hardware of this server exceeds the needs of the service (8 CPU cores, 8 Gb RAM, and 1 TB HDD), but the experimental results are not significantly affected by the hardware choice. Comparable results were obtained with smaller servers of equivalent CPU architecture in preliminary experiments. The server is connected at 100 Mbps to the Guifi.net backbone. We had 10 users involved as participants in the experiment, running a Syncthing instance each, and 10 instances on the server.

The experiment consisted of monitoring the resources used to provide the FBSS to these 10 participating users during a period of two weeks. To do so, the users were required to sign up to the SwebFS server, install Syncthing on at least one of their devices (desktop computer, laptop, mobile device, etc.), link them, and share at least one file repository between them. The users were asked to copy at least 1 GB of data of any kind to the shared repository across their devices and the SwebFS server during the first week and to use this service to synchronise and backup their files as they would with any other commercial service they might be using. No specific protection measures were taken for this experiment to ensure privacy and security. Thus, users were recommended not to use files with personal information.

The following metrics (per user) were measured as a reference to estimate values in larger scenarios: *CPU usage*, *RAM consumption* and *network traffic* with a group of 10 users (1 server and 10 client devices). The results were very encouraging: only 0.1 (10 %) CPU usage during active periods and negligible daily CPU usage averages, 27.6 MB RAM usage per user during active periods, and 12.5 MB on idle periods, less than 0.25 kbps data traffic on idle periods, and negligible control data traffic overhead during synchronisation periods, given the amount

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[18]BST: https://github.com/Clommunity/bst-mux.
[19]Dropbox: http://www.dropbox.com. Google Drive: http://drive.google.com, SpiderOak: http://spideroak.com, Box: http://www.box.com, and SugarSync: http://www.sugarsync.com
[20]rsync: https://rsync.samba.org/ OwnCloud: http://owncloud.org/, Seafile: http://seafile.com, SparkleShare: http://sparkleshare.org/, Duplicati: https://www.duplicati.com/

Hardware requirements			Costs			
Resource	**Per user**	**Per unit**	**Item**	**Base**	**Per unit**	**Per year**
RAM	27.6 MB (Active sync)	37 users (1 GB)	**Server**	3,000 €	Depreciation over 4 years	750 €
CPU	0.1 (Active sync)	10 users (1 core)	**Operation**	1 hour/month	23 €/hour	276 €
Storage	50 GB (Average)	20 users (1 TB)	**Hard disk**	0.1 €/GB	Depreciation over 4 years	0.025 €/GB
Energy	–	135 W server 30 % avg. load	**Energy**	355 kWh/year	0.14 €/KWh	50 €

Table 7.1: Estimated costs of resources.

of data exchanged and the number of nodes involved. We use these numbers in the following economic analysis assuming resource usage scales linearly with the number of users or files, due to infrequent activity periods and file changes, and independent users. A super-linear growth in resource usage would require a redesign of the file storage service, with a lower ratio of users per server, or a redesign of the algorithms to have a sub-linear growth.

7.5.3 Findings and implications

We use the previous experimental technical assessment to extrapolate to many more users for an economic assessment regarding hardware, setup, operation, and service pricing. The summary of costs per resource appear in Table 7.1 and the costs per number of users appear in Table 7.2.

Hardware requirements Although a storage service can have multiple servers, here we focus on a single service instance. Extrapolating from the experimental results, any server instance of the service with similar hardware specifications to the one used in the experiment, per each GB of RAM, can provide service to 82 concurrent idle users or to 37 concurrent active users.[21] In terms of CPU, one core can serve 10 concurrent active users[22] or virtually any number of idle users. The concurrent all-active scenario considered above, however, is very unlikely to occur, as files typically do not change often. Thus, active periods are quite infrequent and short-lived. In addition, we expect that most of the users to be disconnected most of the time, with periodic or sporadic connections to synchronise, which is a short active period between the long idle periods. Although usage patterns may vary significantly according to scenarios, we can assume a 100x ratio of disconnected over connected users at any time. In fact, memory, processing, or network congestion due to many concurrent active sessions would only lead to longer synchronisation time, which is unnoticeable in most cases. Consequently, the service resources can probably be oversubscribed with much higher order of magnitude without affecting the quality of the service.

Therefore, our 10 GB RAM and eight-core server can probably effectively handle thousands of users. In terms of data storage usage, we have considered an average of 50 GB per user (assuming an uneven distribution, with many users storing less, and a few storing much more), that is, 1 TB for every 20 users. However, in a group file-sharing scenario, or with de-duplication mechanisms, the average user usage estimation can be safely reduced.

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[21]$((1024 Mb)/(12.5 Mb/user))$ and $((1024 Mb)/(27.6 Mb/user))$, respectively.

[22]$((1 cores)/(0.1 core/user))$

Total # users	Storage [TB]	Storage [€/year]	Storage [€/GB/year]	Service [€/year]	Service [€/GB/month]	Market prices (comparison)
50	2.5	62.5	0.45	1,125	0.038	N/A
65	3.25	81.25	0.36	1,170	0.030	0.030 (hot)
100	5	125	0.24	1,200	0.02	0.024 (warm)
180	9	225	0.14	1,260	0.012	0.012 (cool)
1,000	50	1,250	0.05	2,500	0.004	N/A
5,000	250	6,250	0.029	7,250	0.002	0.002 (HDD)

Table 7.2: Estimated costs per user (monthly and yearly, in €) of the FBSS for different number of subscribed users. However, market prices that are heavily influenced by network transfers are not included (e.g., price can x4 for 10 % transferred, x10 for 100 %).

Costs The yearly operation cost of a server, with similar specifications to the one used in the experiments in a data centre facility, excluding the hardware storage for the service, plus the personnel costs for maintaining it online is estimated as 1,076 €/year[23] (last column of Table 7.1), for which 70 % corresponds to equipment depreciation, 25 % is server operation, and 5 % is electrical power.[24] Although values can vary significantly in different contexts, it is interesting to note the dominance of the hardware purchase costs. The server consolidation approach can help mitigate the hardware costs notably.

We estimated the cost of the hardware for storage for the service (HDD) at 0.025 €/GB/year. For 1,000 users (see Table 7.2), this represents 1,250 € of yearly pure hardware storage cost that, including the operation cost, nearly duplicates reaching 2,500 €.[25]

The network usage can generate substantial amounts of traffic but only internal to the CN. According to the compensation system (see Section 4.4), that would result in a compensation fee for the network maintenance and improvement, proportional to the share of network traffic for each user. In this section, we assume that this contribution is already included in whatever network service fee the participants pay (e.g., 12 € per month in the Guifi.net community in Barcelona). Traffic to and from the Internet to exchange data with a traditional Internet-based cloud provider would be more expensive, particularly in peak hours. This is an important cost saving in a CN compared to a remote cloud provider.

Service pricing Considering a constant yearly operation cost of 1,075 € for the server and a variable cost according to the required amount of storage capacity, as the number of users increases, the total storage costs grow, but the cost per GB decreases towards the pure cost of the raw storage (HDD), as the effect of operation cost becomes less significant. Table 7.2 summarises the minimum service pricing according to the number of subscribed users, assuming 50 GB per user, all part of the CN.

