Ph.D. Thesis

Energy and cost management in shared heterogeneous network deployments

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Abstract

During the recent years, a huge augmentation of the data traffic volume has been noticed, while a further steep increase is expected in the following years. As a result, questions have been raised over the years about the energy consumption needs of the wireless telecommunication networks, their carbon dioxide emissions and their operational expenses.

Aiming at meeting the high traffic demands with flat energy consumption and flat incurred expenses, mobile network operators (MNOs) have opted to improve their position (i) by deploying heterogeneous networks (HetNets), which are consisted of macrocell base stations (MBSs) and small cell base stations (SBSs) and (ii) by sharing their infrastructure.

However, questions could be raised about the extend to which HetNet densification is of aid. Given that network planning is executed according to high traffic load volumes, BS underutilisation during low-traffic hours cannot be neglected. Similarly, the aggregated energy needs of multiple SBSs equals the ones of an energy hungry MBS, having thus a respectable share of the net energy consumption.

In this context, a set of research opportunities have been identified. This thesis provides contribution toward the achievement of a greener and more cost efficient operation of HetNet deployments, where multiple stakeholders develop their activity and where energy support can have the form of various alternate schemes, including renewable energy (RE) sources. Depending on the network energy support, i.e., whether RE sources are used in the network or not, the main body of this thesis is divided in two research directions.

The first part of the thesis uses the technology of switching off strategies in order to explore their efficiency in terms of both energy and costs in a HetNet. The HetNet is assumed to be a roaming-based cooperative activity of multiple MNOs that is powered exclusively by grid energy. A switching off and a cost allocation scheme are proposed, using as criteria the BS type, the BS load and the roaming cost for traffic offloading. The performance of the proposed schemes is evaluated with respect to energy efficiency, cost savings and fairness, using computer-based simulations.

The second part of the thesis explores energy and cost management issues in energy harvesting (EH) HetNet deployments where EH-BSs use an EH system (EHS),

an energy storage system (ESS) and the smart grid (SG) as energy procurement sources. The EH-HetNet is assumed a two-tier network deployment of EH-MBSs that are passively shared among an MNO set and EH-SBSs that are provided to MNOs by an infrastructure provider. Taking into consideration the infrastructure location and the variety of stakeholders involved in the network deployment, approaches of RE exchange (REE) are proposed as a cooperative RE sharing for the shared EH-MBSs, based on bankruptcy theory, and a non-cooperative, aggregator-assisted RE trading, based on double auctions, for the EH-SBSs. The performance of the proposed schemes is evaluated in terms of the hours of independence of the studied system from the SG, the fairness regulated by the provided solution and the economical payoffs extracted for the stakeholders.

Resumen

Durante los últimos años, se ha notado un aumento enorme del volumen de tráfico de datos, mientras que se espera un nuevo aumento en los próximos años. Como resultado, se han planteado preguntas sobre las necesidades de consumo de energía de las redes inalámbricas de telecomunicaciones, sus emisiones de dióxido de carbono y sus gastos operativos.

Con el objetivo de satisfacer las altas demandas de tráfico con consumo de energía constante y con gastos incurridos constantes, además de utilizar soluciones basadas en la nube, los operadores de redes móviles (MNOs) han optado por mejorar su posición (i) desplegando redes heterogéneas (HetNets), que consisten en estaciones base de macro-células (MBSs) y estaciones base de células pequeñas (SBSs), y (ii) compartiendo su infraestructura.

Sin embargo, podrían plantearse preguntas sobre hasta qué punto la densificación de una HetNet es de ayuda. Dado que la planificación de la red se ejecuta de acuerdo con los volúmenes de carga de tráfico más elevados, no se puede descuidar la subutilización de las estaciones base (BS) durante las horas de poco tráfico. De manera similar, las necesidades de energía agregadas de múltiples SBSs son iguales a las de una MBS que consume mucha energía, teniendo así una parte respetable del consumo neto de energía.

En este contexto, se ha identificado un conjunto de oportunidades de investigación. Esta tesis contribuye al logro de una operación más ecológica y rentable de las implementaciones de HetNet, donde múltiples partes interesadas desarrollan su actividad y donde el apoyo energético puede tener la forma de varios esquemas alternativos, incluidas las fuentes de energía renovables (RE). Dependiendo del soporte de energía de red, es decir, si las fuentes de RE se usan en la red o no, el cuerpo principal de esta tesis se divide en dos direcciones de investigación.

La primera parte de la tesis utiliza la tecnología de las estrategias de apagado con el objetivo de explorar su eficiencia en términos de energía y gastos en una HetNet. Se asume que la HetNet es una actividad cooperativa basada en la itinerancia de múltiples MNO que se alimenta exclusivamente de energía de la red. Se propone un esquema de desconexión y de asignación de costes, que utiliza como criterios el tipo de BS, la carga de BS y el coste de la itinerancia para la descarga de tráfico. El rendimiento de los esquemas propuestos se evalúa con respecto a la eficiencia

energética, el ahorro de costes y la equidad, usando simulaciones en computadora.

La segunda parte de la tesis explora los problemas de gestión de energía y de costes en las implementaciones de HetNet donde las estaciones base recolectan energía usando un sistema EH (EHS), un sistema de almacenamiento de energía (ESS) y la red eléctrica inteligente (SG) como sistemas de adquisición de energía. Se asume que el EH-HetNet es una implementación de redes de dos niveles donde los EH-MBSs se comparten pasivamente entre un conjunto de MNOs y EH-SBSs se proporcionan a los MNOs de un proveedor de infraestructura. Teniendo en cuenta la ubicación de la infraestructura y la variedad de partes interesadas e involucradas en el despliegue de la red, se proponen enfoques de intercambio de RE (REE) como un intercambio cooperativo de RE para los EH-MBS compartidos, basado en la teoría de bancarrota, y un no cooperativo comercio de RE para los EH-SBSs, que es asistido por un agregador y basado en las subastas dobles. El rendimiento de los esquemas propuestos se evalúa en términos de las horas de independencia del sistema estudiado con respecto al SG, la imparcialidad regulada por la solución proporcionada y los beneficios económicos extraídos para las interesadas.

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The Ph.D. was an experience with many ups and downs. I am happy to reach the end of this era. However, this would not have been possible unless some people provided their assistance through these steps.

I would firstly like to thank the Generalitat of Catalunya, Doctorat Industrial and Iquadrat Informatica S.L. for giving me the opportunity to be part of the program. I would also like to express my sincere gratitude to my advisors, Dr. Christos Verikoukis and Dr. Luis Alonso for their continuous support, motivation and guidance through all the stages of the doctorate program.

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During these past years, I had the opportunity to meet a lot of new people and to reunite with an all time friend. All of them help me in their way to put a closure to this experience. I will make a special mention to my oldest friend, Agapi Mesodiakaki and to a new friend, Georgia Tseliou. Both of them offered me support on both a personal and a professional level. I would also like to thank Akis for encouraging me to press the submission buttons for my articles almost all times.

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Finally, I would like to thank my father for the time he devoted working for his family. I wish I could share my experiences with him. I know he would be proud.

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List of Acronyms

4G	Fourth generation
5G	Fifth generation
AC	Alternate Current
ADA	Aggregator-auctioneer payoff from Double Auction
AMC	Adaptive Modulation and Coding
BBU	BaseBand Unit
BG	Bankruptcy Game
BS	Base Station
BSV	Bankruptcy Shapley Value based cost allocation
CapEx	Capital Expenditure
CAGR	Compound Annual Growth Rate
CCS	Charge Control System
cMTC	critical Machine Type Communication
CO_2	Carbon Dioxide
Cool	Cooling
CSO	Cooperative (base station) Switching Off
D2D	Device to Device
DA	Double Auction
DC	Direct Current
DER	Distributed Energy Resources
DL	DownLink
DOD	Depth of Discharge
EE	Energy Exchange
EH	Energy Harvesting
EHS	Energy Harvesting System
EI	Expectation Index

eMBB	Enhanced Mobile BroadBand
EQ	EQual allocation
ESS	Energy Storage System
FON	Full Operational Network
GIE	Generalized Ibn Ezra value
GPC	Green Power Controlling unit
HetNet	Heterogeneous Network
ICT	Information and Communication Technology
IndSO	Individually applied CSO
InP	Infrastructure Provider
IndREE	Individual (single-MNO) Renewable Energy Exchange
IPU	Integrated Power Unit
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MB	MegaByte
MBS	Macrocell Base Station
MCS	Modulation and Coding Schemes
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
mMTC	massive Machine Type Communication
mmWave	millimetre Wave
MNO	Mobile Network Operator
MS	Main power Supply
NF	Noise Figure
NFV	Network Functions Virtualisation
NoCA	No Cost Allocation
No RE-BG	No Renewable Energy Bankruptcy Game
NoREE	No Renewable Energy Exchange
NR	New Radio
NS	Network Slicing
OFDMA	Orthogonal Frequency Division Multiple Access
OpEx	Operational Expenditures
PA	Power Amplifier
PC	Prioritised-Claim allocation

QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QPSK	Quadrature Phase-Shift Keying
QSO	Q-based Switching Off
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RE	Renewable Energy
RE-BG	Renewable Energy Bankruptcy Game
RE-DA	Renewable Energy Double Auction
REE	Renewable Energy Exchange
RF	Radio Frequency
RSO	Random Switching Off
SBS	Small cell Base Station
SDN	Software Defined Networking
SG	Smart Grid
SG-only	Energy procurement from Smart Grid only
SNR	Signal-to-Noise Ratio
SV	Shapley Value
TRX	Transceiver chains
TU	Transferable Utility
UA	User equipment device Association
UE	User Equipment device
URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle to vehicle/infrastructure
VDC	Virtual Data Centre

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Chapter 1

Introduction

1.1 Motivation

The expectation of the latest years for wireless service provision anywhere, anytime, anyhow and by any means, has lead to a huge augmentation of the data traffic volume. A recent report from Cisco has indicated that the busy-hour internet traffic (or the internet traffic of the busiest 60 minute period in a day) is expected to increase by a factor of 4.6 between 2016 and 2021, while the average Internet traffic by a factor of 3.2. Moreover, mobile data traffic, which has grown 18-fold over the past 5 years, is expected to increase sevenfold between 2016 and 2021 [1]. These expectations on traffic needs indicate that network capacity will have to be augmented considerably in order to provide enough service. The implementation of a network capacity boost to this extend, where it can properly address traffic demands, brings forward issues of significant energy consumption and creation of costs for mobile network operators (MNOs) of the fourth and fifth (4G and 5G, respectively) generation networks.

Three are the main generic 5G services that are planned to be running on top of them so that the high data traffic demands are met [2, 3]:

1. enhanced mobile broadband (eMBB): It represents the provision of increased data rates, as well as continuous and improved quality of user experience (QoE) and latency. Higher data rates, beyond the 4G values, are necessary for high-demand applications, such as augmented reality or remote presence. Ubiquitous and reliable QoE represents the provision of moderate rates (>99%) anywhere and anytime, even in challenging situations, such as in high mobility cases (e.g. in trains) and in very densely or sparsely populated areas. Graceful performance degradation in terms of data rate and latency as the number of users increases represents as well a ubiquitous and reliable QoE.

2. massive machine type communication (mMTC): It provides simultaneous con-

nectivity for a massive number of devices. Low latency and low energy operation for the devices is considered necessary. Therefore, low software and hardware complexity are vital for the use of cost- and energy-constrained devices.

3. critical MTC (cMTC) or ultra-reliable low-latency communications (URLLC): They address the needs for ultra-reliable, time-critical services, such as energy distribution, industrial processes, sensor networking and vehicle-to- vehicle/infrastructure (V2X) applications. The main attribute is high reliability and security, as well as low latency, at levels of milliseconds, since the number of devices and the required data rates are relatively low compared to mMTC.

Towards the implementation of these services, a unique network approach with new and mostly cloud-based service capabilities has been proposed for the 5G wireless networks [4, 5, 3]. The integration of multiple radio access technologies (RAT) for seamless and reliable coverage is an important feature of 5G networks. The Long Term Evolution (LTE) technology has been included in the non-standalone 5G New Radio (NR) framework so that the 5G requirements can be achieved [6]. The use of massive Multiple-Input Multiple-Output (MIMO) technology with extremely accurate beamforming is also considered an integral part of 5G wireless networks so that more possible signal paths with better performance in terms of data rate and link reliability is achieved. Moreover, 5G standards use different frequency bands (low, medium and high), such as millimetre wave (mmWave), while communication with machines, such as the device-to-device communication (D2D) is also enabled for capacity augmentation and service providing to devices located out of the cell coverage via others that are located within it. Software based technologies are used extensively in 5G wireless networks, so that network functions can run over a unified operating system in a number of points, especially at the network edge and so that 5G performance requirements are met. As a result, technologies such as Software Defined Networking (SDN), Network Functions Virtualization (NFV), virtual data centres (VDCs), Mobile Edge Computing (MEC) are fundamental for achieving the required 5G network performance, scalability and agility. Finally, the new air interface of the 5G NR framework allows an optimized and more dynamic usage of resources, while multi-tenancy models that will enable MNOs and other parties to collaborate in new ways, are to be supported. MNO collaborations will be aided greatly by the network slicing (NS) technology, which allows the definition of multiple logical networks (or slices) on top of the same infrastructure.

Despite the extensive use of cloud-based services, which are dominant in 5G wireless networks, the traditional technique for capacity augmentation, i.e., the deployment of denser networks, which has been extensively used for the 4G era, is to be continued as well [7][1]. Denser networks are closely related to the current environmental issues. In detail, Information and Communication Technology (ICT) infrastructure has been held responsible in the past for having a large share in the total global energy consumption and carbon dioxide (CO_2) emissions, with mobile network base stations (BSs) being accounted for the largest contribution [8].

[1] https://www.techradar.com/news/mobile-industry-shouldnt-wait-for-5g-to-roll-out-small-cells

More recent studies have predicted that, unless countermeasures are taken, a global percentage equal to 51% and 23% of energy consumption and CO_2 emissions, respectively, will be generated by the ICT infrastructure [9]. A report from British Telecommunications expects that ICT's own footprint will reach 1.25Gt CO_2e in 2030, or 1.97% of global emissions by 2030 [10]. These numbers are far from negligible and only highlight the need to act towards their limitation.

Energy consumption is also a major contributor to network operating expenditure (OpEx) of MNOs and studies have intended to express in numbers its impact on network expenses. Nokia has concluded that up to 15% of network OpEx is spent on energy in mature markets, while the respective percentage in the developing ones can vary from approximately 15% up to 30% [11]. According to the same report, what seems to be more discouraging is that just 15% of the energy spent on operating a network is used for forwarding bits, which means that 85% of the energy does not contribute to generating revenues.

The impact of excess OpEx is also imprinted on the revenues of MNOs. In detail, GSMA predicts that global revenue will grow only by around 1% between 2017 and 2020 (Compound Annual Growth Rate, CAGR) and will roughly stabilise beyond 2020 at $1.1 trillion [12]. However, this is expected to happen mostly thanks to only one market, i.e., the Chinese one, while other big markets are foreseen to struggle with the growth of their revenues. Indicative examples are the USA and the European market. The former, despite being one of the largest markets by revenue, its revenue growth is expected to be near-stable, while the latter is expected to see only small benefits by 2025, after a decade of continuously declining mobile revenues (since 2008) [12]. With the increasing number of data-hungry end users, whose service providing demands significant investments from MNOs' part, profit generation is foreseen only as marginal, highlighting thus the need for MNOs to improve their current and future cost position.

However, augmenting network capacity of large-scale networks on flat energy and costs is not an easy task for MNOs to deliver. It is without a doubt though that efforts have already been made towards the achievement of this goal. Typical examples are the extensive deployment of heterogeneous networks (HetNets) and the operation of networks, including HetNets, in various business model forms of operation, such as infrastructure sharing.

HetNets, which have been widely embraced over the last years, are an outcome of the densification of wireless cellular networks with small cells [13]. A small cell is a radio access point, of varying radio access technologies and with low RF power output, footprint and range. It is operator-controlled, and can be deployed indoors or outdoors, and in licensed, shared or unlicensed spectrum [14]. The deployment of multiple small cell base stations (SBSs) has aided capacity augmentation thanks to (i) the reduced distance achieved between user equipment devices (UEs) and BSs, which in turn leads to higher signal-to-noise ration and data rates, while (ii) it has multiplied the possibilities for the employment of higher frequency reuse within the network, resulting in higher spectrum efficiency (bps/Hz/m^2) (i.e., for given bandwidth more users can be served in a specific area). Moreover, an individual

SBS creates less energy demands [15] and is easier and cheaper to deploy thanks to its smaller and cheaper equipment in comparison to the big and energy hungry macrocell BS (MBS). Finally, its site acquisition is also both cheaper and easier to encounter than the one of an MBS in dense urban environments, since finding new locations for MBSs, so that the in-between them distance is the proper one, can prove to be extremely expensive [16].

As a result, the popularity of small cells and, therefore, HetNets, has become abundantly clear during the last years and is expected to continue in the future with MNOs planning for denser HetNets, even if they do not intend to deploy a 5G radio network at scale until well into the 2020s [17]. According to a Small Cell Forum report, the biggest uptake in new small cell deployments is expected to be seen in the 2018-2020 period with a 50% increase. Moreover, the same report states that, a second sharp increase is expected between 2023-2024, which is when 5G densification will be getting into full swing [17].

However, given the high number of SBSs that is expected to be deployed, aggregated SBS energy consumption is far from negligible. This is based to the fact that, although the energy consumption of an individual SBS is not considerable, the summed up energy consumption of multiple SBSs can equal the one of a single MBS. A simple mathematical calculation is needed to confirm that. Moreover, given that in dense urban environments, network planning is implemented based on the high peak traffic volume patterns, plenty SBSs and MBSs are underutilised during low-traffic periods. Thus, both energy and money that could be saved, are instead wasted. The phenomenon of inefficient energy and cost management is further highlighted, in urban environments, since multiple MNOs roll out their deployments and develop their activity on a stand-alone business model. The impact of these issues is already apparent in the expected numbers on network energy consumption and costs and MNOs have to make more efforts in order to resolve them.

Infrastructure sharing, which was mentioned earlier, was used as a counteract approach against this inefficiency of energy and cost management in areas of multi-operator activity and with an aim to efficiently utilise their network capacity [18, 19]. By applying a form of infrastructure sharing, MNOs are able to quit the model of single ownership of all network layers and elements that require individual activities, such as building, rolling out, maintaining and expanding an infrastructure consisted of a combination of diverse types of assets. These assets include passive infrastructure assets, such as masts or ducts, active infrastructure assets, such as antennas or transmission components, and intangible assets like spectrum licenses [20]. Thus, when MNOs set agreements, either among them or with other stakeholders, e.g., infrastructure providers, in order to regulate a level of cooperation on sharing network infrastructure, spectrum or both [21, 22], apart from multiplying the number of their access points, improving in consequence their individual network coverage, they are also relieved of a heavy financial burden of holding complete responsibility of the financial investments, capital expenditure (CapEx) and OpEx for their networks.

In order to extend the benefits of the HetNet deployments and network sharing in terms of energy and cost savings, MNOs have turned to the deactivation or sleeping of a whole network or of network elements [23, 24, 25]. Infrastructure switching off relies on the deactivation of BSs based on different criteria, such as the low traffic load, with simultaneous traffic offloading to other (usually neighbouring) BSs that are capable to provide service. It emerged as one of the green technologies that does not require upgrade of equipment to reduce the total network energy consumption, while it also offers low implementation costs. It was also motivated by the need to overcome the issue of network infrastructure underutilisation and to achieve a network operation approach that could be adaptive to the traffic load variations. The effectiveness of the method is based on a selection of the network infrastructure portion that will be deactivated so that the service to the offloaded traffic is reassured. Therefore, proper criteria need to be selected so that they do not render switching-off algorithms ineffective, while when it comes to network sharing scenarios, the conflicting interests of the involved stakeholders have to be given consideration.

In the same context, more recently, a shift of MNOs towards a green and cost saving network operation based on the usage of renewable energy (RE) sources for powering the RANs has been noticed [26]. In spite of the high CapEx that may come along with the deployment of energy harvesting (EH) infrastructure, the use of RE sources comes with valuable benefits. More specifically, not only does it imply the reduction of CO_2 emissions during their period of use, but also, in the long run, a bulk of savings in OpEx by replacing the use of grid energy. Apart from that, network elements powered by RE sources are trusted to provide a more reliable use and recovery of the network operation in cases of emergency, e.g., an earthquake or a tsunami. Usage of RE sources in order to support or entirely power network elements is gaining popularity as great focus has been concentrated on the implementation possibilities of EH MBSs and SBSs (EH-MBS, EH-SBS) [27, 28, 29].

It is worth noting that the consideration of RE as a power source for wireless telecommunication networks has been aided greatly by the evolutionary steps that have been made in the recent past for the deployment of smart grid (SG) networks [30, 31, 32]. The overall aim of the SG use was the implementation of an energy efficient ICT system that would include the integration of RE sources as an energy procurement source, as well as the introduction of a smart demand-response management system in energy allocation. The real-time observation of the network infrastructure that is allowed with the SG, thanks to the installation of smart meters, enables techniques that can improve the system observation in terms of energy availability and shortage. Moreover, it balances, up to a certain degree, the unpredictability that characterises the generation profile of RE sources. Thus, techniques that promote cooperation schemes for an effective energy and cost management are enabled. Indicative examples are energy exchange (EE), in the form of energy sharing or trading, variable pricing and corresponding billing actions [33, 34, 35]. Consequently, usage of RE sources in combination with the one of SG has been an attractive energy and cost efficient solution for wireless networks.

Although the energy and economic benefits gained from the aforementioned technologies have been studied individually for the case of HetNets, we believe that steps are left to be made towards studying the combined use of these technologies in shared HetNet deployments. As HetNets become denser and UE demands rise, energy requirements are higher and new technologies are used. Thus, the need is created to study novel possible cooperative endeavours that would use these technologies while keeping intact the operation of different HetNets in terms of quality of service as if they were individually managed. At the same time, the cooperative schemes could reassure a greener approach in network operation for the protection of the environment. Moreover, as new technologies are deployed, stakeholders of different profiles and interests may be involved in such collaborative activities. Thus, the perception of a profitable cooperation agreement becomes disputable and the individual interests of the parties within it are considerably heterogeneous. It is more than necessary to strictly define a cooperation agreement among such different stakeholders so that the requirements of a healthy competition are fulfilled and so that both holistic and individual profitability of the cooperation is reassured. Hence, the design of novel analytical frameworks that promote the combined use of such different technologies in shared HetNet deployments is imperative.

To this end, the present thesis aims at filling the gap in the literature by bringing forward the issues in relation to fair and energy and cost efficient management techniques in multi-operator shared heterogeneous deployments of 4G and, dynamically, of 5G wireless networks. When it comes to a cooperative energy management, we take into consideration the network characteristics of the cooperative stakeholders, i.e., the type and quantity of infrastructure composing their network, so that they improve the energy efficiency of their HetNets and, at the same time preserve their service providing and network coverage. Consideration is also given to the fact that BS underutilization may be different for each involved stakeholder over a 24 hour period, due to different data traffic patterns and volume profiles. When RE sources are introduced in the network, apart from the traffic load patterns that affect BS and MNO aggregated energy needs in the traditional grid-connected HetNets, the variability in RE generation profiles and availability of EH equipment are also considered, as they may result in mismatching energy availability profiles of the network's EH-BSs. When it comes to a cooperative cost management, energy management procedures that have preceded are taken into account, since energy is a major contributor to network OpEx and thus greatly affects the stakeholders' revenues and profits. Moreover, in both cases of the traditional grid-dependent HetNets and the grid-connected HetNets that powered by hybrid energy sources, i.e., grid and RE sources, we value the exchange of information among the different stakeholders accordingly. Expectations on traffic loads and RE generation, as well as limitations introduced by the used infrastructure, are considered as information for an agreement's regulation so that disgruntlement for the cooperation schemes is avoided.

The structure of the thesis and the main contributions of this work will be discussed in detail in the following section.

1.2 Structure of the Thesis and Contributions

The present thesis aims at bringing forward energy and cost management techniques for multi-operator shared heterogeneous deployments. More specifically, the contribution of this thesis relies on the proposition of novel schemes that (i) address the open issues described in Section 1.1 and (ii) regulate energy saving mechanisms and cost efficient operation frameworks, for networks that primarily use 4G technologies. In order to achieve that, there are two conceptual roads that are followed. The first one studies typical HetNets that are shared by multiple MNOs and powered exclusively by the electrical energy of the grid. In this case, deactivation of network elements, and more specifically of BSs, is used as the chosen energy saving technique. Cost related issues that motivate cooperation of MNOs are addressed with a study on cost allocating schemes. The second conceptual road also aims at addressing energy and cost management issues, though in multi-operator HetNet deployments powered by hybrid energy sources, and more specifically by an EH system (EHS) that uses RE sources, an energy storage system (ESS) to save the harvested RE and the SG. Energy sharing and trading schemes among different stakeholders, such as MNOs, are studied with regard to energy management issues, while focus is also given to the cost related issues that come up with the adoption of energy trading. In particular

- Chapter 2 that follows, provides some necessary background information concerning the technologies that are used in the thesis.
- Chapter 3 and Chapter 4 provide the innovative contributions of the thesis. More specifically,
  - Chapter 3 is the first part of the thesis and it studies energy and cost issues of a HetNet that is a cooperation result of many MNOs and is powered by the grid exclusively. Each MNO owns a HetNet of LTE-Advanced (LTE-A) technology, while MNOs share their infrastructure and cooperate by switching off a part of it. We propose a cooperative BS switching off scheme (CSO) that uses BS types and traffic load as switching off criteria. CSO also incorporates a proposed roaming-cost-based user association scheme to roam traffic to neighbouring BSs. In order to assess cost alterations created by the possible MNO coalitions, we propose a Bankruptcy Shapley Value based cost allocation scheme (BSV) to allocate the obtained cost to the cooperative MNOs and to motivate them thus to maintain their sharing agreement instead of following a non-cooperative tactic.
  - Chapter 4 is the second part of the thesis and investigates energy and cost issues in multi-operator HetNet deployments of LTE-A technology that are grid-connected, i.e., they are supported by both the SG and RE sources. Aiming at reducing cost and SG energy consumption, this chapter studies possibilities of RE exchange (REE) in late-trend network deployments of EH-MBSs and EH-SBSs, that use an EHS, an ESS and the SG as energy procurement sources. On this basis, the chapter studies

a two-tier network composed of passively shared, among a set of MNOs, EH-MBSs, and EH-SBSs that are provided to MNOs by an infrastructure provider (InP). Taking into consideration the infrastructure location and the variety of stakeholders involved in the network deployment, REE approaches are proposed as (i) a cooperative RE sharing for the shared EH-MBSs, namely RE bankruptcy game (RE-BG), based on cooperative game theory and more specifically based on bankruptcy games, and (ii) a non-cooperative, aggregator-assisted RE trading for the InP provided EH-SBSs, namely RE double auction (RE-DA), which uses double auctions.

Finally,

- Chapter 5 discusses the conclusions of the presented work, making some recommendations on how the proposed schemes could be formed for application to 5G networks and identifies potential lines for future investigation.

In continuation, the main contribution of the thesis will be outlined in more detail.

1.3 Research Contributions

The novel proposals discussed in this thesis have been included in two journals and two international conferences, cited next:

[J2] **M. Oikonomakou**, A. Antonopoulos, L. Alonso, and C. Verikoukis, "Energy Sharing and Trading in Multi-Operator Heterogeneous Network Deployments," *under review* in the *IEEE Transactions on Vehicular Technology.*

[J1] **M. Oikonomakou**, A. Antonopoulos, L. Alonso and C. Verikoukis, "Evaluating Cost Allocation Imposed by Cooperative Switching Off in Multioperator Shared HetNets," in *IEEE Transactions on Vehicular Technology*, vol. 66, no. 12, pp. 11352-11365, Dec. 2017.

[C2] **M. Oikonomakou**, A. Antonopoulos, L. Alonso and C. Verikoukis, "Fairness in Multi-Operator Energy Sharing," in *2016 IEEE International Conference on Communications (ICC)*, Paris, 2016, pp. 1-6.

[C1] **M. Oikonomakou**, A. Antonopoulos, L. Alonso and C. Verikoukis, "Cooperative Base Station Switching Off in Multi-Operator Shared Heterogeneous Network," in *2015 IEEE Global Communications Conference (GLOBECOM)*, San Diego, CA, 2015, pp. 1-6.

1.3.1 Other Research Contributions

Apart from publications directly related to the thesis contributions, a number of other research works have been carried out during the elaboration of this thesis:

[C5] **M. Oikonomakou**, P. Kaloudis, A. Antonopoulos, P. Maniotis, E. Kartsakli and J. S. Vardakas, "Internet services market across Europe during crisis: A study focused on low-income groups," in *2017 IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Lund, 2017, pp. 1-5.

[C4] G. Kalfas, P. Maniotis, **M. Oikonomakou**, E. Kartsakli, J. Vardakas, N. Pleros and C. Verikoukis, "On converged Medium-Transparent MAC protocols for mm-wave Fiber-Wireless Networks," in *2017 IEEE 22nd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*, Lund, 2017, pp. 1-5.

[C3] J. Vardakas, I. Zenginis and **M. Oikonomakou**, "Peak demand reduction through demand control: A mathematical analysis," *2016 IEICE Information and Communication Technology Forum (ICTF)*, Patras, 2016.

Chapter 2

Background

2.1 Introduction

The aim of this thesis is to provide energy and cost efficient frameworks for multi-operators shared deployments of heterogeneous networks (HetNets). In this context, we will focus on the energy and costs saving approaches of switching off network elements and using renewable energy sources for the power support of the network. Each of these techniques has individually a different impact on single operated cellular networks and HetNets, that has to be understood before examining their effect on shared network architectures. To that end, in this chapter, we provide background information and the main principles of these fundamental concepts.

2.2 Heterogeneous networks (HetNets)

The major challenge of mobile network operators (MNOs) lately has been to provide uniform coverage especially in urban areas, which are densely populated with end users of high data demands. As mentioned in Chapter 1, a way to achieve this challenging network augmentation, which has been traditionally used in the past, is to expand the existing network through the addition of extra infrastructure. During the recent years, adding infrastructure refers mostly to the installation of multiple small cell base stations (SBSs) and less to the addition of macrocell ones (MBSs), resulting thus in the formation of HetNets [16].

Small cells allow HetNets to dynamically provide increased bit-rates per unit area [36]. This is due to the fact that they are primarily added to increase capacity in hotspots with high user demand and to fill in areas which are not covered by the macro-tier network, such as the cell edge, while they can be used both outdoors and indoors. They also improve network performance and service quality by offloading traffic from the large macrocells and they are able to increase the quality of service during high traffic load periods. However, in order to achieve a successful network planning from a coverage, energy and cost point of view, the coverage range of the base station (BS) type that will be chosen for installation in each of these positions is of utmost importance.

The coverage range of a BS is related to its power consumption levels. MBSs, who are more energy demanding than SBSs, can have a coverage of hundreds of meters. On the contrary, an SBS, whose power consumption is low and varying, can have different coverage ranges, starting from ten until several hundred meters. Depending on their coverage ranges and power consumption levels, SBSs can be referred to as femtocells, picocells, microcells and metrocells [14]. In Section 2.3 that follows, we present the parameters that can affect the power consumption of a BS, while we also present formulas that attempt the mathematical formulation of the BS power consumption.

2.3 BS energy consumption

The variations on the energy volume that is consumed by the BS equipment is related to the BS system components and network system parameters. Their characteristics highly depend on the BS type, due to constraints in output power, size and cost, mandating thus the extraction of a power model that is tailored to a specific BS type. The aim of this section is to present power consumption models that have been extracted for the different types of BSs and that have been frequently used in the past, with a focus on the Long Term Evolution (LTE) technology.

A widely known energy consumption model for both MBSs and SBSs are provided in [37]. The aforementioned work provides two different models of a site's power consumption, which changes accordingly the minimum and maximum network coverage of the site. Dividing BSs into two categories, i.e., MBSs and SBSs and assuming average power consumption and radiated power per site, the work employs linear models of power consumption.

In the case of MBSs, the linear model is described as

$$P_{MBS} = a_{MBS} \cdot P_{tx} + b_{MBS}, \tag{2.1}$$

where P_{MBS} and P_{tx} denote the average consumed and radiated power per site, respectively. Moreover, parameter a_{MBS} is considered constant and accounts for the power consumption that scales with the average radiated power due to amplifier and feeder losses as well as due to the cooling at the MBS site. Lastly, parameter b_{MBS} represents an offset of site power that is consumed independently of the average transmit power due to signal processing, battery backup, as well as site cooling. The work makes reference to the fact that the cooling equipment and the number of sectors (and in general the transmission lines) have an impact on the site's energy needs, both for the transmission and simpler BS processes, which are expressed via the a_{MBS} and b_{MBS} of eq. (2.1).