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[23]750 + 276 + 50

[24]Reference values in our experiment. Yearly server costs: 3,000 € CAPEX over four years depreciation, 30 % load of a 135 W server at 0.14 €/KWh = 50 € electricity, 12 hours of maintenance at 23 €/hour.

[25]Yearly storage costs: assuming 100 € purchase cost per TB of low-cost HDDs with redundancy, depreciated over four years.

Offers for a server (no storage or traffic)	**Monthly cost**
Amazon (Central Europe zone, September 2017)	
'Disaster recovery and backup' (per server)	233
Single EC2 4 cores (m3.xlarge)	179
Single EC2 4 cores (c4.xlarge, m4.xlarge)	138
Smallest dedicated host (c3)	1,528
Community cloud (Small 4 core Intel NUC server, 33 W, 400 €)	
Depreciation over 3 years + energy (0.14 €/KWh)	12 + 4

Table 7.3: Price (monthly, in €) comparison for a server between a commercial offer and a community cloud.

7.5.4 Comparison to commercial cloud providers

The comparison of the results of Section 7.5.3 with estimates for minimum prices of commercial storage services[26] of large cloud providers (last column of Table 7.2), shows that, beyond 65 users, the cost of our service matches the standard *hot* storage service costs of the main cloud providers (Amazon S3, Microsoft Azure, or Google Cloud Storage). However, these costs do not include data transfers or replication. Depending on the read/write traffic patterns of the storage usage, these costs could easy multiply, making data transfer more relevant than pure storage in the contribution to overall cost.[27] The references for the *warm* and *cool* storage costs are matched with 100 users and 180 users, respectively. Increasing the number of users, the server part becomes less relevant. As a reference, the pure cost of hardware storage only (HDD) corresponds to 0.002 €/GB/month (or 25 €/GB/year).

Table 7.3 compares the prices of a commercial server offer (Amazon, September 2017) with the cost of a small home server. A CC with these small servers running Cloudy could benefit from the difference in the cost of a server (16 € vs. 138 € or 1528 €). However, there are obvious huge differences between both models: one at home inside a CN managed by volunteers or professionals from the local community not relying on an Internet connection, the other in a remote data centre over the Internet professionally managed at huge scale. We need to account for the maintenance and operation costs of the infrastructure and the software, and the required level of replication for comparable reliability. However, the table shows that, after certain costs are included, the economies of sharing in a CC infrastructure leave an economic margin for local initiatives to provide useful local services given the small cost of sharing a set of computing, storage, and communication resources on stand-by for a pool of running services.

7.5.5 Findings and implications

The technical measurements provided data to estimate costs and prices for a commercial initiative in our CC. The viability of the commercial service depends on the number of users. With 65 users, the FBSS matches the minimum current prices of commercial cloud providers operating on the Internet. With these, or any other number of users, the more read or write access to the

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[26]We consider three classes of storage service: *hot* means high performance, such as in SSD; *cold* means low performance, with infrequent and slow read access, such as Amazon Glacier; and *warm*, with medium performance and cost.

[27]The pricing of commercial services depends on a detailed profile of resource consumption. For instance, there are web applications to estimate costs for Microsoft Azure `https://azure.microsoft.com/en-us/pricing/calculator/` or Amazon AWS `http://calculator.s3.amazonaws.com/index.html`.

data, the more cost-effective CCs become, due to the large difference of costs for local vs remote data transfer. Beyond that number of users, the CC solution has cheaper prices. In terms of costs, the local CC computing servers (virtualised servers or dedicated hosts) are clearly cheaper than Internet cloud providers. We have not considered the cost of software development and maintenance because there are several mature open-source software products for these functions. In our study, we assumed dedicated hardware, but slight additional economies of sharing can be achieved through IaaS CPR. Considering locality in terms of latency, performance, independence from Internet connectivity when it is fragile, and data protection, we can conclude that the CC is reasonably attractive for end users, and it appears to be financially viable, advantageous in cost, and therefore sustainable. There is the additional benefit of promoting local money flows, that is, contributing to local socio-economic development. Furthermore there is a preference in communities to keep data nearby, for privacy and availability reasons, away from excessive data retention and potential exploitation from cloud providers, blockade from attackers or censorship from governments. These results, combined with the discussions of other aspects that emerged in the pilot, allow to qualify the levels of feasibility and sustainability reached.

7.6 Discussion

In previous sections, we elaborated on key aspects of the governance and implementation of CCs, which determine the degree of technological readiness (feasibility) and (organisational, governance, and economic) sustainability of CCs as commons, which relate to our main research questions. Here we discuss several reflections about factors and artefacts that appeared during the collaboration and discussions, as part of the action research, with the Guifi.net community and their participants directly involved: (i) the nature of CCs as CPR, in Section 7.6.1; (ii) the development of the software implementation, in Section 7.6.2; (iii) the experience gained with the deployed system and prototype storage service as it relates to other user-oriented services, in Section 7.6.3. For each topic, we first describe the idea and its relevance, and then we discuss the analysis and lessons learned.

7.6.1 Community cloud infrastructure as a common-pool resource

Despite the lack of benefits from economies of scale in unit costs compared to large remote cloud data centres, local infrastructures have their own technological advantages in terms of latency, better connectivity with end users, partition tolerance, or faster and more regular transfer rates. As a result of local cooperation and sharing, users enjoy cheaper or even free local network traffic, cheaper local cloud infrastructure, and socio-economic advantages from local interactions, investing and contributing to the local economy and promoting local development. The most relevant factors that emerged during the pilot are detailed next.

Participation with contributions Users must be willing to participate with contributions to the CC. These contributions can be in terms of hardware, locations, maintenance, and so on. The entry cost is relatively small: a low-capacity and low-power device[28] is enough to start. The installation process is relatively simple, and the devices require little maintenance. These tasks can even be delegated to a friend or trusted member of the community. A large body of research and practical experience in the past has already shown that users are often willing to donate spare computing resources to third-party

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[28]e.g., mini-computers or single-board computers, such as the Raspberry Pi or a NUC device.

propositions in exchange for added value [3]. Economic or social incentive mechanisms building on that have been proposed in CCs [93] and CNs [4] research.

Access to nearby strategic locations (e.g., homes, service rooms in buildings, street cabinets, warehouses, and public data centres) is another beneficial factor from CPR clouds. Many key local public and private stakeholders can offer these locations to voluntary and commercial service providers for the local interest. The locations of the resources are valuable assets for enabling innovative locality-critical services without relying on Internet connectivity. In addition, privacy regulations and privacy protection can be more easily fulfilled if a commercial service runs on local CPR-provided cloud infrastructures due to lower costs and more opportunities to audit and control the collection of personal data. Such an approach has enormous potential to address use cases in the smart-city and IoT domains.

Locality and cooperative cost sharing Therefore, there is a local opportunity to beat or complement traditional Internet cloud infrastructure and service providers in terms of pricing or features that stem from locality and the cooperative model of cost sharing in CNs [P3], taking advantage of the shared collective network and cloud infrastructure. In such a model, local entrepreneurs can venture in setting up garage or warehouse data centres, or established organisations, like companies, governments, schools, farms, or factories, can lower their costs by venturing into the IaaS business for local cloud users.

Cost-oriented pricing for local sustainability From a business perspective, CCs offer resources and basic services according to a cooperative commons model with a cost-oriented pricing. The costs should include fair remuneration and local reinvestment to preserve the sustainability of the commons. For SMEs and entrepreneurs, the CPR is a suitable context for experimentation and learning and an opportunity to explore commercial services without a strong initial risk or capital investment. Research about cost sharing in CNs [P3] explores this factor.

Voluntary and professional effort In the commons, we find coexistence and cooperation between voluntary and professional schemes. The first usually comes with no service commitment (best effort or less), while the second involves specific commitments (SLOs) in exchange for service fees. Ideally, both schemes can complement each other. Volunteers can buy and include professionally maintained resources in their voluntary efforts, and professionals can occasionally leverage from voluntary resources or efforts in their services (e.g., software tools and peer-assisted cloud services) in exchange for contributions back to the commons. This close collaboration allows pooling and growth at smaller steps with smaller upfront costs. The FBSS, for instance, can be deployed on a hybrid schema combining a stable server infrastructure with less stable resources from volunteers to handle peaks or growth at the expense of a compensation fee. Local currencies have been explored [5] to regulate these transfers without involving fiat money.

Influence of underlying conditions Community clouds can, in principle, develop over any kind of network infrastructure. While the commoditisation of hardware (low cost), software (free and open), networking (flat rates), and access to locations (facilities for deployment and right of pass) is a major enabling factor for sharing, the major barriers come from differentiation, such as with traffic-based (instead of capacity-based) charging or lack of traffic neutrality (when ISPs do traffic discrimination by throttling or blocking local servers and promote paid fast lanes for major Internet cloud and content providers), or provide asymmetric access (a TV-like Internet).

Scalability Local community commons can also benefit from economies of scale through the local aggregation of resources (e.g., pooling of needs for data stores, remote backups, server consolidation for public websites, databases, hosts, and containers). This way, a group of small and medium local cloud users can act as wholesale intermediaries and benefit from volume pricing from large Internet cloud providers. This requires interoperability and federation mechanisms to group resource needs and to transparently integrate Internet cloud providers as a backend. The wholesale access to Internet carriers or Voice over IP providers by service providers involved in the Guifi.net CN or the digital exchanges discussed in Section 7.2.1 are good real examples of that.

Second-layer organisations A cloud commons can act together as a larger organisational umbrella representing and protecting their collective interests in the face of external agents, like governments, companies, users, regulators, research organisations, investors, and standardisation bodies. Guifi.net foundation, which has played that role for the CN, sees similar challenges for CCs, and an umbrella organisation can represent and more effectively protect a group of emerging local CCs better than CCs can individually.

Validation of the CC model Regarding the validation of the CC commons model, our experience with the Guifi.net CC shows the value of the scenario of 'platform commons' (scenario *c* in Figure 7.1) but also its difficulties. We managed to work with different stakeholders, for example, many volunteers and two professionals interested in the feasibility and sustainability analysis of the file storage service. We also worked with software developers, some supported by research projects and others as volunteers, and we counted on the support of Guifi.net foundation. In the context of the participation framework, we started the dialogues for the cloud computing licence and the compensation system, and although such social processes of deliberation take time to deliver results, the interim results are positive. Therefore, we can conclude we have developed a functional organisational and governance model for a CC infrastructure as an open commons reaching TRL9 'actual system proven in operational environment', in the specific environment of the Guifi.net community. Applied to other different environments, that may require adaptation, it can be considered at least a 'field demonstration' (TRL6) or 'system prototype demonstration in operational environment'(TRL7). From the perspective of demand-readiness levels [159], we have moved from the feeling of 'something is missing' in level 1 to 'building the adapted answer to the expressed need in the market' in level 9, in the specific environment of the Guifi.net community. Furthermore, the model and its discussion can be applied to other communities, as the only requirements are the feasibility factors described in Section 7.2.7, and then the pooling by the CC community of networking, computing, or storage resources.

7.6.2   Community cloud software platform

Throughout our research and interaction with the pilot community and other interested CNs, we identified several factors and artefacts related to the software platform that are detailed next.

Emphasis on digital self-reliance or self-determination This translates in a preference for resilient decentralised CC infrastructures, capable of continuing to deliver their services when facing functional, environmental, or technological changes to a degree that they can support and enhance other critical local infrastructures, services, and applications. We have also perceived a growing concern about the risks of extraction and exploitation of

personal data. Some of the main domains we have identified, where these aspects are particularly relevant, include smart infrastructures, such as energy, transportation, waste and sewage, and communications; services for citizens, governments, and industry based on smart monitoring and control; and applications for smart communities to improve the efficiency of services and meet residents' needs.

Software tools and services for the deployment and operation of a CC infrastructure We observe that, similar to the operation of the network infrastructure, a set of software tools and services are needed to ease the tasks of deploying the cloud infrastructure and coordinating its operation and usage. The Cloudy software stack we developed materialises the most urgent services we have identified and facilitates the adoption of the required software components by the users, such as the common user authentication and the DADS services. Therefore, Cloudy is expected to help standardise and unify the cloud infrastructure and service level in CNs, similarly as Guifi.net has achieved through the website and other tools at the network infrastructure level.

The complexity of software However, this results in software complexity that requires a committed community of developers, maintainers, and users. The Guifi.net experience shows that an effective approach to face this challenge is through a combination of volunteers (for testing, reporting bugs, making suggestions, contributing code, documentation, etc.) and professionals (for delivering professional code). To this end, it is necessary to develop a value chain that ensures a minimum revenue stream to pay the professional developers and volunteers. Software that can be customised to work for multiple CCs creates opportunities for more sustainable crowdfunding of these developments. Moreover, this surplus must also allow maintaining, updating, and expanding the existing hardware to keep the value chain alive and avoid a spiral of decline, which is more pronounced in low-cost devices (e.g., we have experienced cases of nodes suffering from cell burnout in compact flash storage and power supply burnout).

Resilience Compared to proprietary cloud environments, community-owned clouds are prone to node failures given their more fragile environment. Replication techniques are therefore essential for resilience so that users will not lose their data. For instance, the Tahoe-LAFS data objects are typically stored on 10 nodes of the storage server pool, but only any three of these are required to retrieve the data. Obviously, this resilience has a cost in terms of network traffic and storage capacity.

Validation of the CC software platform We can conclude that we have reached TRL9 'actual system proven in operational environment' or, at least, TRL7 in other different environments. Although being in continuous evolution and improvement, the software platform is applicable to other communities. Adoption by other communities will define new requirements but will also bring in new contributions. This is the case with a new community in Italy that is preparing a pilot trial of Cloudy.