In the case of SBSs, a respective power consumption description is given for microcell BSs with one omni-directional antenna, as follows

$$P_{SBS} = L \cdot (a_{SBS} \cdot P_{tx} + b_{SBS}) \,. \tag{2.2}$$

In eq. (2.2), factor L reflects the dependence of the site's power consumption on its current activity level. The rest of the parameters in eq. (2.2) have a respective meaning as in eq. (2.1), though for a microcell BS. Thus, the numerical representations of a_{SBS} and b_{SBS} value are different from the respective ones of a_{MBS} and b_{MBS}.

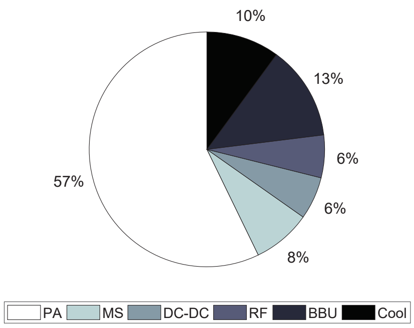
One of the most accepted energy consumption models was provided by the EARTH project [15, 38], since it proceeds to a detailed breakdown of a site's power consumption. More specifically, in the aforementioned works, a description is given on how the power consumption of a BS type is affected by its components. The BS components of the antenna interface that are mentioned are the power amplifier (PA), the radio frequency (RF) chains, the baseband unit (BBU), the main power supply (MS), the cooling (Cool) and the direct-current to direct-current (DC-DC). The work highlights the dependency of power consumption on the traffic load that is served by a BS, depending on its type and its components. More specifically, MBSs are characterised as more energy demanding, with their power consumption having higher dependence on the changes in the served traffic load volume in comparison to any type of SBS. On the contrary, power consumption of the less energy hungry SBSs is more rigid to changes in traffic load volumes.

Based on [15] and [38], we provide Fig. 2.1, which indicates the distribution of power consumption at each individual component system in selected BS types and at maximum traffic load. As can be observed, the power consumption distribution to each component varies for the different kinds of BSs. More intense differences are noticed for the case of SBSs of Fig. 2.1b, Fig. 2.1c and Fig. 2.1d, in comparison to the case of the MBS, which is apparent in Fig. 2.1a. The figures confirm the higher dependency of the MBS power consumption on the traffic load volume, mainly due to the energy needs of the PA. In the case of SBSs, smaller are the power consumption proportions that correspond to the PA in an operation at maximum traffic load, while larger the ones that correspond to the RF chains and the signalling processes of the site's BBU. Thus, power consumption of an MBS is more dependent on the volume of its traffic load in comparison to the one of an SBS.

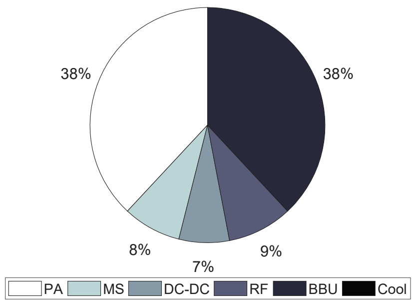
The EARTH project provided two versions of a power consumption model that can be used for every BS type, a detailed and a short one, with the values of some parameters changing, depending on the case of studied BS. Assuming that the BS power consumption, P_{in}, grows proportionally with the number of transceiver chains (TRX), N_{TRX}, the breakdown of the BS power consumption at maximum load amounts to

$$P_{in} = N_{TRX} \cdot \frac{\frac{P_{out}}{\eta_{PA} \cdot (1-\sigma_{feed})} + P_{RF} + P_{BB}}{(1-\sigma_{DC})\,(1-\sigma_{MS})\,(1-\sigma_{cool})}, \tag{2.3}$$

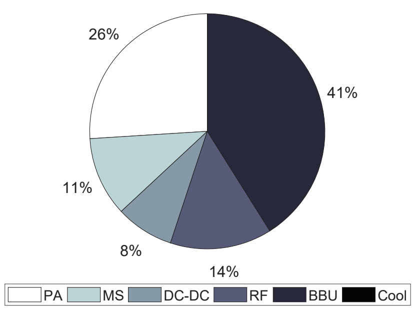
where the term P_{out} denotes the output power of the BS, with $P_{out} = P_{max}$, since



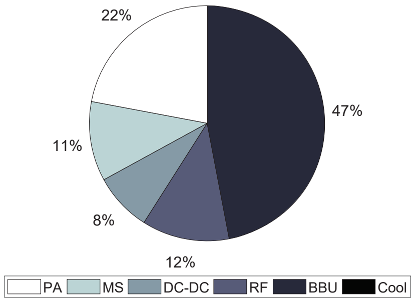
(a) Macrocell



(b) Microcell



(c) Picocell



(d) Femtocell

Figure 2.1: DC power consumption breakdown for different types of base stations (BSs) at maximum traffic load.

the BS is assumed to be operating at maximum traffic load conditions. Moreover, η_{PA} accounts for the PA efficiency, while P_{RF} and P_{BBU} stand for the power consumption at the RF units and the BBU, respectively. Finally, losses incurred by DC-DC power supply, main supply, and active cooling are represented by σ_{DC}, σ_{MS} and σ_{cool}, respectively, and they are assumed to scale linearly with the power consumption of the other components.

The shorter version incorporates the loss parameters in single variables that provide a simpler linear form of the formula in eq. (2.3) as

$$P_{in} = \begin{cases} N_{TRX} \cdot (P_0 + \Delta_P \cdot P_{out}), & 0 < P_{out} \leq P_{max} \\ N_{TRX} \cdot P_{sleep}, \quad P_{out} = 0. \end{cases} \tag{2.4}$$

In eq. (2.4), P_0 is the linear model parameter that represents power consumption at the zero RF output power and Δ_P is the slope of the load dependent power consumption. Finally, P_{sleep} indicates the BS power consumption at sleep mode, i.e., in the case when BS components are deactivated, e.g., when there is nothing to transmit, in order to save energy.

Although aforementioned works of [37] and of the EARTH project were published around 2009 and 2012, respectively, and thus were based on measurements and estimations of past BS models, they are often encountered as the chosen BS power consumption model on current state-of-the-art works. Special reference is made to the work of project EARTH [15, 38], which is probably the most encountered BS power consumption model.

The deactivation of some BS components, which is mentioned in eq. (2.4), or even of a whole BS, is believed to be a solution with prospects to save considerable amounts of energy for a network. The technique falls into the area of our interest and, therefore, the following section provides information on the concept.

2.4 BS Switching off in HetNets

As explained in Chapter 1, switching off a network or a part of is based on a simultaneous traffic offloading to neighbouring BS sites that remain in an active mode and whose range can reach the area covered by the switched off BS. The main aim of switching off network elements is to optimise the utilization of energy, meanwhile keeping user experience intact. The technique is enabled by the fact that network planning aims at satisfying MNOs' peak traffic, which in turn leads to infrastructure underutilization at low traffic conditions. As a result, a part of the BS infrastructure can be deactivated, while a smaller portion of the network infrastructure can remain active and provide service to the region [39].

The critical task that MNOs face in such cases is determining the criteria according to which BS deactivation will be performed. In the case of HetNets, switching off strategies could be designed either for SBSs or for the coverage-overlapped MBSs. The deactivation of the latter though may affect gravely network coverage since they can provide the largest network capacity in the area. Thus, many efforts have been put by people into designing switching off strategies for SBSs, while keeping the MBS always active to guarantee coverage [25, 39].

The main criteria categories that have been presented for BS switching off strategies are the following [25]:

- **Random strategy**: This is the simplest strategy that can be followed in order to switch off BSs. It can be implemented based on the geographic position of the BSs or by deactivating them based on a certain probability [40, 41, 42].

- **Distance-aware strategy**: This method has been based on the attribute of the distance that either user equipment devices (UEs) or BSs have in relation to a specific BS, which is usually the MBS of the macrocell that covers their position. The attribute firstly appeared as a criterion in the work of [43], which designs an intelligent BS switching-off scheme based on the average distance that UEs have in relation to their associate MBS, while in [44] the distance of SBSs from the MBS of the area was used as the switching off criterion[1].

- **Load-aware strategy**: The traffic load distribution in time and space has been the most popular switching off criterion that can be encountered at research works, since it is closely associated with the phenomenon of BS underutilisation [45, 46, 47]. As far as traffic load fluctuations in time are concerned, during the day hours, people are working and doing the majority of their activities, creating thus higher data traffic volumes than during the night hours, when the majority of people are sleeping. As far as traffic load fluctuations in space are concerned, business areas correspond to higher levels of data traffic during working days and hours, as people usually are occupied with their work, whereas residential areas present larger data traffic volumes during evening hours and weekends, when people are more likely to be at home [15, 48].

- **Game-theoretic models**: Game theory has been used in switching off schemes in order to relate the method to cost related issues of the network. In this context, game theoretic schemes that regulate resource allocation or a kind of leasing infrastructure to offloaded traffic have been used for activation and deactivation policies of BSs. The ultimate aim though is to avoid significantly increased capital and operational expenditure (CapEx and OpEx) caused by densely deployed SBSs [49, 50, 51].

Fig. 2.2 illustrates an example of a switching off process in a single operator HetNet deployment, with the responsible MNO controlling and operating spectrum and infrastructure. In the example of the figure, SBSs, with low or no traffic load and overlaid in a macrocell area, are switched off offloading their traffic to the MBS with whom the UEs have better reception signal.

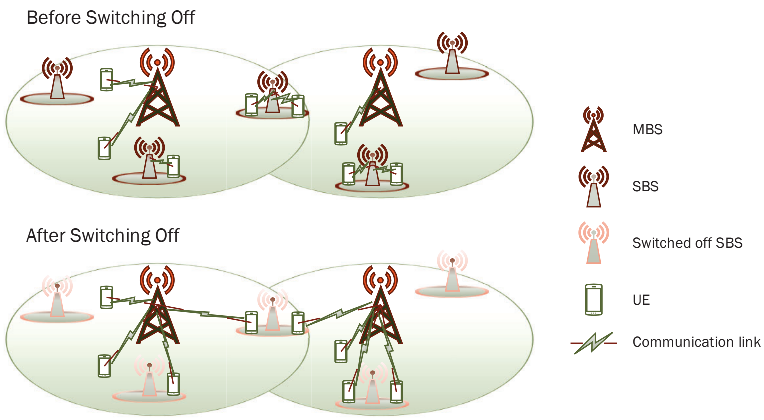


Figure 2.2: Indicative example of BS switching off in a single operator HetNet deployment.

[1]It is noted that work in [43], along with the one in [40] that was mentioned in the random strategy criterion, do not refer to HetNet deployments. However, they are conceptually easy to apply to them and therefore were mentioned in our description.

2.5 Use of Renewable energy sources in HetNets

The present chapter has referred so far to HetNets that procure energy exclusively from the traditional energy procurement source, i.e., the grid. In the new era of wireless telecommunications though, when data traffic volume will be larger, the use of renewable energy (RE) sources gains popularity as an alternative energy procurement source of wireless networks. The use of RE can reduce usage of grid electricity and thus network OpEx and carbon dioxide (CO_2) emissions [9, 39]. Wireless telecommunication networks that support energy harvesting (EH) from RE sources, or the EH networks as we will call them hereafter, can use different approaches in terms of energy procurement and exploitation. Moreover, they can have as network elements BSs that are supported by an energy harvesting system, the EH BSs (EH-BSs). In the following, we refer to the main approaches of energy procurement and exploitation, as well as to the structure of an EH-BS that can be encountered.

Component structure of EH-BSs

A typical EH-BS is usually composed of a(n) [52, 26, 53]

- **EH system (EHS)**: it refers to the equipment that will primarily be used to harvest RE. For example, in the case of solar RE the main RE equipment is a photovoltaic panel, while in the case of wind RE that is a wind turbine. The RE that is harvested from this main RE equipment is then converted to electricity (48V of DC current, [52]) with the aid of converters. The power generated by the main RE equipment is communicated to a green power controlling unit (GPC) that keeps track of the availability in RE at the site and is provided either for consumption to the load, i.e., the radio equipment, or for charging the energy storage system, if there is any.
- **Energy storage system (ESS)**: It is usually an equipment of battery banks that powers the load in periods when RE generation is low or non-existent. According to the usual network operation, batteries are charged when excess RE is harvested. More specifically, the harvested RE is primarily used to fulfil the current needs of the EH-BS and then any excess harvested RE is stored in the available ESS. Characteristics that need to be given consideration for the choice of battery that will be installed are (i) its purchase cost, (ii) its predicted lifetime, (iii) its capacity, and (iv) its size. The purchase cost of a battery needs to be balanced by the cost savings that will be achieved with its use. The predicted battery lifetime is of critical importance as it is largely affected by the battery's depth of discharge (DOD), i.e., the percentage of the maximum battery capacity that can be discharged so that battery health is preserved. The capacity of the ESS has to be properly calculated so that it fulfils the needs of its load, while the size characteristics are related as well with the space availability at the site. Batteries are also characterized by an charge efficiency indicator, which is connected with its ability to accept

charge. Various battery types used to support BSs, such as the lead-acid, nickel-cadmium and lithium-ion battery [54].

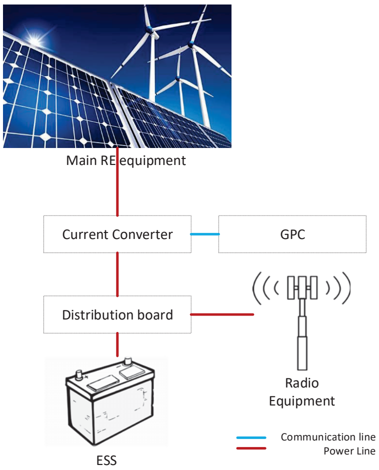
- **Integrated power unit (IPU)**: The power requirements of a typical BS include the load offered by the transceiver equipment, cooling and other miscellaneous loads (e.g. lights). The power supply to these loads, as well as the conversion and storage of the harvested RE is managed by the IPU. A typical IPU consists of alternate current (AC) and DC converters, battery charger, charge level monitors and regulators and a GPC unit. DC-DC converters are used to supply power to the transceiver equipment and to store the harvested RE in the batteries, while DC-AC converters supply power to the AC loads, such as the cooling equipment. The battery charge regulator monitors the battery state and disconnects it from the system when the overall charge goes below a specified DOD (generally 50-80%). Finally, the GPC unit controls the power supply from the RE source to the main RE equipment.

Procurement configurations for EH-BSs

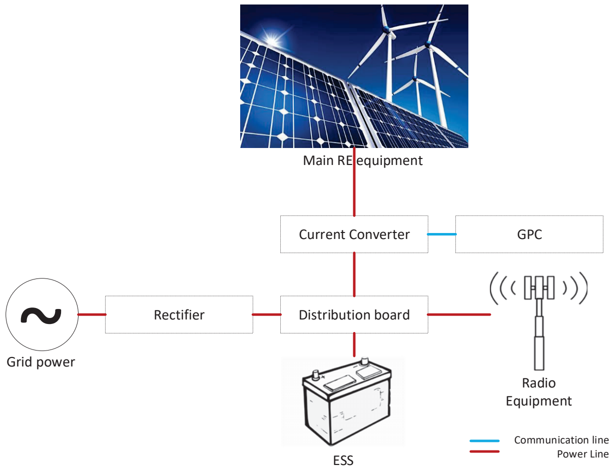
In a traditional configuration of a BS, energy procurement is performed exclusively from the grid, with each BS using existing rectifiers to support its operation. When considering though the possibility of having RE sources, configurations of power management may vary. More specifically, depending on the availability of grid and other RE sources, a BS may be powered solely or partially by either of them. The following configurations can be encountered for an EH-BS [26]:

- **Stand-alone operation**: The BS is powered exclusively by RE sources, while an ESS is usually available at the site to store energy for future use.
- **Fuel-supported**: The BS is primarily powered using the harvested RE. However, in cases of prolonged periods of minimal or zero RE generation, diesel generators are used to meet the power needs of the BS.
- **Grid-connected**: The BS is primarily powered by the harvested RE. However, in cases of RE shortage, it procures energy from the grid. An ESS might also be available at the site to store energy for future use.
- **Hybrid**: Such an operation scheme includes a combination of RE equipment, grid power, diesel generators, etc., at the BS site.

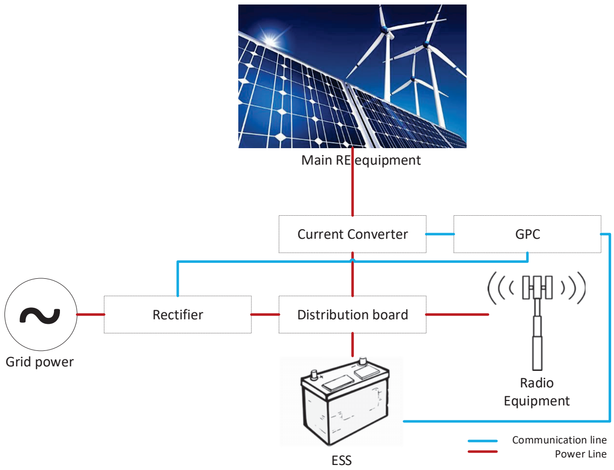
The stand-alone operation, as well as the fuel-supported one, are usually encountered in remote locations where commercial power of the grid is not available. In these stations, the surplus of generated RE is that is not consumed by the BS, i.e., the load, is either lost or used to charge the available at the site ESS. Moreover, in these cases, where there is usually plenty of space availability, the power supplies at the site are designed so that BSs can operate for a considerable amount of time. In the cases though, when a BS site is located within the grid network range, the BS



(a) Stand-alone BS



(b) Grid-connected BS



(c) Grid-connected BS, NTT DOCOMO model

Figure 2.3: Power configurations of an EH-BS.

usually consumes the harvested and stored RE on a first place and then proceeds to the procuring energy from the grid.

In order to visualise the concept of the exploitation of RE sources in the network and the structure model of an EH-BS, we provide selected architectures in Fig. 2.3 [52]. Fig. 2.3a describes the model of an EH-BS following the stand-alone procurement scheme. The main RE harvesting equipment, i.e., the EHS, generates energy that is converted to, the necessary for the support of the radio equipment, electricity voltage thanks to the available current converters. Then, the availability in harvested RE is communicated to the GPC. The distribution board, which connects all power sources, i.e., the main RE harvesting equipment (or EHS) and the ESS, to the radio equipment, changes the energy procurement source based on the energy availability. In the figure, the current converters, the GPC unit and the distribution board constitute the IPU of the EH-BS. Fig. 2.3b provides the structure model of a grid-connected BS, in its usually encountered commercial model. This EH-BS model is identical to the one of Fig. 2.3a, with the difference that the site of Fig. 2.3b is also connected to the grid via rectifiers that change the AC current of the grid to the suitable for the load DC one. Finally, Fig. 2.3c displays a proposed by NTT DOCOMO EH-BS model in a grid-connected power configuration [52]. The difference between Figs. 2.3b and 2.3c, is the activity of the GPC unit. More specifically, in Fig. 2.3b, GPC controls the energy at the main RE equipment only, whereas in Fig. 2.3c, it also has the control of the ESS charging and of the grid power supply. Thanks to this change, it provides a remote control of the combination of the three power sources and enables the "power virtualisation" of RE generation data, battery charge levels, etc.

2.6 Energy exchange

Although the adoption of RE sources and the use of EH-BSs can lead to significant energy savings due to purchases of grid energy, it is often a challenging problem for operators to handle the mismatch between network energy demands and RE generation at the EH sites. A typical example is the one of solar energy harvesting, whose peak hours of RE generation are normally in the noon. A wireless telecommunication network also has the peak hours of its energy demands in similar hours, leading thus to an effective exploitation of energy during this specific time period. However, it is possible that the traffic load volume is large during evening hours as well, when solar energy is not generated. In such cases, covering the energy deficits is a task that is usually addressed either with a connection to an ESS system, which stores redundant RE for future use, or by procuring commercial energy from the grid. However, the progress that has been noticed in relation to smart grid (SG) networks has enabled more innovative energy management techniques that aim at a greener operation of the network and at a lower cost. An indicative example of such techniques is the concept of energy exchange (EE) within a network.

The technique of EE represents the act of energy transfer between entities that have abundance in energy and entities with energy shortage. Depending on whether economical transactions are used, it is expressed via energy sharing policies and energy trading agreements. On one hand, energy sharing refers to exchange of energy with the involvement of no economical transaction, using for example power lines [33]. On the other hand, the term energy trading has been historically used to refer to the act of buying and selling energy, e.g. electricity and gas, in wholesale markets, such as the European Energy Exchange[2]. Moreover, it traditionally takes place between producers, retailers and traders, as well as large industrial users, while more recently, the use of the term refers as well to the "local" transfer of

[2] http://www.ecc.de/ecc-en/

energy between users or small groups within a SG [55].

In such scenarios, the task for MNOs is to find optimal strategies for each entity such that EE would be implemented in the best matching amount possible. In its turn, the aforementioned matching would result in a better exploitation of the generated green energy. In order to do that though, it is important to decide first the way that the actual EE will be performed. Depending on the decision taken on this issue, we extract the following ways for performing EE:

- **Power lines**: When electricity is generated at power plants, it then moves through the grid elements, i.e., electricity substations and transformers via power lines, connecting thus electricity producers and consumer entities. Interconnection of sites via power lines facilitates the coordination and planning of electricity supply [56]. Moreover, a connection of power lines avoids a possible destabilisation of the power system that may occur when energy is transmitted through an AC line. Compared with traditional AC line, a short DC power line has lower power losses [57]. Moreover, it is the most cost-efficient solution when no third party entities are involved in the EE procedure.

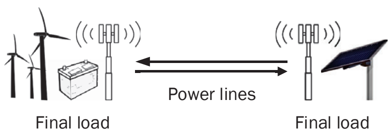
- **Smart Grid (SG)**: The SG has enabled a continuous and more precise monitoring of the electric energy usage thanks to the use of smart meters. Depending on the feature set, the meter may also notify the utility of a power outage or allow the utility to remotely switch electricity service on or off. Moreover, the SG enables selling and buying energy under variable pricing policies that permits flexible economical management. The options are to purchase energy either from the day-ahead market, which is mostly based on historical (collected over the years) data, or from the real-time market, which uses the hour-to-hour electricity price. In either of these options, SG energy has higher price during high-demand periods than the price set for the low-demand ones. This operation approach serves energy trading with abundant harvested RE being sold back to the SG and with energy shortages being served by SG energy purchases [31].

- **Aggregator**: The utility of the aggregator is attributed to a threshold energy volume that is usually required by the current SG market structure. This threshold of minimum 10 MW is usually required for a bid in energy markets[3] and thus for a direct energy transfer through the SG lines. Therefore, the concept of an aggregator is related to the existence of distributed energy resources (DERs) that have the potential to deliver the valuable electricity services that have traditionally been provided by centralized generating units and new ones based on their distributed nature. The term is referring to a company[4] that acts as an intermediary between electricity end users, DER owners and the power system participants that wish to serve these end users or exploit the services provided by the DERs [58, 59]. Thus, aggregators possess the technology to perform demand-response energy transactions and can

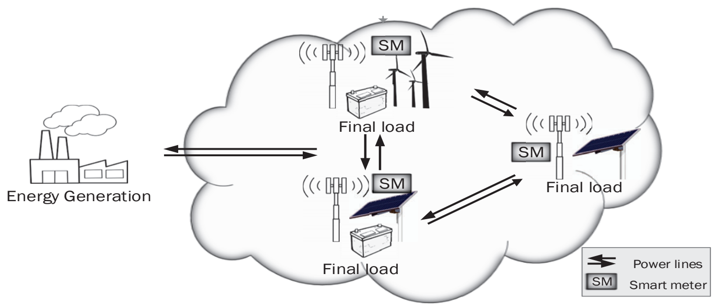
[3]http://econgrid.com/index.php/the-role-of-aggregator/?lang=en
[4]http://econgrid.com/?lang=en, https://reaggregators.com/

take on the negotiations from the part of end users more efficiently. This happens in the sense that the aggregator buys energy from a utility company through a wholesale market and provides it to its customers. An EE act is usually executed by the aggregator at the cost of a fee. However, aggregators can reduce searching costs (i.e., transaction costs) for market agents, as the aggregator can benefit from the centrality in the marketplace and scopes in managing information. More specifically, aggregation mitigates uncertainty by gathering all data relevant to potential demand or generation and translating this data into quantity bids in a market. This could be done by a number of small aggregators or by a single aggregator (e.g., a system operator) for all uncertain variables in a market (e.g., the output of variable generators or the behaviour of a number of consumers) [59].

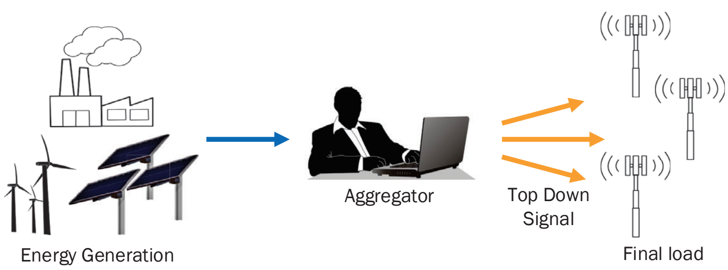
Figure 2.4 shows in detail the aforementioned configurations with which EE can be performed.



(a) Power lines



(b) Smart Grid (SG)



(c) Aggregator

Figure 2.4: Configurations for performing energy exchange (EE).

2.7 Open issues and challenges

As has been discussed so far, respectable efforts have been done aiming at improving the energy and cost efficiency of wireless networks, whether they procure energy exclusively from the grid or from other energy sources as well, i.e., the renewable ones. What is missing so far from our study though is to present the main obstacles that each of the aforementioned techniques brings forward in the case of shared networks, which of them have been addressed and which remain unresolved. In the remaining sectors of the chapter, we firstly describe some basic principles of infrastructure sharing in Section 2.7.1 and then, in Section 2.7.2 we present open issues that arise when the concepts that were described in the previous sectors of this chapter are applied in multi-operator HetNet deployments.

2.7.1 Multi-Operator ventures

Multi-operator ventures on network management, in the form of infrastructure sharing, raised as alternative to complement the downsides of single-handed efforts. Infrastructure sharing in telecommunications refers to a multi-operator network management based on established and pre-defined agreements of the involved stakeholders for joint utilization of assets and/or services necessary to provide telecommunication service, aiming at reducing the costs of building, operating and maintaining network infrastructure and thus at increasing profits. [12, 18, 21, 60].

Depending on the availability of infrastructure in an area, different forms of network sharing agreements are possible, ranging from basic unbundling and national roaming, to advanced forms like collocation and spectrum sharing [61]. Three are the cases in which infrastructure sharing can be considered an option based on the type of the studied area:

1. **Areas where there is no prior network infrastructure:** Indicative example of such cases are the rural areas. Due to high initial CapEx that MNOs are called to make in such cases, MNOs can make a joint investment so as to deploy infrastructure from scratch.

2. **Areas where only certain stakeholders are active:** In such cases, MNOs whose coverage does not reach the area can cooperate with the stakeholders, i.e., MNOs or a third party that have activity in the area. This stakeholders can act as the infrastructure provider (InP) for MNOs who seek to expand their coverage and agree with them to provide a type of service providing, such as roaming.

3. **Areas where MNOs have a part or the whole of their network active in the same areas:** In such cases as well, MNOs can reach an in-between them agreement or an agreement with a third party so as to reassure a type of service providing.

For each of these cases, three main forms of infrastructure sharing have been adopted based on the way that MNOs can exploit their facilities [60, 21, 22, 62]:

1. **Passive sharing**, which refers to the sharing of space in passive infrastructure, such as building premises, sites and masts. Passive sharing is typically a moderate form of network sharing, where there are still separate networks that simply share physical space.

2. **Active sharing**, which is a more complex type of sharing, where operators share elements of the active layer of a mobile network, such as antennas, radio nodes, node controllers, backhaul and backbone transmission, as well as elements of the core network (such as switches).

3. **Roaming-based sharing**, where, in the context of sharing, an MNO relies on another MNO's coverage for a certain, defined footprint on a permanent basis.

In emerging and developing markets passive and active sharing are more frequently adopted by MNOs, since the latter have to make considerable investments so as to improve their coverage and capacity growth. Thus, they are more inclined to approaches that minimise investment costs on new technologies. In developed markets, where the majority of the networks are already rolled out to a high degree, all aforementioned types of network sharing are an option.

The option of a third party providing the infrastructure to service providers has become popular in urban areas with multi-operator heterogeneous architecture models. In such cases the BSs are a property of the independent third party, or an MNO acting as an InP, and thus the latter is the one who rolls out the infrastructure. Then, an operator, who holds a spectrum license, leases the provided infrastructure, starting thus the operation of its network. This architecture implies lower capital expenses for the MNO, who is only responsible for the service provision to its users. However, the OpEx that correspond to such operation schemes depend on the agreements between the involved stakeholders.

In the present thesis, we focus our proposals on the study case when MNOs operate a part or the whole of their network in the same areas. This is because we are interested in proving energy and cost efficient solutions for densely populated urban areas, where telecommunication companies are often forced to deploy the BSs on the same building or close to each other due to legal regulations. This in turn results in multiple BSs of multiple MNOs covering the same area [63, 64]. Moreover, in such areas, there are cases where infrastructure sharing is mandated by governmental regulation as a way of achieving competition between network providers [65].

Fig. 2.5 displays an example of a HetNet scenario where a multi-operator venture among the HetNets of rival MNOs serving the same area could be possible. The macrocell area is overlaid by SBSs that are used for capacity enhancement.

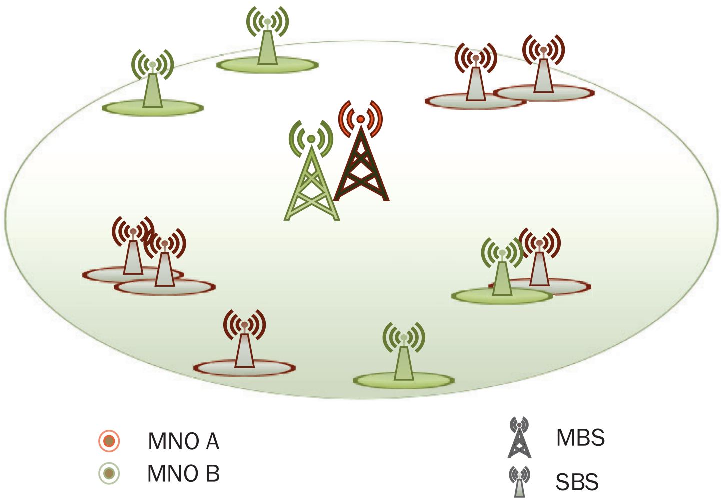


Figure 2.5: Indicative example of a multi-operator HetNet deployment.

2.7.2 Open issues in multi-operator HetNet deployments

In the case of multi-operator HetNet deployments, there are some different approaches of the concepts that were described so far that could be followed for the achievement of an efficient energy and cost management activity.

With reference to the operation of HetNets in alternate operation modes, active or inactive, the roles of the MNOs who are involved in the agreement for sharing the HetNet have to be clearly defined. Issues, such as which MNO will allow its BSs to accept traffic of rival MNOs without endangering the service provision of its own network and, dynamically, its market share, are critical. The financial impact that such actions have on the MNO revenues is also not an issue to be neglected. Some efforts have intended to provide contribution in these questions, such as [66, 67, 68] and [51], where entire networks are intended to be switched off or the infrastructure of a third party is attempted to be used for traffic offloading. However, characteristics, such as the type of the BS that should be switched off or that would take on offloaded traffic of a switching off event, are not taken into consideration. Therefore, it would be interesting to study how MNOs would react if the switching off and offloading procedure would take place on smaller scales than the one of a whole network. Moreover, the calculation of the costs that correspond to an MNO participating in a sharing agreement is also critical, as a bad management could intrigue fairness issues and disgruntlement for the continuation of the cooperation. In Chapter 3, we plan to focus on these issues and propose novel strategies not only with reference to the switching off technique that addresses the problem of energy management is these scenarios, but also with regard to relevant cost allocation issues for a cost efficient management of multi-operator shared HetNets.

With reference to the operation of grid-connected HetNets, or EH-HetNets as we may also be calling them interchangeably hereafter, that use RE sources for network powering except from the SG, different energy and cost management issues also arise in relation to the single operated HetNets that were described earlier. Multi-operator scenarios have been presented for energy buying from the grid or an energy market [69, 70]. However, in cooperative scenarios, the densely populated areas compel the composition of complex EE approaches due to the variety of stakeholders that may develop their activity in an area. Collocation of BSs may imply as well the necessity for a shared ESS among multiple stakeholders. Moreover, the inability to directly connect all HetNet BSs with power lines mandates the need for a framework that would permit profitable EE acts among these stakeholders with simultaneous preservation of the private strategy. In Chapter 4, we focus extensively on the management of EE activities in multi-operator HetNet deployments, making proposals that could be followed.

Chapter 3

Energy and cost issues in multi-operator HetNet deployments

3.1 Introduction

Our investigation on efficient energy and cost management approaches begins with a study in multi-operator heterogeneous network (HetNet) deployments. In order to address the challenges that arise in the case that many mobile network operators (MNOs) are active with their HetNets in the same urban areas, we study scenarios where MNOs may install base station (BS) sites in close proximity due to space scarcity and share their networks based on roaming.