7.6.3 Tailored services at the network edge and effects on users

Our exercise of working with a community is consistent with other experiences of collaborative system design. Several factors that emerged during the pilot are detailed next.

Collaborative system design Identifying requirements and proposing useful applications is a community building exercise that creates social bonds between experimenters, early

adopters, and developers. Sharing knowledge with the rest of the community helps motivate developers to create new services of interest even outside the initial community.

Crowdfunding model of local services In an open environment for innovation, crowdfunding campaigns can sponsor the development of new applications of local interest or of a specialised sector. Some cases from discussions with the volunteers include services required by and for local governments, SMEs, farms, factories, schools, and citizens, regarding environmental monitoring, control of public and private infrastructures, and security or emergencies. A model based on several simple but adapted local solutions can flourish in CCs, opening new markets for the local economy. The idea of micro-services follows this trend [135].

Complementarity to traditional cloud services The presented CC model is complementary to traditional cloud service provisions and can benefit from the integration with it. The inter-cloud integration [26] has been reported to be beneficial in this regard. However, it must be considered that the resources and services at the edge are also more fragile. Thus, the SLAs and guarantees are difficult to achieve for high-demand services [119]. Therefore, interoperability with industry standards like OpenStack or APIs from Internet cloud providers are desirable to merge the benefits of services running on 'big iron' clusters and data centres with the local decentralised structures that Cloudy supports. The resulting hybrid clouds pose interesting research and innovation challenges like the federation of very diverse computing, storage, and networking resources.

Validation of the file storage SaaS Regarding this storage service, we can conclude that we also have reached not only TRL7 but also reached TRL9, which implies identifying and implementing the social and technological factors to bootstrap (feasibility) but also to sustain the service (sustainability). The results are relevant and applicable to other end-user oriented applications and other communities adopting the CC model. As Ostrom said [113], regimes should adapt to local conditions, not the other way around.

7.7 Conclusion

CCs at the network edge are motivated by their disruptive potential for changing the future cloud service landscape by expanding the current cloud service offerings with local cloud resources and service infrastructures open for access (usage) and open for participation (construction, operation, and governance). This chapter presents an analysis, design, and evaluation of the artefacts and enabling factors for the feasibility and sustainability of local CCs. It does this through the development of an organisational and governance model, a system architecture, its hardware/software implementation in Cloudy, and the technical and economic experimental evaluation of a storage application. The research combines action research with a community of users from the Guifi.net CN and experimentally driven research on a real deployment.

The first key aspect is about organisational models. The chapter first reviews the mechanisms that led the Guifi.net CN, a case of network infrastructure as open commons, to start up and become sustainable. Then, specific issues for the applicability of these mechanisms in CC-based services are discussed. The model we propose, inspired by the experience of Guifi.net but applicable to other communities, implements a CC with the IaaS and PaaS layers organised as an open CPR. A framework of tools (artefacts) to govern such a CC is presented. Some of these components have already been implemented in the Cloudy software stack.

The software implementation and its deployment in the field is the second key aspect. The overall CC model, implementation, pilot deployment, and services were put intooperation in Guifi.net for more than two years with about 60 end-user devices and 64 participants from the community. The results of that experimentation confirm the feasibility of CCs as open commons in a real setting (TRL 9 in the Guifi.net environment, TRL 7 for others), from concept to implementation and governance.

The Cloudy software stack can be extended by its users with new application-oriented services (SaaS). As such, the third key aspect is the evaluation of a storage service from technological and socio-economic viewpoints to assess the technical feasibility and the economic sustainability of CC application services in comparison with commercial cloud solutions. The technical analysis shows the application can be implemented and integrated in Cloudy, and it operates correctly. The economic analysis for the storage application service shows competitive long-term costs from a rather small number of users. The extended period of experimentation with the Guifi.net CC, combined with the technological and socio-economic analysis of a representative SaaS, confirms the potential for the sustainability of CCs as open commons.

We identify a set of key enabling factors for feasibility (demand, early adopters, technology availability, ease of participation, and licence), and a set of governance tools (governance: licence and collaboration agreements; socio-economic: conflict-resolution and sanctioning systems, economic compensation; and coordination: management and provisioning, and communication) for sustainable CPR CCs.

Although we provide compelling findings for an 'adapted answer to the expressed need' (DRL 9), further studies are required to extend the results to other services and to evaluate replication in other regions, other socio-economic environments, other CNs, and on a larger scale. It is interesting to note that CCs as open commons, despite being inspired by CNs, can develop in diverse environments, including Internet access networks provided by commercial service providers.

From a broader perspective, our findings on the similarities between CNs and CCs in terms of the capacity of being successfully implemented as participatory CPRs suggest that this approach might be suitable for other types of infrastructure. On this basis, and taking into account the results on the scalability potential investigated in Chapter 6, we conclude that further investigation is required to (i) gain insight into the approach to other particular types of infrastructure, and (ii) derive general lessons and where possible, models.

8

Potential generalisation

Preface

In this chapter we propose a generic model for the development and management of infrastructure as a participatory commons, and elaborate on its applicability to other types of infrastructure. Our following proposal builds on the positive results of our previous investigation on the ability of the Guifi.net model to scale and its potential to be exported to other domains. In terms of its applicability, we propose the attribute *extensible* to refer to infrastructure that is relatively easy to expand and maintain, and we claim that the model is, at least, applicable to infrastructure this type of infrastructure. The reader must be aware that the model we present is a preliminary result of our current research work, thus it requires further analysis and refinement. Nevertheless, we have decided to include it in this dissertation as we believe that in its present state it can already be of interest to some practitioners and researchers.

8.1   Introduction

In the previous chapters we have (i) studied the positive results achieved by the Guifi.net project (see Chapter 3), (ii) obtained a model for its governance (see Chapter 4) and its economic (see Chapter 5) systems, (iii) confirmed the capability of the model to scale (Chapter 6), as well as (iv) its suitability (i.e. feasibility and sustainability) for being exported to other infrastructure (Chapter 7). On this basis, in this chapter we develop a model intended for (i) initiatives similar to Guifi.net, that is to say, within the same infrastructure domain (IP networks), and (ii) communities working with other types of infrastructure. Thus, the applicability domain is broader and, as a consequence, the overall approach is necessarily more generic and abstract. As part of the generalisation exercise we eliminated all the implementation particularities and focused on the essential parts. Therefore, it has to be understood that any attempt to implement the model is subject to specific constrains and needs.

Figure 8.1 shows what we believe are the three main strategies for growth, that is, to increase the amount of operational deployed infrastructure and of users served. *Extension* refers to expanding an existing *instance* of the model. For example, in an existing CN (an instance of the model), by adding more infrastructure, by expanding an existing deployment, or starting a new one. *Replication* refers to the launch of newer instances of the model. For instance, remaining in the same domain of network infrastructure, by starting a new initiative (a new instance) in another region or country. Finally, *exportation* refers to implement the model in a new type of infrastructure (a new *domain*), which can only be achieved through a new instance. All require local adaptations, although in significantly different degrees. In the case of an extension of an
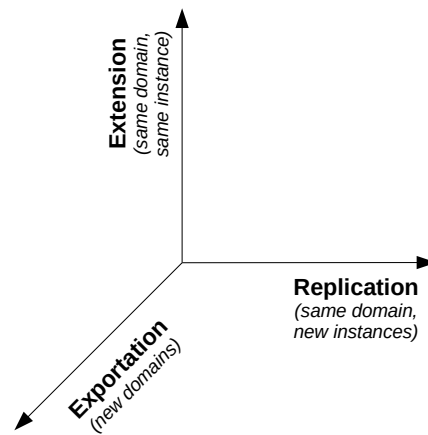
Figure 8.1: Growth coordinates.

existing instance, at most, just minor changes of specific implementation aspects are expected, namely those needed to meet local practitioners' needs. For replication within the same domain by adding new instances, the adaptations required can be more far-reaching because, despite the technologies being similar, there might be relevant changes in legal contexts, economic capacity of the beneficiaries, and so on. Even in the case of keeping the same local conditions, exportation to other infrastructure types may also involve substantial adaptation effort due to the change in technologies, market dynamics, sector-specific regulation, and so on.

Extension of an existing instance contributes to improve its success indicators and enhance internal procedures. Replication contributes to make the whole community of practice more resilient, as the addition of new instances allows for mutual support, and can contribute to refine the general model as a result of its exposure to new contexts and social groups. Exportation can contribute, on the one hand, to improve the model due to the inherent challenges posed by a change in the application domain, and, on the other hand, to make it less dependant on specific infrastructure traits. In an analogy between the axes of Figure 8.1 and a 3-dimensional Euclidean space, extension implies growth in a single dimension, that is, along a line; replication entails the addition of a second dimension, that is, the creation of a plane; and, exportation adds a third dimension, that is, a volume. Taking the analogy further, extension can be seen as a sort of linear growth, and replication and exportation as quadratic and cubic growth, respectively. The rest of the chapter is structured as follows. (i) In Section 8.2 we present and discuss the model and the assumptions for its application. (ii) In Section 8.3 we elaborate on the most general expected benefits. (iii) In Section 8.4 we discuss the infrastructure in which we believe the model is applicable, and (iv) finally, in Section 8.5 we summarise our conclusions.

8.2 Generic model

8.2.1 Assumptions

The model we present in the following section is applicable under the following assumptions:

A1 The main goal is to meet the participants' need for meaningful infrastructure.

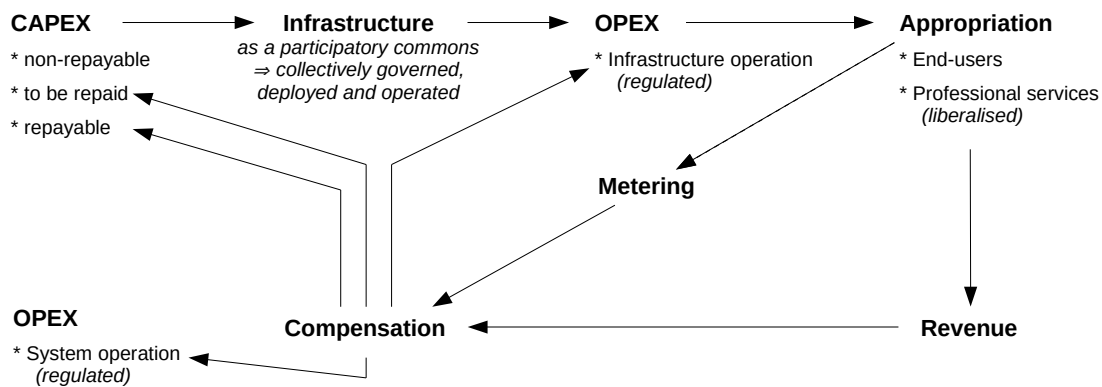A2 A unified infrastructure is collectively built, managed and used as a participatory CPR.

Figure 8.2: Flowchart of the model proposed.

A3 The regulated activities (operation of the infrastructure and operation of the system) are compensated on a fair base.

A4 The contribution of each participant to the construction and maintenance of the infrastructure is established based on the *appropriation* the participant makes of the infrastructure.

A5 The infrastructure can be used for any purpose, including commercial exploitation.

A6 The tasks which entails conflicts of interest cannot be performed by the same participant.

8.2.2 Model

Figure 8.2 presents the general flowchart of the model we propose. The main objective is to maximise the services delivered. To achieve this objective, an infrastructure is built and operated as a participatory CPR. Once the infrastructure is in place, it is operated and becomes available for service delivery. The infrastructure is used (appropriated) by the beneficiaries (the appropriators) through the provisioning and consumption of services that generate revenue. Appropriation is *metered* according to the necessities of the targeted infrastructure (meaningful metrics) and to each community's rules (usually at individual level). On this basis costs are assigned to the appropriators by the *cost-compensation system*, the implementation details of which also depend on the infrastructure nature as well as each community needs. It is worth noting that besides monetary compensation other types of compensation are possible such as in-kind contribution.

To build or extend the infrastructure, capital resources are needed (CAPEX). The capital resources can either be *non-repayable*, or *to be repaid*, or *repayable*. Non-repayable contributions include those contributed by the beneficiaries of the resultant infrastructure, donations, subsidies, and so on. To be repaid contributions are loans (with or without interest). Repayable are contributions that at some point might be repaid by entitled participants such as the final beneficiaries.[1]

Operational costs (OPEX) include the *infrastructure operation* and *system operation* costs. All these activities are necessary for the proper functioning of the CPR, hence, they are (internally)

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[1]Repayable contributions can be made, for instance, by beneficiaries interested in accelerating the execution of a deployment, who retain the right of reclaiming part of their contributions as long as new beneficiaries are acquired, or by investors who are allowed to charge the end beneficiaries a rental fee as long as the beneficiaries do not repay the capital.

regulated and fairly compensated. Conversely, the provision of services on top of the infrastructure is liberalised.

The main roles with their main tasks and the participants performing those are the following:

Governance It is performed by the community as a whole in a participatory manner. The main tasks are:

> **Internal regulations development** The internal regulations must define the scope of the project, the principles, how internal rules can be established or changed, and so on. It must also provide the legal tools for safeguarding the infrastructure and its participants. It is likely to be structured in layers.[2] Internal regulations can neither contradict the generic model's assumptions nor its general rules (both presented in this section).

> **Implementation oversight** Although operational tasks can be delegated to the system operation, the ultimate responsibility for ensuring the proper functioning of the whole system lies within the community. Thus, it is also the responsibility of the community to develop appropriate tools for the proper implementation of the internal regulations.

System operation The *system operators* implement the *system operational tasks* derived from the internal regulations. They are accountable to the community. Their tasks include:

> **Contributions recognition** Validation of the claims of the participants regarding their contributions.

> **Appropriation metering** Establishment of the CPR's appropriation.

> **Compensation calculation** Establishment of the costs assignment.

> **Inventory maintenance** The inventory must include the assets of the CPR, the contributions recognised as well as compensated, the revenue, and the appropriation.

> **Other** Conflict management, facilitate internal regulations development processes, and so on.