Motivated by the benefits of the switching off method that were described in Chapter 2 for the case of single operated networks [42, 44, 71, 72], we study the method in multi-operator shared networks, attempting to address related issues that remain unresolved. Therefore, taking into account concerns about cost and revenue issues on shared networks that have been raised in the past, [51, 73, 74, 75, 76], we study the switching off method in shared HetNet deployments giving consideration to the kind of infrastructure that should be switched off, i.e., macrocell BS (MBS) or small cell BS (SBS), and the magnitude of traffic load volumes that correspond to the MNOs who share their infrastructure.

In addition, we intend not to neglect the profitability of the MNO coalition in relation to the chosen switching off strategy, as the latter can strongly affect the former. For achieving a successful cost management in infrastructure sharing, there needs to be sincerity amongst the cooperative MNOs. Apart from realising and acknowledging the economic benefits of sharing, an incentive-based policy must be put in place for MNOs, as a way of encouraging and growing the culture of infrastructure sharing on a level playing field. This policy should recognise the individual contribution of MNOs to the cooperation scheme and ensure that there is less or none disgruntlement of MNOs within it. To that end, we investigate the prospect of MNOs applying a cost allocating strategy that would fairly extract their individual cost shares from the expenses of the cooperative switching off activity, allowing them to maintain control of their investments and growth strategies.

Thus, the contribution of this chapter can be summarized as

- A cooperative switching off scheme for HetNets that are shared by multiple MNOs based on roaming rules. More specifically, the proposed cooperative (BS) switching off scheme, namely CSO, considers as switching off criteria the BS type and load, and uses a cooperative roaming-based association scheme for offloading the user equipment devices (UEs) of the switched off site. Moreover it is conceptually rather simple and easy to implement, while it is efficient so as to encounter a configuration of BS operation and UE association states that improves energy efficiency of the shared HetNet meanwhile capturing cooperation issues.
- A model for the cooperation and cost sharing decisions among MNOs based on game theory is introduced, the Bankruptcy Shapley Value based cost allocation scheme (BSV). The effect of different traffic load magnitudes of MNOs on the model is studied.
- The proposed CSO algorithm is compared with three relevant switching off schemes. Simulation results show that the proposed scheme outperforms its counterparts in terms of energy efficiency.
- The proposed BSV cost allocation scheme is compared with two relevant cost allocation schemes. Simulation results show that the proposed scheme achieves a fairer distribution of network cost among the owner MNOs of the shared HetNet, motivating their cooperation.

The remainder of this chapter is organised as follows: Section 3.2 briefly reviews the related work. The system model and network configuration are presented in Section 3.3. Sections 3.4 and 3.5 describe the problem formulations and the proposed CSO and BSV schemes, respectively. A performance assessment of the proposals are given in Section 3.6. Finally, concluding remarks can be found in Section 3.7.

3.2 Related Work

Since network infrastructure is the most power consuming part of the network, extensive work has already been devoted to energy saving strategies, such as [40] and [77]. Switching off algorithms have been presented towards this effort for both single- and multi-operator networks. Indicative examples for a single-operator HetNet is (i) the work in [71], where open-access femtocells are switched ON and OFF dynamically provided that a power saving UE association (UA) scheme can ensure the service of UEs and (ii) the work in [72], which proposes a distributed graph based game that enables BSs to optimise their switching strategies for energy saving, meanwhile guaranteeing the minimum service of their UEs. In addition, [44] presents a different switching off procedure that is applied to SBSs only, depending on the UE distribution within each small cell area. In detail, when UE distribution within each small cell area is uniform, SBSs are switched off dynamically according to their distance from the central MBS. When UE distribution within each small cell area though is non-uniform, SBSs are switched off according to power saving lists that are formatted based on a power-saving efficiency indicator Q. This power-saving efficiency indicator Q practically represents the induced power-saving efficiency in the case that an SBS is deactivated, which gives the saved power consumption by deactivating this SBS per unit load. In both cases, SBS deactivation is applied with traffic offloading to the MBS and until either no further improvement of the HetNet power consumption can be achieved or the MBS has reached its capacity or power limitations. Two sleeping schemes are also presented and compared in [42]: *(a)* a random one and *(b)* a traffic load based one, with the traffic load being counted as the number of UEs that are the nearest to the BS. A common characteristic of the aforementioned works is that they focus on the dynamic BS operation by a single operator.

For the case of multi-operator scenarios, the authors of [51] and [73] study the relations between multiple MNOs and a third party. More specifically, in [51], they propose a non-cooperative auction-based game that aims at MNOs switching off their MBSs by totally offloading the MBS traffic to leased from a third party SBSs. In [73], they refer to cost sharing policies with reference to a third party. Other works consider only multi-operator scenarios. In detail, [74] discusses the deployment of extra SBSs by cooperative MNOs based on the achievable UE throughput and the individual MNO revenues, as a result of their respective investments and the payments of their UEs. Moreover, [75] refers to a budget-balanced mechanism designed for MNOs of cellular networks with similar load distributions, while in [76] cellular network operators switch off their networks in a non-cooperative manner, aiming at energy efficiency. However, works of [75, 76] do not consider a HetNet scenario, which could differentiate the results. Moreover, their discussion on the revenues issues is based on payment only agreements, without considering pricing differentiations among different types of BSs or cost sharing methods.

Unlike the aforementioned works, the contribution described in the present chapter of the thesis refers to a switching off solution that incorporates multiple network characteristics, such as traffic load, BS type and variable roaming charges MNO-dominated scenarios, which constitute neglected elements in the aforementioned works. Moreover, a novel fair cost sharing solution that reassures the profitable network operation is provided.

3.3 System set up

In the present section, we provide the system set up as well as the principles of the network configuration that were used. The basic notation of the present section is provided in Table 3.1.

Table 3.1: Basic Notation of system setup

t	Time slot with duration of hour
$\mathcal{N}$	Set of MNOs, Cardinality: N, Index: n
$\mathcal{M}^n$	Set of MBSs of n, Cardinality: M^n, Index: m^n
$\mathcal{M}$	Set of MBSs of all $n \in \mathcal{N}$, Cardinality: M, Index: m
$\mathcal{S}^n$	Set of SBSs of n, Cardinality: S^n, Index: s^n
$\mathcal{S}$	Set of SBSs of all $n \in \mathcal{N}$, Cardinality: S, Index: s
$\mathcal{L}^n$	Total set of BSs of n, Cardinality: L^n, Index: l^n
$\mathcal{L}$	Total set of BSs, $\mathcal{L} = \mathcal{M} \cup \mathcal{S}$, Cardinality $L = M + S$, Index: l.
$\mathcal{K}^n$	Set of UEs of n, Cardinality: K^n, Index: k^n
$\mathcal{K}$	Set of UEs of all $n \in \mathcal{N}$, Cardinality: K, Index: k
ρ_k	Bit rate demand of a k
ρ^*	Bit rate demand of of HetNet indicated in the * position
q_{kl}	Associate state indicator of k and l
θ_l	Operation state indicator of l
P^*	Power consumption needs of HetNet indicated in the * position
P_l	Power consumption of an $l \in \mathcal{L}$
P_l^{con}	Constant power consumption of l
P_l^{tx}	Transmit power consumption of l
$P_l^{tx,sub}$	Transmit power consumption of 1 sub-carrier of l
P_l^{RB}	Transmit power consumption of 1 RB of l
ΔP_l	Scaling parameter for P_l^{tx}
J_l	Allocated RBs of l
j_{kl}	Allocated RBs from l to k
ee	Network energy efficiency of $\mathcal{L}$

The network energy efficiency $ee(t)$ for the duration of an t can be defined as the total bit rate demand that is served by the network to the power consumption that is needed for the sufficient service provision. Therefore, in order to mathematically express the problem of increasing $ee(t)$ during t in this sector, we proceed to the calculation of the total bit rate demand $\rho^{\mathcal{L}}(t)$ of all UEs served by HetNet $\mathcal{L}$ during t and the respective power consumption.

3.3.1 Network System Model and Operation

We study a densely populated macrocell-sized urban area[1], where a set $\mathcal{N} \triangleq \{1, .., N\}$ of MNOs, indexed by n, have located their Long Term Evolution Advanced

[1] The macrocell-sized area is defined by an the radius of an MBS in the centre of it.

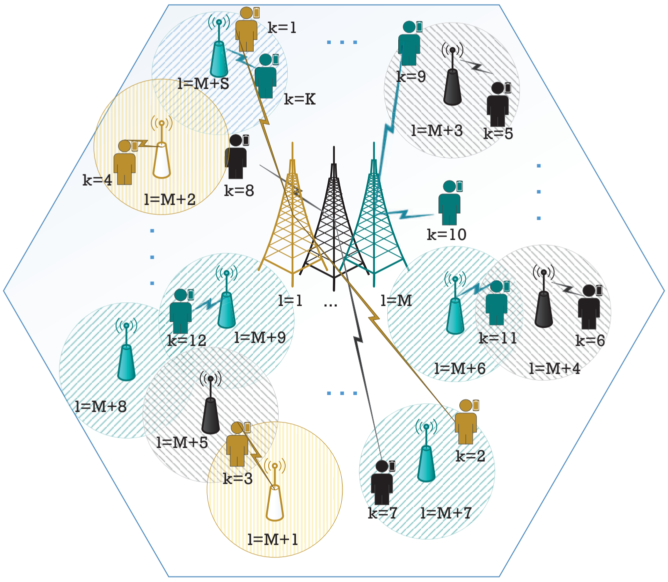


Figure 3.1: Studied macrocell-sized area with a shared HetNet. A set of $\mathcal{N}$ MNOs own the depicted HetNet $\mathcal{L}$, which is composed of M MBSs and S SBSs, while it provides service to the total set $\mathcal{K}$ of subscribed UEs. In the figure, l is used as an index for $\mathcal{L}$ and k is used as an index for $\mathcal{K}$.

(LTE-A) HetNets, as in Fig. 3.1. We assume that each $n \in \mathcal{N}$ is owner of a HetNet, composed of one MBS, located in the centre of the studied area and uniformly distributed SBSs in the rest of it. For generality though, let $\mathcal{M}^n \triangleq \{1,..,M^n\}$ be the set of MBSs owned by MNO n and indexed by m^n, and $\mathcal{S}^n \triangleq \{1,..,S^n\}$ be the set of SBSs owned by MNO n and indexed by s^n. Thus, the HetNet of each MNO $n \in \mathcal{N}$ can be represented as the set $\mathcal{L}^n = \{1,..,m^n,..M^n, M^n+1,..,M^n+s^n,..,M^n+S^n\}$, which is indexed with l^n.

Extending the generalised notation, we represent the total set of all MBSs of all MNOs $n \in \mathcal{N}$ as $\mathcal{M} = \mathcal{M}^1 \cup .. \cup \mathcal{M}^n \cup .. \cup \mathcal{M}^N$, indexed with m, and the total set of all SBSs of all MNOs $n \in \mathcal{N}$ as $\mathcal{S} = \mathcal{S}^1 \cup .. \cup \mathcal{S}^n \cup .. \cup \mathcal{S}^N$, indexed with s. Similarly, we represent all the BSs in the studied area, irrespective of BS type (MBS or SBS) or owner MNO, as the set $\mathcal{L} = \mathcal{M} \cup \mathcal{S}$, with cardinality $L = M + S$ and index l.

We moreover assume that, for a slot t, each $n \in \mathcal{N}$ is the service provider MNO for its own group of UEs, $K^n(t) = 1,..,k^n(t),..K^n(t)$, which are uniformly distributed in the studied area. All MNOs are assumed to have similar traffic load patterns of sinusoidal form, approaching the traffic pattern in [15]. Under the roaming-to-all assumption among the MNOs then, the total group of UEs that has to be served by all MNOs $n \in \mathcal{N}$ is $\mathcal{K}(t) = \mathcal{K}^1(t) \cup .. \cup \mathcal{K}^n(t) \cup .. \cup \mathcal{K}^N(t)$, with cardinality $K = K^1 + .. + K^n + .. + K^N$ and index k.

A UE $k \in \mathcal{K}(t)$ has a specific guaranteed bit rate demand $\rho_k(t)$, equal to one of

I different categories of data throughput demands r_i ($bits$), where $i = \{1, 2, .., I\}$[2]. The probability of encountering r_i is $g_i \in [0, 1]$, with $g_1 + .. + g_i + .. + g_I = 1$. Then, a UE k can have a bit rate demand $\rho_k(t)$ ($bits/sec$) with random probability $g_{ki}(t) \in \{g_1, .., g_i, .., g_I\}$ during t.

Each of the UEs can initially get associated to and served by only one $l \in \mathcal{L}$, from which it receives the best signal-to-noise ratio (SNR). We denote the associate state of a k with an l during t as $q_{kl}(t)$. Then, $q_{kl}(t)$ is equal to 1 when k is associated to l and 0 otherwise.

Each MNO is assumed to operate in a different frequency to avoid interference issues for its network [78]. Also, orthogonal transmission is adopted to avoid intra-cell interference, while inter-cell interference is considered to be mitigated through some form of fractional frequency reuse scheme or sophisticated frequency allocation [79].

We assume a form of roaming-based sharing [21], according to which UEs of different MNOs can be served by the network of any MNO that is active in the certain area, for a pre-defined period of time and at the expense of pre-defined inter-operator charges. Each re-association event of a k from BS l to a neighbouring one l' is considered unique and charged by the owner MNO of l' with a price, c. Each MNO is able to define a different c in order to serve the traffic of other MNOs. In the context of this work, we propose a roaming pricing model described in Section 3.4.3.

BS Power Consumption Model

One of our main interests are the power needs in the studied area. Consequently, we focus on network power needs of BSs, as a result of their signalling processes, cooling, battery needs and transmission activity. The uplink transmissions between UEs and BSs are considered negligible in terms of energy needs and in comparison to downlink (DL) transmissions. Therefore, the DL case is considered only for the network power consumption, where the orthogonal frequency division multiple access (OFDMA) scheme is employed.

The power consumption of a BS l at t is calculated based on eqs. (2.1) and (2.2) as [37]

$$P_l(t) = \theta_l(t) \cdot \left(P_l^{con} + \Delta P_l \cdot P_l^{tx}(t)\right), \tag{3.1}$$

where P_l^{con} is the constant power consumption of l attributed to signal processing, battery backup and cooling. ΔP_l stands for the variable that scales the power consumption of l with the radiated power, due to amplifier and feeder losses and P_l^{tx} refers to the transmit power of the l BS[3]. Finally, each $l \in \mathcal{L}$, has two possible operation modes $\theta_l(t)$ during slot t: (i) *active*, which corresponds to $\theta_l(t) = 1$ and (ii) *inactive*, which corresponds to $\theta_l(t) = 0$.

Thus, the power needs of the HetNet BS set $\mathcal{L}$, which is roaming-based shared

[2] It is noted that, in the general case, I may be equal to $K(t)$, as each k may have different throughput needs.

[3] It is noted that P_l^{con} and ΔP_l take different values when l refers to an MBS, i.e., $l \leq M$, or an SBS, i.e., $M < l \leq M + S$, which are given later in the paper.

during t by all MNOs in $\mathcal{N}$, are

$$P^{\mathcal{L}}(t) = \sum_{l=1}^{L} \theta_l(t) \cdot (P_l^{con} + \Delta P_l \cdot P_l^{tx}(t)). \tag{3.2}$$

Channel Model

The power that a BS needs for its transmission activities, P_l^{tx}, is related to the number of its associate UEs and their respective bit rate demands. Since we study the DL case of an OFDMA scheme, we assume that information is transmitted in pairs of resource blocks (RBs) of 0.5 ms duration in the time domain. Therefore, we calculate $P_l^{tx}(t)$ as the total power needs that correspond to all the RBs that BS l has allocated to its associate UEs during t.

Let $J_l(t)$ be the number of allocated RBs by l (or the traffic load of l as we will call it hereafter) during t. Then, $J_l(t)$ is

$$J_l(t) = \sum_{k \in \mathcal{K}(t)} q_{kl}(t) \cdot j_{kl}(t), \tag{3.3}$$

where $q_{kl}(t)$ denotes the associate state of a k with l at t and $j_{kl}(t)$ is the number of RBs that l has to transmit to k at t in order to provide it with the service it has requested (i.e., the ρ_k that k demands).

Then, P_l^{tx} can be calculated as

$$P_l^{tx}(t) = J_l(t) \cdot P_l^{RB}, \tag{3.4}$$

where P_l^{RB} expressed the power needed for the transmission of 1 RB from BS l.

The value of $j_{kl}(t)$ in eq. (3.3) is dependent on quality of the channel between k and l, and, consequently, on the estimated SNR of their link, $SNR_{kl}(t)$. Based on the above, $j_{kl}(t)$ can be expressed as [79]

$$j_{kl}(t) = \lceil \frac{\rho_k(t)}{W_l^{RB} f(SNR_{kl}(t))} \rceil, \tag{3.5}$$

where W_l^{RB} is the bandwidth that corresponds to an RB pair of l and $f(SNR_{kl}(t))$ is the spectral efficiency of the link between k and l at t. We remind that $\rho_k(t)$ represents the guaranteed bit rate of k during t.

In order to calculate $f(SNR_{kl}(t))$, we first calculate the $SNR_{kl}(t)$ as follows [79]

$$SNR_{kl}(t) = P_l^{tx,sub} + G_l^{tx} - PL_{kl}(t) - FL_{kl} - N_{th} - NF, \tag{3.6}$$

where $P_l^{tx,sub}$ represents the allocated power to each subcarrier of a BS l *(dBm)*, G_l^{tx} denotes the antenna gain (including feeder loss, dBi) and $PL_{kl}(t)$ is the pathloss between k and l at t *(dB)*. FL_{kl} represents the slow fading losses *(dB)* as a random variable of log-normal distribution and with a mean and standard deviation μ_l and σ_l, respectively. Finally, N_{th} is the thermal noise and NF is the noise figure. Moreover, we adopt the adaptive modulation and coding scheme (AMC) over any radio link. Consequently, the appropriate $SNR_{kl}(t)$ will eventually define the modulation and coding scheme (MCS) that will be used over the link. More specifically, QPSK, 16QAM and 64QAM modulation schemes of different respective coding rates are considered. The mapping between requested $\rho_k(t)$ and $SNR_{kl}(t)$ to the achievable $f(SNR_{kl}(t))$ is executed as indicated in [21, Table A.2] [80].

As far as $P_l^{tx,sub}$ is concerned, having assumed that P_l^{tx}, is equally distributed among subcarriers, $P_l^{tx,sub}$ is defined as

$$P_l^{tx,sub} = \frac{P_l^{tx,max}}{12 \cdot h_l \cdot J_{l,max}}, \tag{3.7}$$

where $P_l^{tr,max}$ is the maximum transmit power of l, h_l is the number of antennas of l and $J_{l,max}$ stands for the maximum capacity of l, i.e. the total number of RBs that l can allocate. Based on this, we can calculate P_l^{RB} of eq. (3.4), as

$$P_l^{RB} = \frac{P_l^{tx,max}}{h_l \cdot J_{l,max}}. \tag{3.8}$$

3.4 Energy Efficiency Problem

This sector focuses on the energy management issues in shared HetNet infrastructure with the adoption of switching off. The switching off method aims at increasing energy efficiency by assessing the switching off possibilities of BSs that are underloaded or have no load. A roaming-based network sharing method is adopted to facilitate the switching off procedure by offloading traffic to BSs of all networks. In this context, we formulate the HetNet energy efficiency maximization problem and propose a heuristic solution to address it.

3.4.1 Energy Efficiency Problem Formulation

The network energy efficiency $ee(t)$ for the duration of an t can be defined as the total bit rate demand that is served by the network to the power consumption that is needed for the sufficient service provision. Therefore, in order to mathematically express the problem of increasing $ee(t)$ during t in this sector, we proceed to the calculation of the total bit rate demand $\rho^{\mathcal{L}}(t)$ of all UEs served by HetNet $\mathcal{L}$ during t and the respective power consumption needs $P^{\mathcal{L}}(t)$ of the unified HetNet $\mathcal{L}$. Given that we intend to increase ee through roaming-based sharing and switching off. We also consider the traffic load $J_l(t)$ of each BS l for t as the significant criterion for its operational state and the total HetNet's power consumption.

Let us express first the total bit rate demand of all HetNet UEs, $\rho^{\mathcal{L}}(t)$, in the studied area during t. $\rho^{\mathcal{L}(t)}$ is defined by the individual bit rate demands $\rho^k(t)$ of each $k \in \mathcal{K}(t)$, as well as by their association state $q_{kl}(t)$ of k with a BS l as

$$\rho^{\mathcal{L}}(t) = \sum_{\forall k \in \mathcal{K}(t)} \sum_{\forall l \in \mathcal{L}} q_{kl}(t) \cdot \rho_k(t). \tag{3.9}$$

Based on the above and in accordance with eq. (3.2), the power consumption of the unified HetNet $\mathcal{L}$ is described analytically in eq. (3.10) as

$$P^{\mathcal{L}}(t) = \sum_{l=1}^{l=|\mathcal{L}|} \theta_l(t) \cdot \left(P_l^{con} + \Delta P_l \cdot \frac{P_l^{tx,max}}{h_l \cdot J_{l,max}} \cdot \sum_{k \in \mathcal{K}(t)} q_{kl}(t) \cdot \lceil \frac{\rho_k(t)}{W_l^{RB} f(SNR_{kl}(t))} \rceil \right). \tag{3.10}$$

Consequently, the network energy efficiency problem can be expressed in mathematical terms as follows

$$\max_{\theta_l, q_{kl}} \quad \mathrm{ee}(\theta_l(t), q_{kl}(t)) = \frac{\rho^{\mathcal{L}}(q_{kl}(t))}{P^{\mathcal{L}}(\theta_l(t), q_{kl}(t))} \tag{3.11a}$$

$$\text{s.t.} \quad \sum_{\forall l \in \mathcal{L}} \theta_l(t) \leq |\mathcal{L}|, \ \theta_l(t) \in \{0,1\}, \tag{3.11b}$$

$$\sum_{\forall l \in \mathcal{L}} q_{kl}(t) \leq 1, \ q_{kl}(t) \in \{0,1\}, \tag{3.11c}$$

$$J_l(t) \leq J_{l,max}, \tag{3.11d}$$

$$\sum_{\forall l \in \mathcal{L}} \theta_l(t) \cdot J_l(t) \leq \sum_{\forall l \in \mathcal{L}} J_{l,max}. \tag{3.11e}$$

The problem of eq. (3.11a) practically expresses $ee(t)$ as the fraction of the total bit rate demand that is served by HetNet $\mathcal{L}$, $\rho^{\mathcal{L}}(t)$, to its respective power consumption needs, $P^{\mathcal{L}}(t)$. Moreover, eq. (3.11a) clearly displays that the problem is dependent on the operation state indicator $\theta_l(t)$ of BS l and the association state indicator $q_{kl}(t)$ of UE k with l. Constraint (3.11b) ensures that only the BSs of the cooperative MNOs are studied and that an l can interchange its operation state only between *active* and *inactive*. Constraint (3.11c) ensures that a UE k can only be served by one l, MBS or SBS, and is considered non-associated otherwise. The total traffic load $J_l(t)$ of an l is limited by its maximum capacity, $J_{l,max}$ according to constraint (3.11d). Lastly, as indicated by constraint (3.11e), the total traffic load of active BSs in the studied network cannot exceed the total maximum network capacity.

The problem described in eqs. (3.11a)-(3.11e) is a non-linear[4] integer[5] NP-hard[6]

[4] It is classified as a non-linear problem because it contains at least one non-linear function (i.e., the step function $f(SNR_{k,l}(t))$).

[5] It is classified as an integer problem as the set of integer variables is non-empty. More specifically, all variables θ_l, $q_{k,l}$ of the problem are integers, with θ_l, $q_{kl} \in \{0,1\}$.

[6] It is an NP-hard problem as the solution of problem described in eqs. (3.11a)-(3.11e) typically

problem [82, 83]. In order to address the problem, while taking into consideration the cooperation issues of MNOs, such as which BS of which MNO to deactivate, we propose a greedy heuristic scheme. Our proposal, Cooperative Switching Off Algorithm (CSO), constitutes a switching off scheme suitable for application to a multi-operator shared HetNet and is described in detail in the following Section 3.4.2.

3.4.2 Cooperative Switching Off Algorithm (CSO)

We propose a greedy heuristic algorithm that aims at reducing the network energy consumption by applying the method of switching off to both MBSs and SBSs [84]. At the same time, it offloads the UEs of switched off BSs to neighbouring cells of the unified HetNet, as a result of roaming-based sharing among MNOs. The proposed scheme, namely Cooperative Switching Off (CSO), considers as switching-off criterion the traffic load of each $l \in \mathcal{L}$ in combination with an energy and roaming-cost related UE re-association scheme and is of centralised application. Being a greedy heuristic scheme, CSO follows the mentality of the greedy heuristic schemes. In detail, given a starting solution, the greedy algorithm directs it to an updated solution that gives the largest increase (or reduction, depending on the problem) in the objective of the studied problem. This procedure is repeated until no increase in the objective can be obtained. CSO implements this philosophy following four steps:

1. *Initial Setting*, for setting the starting solution,
2. *Execution of Greedy Component*, for executing the loop that finds the solution that achieves an energy efficiency increase,
3. *Acceptance criterion*, for updating the solutions with the ones that achieve larger increase and
4. *Repetition stage and Termination criterion*, for repeating the procedure until no increase in the objective, i.e., increase of network energy efficiency, can be obtained.

CSO is executed during low-traffic hours (i.e., 00:00 - 06:00), on a t slot basis that is equal to an hour, and is depicted in Algorithm 1 and Fig. 3.2.

Its steps are described as follows:

requires searching big search trees of possible configurations of BS operation states ($\theta_l \in \{0, 1\}$) and UE associations ($q_{kl} \in \{0, 1\}$) that result in various different energy efficiency values. [81]

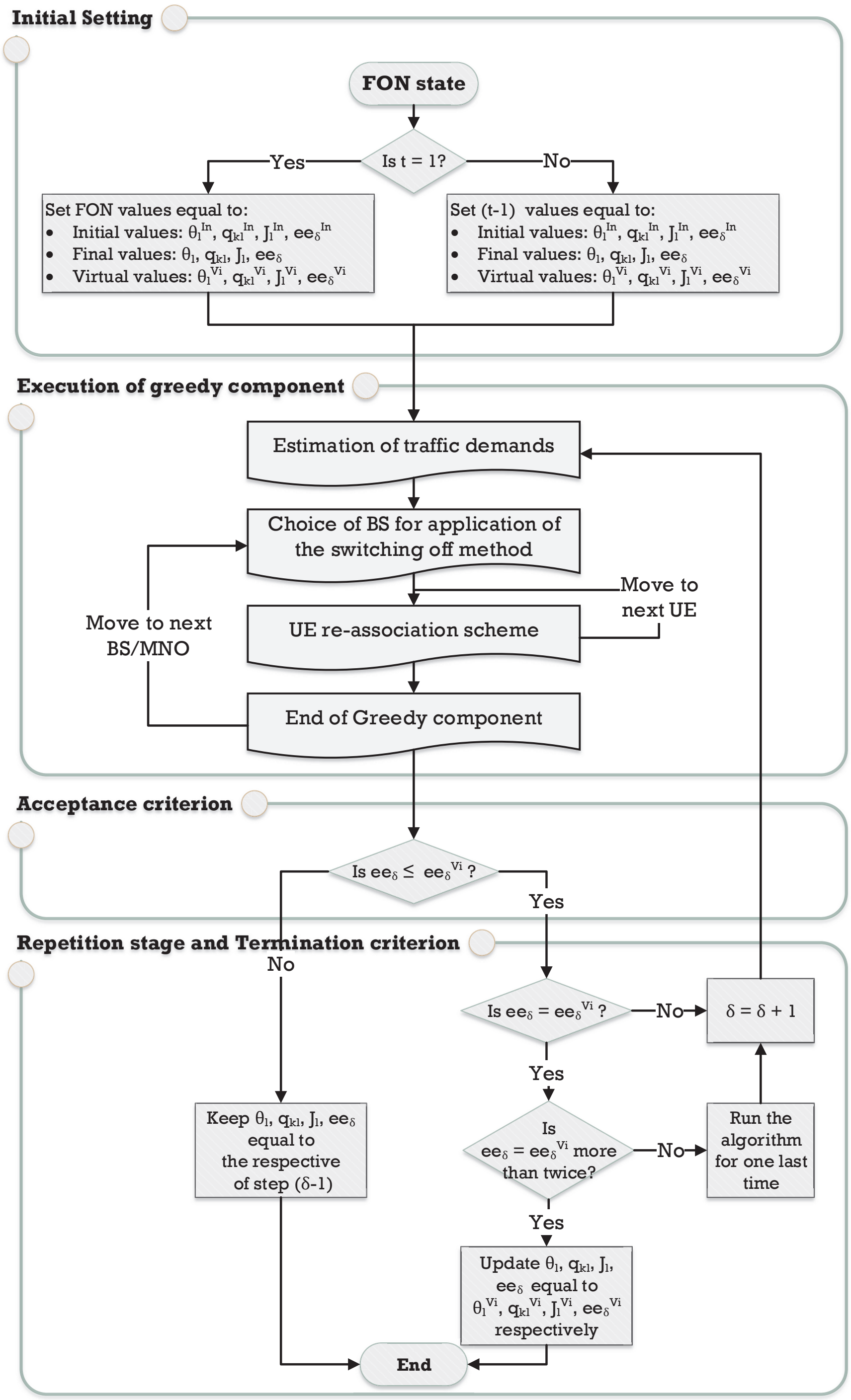


Figure 3.2: CSO flowchart

Algorithm 1 Cooperative Switching Off algorithm (CSO)

Set initial values θ_l^{In}, q_{kl}^{In}, J_l^{In} and ee_δ^{In} according to a FON for $t = 1$ and equal to results of $(t-1)$ otherwise
Set: $\theta_l = \theta_l^{In}$, $q_{kl} = q_{kl}^{In}$, $J_l = J_l^{In}$, $ee_\delta = ee_\delta^{In}$
Set: $\theta_l^{Vi} = \theta_l^{In}$, $q_{kl}^{Vi} = q_{kl}^{In}$, $J_l^{Vi} = J_l^{In}$, $ee_\delta^{Vi} = ee_\delta^{In}$,
while $ee_\delta > ee_\delta^{Vi}$ or ($ee_\delta = ee_\delta^{Vi}$ for two times) **do**
  Update $\forall l \in \mathcal{L}$ and $\forall k \in \mathcal{K}$: θ_l^{Vi}, q_{kl}^{Vi}, J_l^{Vi} of ee_δ^{Vi}
  for $n = 1 : N$ **do**
    Sort all $m^n \in \mathcal{M}^n : \theta_{m^n}^{Vi} = 1, m^n \neq M^N$, by their load $J_{m^n}^{Vi}$ (eq. (3.3) for q_{kl}^{Vi}), in ascending order
    Sort all $s^n \in \mathcal{S}^n$: by their load $J_{s^n}^{Vi}$ (eq. (3.3) for q_{kl}^{Vi}), in ascending order
    for $l = 1 : (L^n)$ with $m^n \in \mathcal{M}^n$ first and $s^n \in \mathcal{S}^n$ following in the previously defined order and as long as $l \neq M^N$ **do**
      for $\forall k : q_{kl} = 1$ **do**
        for $\forall l' : \theta_{l'} = 1$ and $l' \neq l$ **do**
          Calculate $SNR_{kl' \neq l}$ and sort them in ascending order
          Calculate $c_{kl'}$ for the two first BSs of the SNR sorted list
          Select as l_k^{dest} the BS l' with the least $c_{kl'}$
          if BS l_k^{dest} has sufficient RBs **then**
            Associate UE k to it and calculate current available resources
          else
            Move to the next BS l' in the sorted list
          end if
        end for
      end for
      if ALL UEs of l are reassociated **then**
        Switch off BS l
        Update $\forall l \in \mathcal{L}$ and $\forall k \in \mathcal{K}$:
      end if
    end for
  end for
  Calculate ee_δ^{Vi}
  $\delta = \delta + 1$
end while
Update $\forall l \in \mathcal{L}$ and $\forall k \in \mathcal{K}$: $ee_\delta = ee_\delta^{Vi}$, $\theta_l = \theta_l^{Vi}$, $q_{kl} = q_{kl}^{Vi}$, $J_l = J_l^{Vi}$

Initial Setting

Before the application of CSO, i.e., when $t = 1$, networks are considered to be full operational (FON), i.e., all BSs are in active mode and no cooperation scheme exists among MNOs. Then, the BS operation and UE association states of FON and thus, the respective BS traffic load and network energy efficiency of FON are set as input for the procedures of CSO that follow (θ_l^{In}, q_{kl}^{In}, J_l^{In} and ee_δ^{In}, respectively, where δ represents an execution step of CSO). Otherwise, i.e., when $t \neq 1$, each of the aforementioned values is set equal to the respective results of slot $(t-1)$.

Execution of Greedy Component

The greedy part of CSO is the main body of the algorithm and is composed of a BS switching off assessment along with a UE re-association assessment. The BS switching off assessment is described in the present section. The UE re-association assessment is presented in this section and described in Section 3.4.3.
(i) BS Switching off assessment
It aims at saving energy by reducing the number of active BSs. Active BSs, their respective traffic load and UE association states are assessed virtually during this part in order to estimate their final values. Its basic steps consist of:

- *Estimation of traffic demands*: Expected number of UEs $\mathcal{K}(t)$ with their bit rate demands $\rho_k(t)$ for the following slot t are estimated at the beginning of t. Thus, average data traffic demands are calculated according to eq. (3.9).
- *Choice of BS for application of the switching off method:* The traffic load $J_l(t)$ of an l during t is calculated according to eq. (3.3) and constitutes the criterion for assessing l to switch off during t.

  The switching off assessing procedure initiates with a sorting of MNOs in ascending order and according to the total bit rate demands of their subscribed UEs. Then, MNOs are studied consecutively. For each MNO n, the its MBSs is assessed to switch off first, since MBSs are the most power consuming nodes of the network. It is noted though that through the entire procedure of CSO, at least one of the collocated MBSs, $1 \leq l \leq M$, remains active in the studied area. This happens because, despite being the most power consuming node, an MBSs provides the highest coverage to the macrocell area. Moreover, since MNOs with the least bit rate demands are assessed first to enhance network switching off possibilities, an MBS of the MNO with the most traffic load, $l = M$, remains active. CSO proceeds with assessing the switching off possibilities of the rest BSs that belong to the studied MNO n, i.e., its SBSs. The SBSs are sorted by their $J_l(t)$ in ascending order. Therefore, CSO starts assessing the switching off possibilities of the least loaded one.

  Aiming at better coverage, SBSs may transit between *active* and *inactive* operation state over the hourly application of CSO, depending on the expectations over traffic demands in the studied area during t. However, unlike SBSs and in order to avoid extensive extra power consumption, MBSs remain *inactive* during all studied hours, once it is decided by CSO as such.
- *Application of UE re-association scheme:* Associated UEs to BS l need to be offloaded to other BSs so that l can switch off. The UE re-association scheme that is used to this end is based on *(i)* the channel conditions between a UE k and a destination BS l' to which k may get associated to ($SNR_{kl'}(t)$), and *(ii)* the respective roaming charges. The roaming charges $c_{kl'}$ that are attributed to k, so that k can connect to the destination BS l', are considered dependent on the type of l', i.e., if it is an MBS or an SBS, and the owner MNO of l'. The UE re-association scheme and the considered roaming charges are described in detail in Section 3.4.3.

- *End of Greedy component:* If and only if $\forall k \in \mathcal{K}(t)$ for which $q_{kl}^{Vi}(t) = 1$, $l \in \mathcal{L}$ and $l \neq M$, can be re-associated to a neighbouring $l' \in \mathcal{L}$, $l' \neq l$, BS l is eligible to switch off. Otherwise, it remains active. Virtual variables θ_l^{Vi}, q_{kl}^{Vi}, J_l^{Vi} are updated $\forall l \in \mathcal{L}$ and $\forall k \in \mathcal{K}$.

Acceptance criterion

If $ee_\delta \geq ee_\delta^{Vi}$, then ee_δ is set equal to ee_δ^{Vi}. Otherwise, it remains equal to ee_δ. Depending on the chosen value of ee_δ, values of θ_l, q_{kl}, J_l are updated accordingly.

Repetition stage and Termination criterion

Energy efficiency improvement is achieved through the repeated application of the two previous steps, i.e., the *"Execution of the greedy component"* and the *"Acceptance criterion"*. As long as $ee_\delta > ee_\delta^{Vi}$ or $ee_\delta = ee_\delta^{Vi}$ for two steps δ, the virtual values are normally applied to *(i)* the real ones of the next step $(\delta + 1)$, i.e., $ee_{\delta+1} = ee_\delta^{Vi}$, while values of θ_l, q_{kl}, J_l are updated accordingly, and (ii) to the virtual ones of the next step $(\delta + 1)$, i.e., $ee_{\delta+1}^{Vi} = ee_\delta^{Vi}$, while values of θ_l, q_{kl}, J_l are updated accordingly.

3.4.3 Cooperative UA Scheme

As previously described, the UE re-association scheme assesses the channel between a UE k and a neighbouring BS l', and the cost of the re-association process. Apparently, it is highly likely for a k to associate to an MBS, l', $1 \leq l' \leq M$, as the transmitted signal of the latter is often stronger than the one of SBSs. Nevertheless, MBSs have at the same time more load-dependent power consumption. Therefore, in order to achieve further energy saving, the re-association scheme adopts a comparison between two l'. The comparison is a form of biasing on cell selection towards SBSs ($M \leq l' \leq L$), thanks to the calculation of the re-association cost we present in eq. (3.12). The re-association scheme of a k from a BS l to an neighbouring BS l' includes the following steps:

- For every $k \in \mathcal{K}$ for which $q_{kl} = 1$ with a studied BS l: the two BSs l'_1 and l'_2 with the best $SNR_{kl'_1}$ and $SNR_{kl'_2}$ and thus with the minimum $j_{kl'_1}$ and $j_{kl'_2}$, are selected.
- The re-association process cost of a k, subscriber of n, to a destination l', owned by a different n', is

$$c_{kl'}(t) = \begin{cases} c^p q_{kl'}(t) j_{kl'}(t) P_{l'}^{RB} \Delta P_{l'} t, & n = n' \\ c^p q_{kl'}(t) j_{kl'}(t) P_{l'}^{RB} \Delta P_{l'} t + c^n \cdot \rho_k, & n \neq n' \end{cases} \tag{3.12}$$

where c^p is the fixed power consumption charge *(€/kWh)* and c^n is the inter-operator charge *(€/MB)* set among the co-operative MNOs for providing their services to a roamed k. It has to be noted that it is possible that each MNO defines a different c^n in order to host the traffic of rival MNOs.

- Finally, the UE k is associated to the BS l' which results into the minimum re-association cost $c_{kl'}(t)$.

3.4.4 CSO Complexity

Based on the description of CSO in Sections 3.4.2 and 3.4.3, multiple searches are implemented for the extraction of its solution. More specifically, an initial sub-optimal configuration of BS operation states (θ_l) and UE associations (q_{kl}), along with their resulting BS traffic loads (J_l) and network energy efficiency (ee), are provided as an input to CSO at the beginning of a studied period, $T = [t_1, t_2]$. Then, for each of the cooperative MNOs, a quick-sorting of BS $\forall l \in \mathcal{L}$ based on their traffic load $J_l(t)$ is executed. Given that quick-sort complexity is $\mathcal{O}\left(n \cdot log\left(n\right)\right)$ and that no more than $N = L$ MNOs can be found in the studied system, the resulting complexity of CSO is $\mathcal{O}\left(L \cdot L \cdot log\left(L\right)\right)$ or $\mathcal{O}\left(L^2 \cdot log\left(L\right)\right)$. However, CSO continues with the assessment of each BS's switching off possibilities. In detail, for the BSs of each of the sorted HetNets $\mathcal{L}^n$, starting from the MBS and proceeding to SBSs, the UE re-association scheme of Section 3.4.3 is applied. Thus, for each associated k, a BS quick-sorting in executed based on the in-between them SNR (SNR_{kl}). After all the UEs of the studied to switch off l have been considered, a BS quick-sorting may be necessary again so that all BS traffic loads, $J_l(t)$, are updated. Given the two quick-sorting procedures that take place and that the maximum number of UEs that can be associated to l is $max\left(K(t)\right)$, the complexity that is introduced by the procedure of the switching off assessment is
$\mathcal{O}\left(max\left(K(t)\right) \cdot L \cdot log\left(L\right)\right) + \mathcal{O}\left(L \cdot log\left(L\right)\right) = \mathcal{O}\left(max\left(K(t)\right) \cdot L \cdot log\left(L\right)\right)$.
The total complexity of CSO then becomes:
$\mathcal{O}\left(L^2 \cdot log\left(L\right)\right) \cdot \mathcal{O}\left(max\left(K(t)\right) \cdot L \cdot log\left(L\right)\right) = \mathcal{O}\left(max\left(K(t)\right) \cdot L^3 \cdot log^2\left(L\right)\right)$.

Based on the extracted complexity of CSO, it can be noticed that the CSO complexity is affected by the relative number of BSs and UEs. Low number of BSs and high number of UEs make the latter the main contributor to the CSO complexity and vice versa. The CSO procedure takes multiple steps δ in order to extract its solution, as described in Algorithm 1. However, the complexity of CSO is not affected by the number of these steps. It is noted that the BS traffic load volume that associated UEs create affects the performance of CSO in terms of energy efficiency only. Thus, as far as CSO complexity is concerned, CSO has a theoretically high complexity equal to $\mathcal{O}\left(max\left(K(t)\right) \cdot L^3 \cdot log^2\left(L\right)\right)$, but can provide results in a reasonable and acceptable execution time for extreme, though realistic, scenarios.

3.5 Cost allocation Problem

The proposed energy efficient solution is based on network sharing. Thus, MNOs need to always be motivated to refrain from individually applying switching off and

Table 3.2: Basic Notation of Cost allocation problem

$\mathcal{N}$	Set of MNOs, Cardinality: N, Index: n
Ω	Coalition set of MNOs, $\Omega \subseteq \mathcal{N}$
$E^{\mathcal{L}}$	Cost due to energy consumption of $\mathcal{L}$ with CSO
T	Studied time period
c^p	Fixed power consumption charge
$SE^{\mathcal{L}}\{\Omega\}$	Total cost savings between application of CSO and IndSO
$\phi_n\{\Omega\}$	Cost payoff of MNO n from participating in Ω.
ψ_n	Cost due to energy consumption of $\mathcal{L}$ with IndSO or *claim* or *"marginal cost"*
$\Phi'_n\{\Omega\}$	Contribution cost savings of n from participating in Ω
$rev_n\{\Omega\}$	Roaming revenues of MNO n from participating in Ω
P^*	Power consumption needs of HetNet indicated in the * position
B	Bankruptcy problem
$V_B(\Omega)$	Characteristic function of B
$EI_n\{\Omega\}$	Expectation index as metric of satisfaction of n from participating in Ω

instead remain committed to their cooperation. The latter presumes not only that cooperative MNOs reduce their expenses, but also that a fair cost allocation among them is adopted. A predefined agreement that is applied on an set basis could achieve the desirable profitability and fairness. The cost that will be allocated to each MNO after its participation in a coalition should mirror its contribution to the network cost savings acquired from applying CSO. Moreover, revenues obtained from the roamed traffic served by rival host MNOs should not be neglected. The final cost allocation should be validated as fair by each MNO $n \in \mathcal{N}$, while it should also remain profitable in comparison to the non-cooperative action of each MNO.

In this section, we study the parameters of the created cost allocation problem and provide our proposed solution scheme. The basic notation of the section can be observed in Table 3.2.

3.5.1 Cost allocation Problem Formulation

Let $\Omega \subseteq \mathcal{N}$ be a coalition of MNOs who cooperate in order to apply the switching off algorithm CSO on their shared network. Each coalition Ω leads to an amount of total cost $E^{\mathcal{L}}\{\Omega\}$ that is attributed to the total energy consumption of the formed HetNet $\mathcal{L}$. All MNOs $n \in \Omega$ are responsible to share and pay the cost $E^{\mathcal{L}}\{\Omega\}$. Given that we study the low-traffic hours, which correspond to a period $T = [t_1, t_2]$ and that the power consumption of the HetNet, $P^{\mathcal{L}^n}$, is calculated according to eq. (3.10), with $\mathcal{L}^n$ and l^n instead of $\mathcal{L}$ and l, respectively, $E^{\mathcal{L}}\{\Omega\}$ is

$$E^{\mathcal{L}}\{\Omega\} = c^p \sum_{n\in\Omega} \sum_{t\in T} P^{\mathcal{L}^n} t. \tag{3.13}$$

If $\phi_n\{\Omega\}$ is the part of $E^{\mathcal{L}}\{\Omega\}$ that each MNO $n \in \Omega$ will eventually take on to pay, we will proceed to its calculation by defining

- the roaming revenues $rev_n\{\Omega\}$ that correspond to each MNO n when it participates in coalition Ω,
- the contribution $\Phi'_n\{\Omega\}$ of each n to the total cost savings $SE^{\mathcal{L}}\{\Omega\}$ that are achieved from (i) the operation of the total HetNet when CSO is applied and (ii) the operation of the total HetNet when CSO is applied in a non-cooperative application manner, namely Individually applied CSO (IndSO),
- the expenses ψ_n of MNO n when it applies IndSO.

Based on the above, $\phi_n\{\Omega\}$ is calculated as follows

$$\phi_n\{\Omega\} = \psi_n - \Phi'_n\{\Omega\} - rev_n\{\Omega\}. \tag{3.14}$$

Parameters ψ_n and $rev_n\{\Omega\}$ of $n \in \Omega$ can be easily calculated. More specifically, it is

$$\psi_n = \sum_{t \in T} c^p P^{Ind,n}(t)t, \tag{3.15}$$

where $P^{Ind,n}(t)$ denotes the power consumption of L^n in the IndSO case, in accordance with eq. (3.10), with $\mathcal{L}^n$ and l^n instead of $\mathcal{L}$ and l, and

$$rev_n\{\Omega\} = \sum_{t \in T} \sum_{k^n \in \mathcal{K}^n} \sum_{l^n \notin \mathcal{L}^n} \left(c^p q_{k^n l^n}(t) j_{k^n l^n}(t) P^{RB}_{l^n} \Delta P_{l^n} t + c^{n'} p_{k^n}(t) \right), \tag{3.16}$$

where n' is the MNO of coalition Ω to the infrastructure of which UE k is re-associated to and is different than the provider n.

Unlike $rev_n\{\Omega\}$ and ψ_n of $n \in \Omega$ though, calculation of contribution $\Phi'_n\{\Omega\}$ to energy cost savings $SE^{\mathcal{L}}\{\Omega\}$ implicates fairness issues, as other MNOs may contribute to cost savings either by switching off BSs or by serving offloaded traffic, i.e., UEs. It is possible that cooperative MNOs could proceed to an equal allocation of $SE^{\mathcal{L}}\{\Omega\}$ among them to determine $\Phi'_n\{\Omega\}$ or proceed to an allocation based on their individual action. However, such strategies could result into a cost distribution that could be unfair to some MNOs. Thus, we propose a more cooperative approach that could set aside possible fairness issues and provide an applicable solution to the described problem. Our proposal is a centralised solution that models the cost allocation problem as a bankruptcy game.

A bankruptcy game combines the characteristics of a bankruptcy problem [85, 86] and cooperative games [87]. A bankruptcy game is defined by a specific *entity* that needs to be totally allocated among a group of *players*. Each of the players makes a *claim* on the obtained entity. A *utility function* is set for the game, according to cooperative game theory, which eventually allocates to each player a part of the entity, i.e., the *payoff*.

As a consequence, $SE^{\mathcal{L}}\{\Omega\}$ is an entity that has to be completely allocated among the MNOs of a coalition $\Omega \subseteq \mathcal{N}$, so that $\Phi'_n\{\Omega\}$ and eventually $\phi_n\{\Omega\}$ can be determined. Taking into consideration that different coalitions Ω can be formed among the MNOs, $SE^{\mathcal{L}}\{\Omega\}$ is calculated as follows

$$SE^{\mathcal{L}}\{\Omega\} = \sum_{n\in\Omega} \psi_n - E^{\mathcal{L}}\{\Omega\}. \tag{3.17}$$

It is noted that ψ_n is calculated as in eq. (3.15) and serves as an upper limit of the eagerness of n to join Ω. In other words, no MNO would be interested in paying an amount of cost greater than ψ_n while, at the same time, no MNO could save more money than ψ_n for a Ω. Thus, ψ_n represents the *claim* or *"marginal cost"*, as we will name it hereafter, of MNO n.

The obtained allocation problem of the cost savings $SE^{\mathcal{L}}\{\Omega\}$ can be modelled as a bankruptcy problem, B, which allocates to each n its contribution to the network cost savings, $\Phi'_n\{\Omega\}$ and can be expressed in mathematical terms as

$$B = \left\{ \left(SE^{\mathcal{L}}\{\Omega\}, \psi_n \in \mathbb{R}_{++} \times \mathbb{R}_{+}^{|\Omega|} \right) : SE^{\mathcal{L}}\{\Omega\} \leq \sum_{n\in\Omega} \psi_n, \right\} \tag{3.18}$$

We use coalitional game theory, and more specifically, coalitional games of transferable utility (TU), to define the characteristic function, V_B, $V_B : 2^N \times \mathbb{R}$, which will evaluate each bankruptcy problem B and associate it to a real value:

$$V_B(\Omega) = \begin{cases} min\left\{\psi_{n\in\Omega}, SE^{\mathcal{L}}\{\Omega\} - \sum_{n\notin\Omega}\psi_n\right\}, & \Omega = \{n\} \\ min\left\{\sum_{n\in\Omega} V_B(\{n\}), SE^{\mathcal{L}}\{\Omega\} - \sum_{n\notin\Omega}\psi_n\right\}, & \Omega \neq \{n\}. \end{cases} \tag{3.19}$$

It is noted that *if* $V_B(\Omega) < \left(SE^{\mathcal{L}} - \sum_{n\notin\Omega}\psi_n\right)$, *then* $V_B(\Omega) = 0$, since the entity cannot be totally allocated to the cooperative MNOs.

Given the fact that $SE^{\mathcal{L}}\{\Omega\}$ is in any case defined only by the player MNOs of the coalition, (3.19) becomes

$$V_B(\Omega) = \begin{cases} min\left\{\psi_{n\in\Omega}, SE^{\mathcal{L}}\{\Omega\}\right\}, & \Omega = \{n\} \\ min\left\{\sum_{n\in\Omega} V_B(\{n\}), SE^{\mathcal{L}}\{\Omega\}\right\}, & \Omega \neq \{n\}, \end{cases} \tag{3.20}$$

with $V_B(\Omega) = 0$ when $V_B(\Omega) < SE^{\mathcal{L}}$. Based on eq. (3.20), the value of the game among MNOs of coalition Ω, $V_B(\Omega)$, is calculated based on the game values in case of an MNO individual activity, i.e., when $\Omega = \{n\}$.

Payoff of cost savings for each n, $\Phi'_n\{\Omega\}$ or $\Phi'_n(V_B(\Omega))$, as it can be written in the case of the B game with utility function V_B, is subjected to the following constraints so that the bankruptcy game holds:

- The sum of allocated payoffs should equal $V_B(\Omega)$:

$$\sum_{n\in\Omega} \Phi'_n(V_B(\Omega)) = V_B(\Omega). \tag{3.21}$$

- The payoff of a player n in a coalition Ω should not be less than the respective one of the player's stand-alone action:

$$\Phi'_n\left(\{n\}\right) \leq \Phi'_n\left(V_B(\Omega)\right). \tag{3.22}$$

- A player n cannot receive a higher payoff than its claim, so that fairness is preserved.

$$0 \leq \Phi'_n\left(V_B(\Omega)\right) \leq \psi_n. \tag{3.23}$$

3.5.2 Bankruptcy game with Shapley Value

We use Shapley Value (SV) to determine the payoffs, $\Phi'_n\left(V_B(\Omega)\right)$, of each $n \in \Omega$, player of the bankruptcy game, with eq. (3.20) set as the characteristic function which corresponds each game to a value. SV has the important characteristic of quantifying the contribution of a player, i.e., its worth and value, in a game when the player joins a coalition, which highly motivated us to selected it as part of our solution. Similarly, in the present work, SV rewards a player n with a payoff $\Phi'_n\left(V_B(\Omega)\right)$ according to its contribution in the obtained cost which. SV is based on four basic axioms [87]:

- **Efficiency axiom**: $\sum_{n\in\Omega} \Phi'_n\left(V_B(\Omega)\right) = V_B\left(\Omega\right)$.
- **Symmetry axiom**: if two players n_1 and n_2 are such that $V_B\left(\Omega \cup \{n_1\}\right) = V_B\left(\Omega \cup \{n_2\}\right)$, for every coalition Ω containing the player n_1 and n_2, then $\Phi'_{n_1}\left(V_B(\Omega)\right) = \Phi'_{n_2}\left(V_B(\Omega)\right)$.
- **Dummy axiom**: If a player n is such that $V_B\left(\Omega\right) = V_B\left(\Omega \cup \{n\}\right)$, for every coalition Ω not containing n, then $\Phi'_n\left(V_B(\Omega)\right) = 0$.
- **Additivity axiom**: if u and v are characteristic functions, then $\Phi'\left(u+v\right) = \Phi'\left(v+u\right) = \Phi'\left(u\right) + \Phi'\left(v\right)$.

SV payoff of a player in a game when it joins coalition Ω, is computed based on the chosen utility function of the game, V_B, as follows [87]

$$\Phi'_n\left(V_B(\Omega)\right) = \sum_{\Omega\subseteq\mathcal{N}\setminus\{n\}} \frac{|\Omega|!(N-|\Omega|-1)!}{N!}\left[V_B\left(\Omega\cup\{n\}\right) - V_B\left(\Omega\right)\right]. \tag{3.24}$$

With the contribution $\Phi'_n\left(V_B(\Omega)\right)$ defined from SV, the cost $\phi_n\left\{\Omega\right\}$ that each n will eventually take on to pay can be calculated according to eq. (3.14). Our proposal, namely bankruptcy SV based cost allocation scheme (BSV), is presented in Fig.3.3.

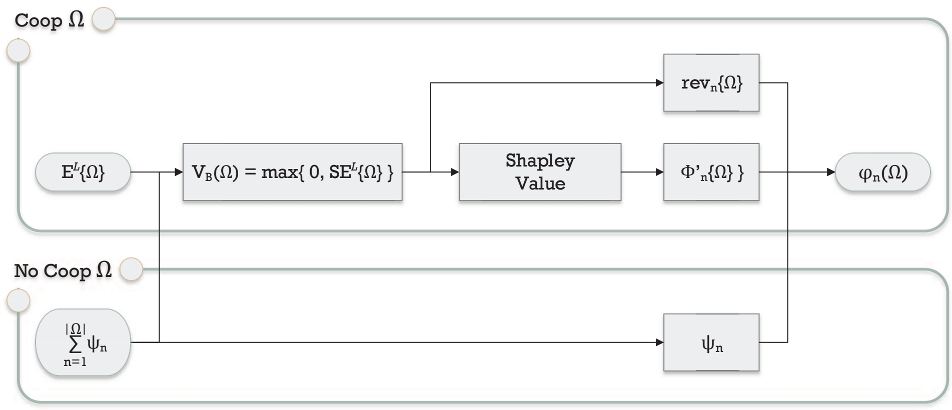


Figure 3.3: BSV flowchart: Flowchart of the bankruptcy Shapley Value based cost allocation scheme (BSV)

Aiming at further portraying the fairness of the allocated cost to each MNO, $\phi_n\{\Omega\}$, we employ an expectation index, $EI_n\{\Omega\}$, corresponding to each $n \in \Omega$ defined as

$$EI_n\{\Omega\} = \frac{(\psi_n - \phi_n\{\Omega\})}{\psi_n}, \ \forall n \in \Omega, \tag{3.25}$$

where $\phi_n\{\Omega\}$ and ψ_n are calculated according to eq. (3.14) and (3.15), respectively. The meaning of $EI_n\{\Omega\}$ is to portray a metric of satisfaction for an MNO n between the case of being in a coalition Ω and opting for an individual action, based on the achieved cost difference. An estimation for the whole method's fairness is extracted based on the mean value of $EI_n\{\Omega\}$.

3.6 Performance Evaluation

We implemented a system-level simulator in MATLAB in order to examine the performance of CSO and bankruptcy cost allocation scheme. In the present section, we present the considered simulation scenario and the performance evaluation results that we extracted.

3.6.1 Simulation Scenario

We study seven macrocell sized areas, with the system model described in Section 3.3.1. Without loss of generality, we assume that $N = 3$ MNOs are active in each macrocell sized area. We consider that all MNOs are motivated to cooperate, aiming at increasing the energy savings of their shared network and then proceed in a fair balancing of their expenses. We consider uniform UE distribution in each

Table 3.3: Simulation Parameter Values

Parameter	Value
$h_{l\leq M}$	6
$h_{l>M}$	2
$P^{tx,max}_{l\leq M}$	46 dBm
$P^{tx,max}_{l>M}$	30 dBm
$G^{tx}_{kl\leq M}$	15 dBi
$G^{tx}_{kl>M}$	5 dBi
$PL_{kl\leq M}$	128.1+37.6logd_{kl},d in km
$PL_{kl>M}$	140.7+36.7logd_{kl},d in km
$\mu_{l\leq M}$	0 dB
$\mu_{l>M}$	0 dB
$\sigma_{l\leq M}$	8 dB
$\sigma_{l>M}$	10 dB
N_{th}	-174 dBm/Hz
NF	5 dB
$\Delta P_{l\leq M}$	21.45
$\Delta P_{l>M}$	7.4
$P^{con}_{l\leq M}$	354.44 W
$P^{con}_{l>M}$	71 W

macrocell sized area, with all MNOs having similar traffic load patterns of sinusoidal form, approaching the traffic pattern in [15] as in Fig. 3.4, unless otherwise stated. Their traffic loads, expressed in number of UEs, are equal to $\xi \cdot K^1$, $K^2 = 2 \cdot \xi \cdot K^1$ and $K^3 = 3 \cdot \xi \cdot K^1$. Parameter ξ is a multiplicative real-number factor, $\xi \in \Re$, which is multiplied by the whole MNO traffic pattern curve thus differentiating both the load magnitudes for each MNO and the total traffic load volume served by the cooperative HetNet and intensifying load differences among MNOs. Unless otherwise stated, ξ is set equal to 1. The network infrastructure in each macrocell sized area is in total $L = 45$ with $L^1 = 11$, $L^2 = 15$ and $L^3 = 19$. One MBS corresponds to each of the three MNOs from the aforementioned infrastructure. The MBSs are collocated in the centre of each macrocell sized area, while the SBSs, are uniformly distributed in it. We assume two possible BS operational states, *active* and *inactive* and represent their state with the θ_l value, as mentioned in Section 3.3.1. All MNOs adopt orthogonal LTE-A transmission of $W_l = 20$ MHz. Therefore $J_{l,max} = 100$ RBs, $\forall l \in \mathcal{L}$ [80]. We set $I = 3$ classes of data throughput demands. Thus, a k may require $\rho_1 = 1.5$ Mbps, $\rho_2 = 1$ Mbps or $\rho_3 = 0.75$ Mbps with random probability $g_{ki} \in [0, 1]$. We set $c^p = 0.1$ €/kWh [88] as a cost of power consumption and an inter-operator roaming charge equal to $c^n = 0.003$ €/MB[7] [89]. Each $k \in \mathcal{K}$ is initially associated to an $l \in \mathcal{L}^n$ that is owned by the MNO n to which k is

[7]Different inter-operator roaming charges could be applied by each MNO for accepting offloaded traffic of rival networks. However, in such a case the simulation scenario would then become case specific. Therefore, same inter-operator roaming charges were considered. Moreover, it is noted that the inter-operator roaming charge value can affect the roaming revenues for MNOs. The proposed cost allocation scheme, BSV, can be then used for balancing cost differences.

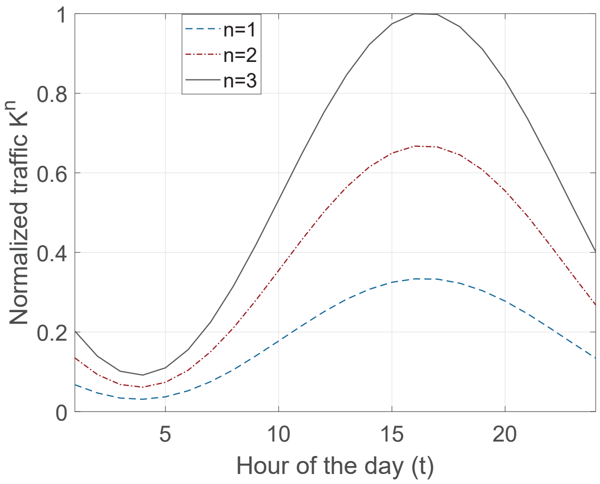


Figure 3.4: Normalised MNO UE traffic, K^n, with n=1, 2 and 3 corresponding to MNO 1, 2 and 3, respectively.

subscribed and that provides the highest SNR_{kl}. We set the threshold SNR for the establishment of a channel $SNR_{threshold} = -10$ dB [80]. Our focus is on the low traffic hours of a day $(00:00)-(06:00)$, when switching off probabilities are higher. The rest of the simulation parameters are summarized in Table I [15, 90, 80, 37].

The proposed CSO algorithm is compared with

1. a full operational network (FON), when all $l \in \mathcal{L}$ are in active mode and no cooperation scheme exists among MNOs,

2. an individual network operation according to the proposed CSO, namely Individually applied CSO (IndSO), when each $n \in \mathcal{N}$ individually applies CSO,

3. a random switching off scheme (RSO), when MNOs apply both the switching off and roaming-based network sharing method by switching off half BSs of the united network in a random manner so that the geographic area corresponding to a switched off $l' \in \mathcal{L}$ is covered by the remaining active ones [40] and

4. a switching off scheme that is based on a power saving efficiency indicator Q. We will hereafter call it Q-based switching off scheme (QSO) [44]. As QSO is designed for a single-operator system model, we adjust it in our results for a multi-operator one by using a roaming-based shared network with traffic offloading to an MBS with available resources and giving priority to the MBS of their provider MNO. We also apply QSO on an hourly basis, as in our work.

The proposed BSV cost allocation scheme is compared with

1. an equal cost allocation (EQ) among the cooperative MNOs participants of a

coalition Ω, when each n takes on the responsibility of paying an equal part of the network expenses except from the roaming revenues and

2. the Generalized Ibn Ezra (GIE) value [86], when the allocated cost $\phi_n^{GIE}\left(E^{Het}, \psi_n\right)$ to each MNO n is dependent on their marginal costs, ψ_n.

Moreover, when necessary, we consider in our results the case when no cost allocation strategy is adopted (NoCA).

Finally, network energy efficiency *(bits/Joule)* and network operation cost *(€)* were used as indicative metrics for validating the algorithms' performance results. Concerning the MNO satisfaction from the cost allocation methods, we used as a metric the EI which is given in (3.25), while the mean value of EI is used for assessing the overall fairness of the methods.

3.6.2 Performance Results

Fig. 3.5 depicts the average network energy efficiency for the studied area during low-traffic hours, when MNO traffic variations are as in Fig. 3.4 and with the consideration of four different switching off schemes that were described in Section 3.6.1: IndSO, RSO, QSO and CSO. It can be observed that CSO outperforms its counterparts throughout the studied hours, as it manages to serve the same amount of traffic with less active infrastructure. QSO, performs worse than CSO in spite of the network sharing assumption, as it offloads traffic only to MBSs and does not exploit the available resources of other SBSs, as CSO does. QSO though outperforms IndSO and RSO. On one hand, IndSO is outperformed by both CSO and QSO, because it does not apply network sharing. Moreover, in a macrocell sized area, IndSO

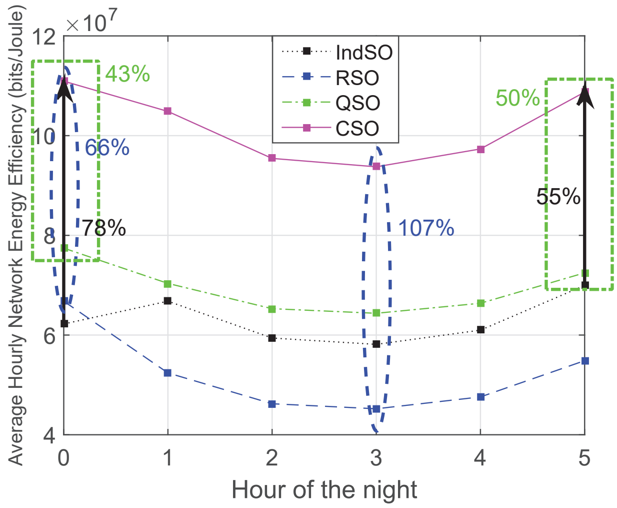


Figure 3.5: Average hourly network energy efficiency vs. switching off schemes.

keeps the MBSs of each MNO active and adjusts the SBS operational states to traffic variations. In comparison to QSO, this results in higher power consumption for IndSO and thus, in lower network energy efficiency. On the other hand, RSO limits the amount of active infrastructure to half to save energy and provide coverage. In each macrocell sized area thus, more than one MBS may remain active, along with some underloaded SBSs. This results in poorer performance in comparison to its counterparts. Interesting is the fact that when traffic is a bit higher, i.e., 00:00-01:00, IndSO is outperformed by RSO, as RSO exploits more efficiently the active infrastructure. On the other hand, IndSO performs better than RSO for the rest of studied hours, since IndSO adjusts to traffic variations with SBSs. In order to quantify the differences to its counterparts, it can be noticed that CSO can achieve an increase in energy efficiency between 55–78% in comparison to IndSO, 66–107% in comparison to RSO and 43–50% in comparison to QSO.