Infrastructure operation Includes all the tasks directly related to the infrastructure. They can be classified into the following main categories:

> **Planning** The design tasks (general planning, technical bureau, etc.).

> **Development** The tasks related to the construction (procurement, construction permits, deployment, etc.).

> **Maintenance** The tasks aimed at keeping the infrastructure operational (infrastructure operation as well as maintenance).

Service delivery As already stated, service provisioning using the infrastructure is liberalised.

As a result of assumption A6, the system operators and the infrastructure operators are excluded from many of the governance tasks as well as from performing other professional activities related to the infrastructure for incompatibility reasons due to conflicts of interest.

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[2]For instance, in [113] internal regulations are classified into three categories: *constitutional*, *collective choice*, and *operational*.

8.3   Expected benefits

The expected benefits derive from the model as well as from the assumptions for its application outlined in the previous section. We summarise them as follow:

Optimisation of resource usage The deployment of superfluous infrastructure due to reasons other than meeting the needs of the population is excluded in principle (A1). Thus, deployments made to meet other purposes are discarded.[3] Furthermore, the construction of a unified infrastructure (A2) also eradicates the inefficiencies of duplicated infrastructure.

Non-discrimination The conception of the infrastructure as a CPR levels the playing field, thus allows for equal opportunities for participation at all layers, including the governance, the system and infrastructure operation, as well as service provision.

True single market The unified infrastructure combined with the right to use it for any purpose (A5) translates, on the supply side, into equal opportunities for offering services, and, similarly, on the demand side, into equal opportunities for contracting services.

Lower prices The price reductions do not only result from the optimisation of the use of resources, but also from the reduction of inefficiencies due to competition at the operational level.

Self-sustainable ecosystem The system as a whole (the governance, the system operation, etc.) develops organically, essentially by matching the needs of the participants with the availability of funding. The conception of the infrastructure as a CPR in conjunction with the equalisation of business opportunities protects against speculative practices and short-term investments.

Collective empowerment The bottom-up approach strengthens citizen involvement, knowledge transfer, sovereignty, and so on.

Local small-scale economy and funding As a result of the citizen empowerment and the increasing business opportunities, a local economy develops. Similarly, the introduction of funding instruments, that allow for aggregation of small capital and direct investment in specific deployments, boosts local funding.

Innovation The incorporation of traditionally excluded actors opens the door to radical proposals entailing profound reforms and other unforeseen scenarios.

Self-governed The direct implication of the beneficiaries in the governance affairs ease the adaptation to internal needs and external challenges.

Replication and federation The model allows for multiple instances and coordination among them.

Decentralisation The organisation around local communities which take action to develop the infrastructure they need and federate the resultant infrastructures, leads to more horizontal and distributed topologies, reducing single point of failures, thus increasing infrastructure resilience.

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[3]The existing amount of underused infrastructure such as dark fibre illustrates the existence of other reasons to deploy and even to operate infrastructure.

8.4   Applicability

8.4.1   Extensible infrastructure

The model is designed to leverage the potential of small investments, thus, it is suitable for affordable infrastructures that can be extended through small iterations. Examples of infrastructure that meets these attributes abound: in the ICT sector, besides the already analysed technologies, namely computer networks and cloud computing, Long Range (LoRa)[4] and 5G networks, electric and water grids, domestic electricity generation, and so on.

On this basis, we propose the attribute extensible to refer to any infrastructure that meets these two attributes: (i) affordable, and (ii) capable to be extended through small iterations, or, less formally, to refer to infrastructure that is relatively easy to expand and maintain, and propose our model as a suitable model for developing and managing extensible infrastructure.

8.4.2   Other infrastructure

The ability to deal with extensible infrastructure is not a limitation but a capacity, meaning that the model is not necessarily constrained to this type of infrastructure. On the contrary, we do not foresee any impediment for the model to be applied to infrastructure that requires lager financing rounds, at least from the economic perspective. We also do not foresee major impediments from other perspectives (e.g. the existence of the Linux Kernel shows that complex technical problems can be addressed collaboratively), thus, we believe that the model can also be applied to other infrastructure, or, at least, may be a source of inspiration for the development of new collaborative models.

8.5   Conclusions

In this section we have presented a model for developing and managing *extensible* infrastructure, a term to refer to affordable infrastructure that can be expanded through small iterations. Deeply inspired by Guifi.net, in our model a unified infrastructure is collectively built, managed and used as a participatory CPR. We believe that our model is also suitable for even profoundly different types of infrastructure. We consider these results relevant enough to be shared with the research community. Needless to say that they are just a preliminary proposal, hence, for proper solid results further research is required.

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[4]In Catalonia a Long Range Wide Area Network (LoRaWAN) is being deployed following an approach inspired by the Guifi.net model: https://thethingsnetwork.cat/index.php/The_Things_Network_Catalunya.

9

Conclusions

9.1 Concluding remarks

Hoping to contribute to the search for innovative models for infrastructure development and management that overcome the limitations of those currently used, in this dissertation we investigated more participatory models for financing, deploying, and operating network and cloud computing infrastructure. More efficient models are necessary to attain and accelerate the delivery of minimum services worldwide, including a decent access to digital infrastructure. Improvements in efficiency translate into a reduction of the consumption of natural resources, reducing waste and environmental impact. Accordingly, several international organisations are tackling the challenge of improving infrastructure management efficiency. In the ICT sector some examples are IEEE and ISOC, and more comprehensively, advances in infrastructure development and management are key for attaining many of the UNESCO's SDGs.

We focused on participation because we believe that the main problem of the way infrastructure is handled in current dominant models is the lack of social involvement in addressing the challenges that infrastructure management poses. The detachment between society and infrastructural affairs has resulted in a vicious circle: the bigger the gap, the more hermetic the processes through which infrastructure is planned, designed, and deployed. Even more, we suspect that current trends to present public affairs as more transparent and accountable worsen the problem. These suspicions are based on our direct practical experience: during our research we witnessed the clear differences in treatment by public authorities between bottom-up initiatives and the major corporations.

Extending this logic further, because of the aforementioned vicious circle, there is an excessive influence by the private sector. This excess of influence is detrimental to the optimal planning, execution, and exploitation of infrastructure for two main reasons. First, to evade social control, a very narrow and technocratic conceptual vision of infrastructure management is established. Second, to reduce competition, any potential alternative is systematically marginalised. Consequently, in our comparative studies, we took the private sector model as a reference, putting aside the PPP and public-sector models.

A satisfactory answer to the challenges of our research demanded a multidisciplinary approach and substantial field work and interaction with communities of practice. Our technological background enabled us to focus our effort on acquiring the necessary competences in social sciences, economics, and law. In consonance with the holistic approach required, in this dissertation, the term *model* is used in a broad sense, including planning, design, finance, procurement,

deployment, operation, maintenance, commercialisation, and service delivery, unless otherwise indicated. Three other concepts play a central role in this dissertation: *governance*, *common-pool resources (CPRs)*, and *community networks (CNs)*. Governance refers to all the internal processes of ruling and managing that a community undertakes. CPRs are systems of resources collectively built and managed in a participatory and open manner. CNs are bottom-up initiatives aimed at building network infrastructure by pooling resources and managing them collectively.