With an aim to study the performance of CSO under different traffic scenarios, we have also assumed a scenario where the load peaks of all MNOs take place during the night hours (e.g., at a student residence) in Fig. 3.6. A general comment for Fig. 3.6 is that all studied schemes are more energy efficient in comparison to their performances in Fig. 3.5, as higher traffic load is served by the network. Amongst all schemes, CSO is the most energy efficient one, as it serves the traffic with less power consumption. In detail, it is mainly the network of MNO 3, that serves the majority of traffic. Its infrastructure is quite loaded, with some SBSs of other MNOs being active, too. MNO cooperation though allows MBSs and several SBSs to switch off, which leads to energy savings. Although CSO performs better than its counterparts in Fig. 3.6 as it also did in Fig. 3.5, the performance results of the rest considered schemes have changed. RSO has now the second best performance. It is outperformed by CSO, as it keeps more MBSs active in each macrocell sized

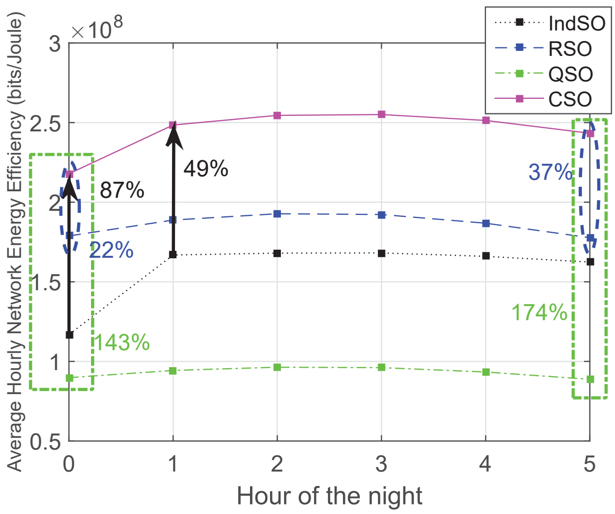


Figure 3.6: Average hourly network energy efficiency vs. switching off schemes with night peak MNO traffic profiles.

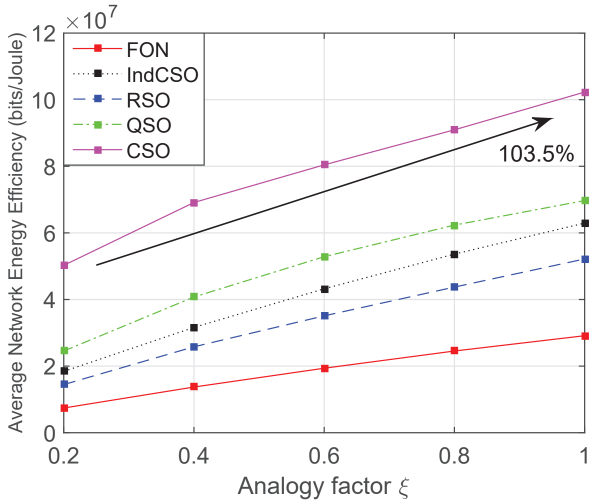


Figure 3.7: Average network energy efficiency vs. analogy factor ξ and switching off schemes.

area. However, RSO energy efficiency results are better than those of QSO and IndSO. With RSO, SBSs serve more traffic, whereas with QSO and IndSO, all MBSs are active and serve the majority of traffic. QSO is outperformed by IndSO in Fig. 3.6 despite the adoption of network sharing, because IndSO applies offloading to both MBSs and SBSs, whereas QSO allows traffic offloading only from SBSs to MBSs. Concluding, CSO achieves an increase in energy efficiency between 49–87% in comparison to IndSO, 22–37% in comparison to RSO and 143–174% in comparison to QSO.

In order to obtain further insights on the performance of the studied schemes in terms of network energy efficiency, in Fig. 3.7, we alter the differences among the traffic load volumes of each MNO. More specifically, assuming the traffic pattern curves of Fig. 3.4, the magnitude of the individual MNO traffic load volumes is altered with the help of the factor ξ, which was described in Section 3.6.1 [8]. Having already assumed MNOs of different traffic loads, as described in Section 3.6.1, a cooperation of MNOs, whose traffic load discrepancies change, could result in a different load offloading among BSs and thus alter the energy efficiency of the considered system for the different switching off schemes. According to Fig. 3.7, CSO outperforms its counterparts for low and high traffic load differences with changes of ξ, thanks to the joint consideration of its switching off and network sharing scheme. Meanwhile though, CSO improves its energy efficiency by 103.5% for different ξ, while the respective numbers for its counterparts are 184.2% for QSO, 260.9% for RSO, 241.8% for IndSO and 292.7% for FON. The more moderate responses to

[8]It is reminded at this point that parameter ξ is a multiplicative real-number factor, $\xi \in \Re$, that is multiplied by the whole MNO traffic pattern curve, thus differentiating both the load magnitudes for each MNO and the total traffic load volume served by the cooperative HetNet and intensifying load differences among MNOs.

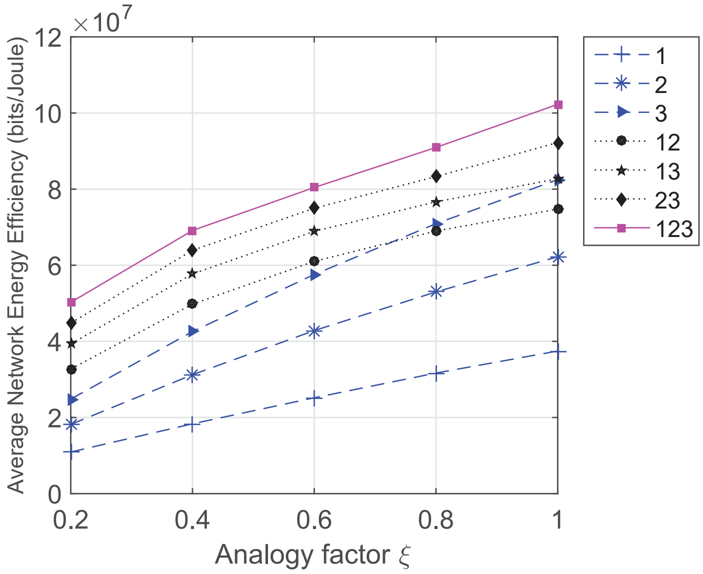


Figure 3.8: Average Network Energy Efficiency vs. analogy factor ξ and Coalitions.

traffic load changes of CSO, QSO and IndSO in comparison to RSO and FON are attributed to the fact that the former increase active infrastructure to cover the traffic, while the latter keep it stable.

The content of Fig. 3.7 is extended in Fig. 3.8 out of interest to assess the effects of the different coalitions that MNOs can form on the performance of CSO, in terms of energy efficiency. In more detail, applying CSO, three kinds of coalition can be noticed: *(i)* one MNO (blue dashed line), *(ii)* two MNOs (black dotted line) and *(iii)* three MNOs (pink solid line). It is noted that *case (i)* represents the application of IndSO, as it was described in Section 3.6.1. According to Fig. 3.8, in most cases, IndSO is less energy efficient in comparison to any other coalition of MNOs, since MNOs do not reap the benefits of sharing, i.e., offloading their traffic to any BS in the area. Comparing a coalition of two and three MNOs, the coalition of three proves to be more energy efficient that a coalition of two. Even though the amount of traffic that needs to be offloaded increases with the consideration of more cooperative MNOs, the traffic can be better distributed among the extra infrastructure that is available from the extra participant MNO, increasing thus the network energy efficiency.

Fig. 3.9 indicates the distribution of the total HetNet cost to each of the three MNOs. This network cost that corresponds to each MNO n, with $n = 1, 2 \textit{ or } 3$ is represented with ϕ_n in eq. (3.14) and three cooperation cases are studied for it:

- IndSO-NoCA: It corresponds to an individual switching off action of all MNOs and thus no cost allocation method is needed. However, MNOs are responsible for the expenses of their own network, ψ_n. Therefore, in this case, the MNO

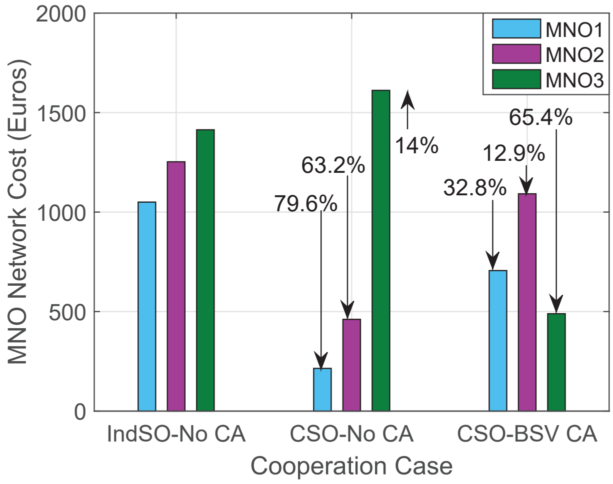


Figure 3.9: Average MNO network cost, ϕ_n, vs. cooperation cases.

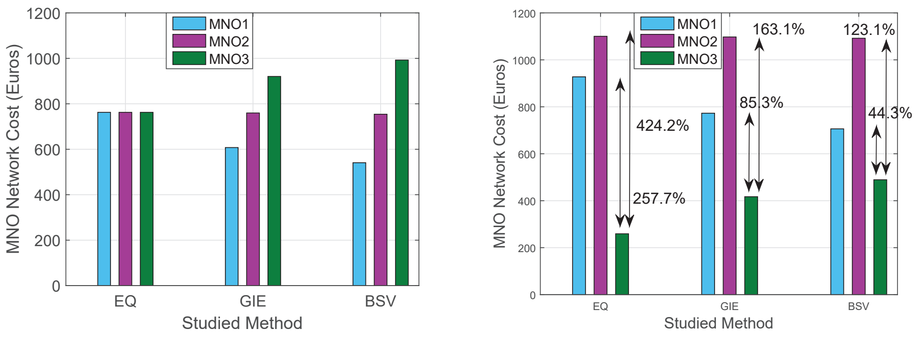
costs of eq. (3.14) are calculated as: $\phi_n = \psi_n$.

- CSO-NoCA: It corresponds to a coalition of the three MNOs, with no adoption of a cost allocation method. Instead, MNOs are responsible for the cost corresponding to their active infrastructure, ψ_n, and for their roaming revenues, rev_n. Therefore, in this case, the MNO costs of eq. (3.14) are calculated as: $\phi_n = \psi_n - rev_n$.

- CSO-BSV: It represents a coalition of the three MNOs and the adoption of the proposed BSV cost allocation method. Therefore, in this case, the contribution of each MNO to saving costs through the coalition is recognised and the MNO costs are calculated as in eq. (3.14).

As can be observed in Fig. 3.9, with CSO-NoCA, there is a big decrease of 79.6% and 63.2% for the network costs of MNOs 1 and 2, respectively, in comparison to the IndSO-NoCA case, as their infrastructure is assessed first to switch off, according to CSO. Despite the fact that the benefits of infrastructure sharing are already apparent for MNOs 1 and 2 with CSO-NoCA, MNO 3 has an increase of 14% in its costs. This phenomenon can be considered unfair for MNO 3, since it takes on the majority of total traffic, when at the same time MNOs 1 and 2 have most of their infrastructure switched off. In addition, MNO 3 is also faced with increased expenses in comparison to the strictly non-cooperative approach of IndSO-NoCA, when at the same time MNOs 1 and 2 notice considerable reduction of their costs in the respective scenario. Thus, at this point, Fig. 3.9 highlights the need for applying a fair cost allocation procedure among the cooperative MNOs. The respective results for CSO-BSV are included in Fig. 3.9 as well. BSV cost allocation indicates a decrease of 32.8% and 12.9% in the costs of MNOs 1 and 2 respectively, in comparison to their respective marginal cost, i.e., IndSO-NoCA case. Both cost reductions, however, are more limited in comparison to the CSO-NoCA case, as BSV allows MNOs 1 and 2 to take on a larger share of the total costs. As far as MNO 3 is concerned, a big decrease of 65.4% is noticed in its allocated cost between the IndSO-NoCA and CSO-BSV cases, in contrast to the cost increase noticed with CSO-NoCA. BSV rewards the contribution of MNO 3 for providing service to the offloaded traffic, limiting thus its BS switching off possibilities. MNO 3 thus is motivated to remain in the coalition. The consideration of SV, which is used in BSV, contributes so that all MNOs reduce their expenses and remain encouraged to share their networks by adopting a cost allocation that portrays each one's contribution to the cost savings.

Fig. 3.10 presents the cost distribution among the MNOs of a coalition Ω, as a result of the different cost allocation methods they can follow. On one hand, Fig. 3.10a displays the influence of the considered methods on the cost that is attributed to network power consumption. EQ cost allocation does not take into consideration any individual contribution of MNOs and thus the allocated costs are equal. The GIE method, being based on the declared marginal cost of each MNO, results in a more balanced cost allocation vector, especially between MNOs 1 and 3. Lastly, given that the BSV method portrays the contribution of each MNO to the cost savings, it approaches the GIE method. On the other hand, Fig. 3.10b depicts the results of Fig. 3.10a, as they are formed after the consideration of each MNO's roaming revenues, rev_n. The results of Fig. 3.10b constitute the final allocated costs. When roaming charges are considered after an EQ cost allocation, big discrepancies appear between MNO 3 and MNOs 1, 2. According to the figure, MNOs 1 and 2 approach their marginal costs and MNO 3 considerably benefits from the roaming charges. Undoubtedly, the big differences of 257.7% and 424.2% between MNO 3 and MNOs 1 and 2, respectively in their allocated costs, raise questions on the fairness of the method. GIE and BSV however, reduce the big gap between MNO 3



(a) Average MNO network cost vs. cost allocation methods.

(b) Average MNO network cost including roaming revenues vs. cost allocation methods.

Figure 3.10: MNO cost allocation before and after consideration of roaming revenues: Allocation of the cost to cooperative MNOs considering different cost allocation methods before and after the consideration of inter-operator roaming revenues.

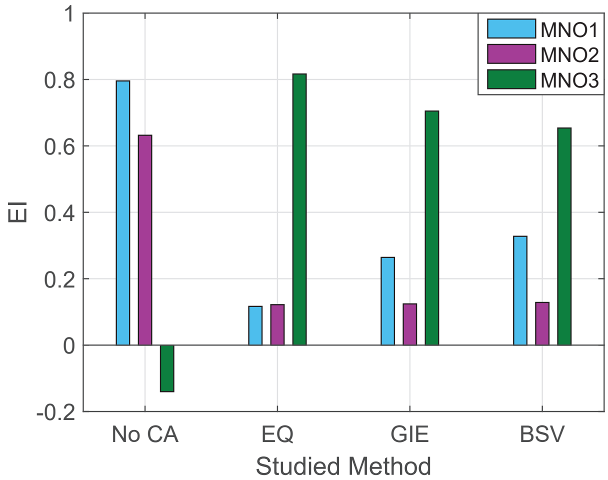


Figure 3.11: MNO EI vs. studied cost allocation methods.

and MNOs 1 and 2, thanks to their criteria. BSV achieves a more balanced cost allocation between MNO 3 and MNOs 1 and 2, with respective differences of 44.3% and 123.1%, in comparison to GIE, where the respective differences are equal to 85.3% and 163.1%. It is noted that, for the three methods, MNO 2 has the least decrease in its allocated cost due to its large roamed traffic load, which induces larger roaming expenses.

The satisfaction of MNOs from the distribution of costs among them, as the latter was extracted Fig. 3.10b, is expressed in Fig. 3.11, via the expectation index (EI) metric of eq. (3.25) [9]. Moreover, the CSO-NoCA case of Fig. 3.9 is also included in the results. According to the figure, MNO 3 has a negative EI in the NoCA case, as the fact that it takes on the majority of the traffic results in increased expenses. It is noticed that when a cost allocation strategy is applied, EI of MNO 3 increases, indicating its satisfaction over the fact that it received a cost reduction as a payoff for providing a considerable part of its network capacity to cover the traffic of MNOs 1 and 2. On the other hand, MNOs 1 and 2, are more satisfied in the NoCA case, i.e., they have higher EI, since they have to pay only for the power consumption of their limited active infrastructure. When a cost allocation method is applied, MNOs 1 and 2 have to take on a larger part of the total network expenses, limiting their individual satisfaction from the cooperation. However, an adoption of a cost allocation method leads to a more balanced distribution of the cost and consequently the reassurance of a minimal satisfaction of all cooperative MNOs. Among the cost allocation methods, the EQ one results in the most unbalanced MNO satisfaction, favouring MNO 3. However, GIE and BSV balance the EQ's method differences of EI for the cooperative MNOs thanks to the adoption of cost

[9] It is reminded that the EI metric of eq. (3.25) represents the satisfaction of an MNO from the achieved difference in the cost (i) that corresponds to its own activity within a coalition with other MNOs and (ii) that is created from its individual activity, away from a coalition.

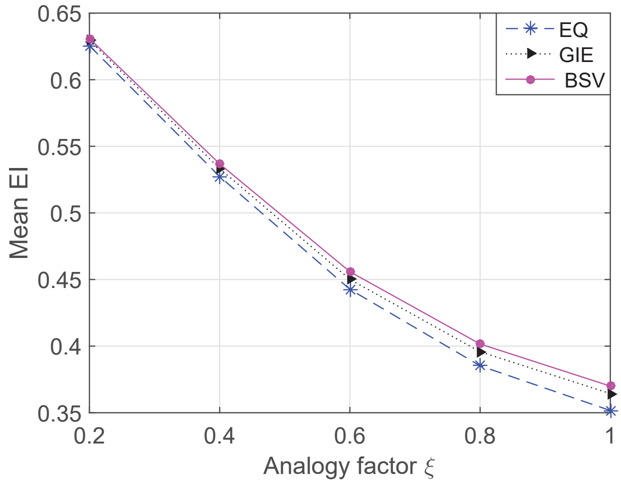


Figure 3.12: Mean EI of each cost allocation method vs. analogy factor ξ for the MNO traffic loads.

allocation criteria (marginal cost and saved energy contribution respectively), with the BSV criteria achieving the most balanced EI for the cooperative MNOs.

Having considered the results of Fig. 3.11, it is only rational to assume that the BSV balanced cost allocation among all cooperative MNOs, which is also representative of their contribution to the achieved reduction of the cost, is a fairer option to follow. Fig. 3.12 confirms the latter conclusion with the display of the mean EI of each cost allocation method, EQ, GIE and BSV, versus the traffic load analogy factor ξ. According to the obtained results, all studied methods provide a fairness of similar levels in the system for various traffic load differences among MNOs. Despite the fact that all studied cost allocation methods result in close performance, especially when traffic load differences are vague among the MNOs, the performance gap among the methods slightly expands as traffic load differences intensify as well. The BSV method though presents a slight precedence that is attributed to the use of SV, as the latter quantifies each MNO's contribution to cost savings for the extraction of their allocated costs. The GIE method, being based to the criterion of each MNO's marginal cost performs close, though still below, to BSV for the various ξ. Finally, there is a slightly more intense deterioration in the performance of EQ in comparison to the others as differences in MNO traffic load volumes broaden, which indicates the necessity of adopting fairer cost allocation criteria.

3.7 Conclusion

With a view to the expected increase in the traffic load volume, the possibility for MNOs to switch off infrastructure and to cooperate, expand the expectations for a greener operation of the wireless telecommunication network, with reduced OpEx and CO_2 emissions and increased energy savings. At the same time, fairness issues are raised over the cost allocation among the cooperative MNOs that could jeopardise their incentive for a cooperation. In this thesis chapter, we introduced a switching off algorithm, CSO, which can achieve an energy efficient network operation during low traffic hours, when infrastructure is underloaded and exploit the benefits of network sharing by roaming traffic to the networks of all cooperative MNOs. By considering the different types of HetNet BSs, their owner MNO and the channel quality among BSs and UEs in the studied area, CSO assesses the best candidate BS to switch off, implements a roaming cost based cooperative UA scheme to offload traffic and eventually defines the operational state of the BSs.

The obtained results highlight not only the network's potential energy efficiency gains, but also the potential cost savings. In order to address the fairness issues over the cost allocation among cooperating MNOs, we proposed a bankruptcy game as a cost allocation method, namely BSV. BSV is Shapley Value based and thus takes into account each MNO's contribution to network cost savings according to its power consumption cost in a cooperative and non-cooperative case. The proposed BSV cost allocation scheme determines the final cost for each MNO based on their roaming revenues. The extracted results project the adaptability of BSV to provide a balanced cost allocation among MNOs for their different traffic loads while managing to be overall satisfying as well.

Chapter 4

Energy and cost issues in grid-connected multi-operator HetNet deployments

4.1 Introduction

Chapter 3 was dedicated to wireless networks that are powered only from the traditional grid. However, with a view to the wireless networks of the next era and the augmented data traffic volumes that are expected, utilisation of renewable energy sources (RE) is becoming more popular in the industrial and research world. Despite the high capital expenditure (CapEx) they may introduce, the adoption of RE sources and the distribution of RE have been both embraced as effective green cost-saving techniques that power network infrastructure, shared or not [91, 92]. On one hand, thanks to the production of low or no carbon dioxide (CO_2) emissions attributed to RE sources, research has been focused on the implementation possibilities of energy harvesting (EH) base stations (BSs) of both macrocell and small cell type, i.e., macrocell BSs (MBSs) and small cell BSs (SBSs) [29, 93, 94]. On the other hand, thanks to the technology revolution in smart grid (SG) networks [30, 31], research on energy exchange (EE) with the SG or among network elements with energy abundance and energy shortage is progressively becoming popular [33, 34, 35, 69, 95, 96]. Motivated by this trend in energy utilisation, this chapter focuses on the incorporation of RE sources and EE to wireless networks so that a greener and more cost efficient operation of the network can be achieved.

Besides the benefits that the adoption of network sharing in combination with the use of RE sources and EE provide to network operation, issues that seek provision arise. With regard to network sharing, protection of individual data and profits, as well as fairness in sharing agreements are critical issues. Towards this direction, related economical issues have been assessed in past works [73, 97, 98]. In cases of RE use, RE shortage events due to RE generation unpredictability is a preoccupation for mobile network operators (MNOs). The use of a supporting energy storage system (ESS), consisted of battery series, is usually adopted as a countermeasure [26]. However, the storage capacity of an ESS is upper limited, while both the RE and ESS equipment aggravate the space scarcity issues that MNOs face when seeking installation points of their network equipment [64]. The EE technique complements the benefits of an ESS, while it balances the drawbacks of storage limitation and space scarcity that come along with its use. Energy can be exchanged at volumes that are adjustable to needs, and with or without payment, which corresponds to energy trading and sharing, respectively.

EE can be implemented using power lines [33], the SG [34, 35, 69, 95] or with the aid of an aggregator [96]. It is reminded that the utility of the aggregator is attributed to a threshold energy volume that is required by the current SG market structure. This threshold of minimum 10 MW is usually required for a bid in energy markets[1] and thus for a direct EE via the SG lines. The aggregator pools several smaller consumers into larger aggregated clumps that are sold on existing power markets or through bilateral agreements. Thus, smaller consumers that do not surpass the 10 MW threshold, e.g., the EH-SBSs, and that therefore have no possibility of direct access to the market, can adopt a more flexible approach of trading that can also save money to those who use it. Gathering energy from different small sources, the aggregator can benefit from the SG lines and, using its software, it can request immediate provision of power at different places of a network.

The basic principles of using RE sources at the BS site and EE have received notable attention. Nevertheless, only limited and recent works explore implications of their adoption in multi-operator environments. This aspect is important as collocation and ownership of networks affect the choice of the EE model that can be adopted. Multi-operator collaborative energy trading agreements with energy retailers and directly with the energy market are studied in [99] and [70], respectively. In detail, the work in [99] describes energy trading acts of MNOs, owners of an EH heterogeneous network (HetNet), that seek collaboration agreements among them in order to achieve profitable RE purchases from energy retailers. The authors use as a main criterion for the agreements the level of produced pollution. Aiming at further cost and CO_2 emissions reduction, they also apply network switching off. The work in [70] studies the economical transactions between only two cellular MNOs and the hybrid energy market. Aiming at optimally saving costs due to purchases from the day-ahead and real-time energy market, the authors study different MNO collaboration schemes in both the purchasing acts and service providing.

The aforementioned works study the activity of multiple MNOs in the same area. However, they omit space scarcity scenarios that oblige sharing of both the network and EH infrastructure. In such cases, allocating harvested RE to the shared network infrastructure should be given careful consideration, as the RE volume may

[1] http://econgrid.com/index.php/the-role-of-aggregator/?lang=en

be insufficient to cover the individual energy needs of the stakeholders involved in the sharing. Unless appropriate allocation schemes are adopted, sharing such strictly defined energy volumes could affect negatively the green operation and profitability of MNO cooperation. Thus, although the aforementioned works explore basic aspects of energy trading in multi-operator environments, there are still critical open issues regarding a fair allocation of RE volumes that need to be addressed.

The issue of fairness in energy sharing was studied only recently in [100] and with respect to the improvement of the communication service quality in the network. The studied scenario though assumes only collocated BSs of rival MNOs, while energy sharing is implemented through the SG. Thus, the work omits exploring challenging EE prospects in multi-MNO scenarios. An indicative example is the use of private power lines among network elements of rival MNOs, which has been studied as a permanent solution only in single-MNO scenarios [33, 35]. Lastly, it leaves out popular multi-MNO architectures, e.g., those involving a third party [20], where EE could be hindered due to the conflicting interests of stakeholders.

More challenges though are encountered in an EE act among multiple MNOs. Achieving energy neutrality for a multi-tier wireless network with EE is a challenging task, as the BS type and location change greatly the EE roads to follow. Energy neutrality for MBSs is more challenging and expensive than for SBSs, since MBSs provide the umbrella coverage in an area and thus are more energy hungry. Moreover, MBSs of rival MNOs are often co-located in urban areas due to the high traffic load volumes and site regulation issues, whereas SBSs are overlaid all over a macrocell area. Thus, the encounter of a both permanent and unified solution for MBSs and SBSs is difficult. At the same time, for all stakeholders that participate in a sharing agreement, disclosure of private information is a hot potato issue. The extend to which they can do it, e.g., for one or for more cells, is a critical decision. Involving an impartial entity might be necessary when information disclosure is considered extensive. Finally, addressing all aforementioned issues with simple approaches, meanwhile ensuring fairness for the stakeholders that participate in a multi-MNO EE act is a more demanding task. Therefore, it is necessary to strictly define an EE cooperation framework that clarifies such issues.

In this chapter, we go beyond the existing literature by exploring EE in late-trend multi-operator HetNet deployments that use EH as energy source, along with the SG. To this end, we study a scenario in which MNOs manage a two-tier wireless HetNet that uses a supporting EH system (EHS) and an ESS at each BS site. More specifically, in our scenario, MNOs apply passive sharing to the macrocell tier, due to the network planning limitations, i.e., encountering a BS placement site [64] and in order to address the high energy needs, CO_2 emissions and costs, of an MBS [15]. The small cell tier infrastructure, is composed of EH-SBSs, i.e., SBSs with respective EHSs and ESSs, and is provided by an infrastructure provider (InP). We aim at studying the prospects of EE in both tiers, meanwhile addressing the challenges of a network sharing model, with multiple stakeholders of different interests involved.

To this end, the contribution of this chapter is described as

- a cooperative energy sharing scheme via power lines, applicable to passively shared EH-MBSs. Passive sharing is assumed as a sharing of not only the MBS infrastructure, but also the EHS and ESS. We propose an energy sharing scheme among EH-MBSs, or their owner MNOs in the case of one-to-one correspondence, that refers to the sharing of the RE that is harvested by the shared EHS and stored at the shared ESS. We assume that EE is carried out via power lines due to the passive sharing, which presumes collocated EH-MBSs that are unlikely to be relocated, even though they belong to rival MNOs. Short-lengthened power lines are assumed, which result in negligible losses on energy transfer and circumvent of additional costs due to the involvement of the SG or an aggregator.

We propose a cooperative energy sharing scheme, as, even though the involved in the sharing MNOs have rival interests, they are of similar characteristics. Cooperative game theory provides the possibility to increase the value of the total sharing effort, meanwhile preserving the individual benefits of players [87]. On this basis, we describe the problem of allocating the harvested and stored RE to the cooperative MNOs as a bankruptcy game (BG). BGs refer to the allocation of a determined entity to a group of players who are interested in it [85]. RE volumes can be such an entity when they are insufficient to cover the individual MNO needs. Our proposal, namely RE BG (RE-BG), uses Shapley Value (SV) so that the cooperative act continues. SV ensures fairness in RE volume allocation among players MNOs, as it assesses their individual contribution to the obtained result [87].

- a non-cooperative aggregator-assisted energy trading scheme, applicable to InP provided EH-SBSs that are managed by rival MNOs. We propose an aggregator-assisted energy trading among the EH-SBSs of rival MNOs that follows after an aggregator-assisted energy trading within the network managed by each single MNO. The aggregator ensures the exchange of low RE volumes among EH-SBSs via the SG, given that they are randomly located within the macrocell area and cannot be connected with power lines. Moreover, the aggregator prevents the extensive disclosure of private MNO information to rival ones, e.g., traffic levels of all their EH-SBSs. However, the aggregator has different characteristics from and rival interests with the MNOs.

  Thus, we propose a non-cooperative RE double auction (DA) scheme, namely RE-DA, for RE trading. DA has been used to describe resource allocation based on price regulations [87, 101, 102, 103, 104], resource allocation in combination with power allocation and interference control [105], e-markets [106, 107] and energy exchange among micro-grids [108]. A DA energy trading scheme is proposed in [34] for wireless networks, without making reference though to multi-MNO implications. Our RE-DA scheme regulates trading of harvested and stored RE of each EH-SBS of the different MNOs, after an initial internal REE has taken place among the EH-SBSs of the same MNO. Eventually, the EH-SBSs of an MNO apply DA either having only abundant or shortage in RE volume, thus acting only as seller or buyer players, respectively. It is noted that a seller EH-SBS enters the DA supplying the RE volume at the price that best fits its future needs. The aggregator acts as auctioneer, preserving privacy of information and receiving a fit compensation.

- an evaluation of the schemes based on (i) the green energy utilisation, (ii) the reduction of expenses on SG energy purchases and (iii) the satisfaction of all parties involved, as they are main aims of our proposed solutions.

The rest of this chapter is organised as follows: Section 4.2 provides the system model of our work and Section 4.3 refers to the challenges it addresses with respect to EE. Sections 4.4 and 4.5 describe our EE proposals. Section 4.6 presents the performance results of our proposals. Section 4.7 concludes the chapter. Finally, it is noted that Table 4.1 provides the basic notation used in this chapter.

Table 4.1: Basic Notation

$\mathcal{N}$	Set of MNOs, Set of EH-MBSs, with cardinality N, indexed by n
$\mathcal{S}$	Set of cooperative MNOs, with cardinality S, indexed by s, $\mathcal{S} \subseteq \mathcal{N}$
t	Time slot with duration τ
$\mathcal{K}$	Set of UEs, with cardinality K, indexed by k
$\mathcal{L}$	Set of EH-SBSs provided by the InP, with cardinality L, indexed by l.
ν_n	Percentage of L managed by MNO n.
$\mathcal{M}$	Set of EH-BSs, MBS or SBS, with cardinality $M = N + L$, indexed by m $m \leq N$: EH-MBS, $N < m \leq (N + L)$: EH-SBS
P_m	Power needs of m, *(Watt)*
P_m^{out}	Output transmit power of m, *(Watt)*
P_m^{pass}	Shared power needs of m at min. non-zero P_m^{out}, *(Watt)*
P_m^{con}	Non-shared power needs of m at min. non-zero P_m^{out}, *(Watt)*
h_m	Harvested RE at m, *(Wh)*
z_m	Stored RE at ESS of m, *(Wh)*
c_b	Unit price of buying energy from the SG, *(€/Wh)*
c_s	Unit price for selling energy to the SG, *(€/Wh)*
c_a	Unit price for practising initial interior REE, *(€/Wh)*
g_m^*	Max. RE volume exchanged by m with the SG, *(Wh)*
e_m^*	Max. RE volume exchanged by m via REE, *(Wh)*
B	Bankruptcy problem
V_B	Utility function for B
Ω	Sum of RE for allocation with bankruptcy
$\mathcal{X}$	Set of seller EH-SBSs, with cardinality X, indexed by x, $\mathcal{X} \subseteq \mathcal{L}$
$\mathcal{Y}$	Set of buyer EH-SBSs, with cardinality Y, indexed by y, $\mathcal{Y} \subseteq \mathcal{L}$
ϵ_r^-	RE supplied by indicated r, member of indicated set $\mathcal{R}$, via IndREE, *(Wh)*
ϵ_l^+	RE received by indicated r, member of indicated set $\mathcal{R}$, via IndREE, *(Wh)*
$E_r^{\mathcal{R}}$	Claim/Reservation RE of indicated r, member of indicated set $\mathcal{R}$, *(Wh)*
$\Phi_r^{\mathcal{R}}$	Reservation price of indicated r, member of indicated set $\mathcal{R}$
$e_r^{\mathcal{R}}$	Payoff RE volume of indicated r, member of indicated set $\mathcal{R}$, *(Wh)*
$\phi_r^{\mathcal{R}}$	Trading price of indicated r, member of indicated set $\mathcal{R}$
G	Critical point of trading with double auction
Q	Total RE volume traded with double auction, *(Wh)*
ADA	Payoff allocated to the auctioneer of double auction

4.2 System Model

In the present section, we describe the technical details of our system model, which can be observed in Fig. 4.1.

4.2.1 System Model and Operation

In accordance to Fig. 4.1a, we assume a set of MNOs $\mathcal{N} = \{1, .., n, .., N\}$ in a macrocell-sized area serving in time slot t a total set $\mathcal{K}(t) = \{1, .., k, .., K(t)\}$ of user equipment devices (UEs), uniformly distributed in space[2]. Each MNO n operates a two-tier HetNet that is consisted of EH-BSs, i.e., BSs powered by a hybrid use of an EHS, an ESS and, finally, the SG with the aid of an aggregator. Thus, based on the categorisation of Chapter 2, all EH-BSs are considered grid-connected, with an ESS. The small cell tier is consisted of a total set $\mathcal{L} = \{1, .., l, .., L\}$ of EH-SBSs, uniformly distributed in the studied area and owned by an InP. Each MNO $n \in \mathcal{N}$ has the management of an ν_n percentage of $\mathcal{L}$. The macrocell tier of each MNO n is consisted of one EH-MBS, forming a total EH-MBS set that is equal to the MNO one, $\mathcal{N}$. The EH-MBSs are owned and passively shared by $\mathcal{N}$. As can be observed in Fig. 4.1b, the passive sharing includes sharing of energy and expenses corresponding to the main supply, cooling system, shelter, ESS and EH infrastructure. On the contrary, operation and expenses corresponding to the baseband unit (BBU), feeders and antennas are an individual and exclusive responsibility of each MNO. Let the total set of BSs in the studied area be $\mathcal{M} = \{1.., N, (N+1), .., (N+L)\}$. If $m \leq N$, then $m \in \mathcal{M}$ corresponds to an EH-MBS, while if $N < m \leq (N+L)$, to an EH-SBS. In case of RE shortage, all $m \in \mathcal{M}$ can proceed to an aggregator-aided energy trade with the SG[3].

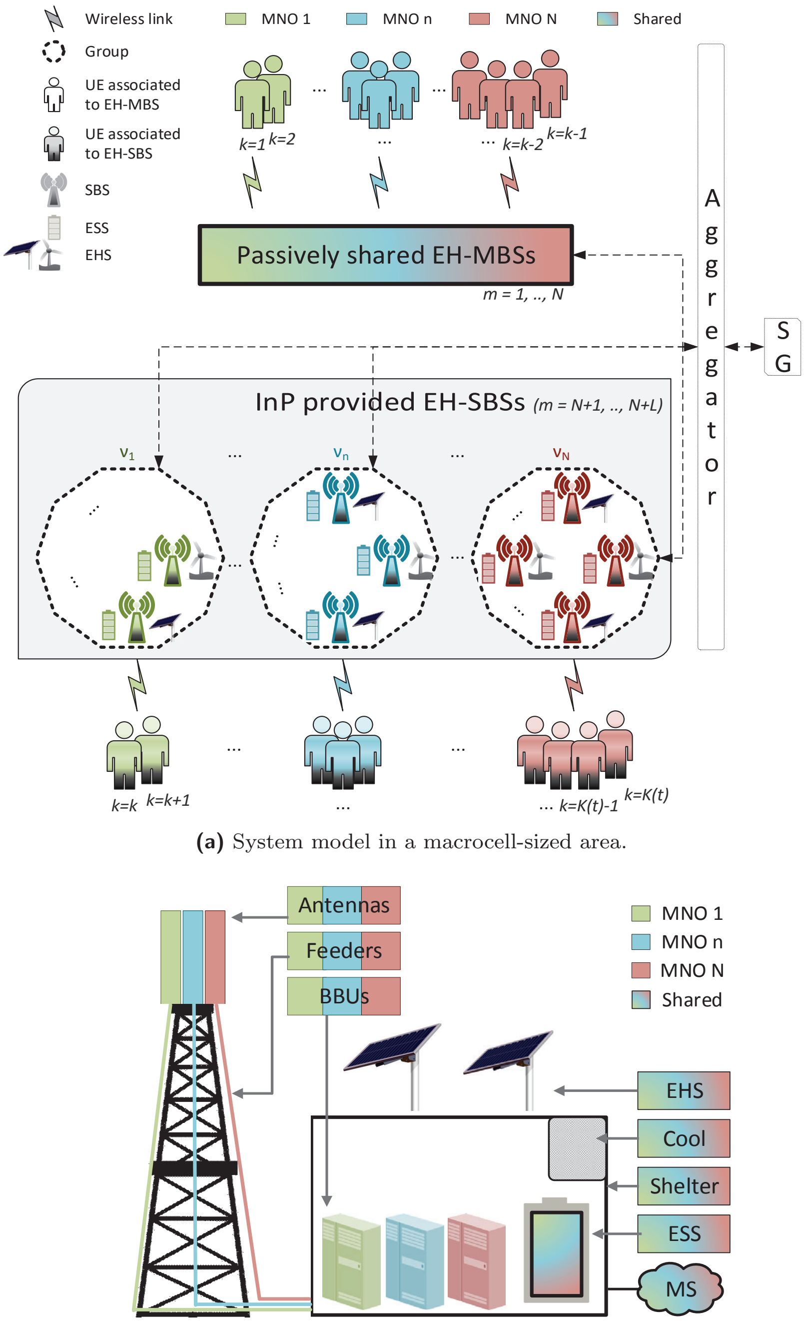
In order to analyse the power consumption at a BS site, we focus on the downlink (DL) network side, where BS power consumption can follow a linear model of power consumption with regard to traffic load volumes [15]. In the DL, orthogonal frequency division multiple access is assumed, with transmission of information in resource blocks (RBs). Sections 4.2.1 and 4.2.1 that follow describe thus the channel and energy consumption model that have been assumed, respectively.

Channel Model

Let $\chi(t)$ be a UE traffic pattern. Then, the UE traffic load of an MNO $n \in \mathcal{N}$ can be described as $\chi_n(t) = \kappa_n \chi(t)$, where $\kappa_n \in \mathbb{R}_{++}$ for a slot t, with uniform space distribution. Thus, a total UE set $\mathcal{K}(t)$ is formed at t, with cardinality $K(t) = \sum_{n=1}^{N} \chi_n(t)$. Each UE $k \in \mathcal{K}(t)$ gets connected to an $m \in \mathcal{M}$, that is owned or managed by its own provider MNO and with which it has the best signal-to-noise

[2]The macrocell-sized area is defined by an the radius of an MBS in the centre of it, while SBSs are uniformly overlaid in its coverage by the InP.

[3]The load of a BS is not larger than 10MW. Therefore trading with the SG has to be aggregator aided.



(a) System model in a macrocell-sized area.

(b) Passively shared infrastructure.

Figure 4.1: Detailed system model.

ratio, $SNR_{km}(t)$, larger than an SNR threshold, SNR_{th}. We calculate $SNR_{km}(t)$ as [79]

$$SNR_{km}(t) = P_m^{tx,sub} + G_m^{tx} - PL_{km}(t) - FL_{km} - N_{th} - NF, \tag{4.1}$$

where $P_m^{tx,sub} = 10log_{10}\left(P_m^{tr} / \left(12TRX_m PRB_m\right)\right)$ represents the power allocated to each subcarrier of EH-BS m *(dBm)*, with P_m^{tr} being the maximum transmission power of m *(W)*, TRX_m being the number of transceiver chains at m and PRB_m being the number of allocated RBs to m [4]. Moreover, in eq. (4.1), G_m^{tx} denotes the antenna gain of m (including feeder losses *(dBi)*) and $PL_{km}(t)$ is the pathloss between UE k and BS m at t *(dB)*. Finally, FL_{km} represents the slow fading losses *(dB)* as a random variable of log-normal distribution, with zero mean deviation and a standard deviation σ_m, N_{th} is the thermal noise and NF is the noise figure.

The guaranteed bit rate demand, ϱ_k (Mb/s) of a UE $k \in \mathcal{K}(t)$, can be expressed in RBs as

$$w_{km}(t) = \sum_{k\ in \mathcal{K}} \zeta_{km}(t) \cdot \lceil \frac{\varrho_k}{W_m^{RB} f(SNR_{km}(t))} \rceil. \tag{4.2}$$

In eq. (4.2), W_m^{RB} is the bandwidth that corresponds to an RB pair of m and $f(SNR_{km}(t))$ is the spectral efficiency of the link between k and m at slot t. Given that adaptive modulation and coding is adopted over any radio link, we map the requested data rate ϱ_k and $SNR_{km}(t)$ to a respective spectral efficiency as indicated in [80, Table A.2]. We also denote with $\zeta_{km}(t)$ the association state of k with m at t, which is equal to 1 when k is associated to m and 0 otherwise.

Power consumption system model of EH-BSs

Based on [15], we model the power needs $P_m(t)$ of an EH-BS $m \in \mathcal{M}$ at slot t as

$$P_m(t) = TRX_m \left(P_m^{pass} + \Delta_m P_m^{out}(t)\right), \quad P_m^{out}(t) = \frac{\sum_{k=1}^{K} w_{km}(t)}{W_m} P_m^{tr}, \tag{4.3}$$

where Δ_m is the slope of load-dependent power consumption and P_m^{out} is the output transmit power of BS m. P_m^{out} is described as the portion of the maximum transmit power of m, P_m^{tr}, as it is defined by the occupied number of RBs at m during t, i.e., $\sum_{k=1}^{K} w_{km}(t)$, and the total number of RBs, W_m, that is allocated to m by default. It is noted that the consideration of the $\frac{\sum_{k=1}^{K} w_{km}(t)}{W_m}$ term was based on the assumption that P_m^{tr} is equally allocated to the each subcarrier and RB that are available by default at the BS. Finally, P_m^{pass} stands for the total power consumption of m at minimum non-zero output power. Based on [15], we model P_m^{pass} as

$$P_m^{pass} = P_m^{con}/S. \tag{4.4}$$

In eq. (4.4), P_m^{con} represents the power needs of a non-shared BS m at the minimum non-zero output power, while S is the cardinality of the set $\mathcal{S} \subseteq \mathcal{N}$ of MNOs who

[4] It is noted that 1 RB is equal to 12 subcarriers in the frequency domain and 0.5 ms in the time domain.

participate in the passive sharing of m. When $m \leq |\mathcal{S}|$, i.e., when m is an MBS, then, apparently, $|\mathcal{S}| > 1$. Otherwise, $|\mathcal{S}| = 1$.

The energy procurement source of an EH-BS m $\in \mathcal{M}$ is controlled and changed accordingly by a charge control system (CCS)[5] that is able to measure and arrange energy availability from each source. Aiming at achieving a purely green network operation with reduced operational expenses (OpEx), we assume the hereafter described energy sources.

Energy harvesting (EH)

EH is the primary energy procurement source for the EH-BSs and is either solar (harvested with photovoltaic panels) or aeolian (harvested with wind turbines). Solar energy has been opted as RE source for the energy hungry MBSs, since its harvesting is periodic and reduces probability for energy outages. However, we assume both solar and wind as RE source for SBSs to enhance chances of RE availability in the whole network.

Depending on the case, we calculate the amount of harvested RE $h_m(t)$ *(J)* at BS m for the duration τ of a slot t as [109, 110]

$$h_m(t) = \begin{cases} PV_m \cdot H_m \cdot \tau \cdot (1 - \eta_{sol,m}) \cdot sin(2\pi\tau/T_{RE}), & sun \\ \frac{1}{2} \cdot WN_m \cdot \rho \cdot A \cdot v^3 \cdot C_m \cdot \tau, & wind. \end{cases} \tag{4.5}$$

In the *sun* case of eq. (4.5), PV_m is the number of photovoltaic panels at BS m, H_m stands for the average solar generation of the panel at m and in the studied area $(Wh/m^2/hour)$, while $\eta_{sol,m} \in [0, 1]$ is the percentage of panel RE losses due to temperature, cleanness and shading, mismatching operation of elements, wiring and ageing [111]. Lastly, T_{RE} is the period of solar generation. In the *wind* case of eq. (4.5), WN_m is the number of wind turbines at m, ρ is the air density $\left(kg/m^3\right)$ and v is the wind velocity (m/s). $A = \pi b^2$ is the area swept by the turbine rotor blades $\left(m^2\right)$, where b corresponds to the rotor blade radius. Lastly, C_m is the power coefficient or rotor efficiency and is a function of tip speed ratio and pitch angle.

ESS

The utility of an ESS is described as the storage of abundant harvested RE, i.e., $max\left\{h_m(t) - \tau P_m(t), 0\right\}$, as a provision against RE shortage events. Therefore, it is the second energy procurement source to which the CCS prompts the EH-BS. The RE volume that is stored in the ESS during slot t is $max\left\{(h_m(t-1) - \tau P_m(t-1)) \cdot (1 - \eta_{ESS,m}), 0\right\}$, where $\eta_{ESS,m} \in [0, 1]$ is an energy loss factor due to battery deficiencies [54]. However, if $z_m(t)$ is the energy available at the ESS of m at the beginning of slot t, $z_m(t)$ has an upper and lower bound. $z_m(t)$ is upper bounded by the maximum storage capacity Z_m at m. We calculate Z_m based on the nominal values of the batteries

[5]CCS is referred to as integrated power unit (IPU) in Chapter 2.

used to compose the ESS and their number. More specifically, it is

$$Z_m = \Psi_m V_m I_m, \tag{4.6}$$

where Ψ_m is the total number of batteries composing the ESS (in serial connection) of BS m, while V_m and I_m is the nominal voltage and capacity, respectively, of each battery. Each ESS battery is also characterised by its depth of discharge, DOD, which prevents the degradation of its health. Thus, $z_m(t)$ is both upper and lower bounded with: $(1 - DOD) \cdot Z_m \leq z_m(t) \leq Z_m$.

Aggregator and Smart grid (SG)

SG connection via an aggregator is assumed for every BS $m \in \mathcal{M}$ as the last energy procurement source for the EH-BS, so that energy provision is reassured in case of RE outages and so that MNOs can trade with the SG. In detail, EH-BSs can trade an energy amount g_m with the SG via the aggregator. The trade can be either a purchase from the SG at a unit price c_b *(€/J)* or a sale to the SG at a unit price c_s *(€/J)*, with $c_s \leq c_b$, of an energy amount with maximum absolute value

$$|g_m^*(t)| = \left|h_m(t) + z_m(t^-) - \tau P_m(t)\right|. \tag{4.7}$$

In eq. (4.7), $z_m(t^-) = max\{(h_m(t-1) - \tau P_m(t-1)) \cdot (1 - \eta_{ESS,m}), 0\}$ represents the ESS energy that BS m has at the beginning of slot t, before any energy procurement takes place from it.

4.3 RE exchange (REE) and challenges

Aiming at further extending the prospects of cost and energy saving in the multi-stakeholder network deployment of our system model, we suggest the inclusion of RE exchange (REE) acts among the EH-BSs of both the macro- and small cell tier, before their MNOs proceed to trades with the SG. In detail, we suggest that REE acts occur if the sum of stored and abundant RE is

- sufficient to cover the energy needs of EH-BS $m \in \mathcal{M}$, i.e., $\tau P_m(t) \leq h_m(t) + z_m(t^-)$.
- insufficient to cover the energy needs of EH-BS $m \in \mathcal{M}$, i.e., $\tau P_m(t) > h_m(t) + z_m(t^-)$.

Let $e_m(t)$ *(J)* be the RE volume that m exchanges through REE acts for slot t. The highest absolute value of $e_m(t)$ is

$$|e_m^*(t)| = \left|h_m(t) + z_m(t^-) - \tau P_m(t)\right|, \tag{4.8}$$

while energy volume traded with the SG of eq. (4.7) becomes

$$|g_m^*(t)| = \left|h_m(t) + z_m(t^-) \pm e_m^*(t) - \tau P_m(t)\right|. \tag{4.9}$$

However, challenges are presented about how to extract the $e_m(t)$ RE volumes with an REE scheme that is, firstly, applicable to multi-MNO and multi-tiered network architectures, and, secondly, fairly regulated among the stakeholders of the REE. As explained in Section 4.1, in order to address this challenge, we proceed to study the REE prospects in our system model as a two-branched study case, which is described as *(i)* the passively shared EH-MBSs and *(ii)* the InP provided EH-SBSs.

For the first case, we formulate REE as a cooperative energy sharing scheme via power lines for the energy transfer that addresses fairness issues. The passively shared EH-MBSs of our system model, have the fundamental role of providing seamless umbrella coverage, while doing a green and economic energy management of the utmost fairness for the owner MNOs. Thus, fairness in sharing the harvested and stored RE volumes of the site's EHS and ESS, respectively, is a critical issue to address, as both group and individual MNO profits have to be protected. Simple strategies, such as equal allocation of the total RE volume or allocation with demand magnitude priority could be easy solutions to adopt and ultimately extract the $e_m(t)$ RE volumes. However, such strategies may result into a distribution that could be not only energy and cost inefficient, but also unfair to some MNOs. MNOs have to overcome any arisen inefficiency and fairness issues and seek an energy neutral EH-MBS operation.

For the second case, we formulate REE as a non-cooperative aggregator-assisted energy trading scheme. The EH-SBSs are overlaid in the whole macrocell area and an REE act among them would demand revealing extensive information on the individual MNO activity. However, MNOs may prefer to keep this information private, especially when sharing of the macrocell tier makes public some of their characteristics. MNOs could negotiate directly amongst them for the encounter of a solution and the extraction of the $e_m(t)$ RE volumes. However, this can lead to strategy exposure and hazard both their individual future energy planning and profits, while multiple negotiations for multiple network elements with energy needs increase the complexity of negotiations.

Fig. 4.2 describes our suggested energy procurement strategy to be followed by the EH-MBSs and EH-SBSs. As can be observed, for the passively shared EH-MBSs, we propose an approach, namely RE-BG, that treats the abundant and stored RE as a predefined entity that has to be completely allocated in $e_m(t)$ RE volumes to the passively shared EH-MBSs. RE-BG is executed at the CCS of the site. After the application of RE-BG, EH-MBSs can trade energy with the SG, via the aggregator. For the InP provided EH-SBSs, we propose an aggregator-assisted approach, namely RE-DA, that runs in parallel with the RE-BG scheme. RE-DA can be applied by EH-SBSs of the different MNOs after the EH-SBSs have procured RE, firstly, from the EHS and, secondly, from the ESS of the site. Moreover, for an inter-MNO REE to occur, we assume that an initial interior REE, which is based on the least difference in the abundant and lacked RE volume at the EH-SBSs of the

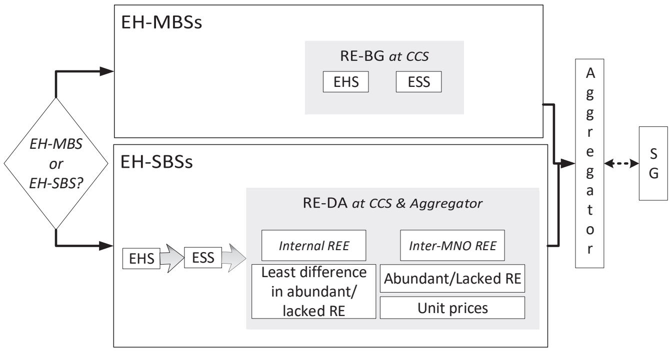


Figure 4.2: Suggested energy procurement order.

same MNO, is preceded. Thus, with RE-DA, MNOs carefully extract at the CCS the information pieces they reveal to rival MNOs, i.e., the abundant or lacked RE at their site and respective unit prices, which they communicate to the impartial aggregator. For a decision, they take into consideration current and, occasionally, future energy needs, as well as the profitability of their options. The latter then extracts the traded multi-MNO $e_m(t)$ RE volumes and respective trading prices. After the application of RE-DA, EH-SBSs can trade energy with the SG, with the help of the aggregator.

4.4 Energy sharing among EH-MBSs

As a result of the adopted passive sharing, we assume that MNOs share an EHS, composed of solar panels, and an ESS along with the equipment of their collocated MBSs. Then, the EH-MBSs apply an REE scheme of sharing the harvested and stored RE in order to ultimately achieve energy neutrality before proceeding to an energy trade with the SG. The transfer of RE is implemented via power lines that have been installed by the MNOs. Energy losses due to power lines are considered negligible due to the short length of power lines.

During daylight, when solar energy generation varies, and at the beginning of a slot t, each shared EH-MBS makes an estimation of its expected energy needs for the duration τ of t. Based on the extracted estimation, the shared CCS makes the energy management of the shared EH-MBSs for the duration τ of t. However, during night-time, when solar energy harvesting is zero[6], a decision has to be made for the REE act, based only on the stored RE. Therefore, each shared EH-MBS makes an estimation of its expected energy needs during a slot t', which corresponds to a set of slots t [7]. Based on the extracted estimation, the shared CCS makes the energy

[6] It is noted that, in terms of simplicity, for periods of non-existent solar energy generation, solar energy harvesting is zero.

[7] In terms of simplicity and without loss of generality, we continue the analysis in the present section making reference to slot t.

management of the shared EH-MBSs for the duration τ' of t'.

We model the energy sharing problem among the shared shared EH-MBSs, using cooperative game theory. Motivated by the utilities of the bankruptcy games, which we explained in Chapter 3, we apply the method in the case of energy sharing as well. In detail, we use the concept of a bankruptcy game, according to which a specific *entity* needs to be completely allocated among a specific group of *players* [85, 86]. Each player makes a *claim* on the entity. A *utility function* is set for the game, which eventually allocates to each player a part of the entity, i.e., the *payoff*.

Regarding the considered scenario, this entity, let $\Omega(t)$, corresponds to the sum of *(i)* the harvested RE $h(t)$ that is collected from the shared EHS and *(ii)* the available stored RE $z(t^-)$ at the shared ESS, when the sum is either over-sufficient or insufficient to cover the power needs $P(t)$ of the passively shared EH-MBSs for the duration τ of a slot t, i.e., $\tau P(t) \leq h(t) + z(t^-) = \Omega(t)$ and $\tau P(t) > h(t) + z(t^-) = \Omega(t)$, respectively. Entity $\Omega(t)$ has to be fairly and completely provided to the EH-MBSs that are passively shared a set of MNOs $\mathcal{S} \subseteq \mathcal{N}$. The EH-MBSs, or, as there is a one-to-one correspondence, their owner MNO, of coalition $\mathcal{S}$ can be portrayed as the players of the game. Each player $s \in \mathcal{S}$ claims an amount $E_s(t) = \tau P_s(t)$ of the entity $\Omega(t)$ so as to achieve an purely green operation of its EH-MBS, s, with $P_s(t)$ being defined as in eq. (4.3).

Thus, we have a bankruptcy problem, $B(t)$ modelled as

$$B(t) = \left\{ \ \left(\Omega(t),\ E_s(t) \in \mathbb{R}_{++} \times \mathbb{R}_+^{|\mathcal{S}|}\right) : \Omega(t) \leq \textstyle\sum_{s=1}^{|\mathcal{S}|} E_s(t) \ \right\}. \tag{4.10}$$

We define the utility function of the bankruptcy game, $V_{B(t)},\ \ V_{B(t)}:\ 2^N \times \mathbb{R}$, which evaluates the bankruptcy problem $B(t)$ and associates it to a real value, as

$$V_{B(t)}\left(\mathcal{S}\right) = \begin{cases} min\left\{E_{s\in\mathcal{S}}(t), \Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right\} & , \mathcal{S} = \{s\} \\ min\left\{\sum_{s\in\mathcal{S}} V_{B(t)}\left(s\right), \Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right\} & , \mathcal{S} \neq \{s\}\,. \end{cases} \tag{4.11}$$

Eq. (4.11) practically represents the amount of energy that can be allocated, after the non-participants in coalition $\mathcal{S}$ have received their claim. Thus, in an individual act of MNO, i.e., $\mathcal{S} = \{s\}$, the game value $V_{B(t)}\left(s\right)$ is equal to either the total amount of its claim, $E_s(t)$, or the remaining amount of $\Omega(t)$, after non-participant MNOs in $\mathcal{S}$ have taken their share. Similarly, in a coalition with more than one participants, i.e., $\mathcal{S} \neq \{s\}$, the game value $V_{B(t)}\left(\mathcal{S}\right)$ can be either the sum of individual act values $V_{B(t)}\left(s\right)$ or the remaining $\Omega(t)$, after non-participant MNOs in $\mathcal{S}$ have satisfied their needs.

However, if $V_{B(t)}\left(\mathcal{S}\right) < \left(\Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right)$, then $V_{B(t)}\left(\mathcal{S}\right) = 0$. This is due to the fact that entity $\Omega(t)$ needs to be totally allocated to the cooperative MNOs [85, 86]. Consequently, when $V_{B(t)}\left(\mathcal{S}\right) < \left(\Omega(t) - \sum_{s\notin\mathcal{S}} E_s(t)\right)$, $\Omega(t)$ is insufficient to cover the energy needs of the total shared system and the game value is 0.

In order to ensure a viable solution for the bankruptcy game, the energy amounts that will eventually be allocated to the participants in a coalition $\mathcal{S}$, i.e., the extracted payoffs, need to fulfil certain constraints. Let $e_s(V_{B(t)}(\mathcal{S}))$ be the payoff of player $s \in \mathcal{S}$ for participating in the bankruptcy game $B(t)$ with the utility function $V_{B(t)}$. Then, $e_s(V_{B(t)}(\mathcal{S}))$ is the volume of $\Omega(t)$ that is allocated to a player $s \in \mathcal{S}$ and is subjected to the following constraints:

- The sum of allocated payoffs should equal $V_{B(t)}(\mathcal{S})$:

$$\sum_{s\in\mathcal{S}} e_s(V_{B(t)}(\mathcal{S})) = V_{B(t)}(\mathcal{S}). \tag{4.12}$$

- The payoff of a player s in a coalition $\mathcal{S}$ should be at least equal to the payoff of its stand-alone action:

$$e_s(V_{B(t)}(\{s\})) \leq e_s(V_{B(t)}(\mathcal{S})). \tag{4.13}$$

- A player s cannot receive a higher payoff than its claim, so that fairness is preserved.

$$0 \leq e_s(V_{B(t)}(\mathcal{S})) \leq E_s(t). \tag{4.14}$$

We use Shapley Value (SV) so as to solve the problem, i.e., to calculate the payoffs $e_s(V_{B(t)}(\mathcal{S}))$ of the described bankruptcy game [87]. SV rewards a player $s \in \mathcal{S}$ with the SV payoff that portrays its marginal contribution to the coalition value, based on the utility function of the game. In the present case, SV payoffs $e_s(V_{B(t)}(\mathcal{S}))$ represent the contribution in generating $\Omega(t)$, when an $\mathcal{S}$ is formed and based on the utility function $V_{B(t)}(\mathcal{S})$ of eq. (4.11). SV has four basic axioms [87]:

- Efficiency axiom: $\sum_{s\in\mathcal{S}} e_s(V_{B(t)}(\mathcal{S})) = V_{B(t)}(\mathcal{S})$.
- Dummy axiom: If a player s is such that $V_{B(t)}(\mathcal{S}) = V_{B(t)}(\mathcal{S} \cup \{s\})$, then for $\forall \mathcal{S}'$, $\mathcal{S}' = \mathcal{S} - \{s\}$, it is $e_s(V_{B(t)}(\mathcal{S}')) = 0$.
- Symmetry axiom: If two players s_1 and s_2 are such that $V_{B(t)}(\mathcal{S} \cup \{s_1\}) = V_{B(t)}(\mathcal{S} \cup \{s_2\})$, then for $\forall \mathcal{S}'$, $\mathcal{S}' = \mathcal{S} \cup \{s_1, s_2\}$ it is $e_{s_1}(V_{B(t)}(\mathcal{S}')) = e_{s_2}(V_{B(t)}(\mathcal{S}'))$.
- Additivity axiom: If V_1 and V_2 are characteristic functions, then $e(V_1 + V_2) = e(V_1 + V_2) = e(V_1) + e(V_2)$.

For the bankruptcy game, the efficiency axiom of SV remains valid when the game is defined by the player set, i.e., coalition S. The remaining axioms remain valid for the proposed game.

SV has an impact as a solution to the described problem since it displays a player's worth in the studied game, when the player joins coalition $\mathcal{S}$. Thus, we calculate the payoff of each player $s \in \mathcal{S}$ via the canonical definition of the SV payoff, which, based on the utility function V_B of eq. (4.11), is

$$e_s\left(V_{B(t)}(\mathcal{S})\right) = \sum_{\mathcal{S}\subseteq\mathcal{N}\setminus\{s\}} \frac{|\mathcal{S}|!\,(|\mathcal{N}| - |\mathcal{S}| - 1)!}{|\mathcal{N}|!} \left[V_{B(t)}(\mathcal{S} \cup \{s\}) - V_{B(t)}(\mathcal{S})\right]. \tag{4.15}$$

The computational complexity of RE-BG is $\mathcal{O}(2^N)$, where N is the number of MNOs participating in the sharing [112]. This is because, results of all different coalition forms of $\mathcal{N}$ MNOs have to be examined. Given a large $|\mathcal{N}|$, the scheme's complexity increases tremendously. In the studied case though, it is acceptable as the number of MNOs, N cannot be too high.

4.5 Energy trading among EH-SBSs

We assume that MNOs lease EH-SBSs from an InP. All EH-SBSs are connected to the SG via an aggregator. We prompt MNOs to adopt an REE scheme of aggregator-assisted energy trading among their EH-SBSs, so as to ultimately achieve energy neutrality before trading energy with the SG. In detail, at the beginning of a slot t, each EH-SBS makes an evaluation of its expected energy needs and harvested RE for the duration τ of t. Taking into consideration the available stored RE at the ESS at the beginning of t, the CCS of the site calculates the RE volume that the EH-SBS is able to supply or demand at a trade.

This information is communicated to the impartial aggregator, who arranges an initial interior REE amongst the EH-SBSs managed by the same MNO. This initial interior REE sorts the buyer EH-SBSs in descending order based on their requested RE volume and matches it to the seller EH-SBS of the same MNO with which it has the least difference between its requested RE volume and the supplied one by each seller EH-SBS. The available RE volumes at the EH-SBSs are updated and the procedure continues until there are no remains either of requested or supplied RE volume at the EH-SBSs of the MNO. The initial internal REE is carried out by the aggregator at the cost of the same unit price $c_a \leq c_b$ *(€/Wh)*. After the initial interior REE, the CCS of each EH-SBS site calculates again the RE volume that the EH-SBS is able to supply or demand for a trade with the EH-SBSs of a different MNO, along with a respective unit price. It is noted that, at this point, the EH-SBSs that are managed by the same MNO enter an energy trading procedure with EH-SBSs of a rival MNO either having abundant RE at their EH-SBSs only or shortage in it.

The new reservation RE volumes and prices of each EH-SBS are communicated to the impartial aggregator, who eventually extracts the new RE trading volume and price for each EH-SBS and for slot t, and the payoff for its service. Payments are executed through monetary transactions among the involved parties, while the aggregator arranges the energy transfer act through the SG. Therefore, we assume that the energy transfer is managed by the aggregator on a cloud level and that the SG delivers RE volumes to recipient EH-SBSs with energy shortage having negligible energy losses.

We model the energy trading problem of the EH-SBSs managed by different MNOs using non-cooperative game theory. More specifically, we use the concept of double auction (DA), which is applicable to cases where multiple *sellers* and *buyers* are active [87]. In a DA, each seller and each buyer supplies and demands, respectively, a number of *items*. All sellers report a price for the item, i.e., the *asking price*, while all buyers propose another price, i.e., the *bidding price*. The prices correspond to a single item unit. A *trading point* among sellers and buyers is eventually determined based on the demanded and supplied quantities of the traded item, as well as from the asking and bidding prices. The DA can be executed in a distributed manner or in a central location by an *auctioneer*.

Regarding the considered scenario, we simulate as a DA the procedure of the aggregator-assisted energy trading among the EH-SBSs that are managed by different MNOs. We set harvested and stored RE, as well as the RE volumes exchanged with initial interior REE, as the trade item of the DA, the EH-SBSs as the DA buyers and sellers and the aggregator as the DA auctioneer. The total set of EH-SBSs, $\mathcal{L} = 1, .., l, .., L$, is consisted of

- a set of EH-SBSs that have abundant RE in comparison to their energy needs $\tau P_l(t)$, i.e., $\tau P_l(t) \leq h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t)$.
- a set of EH-SBSs that have shortage in RE in comparison to their energy needs $\tau P_l(t)$, i.e., $\tau P_l(t) > h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t))$,

where $\epsilon_l^-(t)$ and $\epsilon_l^+(t)$ are the RE volumes provided and received with the initial interior REE, respectively.