Our major underlying concerns were to understand (i) how CNs communities organise themselves; (ii) how can they deploy NGA technology in areas traditionally deemed as unattainable without massive public subsidies (the so-called unprofitable areas); and, more importantly, (iii) whether they are just non-relevant isolated cases that cannot extrapolate; or, on the contrary, (iv) these were experiences from which models and standards could be developed and applied to other network infrastructure, or even to other types of infrastructures; and if so, (v) if we could contribute to making them more efficient. The bulk of our research focused on Guifi.net, which is widely recognised as the largest and the most sophisticated CN.

We selected action research as the main research methodology for its suitability for dealing with communities of practice and for coping with challenges that emerge along the research process. More precisely, the research methodology we followed falls into the domains of ethnographic action research and network action research, combined in many cases with components of experimentally driven research. These methodologies also align with the requirements of the industrial doctorate plan under which this dissertation has been developed.

After significant interaction and critical analysis of the intermediate results with the practitioners, we eventually formulated the following research questions (RQs):

RQ1 Does the approach followed by Guifi.net outperform the private sector model?

RQ2 Does the Guifi.net case have enough unique and beneficial features to be considered a model on its own?

RQ3 Does the Guifi.net model apply to other infrastructures?

To answer the above RQ we conducted the following research activities (RAs):

RA1 Gathering of performance indicators of Guifi.net

RA2 Description of the differences between the Guifi.net approach and the private sector model

RA3 Formalisation of the Guifi.net model

RA4 Identification of key factors in CNs scalability and related patterns

RA5 Analysis of the suitability of the Guifi.net model for cloud computing infrastructure

RA6 Proposal of a commons-based participatory model for financing, deploying and managing extensible infrastructure

RA1 Gathered representative information on the standard indicators of the sector, which mostly focus on depicting the infrastructure in place (technologies, coverage), the investment made (total amount, ROI periods), the commercial offerings (type of services, prices, number of competitors), and the level of adoption (penetration). However, we also looked into aspects related to opportunities for participation. These aspects are frequently ignored or addressed partially. Due to the lack of standard indicators, we had to investigate which aspects were

the most relevant and which indicators were the most appropriate to characterise them. The aspects we finally selected, revolve around participation in the governance and the economic systems and the alternatives for constructing and using the infrastructure beyond commercial options. We analysed them from the perspective of their participatory potential and their effective implementation.

Although a systematic and more extensive research was beyond the scope of this investigation, because of time constraints and the difficulty of data collection, the information gathered suffices to give an unequivocal positive response to RQ1: beyond doubt, many of the results achieved by Guifi.net are greater than those achieved by the private sector model in similar conditions, and the rest are not worse. More precisely, we found that Guifi.net provides more effective means for (i) including civil society in the governance system and including local SMEs in the economic system; (ii) activating and aggregating local funding and financing capacity (even in terms of units of €), deployed in so-called unprofitable areas, even without public support (although the contribution of the public sector—which is not necessarily in terms of funding—can accelerate the deployments in an extraordinary manner); (iii) developing equal conditions for competition (we claim that a commons-based participatory infrastructure results in a single market with nearly perfect competition conditions); and (iv) enabling others besides professionals, such as associations and co-ops of users, DIY, to participate in deployment and operation. Following the comparison with the private sector, we learnt that the two options deliver similar broadband capacity (although not in the same places, as the private sector leaves the less profitable areas unattended), and similar service prices. It must be taken into account that in the private sector model the only existing option for accessing the services is the commercial offerings while Guifi.net has alternative options and it is open to integrating newer ones.

While addressing RA2, we determined that the differences discovered in RA1 are due to profound differences in the most fundamental concepts, starting with the underlying reason for being (*raison d'être*) of each of them. While the legitimate goal of any private (for-profit) initiative is to maximise the profit of the investors and, hence, infrastructure assets are just another resource to achieve this end, the underlying motivation of Guifi.net is to maximise the size and use of the network infrastructure, which is understood as a CPR. These profound differences shape immeasurably the strategies, investments, planning, and ultimately, the features of the resultant infrastructure and how it is exploited. While in Guifi.net terms such as cost-oriented, inclusive, sustainable, redistributive and local apply, terms such as directional pricing, extractive, market failures, speculative, and transnational represent outcomes of the private sector model.

In accordance with our findings on the uniqueness in nature of the driving principles, in the size of the network deployed, in the quality of the services delivered, in the diversity of participants, in the complexity of the organisational structure and the interactions among the participants, we concluded that the Guifi.net approach deserves to be considered a model on its own. Thus, we responded affirmatively to RQ2 and undertook RA3 as the first step to address RQ3. Given that during the literature review we could not find any suitable framework for formalising infrastructure models from a broad perspective, we accepted the challenge of formalising the Guifi.net model based on what we had learnt during our interaction with the community, combined with the key components we believe a generic framework should have. Following this methodology, we identified and classified the stakeholder groups, described their roles, and looked into the organisational rules. As for the stakeholders, we identified three main categories and a score of groups. The organisational rules are structured around a comprehensive set of internal regulations, ranging from the ground rules, which establish the scope and the driving principles of the project and set the legal basis for protecting the entire project, to

a collection of sets of good practices. A crucial piece of the set of internal regulations is the *Agreement model for economic activities and for the participation in the compensation system*, an agreement that all the for-profit participants (the *professionals*) must sign (among other participants). This agreement model regulates the *cost-compensation system*, the key success factor of the fruitful economic system developed by Guifi.net as we understood during the development of RA1.

Our detailed analysis of the organisational system of Guifi.net revealed the centrality that the proper management of the conflicts of interest has in the whole organisational architecture. The participants may have multiple roles and always have a voice. However, exclusions based on conflicts of interest always prevail over the right to participate in the decision-making processes. Consequently, the service providers can neither be members of the governance bodies nor of the system operators. Similarly, the volunteers, or any other stakeholder group including the system operators, cannot interfere in the matters that only concern the service providers or the network operators. Another direct consequence of the centrality of proper management of the conflicts of interest is the difference in treatment between professional activity directly related to the CPR (the network) and the professional use of it. The first, in order to avoid conflicts of interest, is fully standardised (tasks, prices, times, etc.). The second, in compliance with the fundamental principle of freedom of use of the network, is liberalised, thus, any professional is free to charge what they consider most appropriate (although, there are rules to prevent dumping practices).

With the model in hand, we were ready to address RQ3, the RQ on the applicability of the model to other infrastructure. Following an incremental strategy, in RA4 we first investigated its scalability through the comparison of Guifi.net with other CNs that is to say, keeping the infrastructure domain (IP networks), and similar social conditions (bottom-up collaborative initiatives). The comparison with less developed CNs lets us to better identify and understand the key enabling factors of the Guifi.net scalability. Combining these factors with the evolution of the indicators gathered in RA1 and the knowledge we had on the improvements that are being introduced, we concluded that not only the model does not pose insurmountable scalability limitations, but it can also be replicated and nested.