The RE volume $E_l(t)$ that each EH-SBSs l has at this point in abundance or shortage corresponds to the reservation RE volume that the EH-SBS l wants to supply or demand, respectively, by an EH-SBS of a rival MNO. $E_l(t)$ is

$$E_l(t) = h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t) - \tau P_l(t). \tag{4.16}$$

The $E_l(t)$ is communicated to the auctioneer-aggregator, who then separates the set $\mathcal{L}$ to ordered sets of seller and buyer EH-SBSs, $\mathcal{X}$ and $\mathcal{Y}$, respectively. If

- $E_l(t) \geq 0$, then EH-SBS l is a seller and $l \in \mathcal{X}$. We will hereafter refer to the $E_l(t)$ of a seller as $E_l^{\mathcal{X}}(t) = E_l(t)$.
- $E_l(t) < 0$, then EH-SBS l is a buyer and $l \in \mathcal{Y}$. We will hereafter refer to the $E_l(t)$ of a buyer as $E_l^{\mathcal{Y}}(t) = |E_l(t)|$.

Along with the reservation RE volumes, each EH-SBS $l \in \mathcal{L}$ communicates to the auctioneer-aggregator as well its reservation, asking or bidding, unit price *(€/Wh)* to reserve its participation in the DA. Let $\Phi_l^{\mathcal{X}}$ be the reservation asking price of a seller $l \in \mathcal{X}$ and $\Phi_l^{\mathcal{Y}}$ the reservation bidding price of a buyer $l \in \mathcal{Y}$. Let us note that none of the buyers or sellers splits its volume so as to ask a different reservation price for each category. For the extraction of their values, we assume that seller and buyer EH-SBSs follow a different strategy.

4.5.1 Sellers

Each seller EH-SBS $l \in \mathcal{X}$ is characterised by a utility function, $U_l^{\mathcal{X}}(t)$, which values the significance of its $E_l(t)$ in relation to its own energy needs. We set

$$U_l^{\mathcal{X}}(t) = \delta_l^{\mathcal{X}}(t) \cdot ln\left(1 + E_l^{\mathcal{X}}(t)\right) + \Phi_l^{\mathcal{X}}(t) \cdot \left(h_l(t) + z_l(t^-) - \epsilon_l^-(t) + \epsilon_l^+(t) - E_l^{\mathcal{X}}(t)\right), \tag{4.17}$$

where $\delta_l^{\mathcal{X}}(t) = \frac{\frac{\tau P_l(t+1)}{h_l(t)+z_l(t^- - \epsilon_l^-(t)+\epsilon_l^+(t))+h_l(t+1)}}{\frac{\tau P_l(t)}{h_l(t)+z_l(t^- - \epsilon_l^-(t)+\epsilon_l^+(t))}} > 0$ is a preference value, which indicates the value of $E_l^{\mathcal{X}}(t)$ of the seller for the current and next slot, t and $(t+1)$, respectively. Thus, the first part of eq. (4.17) represents the value of $E_l^{\mathcal{X}}(t)$ for a future private use by seller $l \in \mathcal{X}$. The second part of eq. (4.17) corresponds to the revenues that $l \in \mathcal{X}$ can obtain during slot t by selling $E_l^{\mathcal{X}}(t)$ at a price $\Phi_l^{\mathcal{X}}(t)$. $U_l^{\mathcal{X}}(t)$ is strictly concave, i.e., $\frac{\partial^2 U_l^{\mathcal{X}}(t)(E_l^{\mathcal{X}}(t))}{\partial\left(E_l^{\mathcal{X}}(t)\right)^2} < 0$ and has a unique optimal that maximises its value. Hence, for a strictly defined $\Phi_l^{\mathcal{X}}(t)$ and a preference $\delta_l^{\mathcal{X}}(t)$, there is a one-to-one correspondence between the best value of $E_l^{\mathcal{X}}(t)$ and $\Phi_l^{\mathcal{X}}(t)$. In eq. (4.16), we calculated the best value of $E_l^{\mathcal{X}}(t)$, $E_l^{\mathcal{X},*}(t)$. Given the $E_l^{\mathcal{X},*}(t)$, a best reservation asking price $\Phi_l^{\mathcal{X},*}(t)$ can be found for seller l when $\frac{\partial U_l^{\mathcal{X}}(t)(E_l^{\mathcal{X}}(t))}{\partial E_l^{\mathcal{X}}(t)} = 0$, with

$$\Phi_l^{\mathcal{X},*}(t) = \frac{\delta_l^{\mathcal{X}}(t)}{1 + E_l^{\mathcal{X},*}(t)}. \tag{4.18}$$

4.5.2 Buyers

Each buyer EH-SBSs $l \in \mathcal{Y}$ makes a reservation for an RE volume $E_l(t)^{\mathcal{Y}}$ for slot t. The RE volume $E_l(t)^{\mathcal{Y}}$ represents the total energy volume that a buyer EH-SBS demands to purchase so that it ensures energy neutrality for t.

For the extraction of their reservation bidding price $\Phi_l^{\mathcal{Y}}(t)$, we assume that each buyer $l \in \mathcal{Y}$ extracts a random value for $\Phi_l^{\mathcal{Y}}$. However, we assume that $c_s \leq \Phi_l^{\mathcal{Y}}(t) \leq \Phi_l^{\mathcal{Y}}(t) \leq c_b$. The restriction implies that the bidding price of the buyer EH-SBS has to be higher than the offered prices by both the set of sellers and the SG and, and at the same time, lower that the price c_b at the cost of which it is able to buy SG energy.

4.5.3 Auctioneer-aggregator

As the DA auctioneer, the aggregator extracts the sets of seller and buyer EH-SBSs, $\mathcal{X}$ and $\mathcal{Y}$, respectively, from the different MNOs that will trade amongst them. Let us remind that, before the DA, the aggregator firstly applies the initial interior REE among the EH-SBSs of a single MNO, matching its buyer EH-SBSs to its seller ones, based on the least difference in their requested and supplied RE volume and until there are no remains either of requested or supplied RE volume. The aggregator then extracts the new sets of seller and buyer EH-SBSs, $\mathcal{X}$ and $\mathcal{Y}$, respectively, based on the revised reservation RE volumes, $E_l^{\mathcal{X}}(t)$ and $E_l^{\mathcal{Y}}(t)$, and prices, $\Phi_l^{\mathcal{X}}(t)$ and $\Phi_l^{\mathcal{Y}}(t)$, of all the seller and buyer EH-SBSs, respectively. We assume that $E_l^{\mathcal{X}}(t)$, $E_l^{\mathcal{Y}}(t)$, $\Phi_l^{\mathcal{X}}(t)$ and $\Phi_l^{\mathcal{Y}}(t)$ are static, i.e., sellers buyers cannot change their values, once they announce them to the aggregator.

Based on these sets and reservation values, the aim of the aggregator is to determine for slot t

- the set of winner seller EH-SBSs, the final RE volumes they have to supply, $e_l^{\mathcal{X}}(t)$, as well as the trading selling price, $\phi_l^{\mathcal{X}}(t)$, at the cost of which they have to sell $e_l^{\mathcal{X}}(t)$.

- the set of winner buyer EH-SBSs, the final RE volumes they will purchase, $e_l^{\mathcal{Y}}(t)$, as well as the trading selling price, $\phi_l^{\mathcal{Y}}(t)$, at the cost of which they have to buy $e_l^{\mathcal{Y}}(t)$.

The decision of the aggregator is subjected to the following restrictions

- $\sum_{l\in\mathcal{X}} e_l^{\mathcal{X}}(t) \leq E_l^{\mathcal{X}}(t),\ \forall l \in \mathcal{X}$, which ensures that none of the sellers sells more energy than it supplies,
- $\sum_{l\in\mathcal{Y}} e_l^{\mathcal{Y}}(t) \leq E_l^{\mathcal{Y}}(t),\ \forall l \in \mathcal{Y}$, which ensures that none of the buyers buys more energy than it demands,
- $e_l^{\mathcal{X}}(t), e_l^{\mathcal{Y}}(t) \geq 0,\ \forall l \in \mathcal{L}$, which ensures the exchange of a non-zero energy volume,
- $c_s \leq \phi_l^{\mathcal{X}}(t) \leq \phi_l^{\mathcal{Y}}(t) \leq c_b$, which ensures the profitability of the DA trades in relation to ones with the SG.

4.5.4 The auction

For the extraction of the aggregator's final decision, our proposed scheme, namely RE-DA, applies a DA, which fulfils the presented aims and restrictions through the hereafter described procedure.

Step 1

The auctioneer-aggregator applies a Vickrey-like auction on each side of the market, so that buyers and sellers report their reservation prices [87, 106]. Without loss of generality and with prices of the same value being randomly sorted, the auctioneer-aggregator sorts the reservation prices of sellers $\forall l \in \mathcal{X}$ and buyers $\forall l \in \mathcal{Y}$ in ascending and descending order. Let X and Y be the cardinalities of sets $\mathcal{X}$ and $\mathcal{Y}$, respectively, and j and i the indices for the ordered set of $\mathcal{X}$ and $\mathcal{Y}$, respectively. It is

$$\Phi_{j=1}^{\mathcal{X}}(t) \leq ... \leq \Phi_j^{\mathcal{X}}(t) \leq \Phi_{j=X}^{\mathcal{X}}(t), \tag{4.19}$$

and

$$\Phi_{i=1}^{\mathcal{Y}}(t) \geq ... \geq \Phi_i^{\mathcal{Y}}(t) \geq \Phi_{i=Y}^{\mathcal{Y}}(t). \tag{4.20}$$

The reservation prices with the corresponding RE volumes are organised as in Fig. 4.3. The point at which the offered RE volumes and asking prices of sellers intersect with the demanded RE volumes and bidding prices of buyers indicate the critical point of trading G. The critical point G is also the intersection point of the j_{th} seller and the i_{th} buyer EH-SBS. In accordance with the Vickrey auction rules, $(j-1)$ are the winner sellers that trade with $(i-1)$ winner buyers. Two cases are discriminated that can reassure the existence of G:

- Asking and bidding prices satisfy $\Phi_{i+1}^{\mathcal{Y}}(t) \leq \Phi_j^{\mathcal{X}}(t) \leq \Phi_i^{\mathcal{Y}}(t)$ and aggregate energy supply and demand satisfy $\sum_{j=1}^{j=j-1} E_j^{\mathcal{X}}(t) \leq \sum_{i=1}^{i=i} E_i^{\mathcal{Y}}(t) \leq \sum_{j=1}^{j=j} E_j^{\mathcal{X}}(t)$.

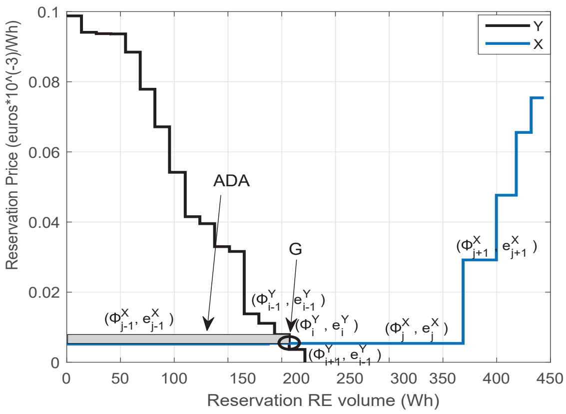


Figure 4.3: Typical DA case between the set of buyer EH-SBSs, $\mathcal{Y}$ and the set of seller EH-SBSs, $\mathcal{X}$ ($\mathcal{Y}$ and $\mathcal{X}$ correspond to the Y and X characters that are indicated in the legend of the figure). The figure depicts the ordering of the DA reservation RE volumes and prices, the critical trade point G with the DA and the DA payoff of the auctioneer-aggregator, ADA.

- Asking and bidding prices satisfy $\Phi_j^{\mathcal{X}}(t) \leq \Phi_i^{\mathcal{Y}}(t) \leq \Phi_{j+1}^{\mathcal{X}}(t)$ and aggregate energy supply and demand satisfy $\sum_{i=1}^{i=i-1} E_i^{\mathcal{Y}}(t) \leq \sum_{j=1}^{j=j} E_j^{\mathcal{X}}(t) \leq \sum_{i=1}^{i=i} E_i^{\mathcal{Y}}(t)$.

In both cases, the market is cleared.

Step 2

The cleared prices of winner sellers and buyers for t, $\phi_{j'}^{\mathcal{X}}(t)$ with $j' = 1, .., j-1$ and $\phi_{i'}^{\mathcal{Y}}(t)$ with $i' = 1, .., i-1$, respectively are set by the auctioneer-aggregator as

$$\begin{cases} \phi_{j'}^{\mathcal{X}}(t) = \Phi_j^{\mathcal{X}}(t), \\ \phi_{i'}^{\mathcal{Y}}(t) = \Phi_i^{\mathcal{Y}}(t). \end{cases} \tag{4.21}$$

The cleared RE volumes for each seller and buyer EH-SBS for t is defined differently for each one of them based on the sum of reservation energy volumes until G. Depending on whether there is RE over-supply from winner sellers or over-demand from winner buyers, the following cases are extracted:

- **Case Overdemand** $\left(\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) \geq \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)\right)$, where the aggregated demanded RE from winner buyers EH-SBSs exceeds the supplied by winner sellers EH-SBSs RE sum. In this case, all winner sellers EH-SBSs sell their total supplied RE volume, i.e., $e_{j'}^{\mathcal{X}}(t) = E_{j'}^{\mathcal{X}}(t)$, $j' = 1, .., j-1$, at the cleared seller price $\phi_{j'}^{\mathcal{X}}(t)$ of eq. (4.21). However, all winner buyers EH-SBSs with indices $i' = 1, .., i-1$ buy at the cleared buyer price $\phi_{i'}^{\mathcal{Y}}(t)$ of eq. (4.21) an RE volume $e_{i'}^{\mathcal{Y}}(t)$ with

$$e_{i'}^{\mathcal{Y}}(t) = E_{i'}^{\mathcal{Y}}(t) - \frac{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) - \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)}{i-1}. \tag{4.22}$$

In the case that $E_{i'}^{\mathcal{Y}}(t) < \frac{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) - \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)}{i-1}$, winner buyer i' pays for a winning traded entity $e_{i'}^{\mathcal{Y}}(t) = E_{i'}^{\mathcal{Y}}(t)$. The remaining RE, described as $\frac{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) - \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)}{i-1} - E_{i'}^{\mathcal{Y}}(t)$, is allocated and bought equally by the remaining winner buyer EH-SBSs.

- **Case Oversupply** $\left(\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t) \leq \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)\right)$, where the aggregated supplied RE from winner seller EH-SBSs exceeds the demanded by winner buyer EH-SBSs RE sum. In this case, all winner buyer EH-SBSs buy their total demanded RE volume, i.e., $e_{i'}^{\mathcal{Y}}(t) = E_{i'}^{\mathcal{Y}}(t)$, $i' = 1, .., i-1$, at the cleared buyer price $\phi_{i'}^{\mathcal{Y}}(t)$ of eq. (4.21). However, all winner seller EH-SBSs with indices $j' = 1, .., j-1$ sell at the cleared seller price $\phi_{j'}^{\mathcal{X}}(t)$ of eq. (4.21) an RE volume $e_{j'}^{\mathcal{X}}(t)$ with

$$e_{j'}^{\mathcal{X}}(t) = E_{j'}^{\mathcal{X}}(t) - \frac{\sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t) - \sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)}{j-1}. \tag{4.23}$$

In the case that $E_{j'}^{\mathcal{X}}(t) < \frac{\sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t) - \sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)}{j-1}$, winner seller j' sells a winning traded entity $e_{j'}^{\mathcal{X}}(t) = E_{j'}^{\mathcal{X}}(t)$. The remaining RE, described as $\frac{\sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t) - \sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)}{j-1} - E_{j'}^{\mathcal{X}}(t)$, is allocated and sold equally by the remaining winner seller EH-SBSs.

Step 3

For the extraction of the payoff compensation corresponding to the auctioneer-aggregator, $ADA(t)$, we consider the total traded RE volume among the winner EH-SBSs, $Q(t)$, as it was extracted from the DA of our scheme RE-DA. $Q(t)$ is calculated as

$$Q(t) = min\left(\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t), \sum_{j'=1}^{j'=j-1} E_{j'}^{\mathcal{X}}(t)\right). \tag{4.24}$$

Thus, we define a payoff for the auctioneer-aggregator $ADA(t)$ at each DA event of slot t equal to

$$ADA(t) = \left(\Phi_i^{\mathcal{Y}}(t) - \Phi_j^{\mathcal{X}}(t)\right) \cdot Q(t), \tag{4.25}$$

where $\Phi_j^{\mathcal{X}}(t)$ and $\Phi_i^{\mathcal{Y}}(t)$ are determined at G. Practically, in order to extract the payoff $ADA(t)$, we take advantage of the difference between the *(i)* trading prices,

$\Phi_j^{\mathcal{X}}(t)$ and $\Phi_i^{\mathcal{Y}}(t)$, at critical point G, and *(ii)* the sum of reservation energies of seller and buyer EH-SBSs until critical point G and winner seller and buyer EH-SBSs.

Step 4

After the extraction of the payoff RE volumes and prices, the values are returned to the winner seller and buyer EH-SBSs. Payments are then implemented through monetary transactions among MNOs and aggregator, while the latter proceeds to energy transfer through the SG.

The complexity of RE-DA is $O(L^2)$. For the execution of RE-DA, the aggregator firstly executes the initial internal REE for each MNO. The initial internal REE makes a quick-sort procedure for the buyer EH-SBSs of each MNO. Then, for each of the buyer EH-SBSs, the RE volume differences with each of the seller EH-SBSs of the MNO is calculated. Finally, a quick-sort procedure of the RE volume differences takes place so that the smallest one can be elected for each of the buyer EH-SBSs of the MNO. The RE volumes of the matched buyer and seller EH-SBSs are updated and the same procedure is repeated for the next buyer EH-SBS in the sorted initial list. The worst case for the initial internal REE of RE-DA occurs when there are two MNO with buyers and sellers whose population is equal in numbers, i.e., their number is equal to $\frac{L}{4}$. Based on the above and given that the quick-sort complexity is $O(nlog(n))$, the complexity of the RE-DA algorithm up to this point is: $O(N) \cdot \left[O(\frac{L}{4}log(\frac{L}{4})) + O(\frac{L}{4}) \cdot \left[O(\frac{L}{4}) + O(\frac{L}{4}log(\frac{L}{4}))\right]\right] = O(N) \cdot O(\frac{L}{4}log(\frac{L}{4})) + O(N) \cdot O(\frac{L}{4}) \cdot O(\frac{L}{4}) + O(N) \cdot O(\frac{L}{4}) \cdot O\left(\frac{L}{4}log(\frac{L}{4})\right) = O(\left(\frac{L}{4}\right)^2) = O(L^2)$, since usually $N << L$. Then, each EH-SBS locally calculates its reservation RE volume and price, while two individual quick-sortings are performed by the auctioneer-aggregator: one for the seller set $\mathcal{X}$ and one for the buyer set $\mathcal{Y}$. The local calculation at the EH-SBSs is of negligible complexity. The quick-sort complexity is $O(nlog(n))$, with $n = L$, i.e., the maximum cardinality that $\mathcal{X}$ or $\mathcal{Y}$ can have. However, the encounter of critical point G and the final payoff extraction that follow are both characterised by an $O(n)$ complexity, with $n = \frac{L}{2}$ in the worst case scenario. Therefore, with a cardinality of $\mathcal{X}$ and $\mathcal{Y}$ equal to $\frac{L}{2}$, the complexity of RE-DA is $O(\left(\frac{L}{4}\right)^2) + O(\frac{L}{2}log(\frac{L}{2})) + O(\frac{L}{2}log(\frac{L}{2})) + O(\frac{L}{2}) + O(\frac{L}{2}) = O(\left(\frac{L}{4}\right)^2) = O(L^2)$.

4.5.5 Analysis on RE-DA

The presents section investigates the properties of the proposed RE-DA scheme, in terms of the adopted DA.

Proposition 1: RE-DA is strategy proof with respect to reservation prices.
Proof: In order to prove this, we have to show that none of the players has a reason to misreport their reservation prices to EH-SBSs of rival MNOs.

A seller EH-SBS may *(i)* misreport its reservation price asking a higher than $\Phi_j^{\mathcal{X}}(t)$ one, *(ii)* misreport its reservation price asking a lower than $\Phi_j^{\mathcal{X}}(t)$ one, or *(iii)* supply a lower than $E_j^{\mathcal{X}}(t)$ reservation RE volume. In the first case, the seller risks its participation in the DA, as its asking price may be a lot higher than the bidding ones of the buyers. Moreover, the trading price might be determined by another seller, while the seller itself cannot have knowledge of other players' private reservation prices so as to ask the ideally high price. Finally, in any case, the seller asks the best price for its supplied RE volume, as it is extracted from its utility function. Thus, the seller has no reason to ask a higher than $\Phi_j^{\mathcal{X}}(t)$ reservation price. In the case that the seller under-reports its reservation price, then it does not value sufficiently the RE volume it is willing to supply. This is proved by its concave utility function of eq. (4.17). Thus, the seller has no reason to ask a lower than $\Phi_j^{\mathcal{X}}(t)$ reservation price. In the last case, the seller does not have a clear vision if under-reporting its reservation RE volume is a more beneficial decision, as the set of winner EH-SBSs is determined by another BS. Therefore, the seller has no reason to under-report its reservation RE volume.

A buyer EH-SBS may *(i)* overbid its reservation price asking a higher than $\Phi_j^{\mathcal{Y}}(t)$ one, *(ii)* underbid its reservation price asking a lower than $\Phi_j^{\mathcal{X}}(t)$ one, or *(iii)* request a higher than $E_i^{\mathcal{Y}}(t)$ reservation RE volume. As far as the two first cases are concerned, buyer EH-SBSs cannot over- or under-estimate their bidding price, as bidding prices are extracted randomly in the proposed scheme. However, a buyer overestimate the demanded RE volume, as no restriction is preserved from our algorithm. Such a decision, does not affect the sellers though, as they value appropriately their supplied RE volumes. Based on the above, it can be said that our proposed scheme is strategy proof with respect to reservation prices.

Proposition 2: RE-DA is weakly budget balanced.
Proof: A DA scheme is weakly budget balanced if the sum of sellers' and buyers' payments sum to a non-negative number. In the DA of RE-DA, buyers and sellers are ordered in descending and ascending order, respectively, until the trading point G is encountered. Therefore, buyer EH-SBSs of RE-DA trade at a unit price $\phi_{i'}^{\mathcal{Y}(t)}$ which is always higher than the one that corresponds to sellers, i.e., $\phi_{j'}^{\mathcal{X}(t)}$. The difference between the two prices though is exploited in eq. (4.25) so that the payoff compensation of the auctioneer-aggregator, $ADA(t)$ is extracted. $ADA(t)$ is always non-negative and equal to the difference of the buyers' payment and sellers' compensation. Based on the above, RE-DA is weakly budget balanced.

Proposition 3: RE-DA is individually rational.
Proof: A DA is characterised as individually rational when individual agents are attracted to voluntarily participate in it, because they expect non-negative ex-ante profits. As far as sellers are concerned, a seller EH-SBS is willing to supply an RE volume $E_j^{\mathcal{X}}(t)$ at the cost of an asking price $\Phi_j^{\mathcal{X}}(t)$, provided that it does not affect negatively its future activity. However, this is taken into consideration by the seller EH-SBS when it extracts the asking price for a specific RE volume that maximizes its utility function of eq. (4.17). In addition, the cleared trading price is always higher than to the reservation one, $\Phi_j^{\mathcal{X}}(t)$ for the winner sellers, due to the sorting. Thus, the trade is always profitable for seller EH-SBSs. Finally, a seller EH-SBS participates in the DA if and only if its asking price is higher than the one it has the right to ask from the SG market, i.e., $\Phi_j^{\mathcal{X}}(t) \geq c_s$. A seller EH-SBS though

cannot participate in the RE-DA unless this restriction is fulfilled. This ensures the profitability of its action. As far as buyers are concerned, a buyer EH-SBS is willing to demand an RE volume $E_i^{\mathcal{Y}}(t)$ at the cost of an asking price $\Phi_i^{\mathcal{Y}}(t)$. Our scheme does not necessarily ensure to buyers the highest price possible. A buyer EH-SBS though cannot participate in the RE-DA unless its bidding price is lower than the one it trades with the SG, i.e., $\Phi_i^{\mathcal{Y}}(t) \geq c_b$. This ensures the profitability of its action. Finally, both seller and buyer EH-SBSs are not burdened with any cost so as to participate in the auction, as the auctioneer-aggregator receives its payoff only from the winner buyer EH-SBSs. Based on the above, none seller or buyer EH-SBS can have a negative profit by participating in the DA. Hence, RE-DA is individually rational for the EH-SBSs.

Proposition 4: RE-DA is asymptotically efficient with respect to the number of players.
Proof: For buyers and sellers, the payoff to the auctioneer-aggregator, $ADA(t)$ is perceived as the total efficiency loss in a DA transaction. However, the auctioneer-aggregator may have specific requests with regard to the payoff it wishes to receive. Therefore, we evaluate the efficiency of the method from both perspectives in Section 4.6.2. In order to do that, we use an efficiency indicator of the game, $ef(t)$:

$$ef(t) = \left(\frac{ADA(t)}{F_1 + F_2 + F_3}\right)^{-1} \tag{4.26a}$$

where

$$F_1 = \sum_{i'=1}^{i'=i-1} \left(\phi_{i'}^{\mathcal{Y}}(t) - \Phi_i^{\mathcal{Y}}(t)\right) \cdot E_{i'}^{\mathcal{Y}}(t), \tag{4.26b}$$

$$F_2 = \sum_{j'=1}^{j'=j-1} \left(\phi_{j'}^{\mathcal{X}}(t) - \Phi_j^{\mathcal{X}}(t)\right) \cdot E_{j'}^{\mathcal{X}}(t), \tag{4.26c}$$

$$F_3 = ADA(t). \tag{4.26d}$$

In eq. (4.26a), the denominator of eq. (4.26a) represents the total market value, with the consideration of all trading entities, i.e., the reservation and trading RE volumes and prices of winner sellers and buyers in eqs. (4.26b) and (4.26c), as well as the payoff of the auctioneer-aggregator in eq. (4.26d). From the players' perspective, an RE-DA is favoured when $ef(t)$ diverges from 0. However, from the perspective of the auctioneer-aggregator, an RE-DA trade is efficient when $ef(t)$ has a value close to 0, while its payoff is over a certain percentage $\lambda(t) = \frac{ADA(t)}{\sum_{i'=1}^{i'=i-1} E_{i'}^{\mathcal{Y}}(t)\phi_{i'}^{\mathcal{Y}}(t)}$. In the following section and more specifically, in Fig. 4.9, we display that RE-DA becomes more efficient when more players participate in the auction. However, the efficiency is upper bounded by $\lambda(t)$.

4.6 Performance Evaluation

In the present section, we introduce in Section 4.6.1 the parameters we used for building our simulation scenario and for evaluating the performance of our proposals, while in Section 4.6.2, we present the relative extracted results.

4.6.1 Simulation scenario

We study a macrocell-sized urban area in Barcelona, Spain, as it can be defined by an MBS with a radius equal to 500 m in the centre of it. $N = 3$ MNOs are assumed to have activity in the studied area with a HetNet as in Fig. 4.1. Each MNO owns the 1 EH-MBS of its HetNet, which is located in the centre of the studied area. All MNOs passively share their EH-MBSs, while MNO $n = 1, 2, 3$ manages the operation of 2, 10 and 13 InP provided EH-SBSs ($L = 25$), respectively. The small cell infrastructure is considered uniformly distributed in the area for each MNO. A bandwidth of 10 MHz and an $SNR_{th} = -10$ dB are used [80]. For the traffic profiles, we use $\kappa_n = 0.3, 1.0, 1.3$ for $n = 1, 2, 3$, respectively, unless otherwise stated, and a $\chi(t)$ of users as in [15]. A UE k has a bit rate demand $\varrho_k = \{1024, 512, 256\}$ kb/s, with random probability.

EH-MBSs and EH-SBSs use photovoltaic panels of 4 kW and 100 W, respectively. EH-SBSs are considered solar powered to a $\beta = 0.6$ degree for each $n \in \mathcal{N}$, unless otherwise stated. The remaining infrastructure uses a wind turbine of 100 W at an EH-SBS m, with power coefficient C_m randomly chosen from a range of $[0.38, 0.45]$ [110], and with statistical data used for the wind velocity value v [113]. All ESSs are consisted of lithium batteries with initial charge $(1 - DOD)$.

The system is studied on the best day of the year in terms of solar insolation (June 21st). For the shared EH-MBSs, we focus on a period slot τ' between 20:00-07:00, when no solar RE is generated. At the beginning of the period slot τ', MNOs of coalition $\mathcal{S} \equiv \mathcal{N}$ have to determine their corresponding stored RE in the ESS for the period slot, which has been previously collected (between 07:00-20:00 of the same day). For the RE-DA procedure, we assume slots of $\tau = 1$ h throughout the day, as different RE sources are used. The RE harvesting profiles used for EH-SBSs, as they were generated with the assumed parameters, can be observed in Fig. 4.4. The remaining simulation parameters are portrayed in Table 4.2 [15, 80, 111].

For the evaluation of the proposed RE-BG, we compare it with

- Equal allocation (EQ), where each MNO $n \in \mathcal{N}$ gets an equal share of the shared RE volume, and
- Prioritised-claim allocation (PC), where MNOs receive their complete claim of RE in a descending order.

We assess the performance of the studied methods based on the hours of SG independence ($hours$) and their fairness in energy allocation based on the indicator of Jain's fairness index J. With α_n defined as the ratio of bought SG energy to each EH-MBS's claim, it is

$$J = \frac{\left(\sum_{n \in \mathcal{N}} \alpha_n\right)^2}{|\mathcal{N}| \sum_{n \in \mathcal{N}} \alpha_n^2}. \tag{4.27}$$

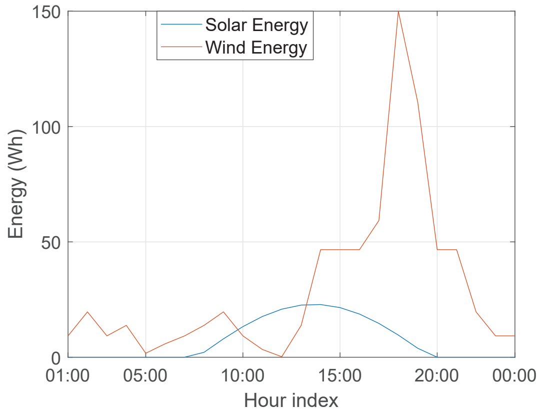


Figure 4.4: RE Generation vs. Time, June 21st, Barcelona, Spain.

Table 4.2: System Parameter Values

Parameter	Value	
N_{th}	-174 dBm	
NF	5 dB	
$Solar\ radiation$	5.14 $kWh/m^2/day$, BCN, Jun.	
$\eta_{sol,m}$	14%	
T_{RE}	24 h	
ρ	1.1849 kg/m^3	
b	0.5 m	
DOD	0.8	
c_b	0.10 €$/kWh$	
c_s	$c_b/100$	
c_a	$c_b/100$	
	$m \leq N$	$N < m \leq M$
P_m^{tr}	20 W	0.13 W
TRX_m	6	2
G_m^{tx}	15 dBi	5 dBi
$PL_{k,m}$	128.1+37.6log$D_{k,m}$	140+36.7log$D_{k,m}$
Δ_m	4.7	4
P_m^{con}	130 W	6.8 W
PV_m	6	1
WN_m	0	1
Ψ_m	3	1
V_m	48 V	12 V
I_m	150 Ah	28 Ah
$\eta_{ESS,m}$	15%	15%

For the evaluation of the proposed RE-DA, we compare it to the cases when the set $\mathcal{L}$ of EH-SBSs is powered by

- the SG only (SG-only),
- its individual EHS, ESS and the SG (NoREE), while no REE scheme is applied, and
- its individual EHS, ESS, an REE act in the form of RE-DA, among a single-MNO managed infrastructure and without the initial internal REE, and the SG (IndREE).

We use for the comparison an indicator

$$\gamma(t) = \frac{\sum_{m=N}^{m=N+L} g_m(t)|_{studied\ scheme}}{\sum_{m=N}^{m=N+L} g_m(t)|_{SG-only}} \tag{4.28}$$

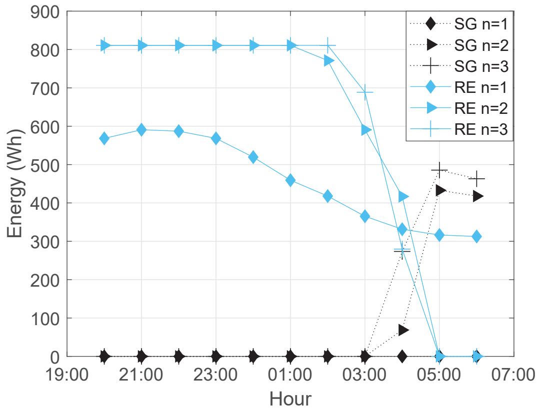
to estimate the SG energy procurements. Thus, γ represents the ratio of SG energy procurements $g_m|_{studied\ scheme}$ in each studied scheme to the SG energy procurements in the SG-only case. Moreover, we assess the normalised payoff distribution produced for the winner sellers and the auctioneer-aggregator from the execution of the DA, based on what the winner buyers pay, while we also evaluate the efficiency of RE-DA based on indicator $ef(t)$.