RA5 pursued a twofold objective. On the one hand, we wanted to learn about exportability to a *not so different type of infrastructure* in similar social conditions, namely whether the general approach was appropriate and the number and type of changes required. On the other hand, we wanted to research the possibilities of extracting a more general model. Under action research as the general research methodology, in RA5 the experimentally driven research components were explicitly present as we designed, implemented and deployed in the Guifi.net community a product, a GNU/Linux distribution (*Cloudy*), as a central piece of our research. Although its adoption by the Guifi.net community was moderate, in our opinion the results of our investigation validated the feasibility and sustainability of a cloud computing infrastructure managed as a participatory CPR.

We believe that the moderated adoption of Cloudy is because the focus of the Guifi.net community is on network infrastructure, and not on cloud computing. Consequently, Cloudy was adopted by some active participants because it better met their cloud computing needs, and attended our collaboration requests, but did not get actively involved in its development and promotion. This experience confirmed that the scope of Guifi.net is limited to network infrastructure, which for us is one of its success factors. Notwithstanding the moderate adoption, our particular assessment of having chosen Guifi.net as the community with which to conduct

our experiments of RA5 is positive taking into account that our familiarity with the community saved us a lot of time and eased a lot the interaction.

Combining the results in terms of the capacity for scaling (RA4) and for being exported (RA5) led us to answer RQ3 in the affirmative. More precisely, because of our exploratory work generalising the model, we proposed the attribute *extensible* to refer to infrastructure that is relatively easy to expand and maintain in contrast to those naturally limited or hard to expand resources such as natural commons, and argued that the generalised model is valid, at least, for any infrastructure meeting this requirement.

At this point, we have enough arguments to state that the private sector model is not the most appropriate to deal with the governance of infrastructure due to the imbalance between the goals of a private sector initiative and the mission of infrastructure. To put it simply, at best, the alignment of the profit maximisation of the investors with the maximisation of the social profit of the infrastructure assets can happen only by coincidence. We claim that such a critical resource for society as infrastructure cannot be left to coincidence, especially when alternatives exist. In this regard, we argue that the Guifi.net model, or more generally, the model derived from the conception of infrastructure as a participatory CPR, better deals with the conflict of interest by design and, as a result, it is in a much better position to confront many of the gaps of the private sector model without diminishing effectiveness in the areas where the last performs satisfactorily. Furthermore, considering that the Guifi.net model does not preclude the private sector initiative at all but only limits its capacity of influence on governance, we consider that the generally used term *private sector model* is misleading and we propose to refer to it as *private sector-driven model*, in contrast with the *participatory CPR model*.

To conclude, we believe that this dissertation brings enough supportive arguments to claim that: (i) at least, network infrastructure can be successfully developed an operated as a CPR at the scale of hundreds of thousands of nodes, (ii) in many aspects the results outperform those from the private sector model or, at worst, it delivers similar results, and (iii) that this approach has the potential to be implemented in many other types of infrastructure.

From the scientific perspective, our main contributions fall under the fields of infrastructure management and the study of the commons. In summary, in the field of infrastructure management, we: (i) conducted the case study of a human-made infrastructure managed as a CPR, (ii) proposed the concept of *extensible* infrastructure, and (iii) proposed a model for the development and management of infrastructures of this type. In our study of the commons, we: (i) provided a case study that belongs to an unexplored area (the intrinsically artificial commons—with substantial CAPEX) and has an unusual size (hundreds of thousands of beneficiaries and hundreds of participants with very diverse roles and interests), and (ii) corroborated the validity of E. Ostrom's principles for our case study, We would be glad if these contributions help to strengthen relations between these two fields, because we are firmly convinced that the concept of participatory CPR has strong potential for developing more efficient infrastructure models, and because we think the community researching the commons should expand its focus to other goods and services and look at them from other angles.

As for the communities of practice we worked with, we wish that, through our scientific approach, we contributed to better structure their information and refine some of their processes. It is our hope that these contributions are at least partially proportionate to the contributions they have made to our research. Finally, we hope that our work eventually translates into the implementation of more effective infrastructure management procedures.

9.2 Future work

Considering the contributions proposed in this dissertation and with all the insight gained during the process, we believe that the following research directions can be of interest.

Could the Guifi.net model be applied to the whole Internet? The main sub-questions we foresee are (i) to clarify the scalability limits of the Guifi.net model and the limiting factors, (ii) to investigate the changes it requires to cope with a very-large-scale network, and (iii) to assess the viability of the resulting model.

We suspect that the current state of the model is suitable for a bigger order of magnitude than in the existing deployed an operated infrastructure under this model (some tens of thousands of nodes). The scalability potential of the model is not only due to the capacity to organise infrastructure in a single instance but also to the possibilities of being federated or nested. In our opinion, one aspect this study should include is a risk assessment of the model because the type and extent of the risks are very much related to the size of the infrastructure. For instance, questions arise about whether the Guifi.net foundation is taking an excessive leading role, hence, it can become a single point of failure. We are also particularly concerned about the scalability of Guifi.net's current legislative power organisation (direct democracy) and we wonder if novel participation models such as liquid democracy could contribute in this regard without undermining its core principles.

Further investigation on our generalised model As has been stated throughout the dissertation, the work presented in Chapter 8 is preliminary and requires further investigation. We envisage at least three additional lines of inquiry: (i) validating and refining the generalised model, (ii) determining the appropriateness of the attribute *extensible* to specify the infrastructure to which the model can be applied, and (iii) investigating the reusability of the model beyond extensible infrastructure. On this basis, several specific questions can be posed. For instance: is it possible to develop a commons-based participatory model for civil infrastructure? Is this type of model suitable for infrastructure involving sensitive information, like the health systems? How would the widespread adoption of these models affect research and innovation?

As in our research, we believe that the research fields presented above demand a substantial level of multidisciplinary expertise. Although, they may require less field work, at least during the initial stages, and fewer technological skills, they require deeper knowledge of economics and law in general and particular knowledge about other infrastructures.

In our study, we identified the following points related to the communities of practice that require further attention, especially by practitioners:

- In many CNs we observed a noteworthy refusal to engage in for-profit activities. The lack of a commercial option means excluding those who are not skilled enough or do not have the time. Frequently it also often involves poor or unreliable network service. Based on the lessons learnt in Guifi.net, we believe that preconceptions against for-profit activity should be reviewed. This recommendation does not imply they that must adopt the Guifi.net economic system. On the contrary, the positive effects of local solutions strongly suggest adapting existing systems and developing new ones.

- We also observed a generalised excessive dependency on specific individuals. We perfectly understand that small communities have very little room to manoeuvre, but we believe

that for the rest, adopting measures to reduce this dependency would be beneficial in the long-term. We see Guifi.net as particularly affected by this thread.

To conclude, this dissertation has been written as part of an industrial doctorate, thus, it has a strong knowledge transfer component. Consequently, we consider that the bulk of its contents can be of interest for communities of practice and other players directly involved in the development and management of infrastructure.

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