Finally, the profitability for each MNO individually from the proposed schemes is evaluated in terms of the created costs.

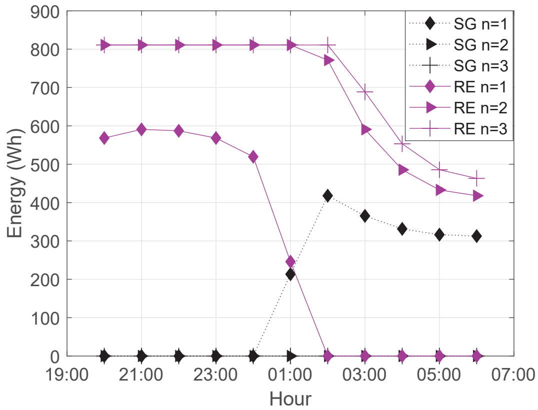
4.6.2 Performance results

In order to display the energy benefits that MNOs can obtain with RE-BG, in Fig. 4.5 we evaluate the hours of SG-independence an EH-MBS n can ensure with the $e_n\left(V_{B(t)}\left(\mathcal{N}\right)\right)$ payoff it receives from the shared ESS and compare it with the EQ and PC allocation strategies[8]. Figs. 4.5a, 4.5b and 4.5c depict the performance of EQ, PC and proposed RE-BG, respectively. According to Fig. 4.5a, $n = 2$ and 3 use their RE payoff for 8 h, while during the $9th$ hour, they need the SG to continue their operation. $n = 1$ though is SG-independent during all night hours, while a part of its RE remains unused. This happens because $n = 1$ gets the same amount of RE as $n = 2$ and 3, even though its traffic volume is considerably lower. However, the stored RE should be exploited to the maximum by all EH-MBSs sharing the ESS for fairness issues. This does not comply with the performance of neither EQ, nor PC, as can be observed for the latter in Fig. 4.5b. In detail, with PC, $n = 2, 3$ procure energy from the ESS all night long, since they have the biggest claim and, thus, are awarded with their total RE claim. $n = 1$ though, is at disadvantage, since its payoff corresponds to no more than 5 h of SG-independence. Unlike EQ and PC, RE-BG allocation offers a satisfying number of SG-independent hours to all coope-

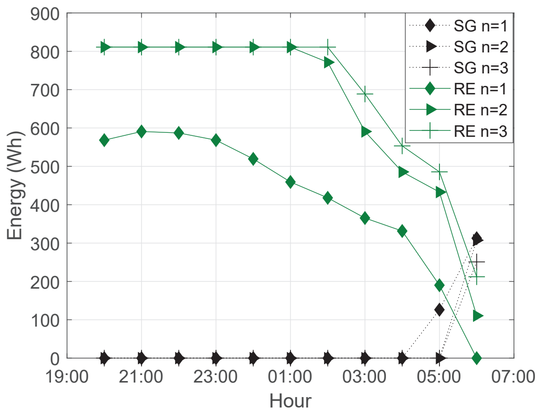
[8]Harvested RE from the shared EHS during the daylight hours was evaluated sufficient for the individual EH-MBSs needs and therefore have not been included in the figures.



(a) Equal allocation (EQ)



(b) Prioritised-claim allocation (PC)

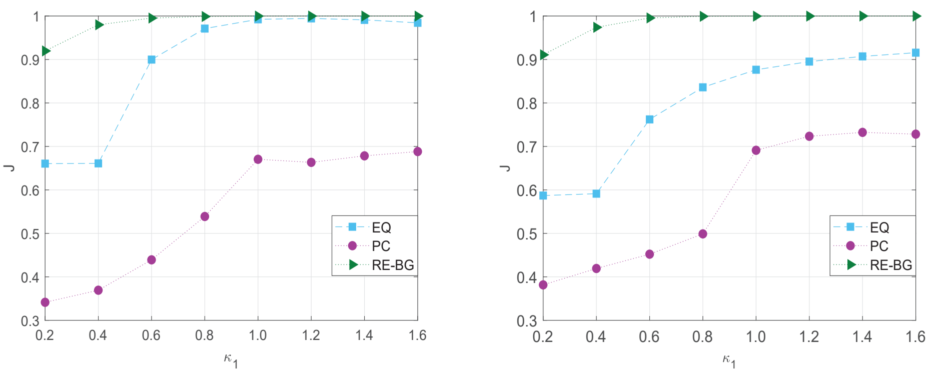


(c) RE bankruptcy game (RE-BG)

Figure 4.5: Monitoring of energy for different energy sharing methods.

rative EH-MBSs. According to Fig. 4.5c, when RE-BG is applied, between 20:00-07:00, it ensures to all EH-MBSs complete SG-independence for 9 h. After that period, they use the remains of their allocated RE payoff and obtain their energy deficits from the SG. In total, RE-BG offers a more balanced period of green network operation to all MNOs, since it considers both their cumulative energy needs and their marginal contribution to completely allocate the stored RE.

As traffic load volumes and profiles differentiate for MNOs making thus energy allocation fairness an issue, in Fig. 4.6 we see the effects of various MNO traffic volumes on each allocation method's fairness, based on their respective Jain's fairness index, J. In detail, we vary traffic load factor κ_1, while κ_2 and κ_3 remain unchanged. We also consider similar and different traffic load peaks of MNOs $n = 1$ and $n = 2, 3$ in Fig. 4.6a and Fig. 4.6b, respectively. It is noticeable in both figures that J of RE-BG remains close to 1 irrespective of any traffic load volume or peak differentiation, since it considers each player's contribution to storing RE. Also, compared to its counterparts, we notice that it performs better than both EQ and PC allocation. More specifically, EQ performs closer to RE-BG when traffic load peaks are similar in Fig. 4.6a, especially for $\kappa_1 > 1$. This is when the traffic volume of MNOs become more similar and all allocated RE payoffs are consumed by their EH-MBSs during the night. However, when peaks are different in Fig. 4.6b, fairness of EQ deteriorates since traffic load differences among MNOs are intensified. Lastly, PC allocation is far below EQ and RE-BG in both figures, as there is always an EH-MBS in the need of SG energy. PC though performs better when traffic peaks are different in Fig. 4.6b. This is attributed to the fact that, when EH-MBS $n = 1$ receives its payoff for its high peak traffic load, MNOs $n = 2, 3$ are in their low peak traffic load and thus, their EH-MBSs cover their energy needs with RE to a high degree. In the reverse case that MNO $n = 1$ is in its low peak traffic load and thus has lower needs in RE than $n = 2, 3$, the EH-MBSs of the latter have more remaining RE to share for their RE needs.



(a) Same traffic load peaks for $n = 1$ and $n = 2, 3$. **(b)** Different traffic load peaks for $n = 1$ and $n = 2, 3$.

Figure 4.6: Jain's fairness index, J, *(i)* for the studied energy sharing methods, EQ, PC and RE-BG, *(ii)* for varied traffic loads, κ_1 and *(iii)* peaks of $n = 1$.

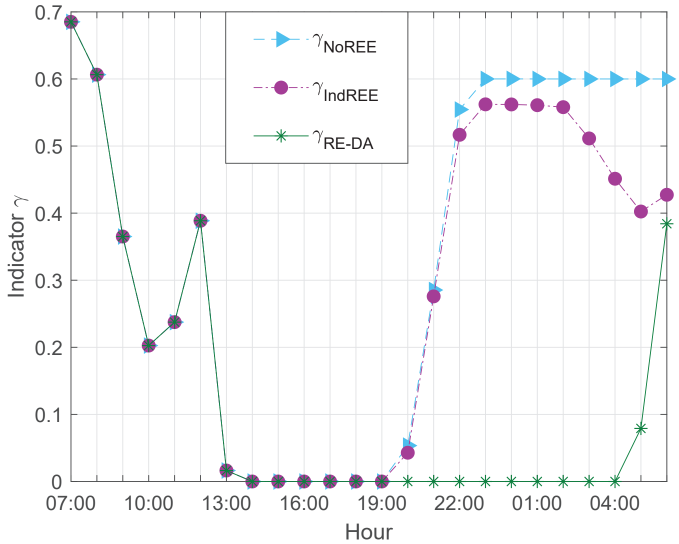


Figure 4.7: 24-hour evaluation of SG energy purchases based on ratio $\gamma(t)$ for the (i) NoREE, (ii) IndREE and (iii) RE-DA energy procurement schemes.

In order to display the energy benefits that MNOs can obtain with RE-DA, in Fig. 4.7, we study the indicator $\gamma(t)$ of eq. (4.28) for the comparison of NoREE, IndREE and, our proposed, RE-DA to the SG-only operation of EH-SBSs in $\mathcal{L}$, during a day. As can be noticed, between 07:00-14:00, the EH-SBSs consume their harvested and stored RE and cover their energy needs with the aid of the SG in all study comparisons. However, SG purchases are still considerably reduced, up to 80% at 11:00 when $\gamma \simeq 2$, for all studied methods. When $\gamma = 0$ between 14:00-19:00, in all cases, EH-SBSs consume only harvested RE, while RE is also stored in their ESSs. After 19:00, IndREE almost coincides with NoREE until 22:00 with support of SG energy as well. With NoREE, the EH-SBSs cannot exchange RE amongst themselves. In the case of IndREE, despite the fact that ESSs of both solar and aeolian EH-SBSs, have abundant stored RE, REE acts do not take place as MNO traffic load volumes are still considerable, making seller EH-SBSs reserved towards selling RE. Nevertheless, IndREE acts then become more intense, especially after 23:00, when traffic load volumes are low and there are EH-SBSs with abundant harvested (mainly aeolian) and stored RE. In contrast to its counterparts, RE-DA ensures SG independence for the studied system after 19:00 and until 04:00. RE-DA overcomes sellers' reservation towards selling energy with the initial interior REE among the EH-SBSs of the same MNO. Then, the trades with EH-SBSs of rival MNOs further reduce SG-energy expenses, especially when MNO traffic load volumes are low. Finally, in the course of a day, NoREE, IndREE and RE-DA reduce significantly the sum of SG energy purchases, reaching a 34%, 31% and 12% of the SG-only case, respectively, while a further 63% and 60% reduction is achieved by RE-DA in comparison to NoREE and IndREE, respectively.

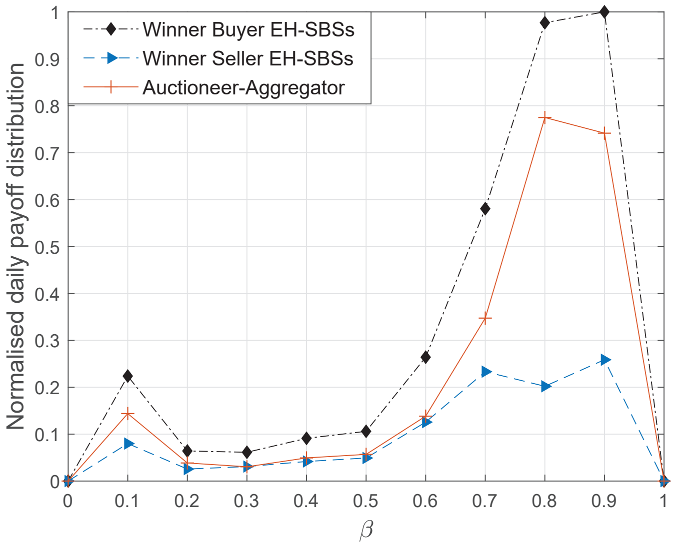


Figure 4.8: Normalised total daily DA *(i)* cost for winner buyers, *(ii)* payoff of winner seller EH-SBSs, and *(iii)* payoff of the auctioneer-aggregator, vs. the ratio of solar powered SBSs, β.

Varying percentages of solar powered EH-SBSs, β, can drastically affect RE availability at EH-SBSs and, thus, the profitability of RE-DA for the stakeholders. Therefore, in Fig. 4.8, we display the total normalised daily DA payoff (i.e., cost) $\sum_{t=1}^{t=T_{RE}} \sum_{i'=1}^{i'=i-1} e_{i'}^{\mathcal{Y}}(t)\phi_{i'}^{\mathcal{Y}}(t)$ of winner buyer EH-SBSs, the total normalised daily DA payoff $\sum_{t=1}^{t=T_{RE}} \sum_{j'=1}^{j'=j-1} e_{j'}^{\mathcal{X}}(t)\phi_{j'}^{\mathcal{X}}(t)$ of winner seller EH-SBSs and the total normalised daily DA payoff $\sum_{t=1}^{t=T_{RE}} ADA(t)$ of the auctioneer-aggregator, for varying β. As can be observed, no profits or costs are created with RE-DA when $\beta = 0$ and $\beta = 1$, as EH-SBSs have completely homogeneous EH profiles for these β values. Hence, no RE-DA trades take place. For $\beta \neq \{0, 1\}$ though, RE-DA acts are executed, with the payoff distribution among winner seller EH-SBSs and auctioneer-aggregator occasionally intensely uneven. In detail, when $\beta \leq 0.5$, the total trades among EH-SBSs of rival MNOs are considerably fewer in comparison to the case $\beta > 0.5$. For $\beta \leq 0.5$, the majority of EH-SBSs are wind powered and therefore, during the night, can power the solar-power EH-SBSs, primarily with an initial internal REE, while during the day, the reverse happens. RE-DA trades with player EH-SBSs of other MNOs take place in the early morning hours, when some ESSs may not be charged. The remaining seller player EH-SBSs though, have enough abundant energy and, based on eq. (4.18), propose not considerably high prices to the buyer EH-SBSs. Thus, as can be observed in Fig. 4.8, a similar distribution of the buyers' expenses is in most cases encountered between the seller EH-SBSs and the auctioneer-aggregator. When $\beta > 0.5$, the majority of EH-SBSs are solar powered and EH is mostly distributed throughout the day. At the same time, there are some wind-powered EH-SBSs to supply RE when solar EH is low or non-available and to allow more frequent RE-DA trades among EH-SBSs of rival MNOs. This explains the higher expenses of buyer EH-SBSs when $\beta = 0.7, 0.8$ and 0.9. RE-DA trades occur mainly during low-traffic hours, when wind RE can compensate energy deficits of solar powered EH-SBSs. However, seller reservation prices are lower than the average buyer reservation prices, creating thus this vast gap noticed in the figure for $\beta = 0.8,\ 0.9$. Therefore, it can be said that mediocre β values allows exchange of RE with RE-DA, reducing thus expenses on SG energy purchases with satisfying payoff for the auctioneer-aggregator.

As β affects the number of winner seller and buyer EH-SBSs, in Fig. 4.9, we study its effect on the efficiency of RE-DA, based on the mean ef value of eq. (4.26a). Our method's efficiency is also evaluated in relation to threshold values $\lambda(t)$ that the auctioneer-aggregator may impose so as to execute the DA of the RE-DA. According to the figure, when no limitation is imposed by the aggregator, i.e., $\lambda = 0$, the method is more efficient for $0.2 \leq \beta \leq 0.6$. This means that for this value of λ, the more diverse the RE sources used at the EH-SBSs are, the more equal the payoff distribution among seller EH-SBSs and the auctioneer-aggregator is. Thus, the mean ef diverges from 0, i.e., the more efficient RE-DA becomes. The efficiency is the highest for $\beta = 0.6$, since for these β value, more players participate in and eventually trade with RE-DA. Therefore, for this case, the method is asymptotically efficient with respect to the number of RE-DA players. However, our method's efficiency is limited by threshold $\lambda(t)$ of higher values. In order to satisfy the requests of the auctioneer-aggregator in these cases, either considerably wind- or solar-powered dominated infrastructure is needed. In these cases, there are periods of time during a day, when available RE at seller EH-SBSs is enough to over-

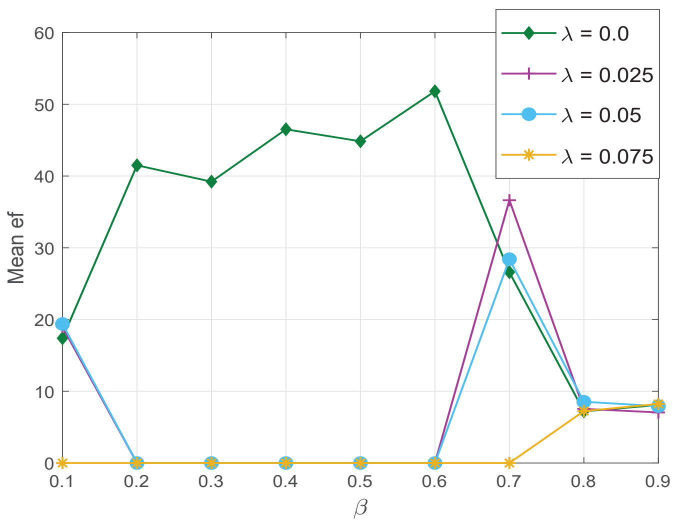


Figure 4.9: Efficiency of RE-DA trades based on mean ef vs. indicator β.

cover the energy needs of their MNO's network and trade energy with EH-SBSs of rival MNOs with large profit margin for the auctioneer-aggregator. Otherwise, the requests of the latter cannot be satisfied and therefore RE-DA is totally prevented. Once again though, when RE-DA is allowed, its efficiency is higher when more players participate in and eventually trade with it. As a conclusion, low λ thresholds are important for RE-DA, while player EH-SBSs need to keep a level of diverse RE-sources as a power source to achieve trades.

In Fig. 4.10, we display the monthly costs that are created by the individual and combined application of our proposed approaches in a macrocell area. We compare the created costs by our applications with the adoption or not of passive sharing and with the SG-only case. In the figure, we display with green shades the case of passive sharing at the EH-MBS site, with the application of our proposed scheme RE-BG. Red shades correspond to the case when no passive sharing is applied to the EH-MBS site, i.e., when MNOs cannot apply the RE-BG scheme (No RE-BG). Dark shades indicate the application of RE-DA, while the light ones stand for the use of SG-only energy for the EH-SBSs. As can be observed, both individual and combined use of the proposed methods in a macrocell area induces significantly lower daily costs to all MNOs, $n = 1, 2, 3$. According to the figure, all MNOs are significantly benefited by both RE-BG (green-red comparison) and RE-DA (dark-light shades comparison), even resulting in an elimination of their produced costs. In detail, in comparison to the SG-only case, MNOs $n = 1, 2$ and 3 achieve a 63%, 44%, 36% reduction of expenses, respectively, thanks to RE-BG and an 85%, 62% and 65% one, respectively thanks to RE-DA.

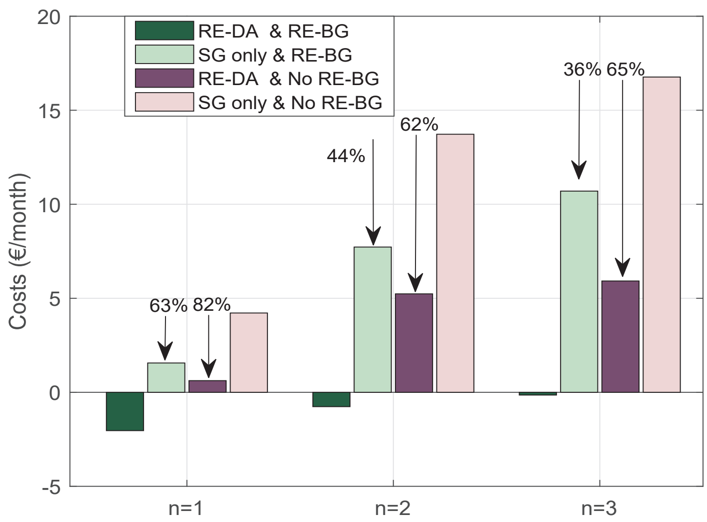


Figure 4.10: Monthly MNO costs per macrocell area with the application of proposed and traditional methods.

4.7 Conclusion

In this chapter, we studied the problem of REE in late-trend multi-MNO networks. In detail, we proposed REE methods (i) among collocated and passively shared EH-MBSs with an RE sharing approach, RE-BG, which is based on co-operative bankruptcy games and (ii) an aggregator-assisted RE trading approach, RE-DA, that applies an initial internal REE followed by a double auction among the InP provided EH-SBSs managed by the same and different MNOs, respectively. In the first case, we showed that RE-BG allows at least 9 hours of SG energy independence for all EH-MBSs of the MNOs during non-solar hours and a fairer RE allocation in comparison to baseline schemes. In the second case, we showed that our proposed scheme, RE-DA, reduces SG energy consumption to a 12% of the one resulted with a SG-only network support. Moreover, combined use of solar and wind powered EH-SBSs at a mediocre analogy indicated more efficient use of RE, with the allocation of sufficient payoffs to both players and the auctioneer-aggregator. Careful consideration though should be given to the limitations imposed by the aggregator who acts as an auctioneer. Finally, the adoption of our proposals considerably reduces individual MNO costs, resulting even to an elimination of MNO expenses on SG energy purchases in their combined application.

Chapter 5

Conclusion and Future Work

This chapter summarizes the main contributions of this dissertation, while it also provides some potential research lines for future investigation. Section 5.1 contains the most significant remarks from each chapter, while Section 5.2 reveals some open issues in relation to the contributions of this thesis.

5.1 Conclusion

The increase in the data traffic demands, which has been noticed in the recent years and which is expected to further augment in the forthcoming ones, has revealed the necessity and main concern of mobile network operators (MNOs) to boost the capacity of their networks, while maintaining flat the energy consumption and the cost expenses for their operation. In this context, rolling out of heterogeneous network (HetNet) deployments and sharing of infrastructure have been techniques that have greatly aided the achievement of this goal. At the same time though, several issues have been left unexplored. For instance:

- How can a successful MNO cooperation be reassured in such architectures?
- And how can it be ensured that, when other technologies, such as infrastructure switching off, the usage of renewable energy (RE) sources and the exploitation of the smart grid (SG) network, are used in order to complement the energy and cost efficiency attributed to the deployment of shared HetNets?
- How can an energy and cost management be characterised as fair towards the stakeholders that are involved in such architectures and initiate them?

The objective of this Ph.D thesis has been to ensure an efficient energy and cost management in shared HetNet deployments, using techniques that exploit the different types of the installed network infrastructure and that take into account the interests and characteristics of the different stakeholders participating in the sharing. In order to achieve this goal, we proposed novel frameworks that regulate various forms of sharing, while optimization and game theory were used as the key mathematical tools to express these frameworks. In particular, two main research directions were followed.

With regard to the first research direction, presented in Chapter 3, the thesis concentrated on the switching off strategies and their feasibility for application in HetNet deployments that are powered exclusively by the grid and where the cooperative activity of multiple MNOs is possible. We proposed a novel greedy heuristic switching off algorithm, namely cooperative switching off algorithm (CSO), that achieved considerable energy savings in comparison to other schemes. Moreover, it emphasized that except from the base station (BS) load, consideration should be given on the type of the BS that would remain active, as both network energy consumption and coverage provision differentiate greatly depending on the studied BS type. The scheme addressed at the same time economical aspects of the switching off procedure, as it takes into account both the different network expenses that are required for service provision from a macrocell base station (MBS) and a small cell base station (SBS), and the roaming charges that are provisioned when traffic is transferred between roaming-based shared networks. The proposed scheme was evaluated in terms of energy efficiency throughout the low traffic hours, for various traffic load differences among the cooperative MNOs and for different coalition formations among them. The results showed that our proposal can significantly improve network energy efficiency, meanwhile promoting the cooperation among multiple MNOs. More cost management issues were addressed with the proposal of a cost allocation scheme that, after taking into account the revenues of each MNO from its roaming activity, fairly extracts the portion of cost corresponding to the activity and contribution to savings of each cooperative MNO. Our proposal, namely bankruptcy Shapley Value based cost allocation scheme (BSV), was evaluated for the fairness of its extracted cost allocation in comparison to baseline schemes, indicating that it achieves a good and balanced performance.

For the support of our second research direction, presented in Chapter 4, we focused on grid-connected energy harvesting (EH) HetNet deployments, where stakeholders of multiple interests may need to form a type of cooperation, e.g., MNOs and an aggregator. In terms of achieving an efficient energy management, RE exchange (REE) in a late-trend multi-operator HetNets with passively shared and collocated EH-MBSs and EH-SBSs provided by an infrastructure provider (InP) was investigated. On this basis, for the former case of the EH-MBSs, we proposed a RE-sharing framework, namely RE bankruptcy game (RE-BG). We proved that it provides a fair solution to the complicating case of EH-MBSs that are passively shared by rival MNOs, along with their EH and energy storage system. Our proposal can allocate to the cooperative MNOs an amount of harvested or stored RE that mirrors their individual energy needs. The proposed scheme was evaluated based on the hours of the system's independent activity from SG purchased energy, and in terms of the fairness of its extracted solution. In all cases, it was compared with baseline schemes, which it outperformed. For the latter case of the EH-SBSs, we used non-cooperative game theory and proposed a energy trading framework, namely RE-DA. Our proposal, provisioned the energy exchange between EH-SBSs, which are provided by an InP and managed by multiple MNOs, with an aim to reduce purchases of energy from the SG and increase utilization of RE sources. In the meantime, it also preserving the individual energy strategy of the EH-SBSs with energy abundance. In order to achieve these goals, our scheme implements a double auction among the EH-SBSs of the different MNOs that have abundant energy or shortage in it, which follows after a process of an initial internal REE amongst the EH-SBSs of the same MNO. Through the RE-DA energy trading framework, we studied the prospects of a fair RE trading among EH-SBSs managed by different MNOs and the way they affect the profitability and activity of the stakeholders involved in the trading. Our performance evaluation showed that the scheme can achieve higher energy savings in comparison to other schemes, especially when different RE sources are used, with satisfactory cost and payoffs for the involved in the trading stakeholders.

5.2 Future work

The research contributions presented in this work can be the starting point of new research lines for investigation. The cloud-based technologies used in the fifth generation (5G) networks introduce new parameters to take into account and change the perspective of managing the problems studied in the present thesis.

The main goals for future work with respect to the first part of the thesis on energy and cost management in multi-operator shared HetNet deployments can be summarized as follows:

- **Application of machine learning techniques**: A weak point of BS switching off has always been the prediction of traffic load density in time and space. An even more challenging task is the coordination of the predictions with the application of the switching off method at accurate time intervals, which are necessary so that the operation mode of a BS can alternate without degradation of service quality. With a view to the 5G era, when traffic outbursts could be more sudden, a more intelligent BS switching off is necessary to the aid of a proper network management. To this end, machine learning techniques, such as neural networks, can be applied to predict the user distribution, the traffic load and the traffic type of each BS. This can be done mainly based on historical data that may refer to the average number of users and their time arrival at the coverage area of a BS. As a consequence, the cooperation capabilities among MNOs could be improved as well. The technical challenges that come along with the 5G technologies mandate further investigation on the implementation possibilities of such approaches as future goal.
- **Wireless backhaul**: Due to the dense urban deployments, not all SBSs in

a HetNet are expected to have a direct link connection to the core network. Thus, wireless backhaul networks have been gaining attention. However, a proper configuration of such networks is more than necessary so that network performance is not limited by bottlenecks that can be created in the resource provision of BSs. Therefore, in the possibility of deactivating an SBS, pressure would be put to the neighbouring SBSs so that they deliver the aggregated data rate requirements. Guaranteeing the effectiveness and scheduling of the procedure is another design factor for both single- and multi-operator HetNets with wireless backhaul on which further research could be implemented.

- **millimeter (mmWave) communications**: It is one of the main 5G technologies, used for large capacity augmentation at SBSs, mainly for line-of-sight transmissions. Thus, the deployment their technology though, can be intriguing for the application of network switching off not only for the amount of traffic load volume whose service will have to be compensated, but also for the high propagation losses to which mmWave communications are vulnerable. Therefore, future research efforts can be focused to finding suitable offloading frameworks among networks that use mmWave communications.

- **Massive MIMO**: Being another fundamental 5G technology, massive MIMO in combination with mmWave could be given consideration in our SBS system. Massive MIMO improve greatly the energy efficiency issue in the transmission components of BSs. However, with that cloud/fog computing and cache communications emerging for 5G networks, more and more data storage and computation processes will be performed at 5G SBSs [114]. It was recently suggested that when power needs for computation processes are considered for massive MIMO systems, apart from transmission power needs, then the energy efficiency of massive MIMO systems decreases for increasing number of antennas and RF chains [115]. On the other hand, when applied in combination with the switching off strategy and mmWave technology, energy efficiency prospects of Massive MIMO are high [116]. Therefore, it would be interesting to explore the prospects of further increasing energy efficiency by applying network switching off with respect to the power consumed for data computation and storage at BSs with massive MIMO systems.

- **Software based 5G technologies**: Upcoming software based 5G technologies, such as network slicing (NS) and network function virtualization, change the perspective from which one of our solutions, CSO, can be observed. NS describes how a physical network is divided into multiple logical networks, with specific capabilities and related to a specific service [117, 118]. It also allows several operators to share the same physical network and thereby save cost for deployment and maintenance of the physical network equipment. However, NS requires a virtualization of the network to be able to run several logical networks on top of the physical network. An effort to exploit the utilities of virtualization in multi-operator environments with respect to energy efficiency, as was intended by CSO, has already been initiated [119]. However, it would be interesting to take the existing literature and the contribution of CSO a step forward by exploring the possibilities of creating an in-depth multi-operator service as a slice for resource allocation and dynamically for switching off, that would simultaneously allow to convey sensitive private details on the operator traffic. For example, thanks to the division of the cloud radio access network into a distributed unit and a centralised unit, then with a functional split, information exchange could be limited to functions of one of the units.

There are also several open issues regarding the second part of this thesis, focusing on energy and cost management in multi-operator EH-HetNets that are also connected to the SG:

- **Alternative mathematical tools**: In the considered scenario, an issue that could be further investigated are the levels of tolerance from the part of InP with reference to the health deterioration of the infrastructure that it provides due to the continuous energy trading acts. The health of a battery deteriorates as the number of charges and discharges cycles of the battery approach the maximum nominal value. This in turn could dynamically create an amount capital expenses for the replacement of infrastructure with deteriorated health. In the long term, this could prove to be a financial burden to the InP that could have been lower. Tools that could be considered for the encounter of a solution for better management of infrastructure and simultaneous energy and cost benefits for the involved entities, are the optimization and matching theory.
- **Alternative energy sharing criteria**: In the considered scenario, we study the cases of the EH- MBSs and SBSs separately and propose different solutions for each case. Another approach would be the assumption that MNOs exchange energy amongst all their EH-BSs. In this case, energy transfer between EH- MBSs and SBSs of the same HetNet could be considered through power lines as well, while exchange of energy with other MNOs could still involve other stakeholders, as is the aggregator. However, exchange of energy amongst BS of such different energy need levels needs further investigation. On one hand, energy transfer from SBSs to an MBS could result in the energy outage in multiple SBSs. In the reverse event that an MBS transfers energy to SBSs, more attention should be paid on the future energy needs of the MBS itself before proceeding to the exchange of energy. These scenarios could prove to be of value for MNOs and give ideas for setting new criteria of energy sharing and trading that worth being studied.
- **Network slicing**: Supporting end-to-end network slices and services across operators has become an important use case of study for 5G networks. Multiple network slices required by different stakeholders may have the same type of service but different requests on the service indicators [117]. On this basis, the proposed RE-DA scheme could be approached on a more software level approach in relation to network slices instead of the aggregator-assisted double auction. In detail, an effort could be made to investigate the prospects of making a slice scheduler that would assign bandwidth slices for each sharing

operator. The assignment of the bandwidth slices by the slice scheduler could become in accordance with a frame scheduler that would implement an custom scheduling policy in accordance with the RE availability during a specific time slot. Based on these inter-operator sharing framework, REE would be performed in a load balancing form. In such a case however, each operator would be able to adopt customized scheduling policies, and even preserve the respective service indicators for its own subscribers or for the visiting subscribers as well. Thus, the management exposure of the operators over the network slices could be arranged accordingly with respect to their individual optimization policies. Practically, such an approach implies circumventing the presence of the aggregator in the case of the SBSs, as low-range energy prosumers.

Concluding, this thesis has complemented the state-of-the-art works by studying the case of shared HetNet deployments and by promoting the deployment of energy saving solutions, such as switching off and exchange of renewable energy. Moreover, in order to provide cost efficiency in the management of wireless networks except from energy efficiency, reference was made to cost issues that may arise. The two parts of the thesis were treated separately. However, it is possible to envision a network were all parts can be combined. The road ahead lies open for further research, following the new lines of investigation that have been identified.

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