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UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Departament de Teoria del Senyal i Comunicacions

Centre Tecnològic de Telecomunicacions de Catalunya

Network Coding-aided MAC Protocols for Cooperative Wireless Networks

PhD Thesis Dissertation

By

Angelos Antonopoulos

Submitted to the Universitat Politècnica de Catalunya (UPC)
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DOCTOR OF PHILOSOPHY

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PhD program on Signal Theory and Communications

A los que buscan, aunque no encuentren...

A los que avanzan, aunque se pierdan...

A los que viven, aunque se mueran...

Mario Benedetti

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Abstract

The introduction of third generation (3G) technologies has caused a vast proliferation of wireless devices and networks, generating an increasing demand for high level Quality of Service (QoS). The wide spread of mobile applications has further reinforced the user need for communication, motivating at the same time the concepts of user cooperation and data dissemination. However, this trend towards continuous exchange of information and ubiquitous connectivity is inherently restricted by the energy-greedy functionalities of high-end devices. These limitations, along with the pressure exerted on the Information and Communications Technology (ICT) industry towards energy awareness, have induced the design of novel energy efficient schemes and algorithms. In this context, the Medium Access Control (MAC) layer plays a key role, since it is mainly responsible for the channel access regulation, the transmission scheduling and the resource allocation, thus constituting an appropriate point to effectively address energy efficiency issues that arise due to the users overcrowding.

This dissertation provides a contribution to the design, analysis and evaluation of novel MAC protocols for cooperative wireless networks. In our attempt to design energy efficient MAC schemes, we were extensively assisted by the introduction of new techniques, such as Network Coding (NC), that intrinsically bring considerable gains in system performance. The main thesis contributions are divided into two parts. The first part presents NCCARQ, a novel NC-aided Cooperative Automatic Repeat reQuest (ARQ) MAC protocol for wireless networks. NCCARQ introduces a new access paradigm for cooperative ARQ schemes, exploiting NC benefits in bidirectional communication among wireless users. The NCCARQ performance in terms of QoS and energy efficiency is assessed by means of analytical probabilistic models and extensive computer-based simulations, revealing the significant gains we can achieve compared

to standardized MAC solutions. In addition, the impact of realistic wireless channel conditions on the MAC protocol operation further motivated us to study the NCCARQ performance in wireless links affected by correlated shadowing, showing that the channel correlation may adversely affect the distributed cooperation benefits.

The second part of the thesis is dedicated to the investigation of MAC issues in wireless data dissemination scenarios. In particular, the existence of multiple source nodes in such scenarios generates conflicting situations, considering the selfish behavior of the wireless devices that want to maximize their battery lifetime. Bearing in mind the energy efficiency importance, we propose game theoretic medium access strategies, applying energy-based utility functions which inherently imply energy awareness. In addition, Random Linear NC (RLNC) techniques are adopted to eliminate the need of exchanging excessive control packets, while Analog NC (ANC) is employed to efface the impact of collisions throughout the communication.

During the elaboration of this thesis, two general key conclusions have been extracted. First, there is a fundamental requirement for implementation of new MAC protocols in order to effectively deal with state-of-the-art techniques (e.g., NC), recently introduced to enhance both the performance and the energy efficiency of the network. Second, we highlight the importance of designing novel energy efficient MAC protocols, taking into account that traditional approaches - designed mainly to assist the collision avoidance in wireless networks - tend to be obsolete.

Resumen

La introducción de la tecnología de tercera generación (3G) ha provocado un incremento considerable del numero de dispositivos y redes inalámbricas, que a su vez requieren una calidad de servicio (QoS) alta. La popularización de las aplicaciones móviles ha acentuado las necesidades de comunicación, motivando la cooperación y la difusión de datos entre usuarios. Sin embargo, esta tendencia hacia el intercambio continuo de información está inherentemente limitada por los elevados requisitos energéticos de los dispositivos modernos. Estas limitaciones, junto con la presión ejercida sobre la industria de las tecnologías de la información y de las comunicaciones para la reducción del consumo energético, han motivado el diseño de nuevos esquemas y algoritmos energéticamente eficientes. En este contexto, la capa de control de acceso al medio (Medium Access Control - MAC) juega un papel fundamental, ya que es responsable de la regulación de acceso al canal, de la programación de la transmisión y de la gestión de recursos, lo que constituye un punto apropiado para abordar eficazmente las cuestiones de eficiencia energética que surgen debido al creciente numero de usuarios.

La presente tesis doctoral contribuye al diseño, análisis y evaluación de nuevos protocolos MAC cooperativos para redes inalámbricas. La introducción de nuevas técnicas, tales como la codificación de red (Network Coding - NC), que intrínsecamente llevan un considerable aumento en el rendimiento del sistema, nos ayudó ampliamente durante el diseño de protocolos MAC energéticamente eficientes. Las principales contribuciones de esta tesis se dividen en dos partes. La primera parte presenta el NCCARQ, un protocolo cooperativo de retransmisión automática (Automatic Repeat reQuest - ARQ), asistido por NC para redes inalámbricas. El protocolo NCCARQ introduce un nuevo paradigma de acceso para los sistemas cooperativos

ARQ, dado que aprovecha los beneficios del NC en la comunicación bidireccional entre usuarios inalámbricos. El rendimiento del protocolo NCCARQ se evalúa en función de la QoS y de la eficiencia energética mediante modelos probabilísticos analíticos y simulaciones por ordenador, lo cual revela una mejora con respeto a los protocolos MAC estándar. Además, el hecho de considerar condiciones de canal realistas supone un impacto sobre la funcionalidad de los protocolos MAC, lo que nos motivó a estudiar el rendimiento del NCCARQ en enlaces inalámbricos que están afectados por "shadowing" correlado. Este estudio demuestra que la correlación del canal puede tener un efecto negativo sobre los beneficios obtenidos de la utilización de cooperación descentralizada.

La segunda parte de la tesis se centra en el diseño de protocolos de capa MAC en escenarios inalámbricos de difusión de datos. En particular, la existencia de múltiples transmisores genera situaciones conflictivas, debido a el comportamiento egoísta de los dispositivos inalámbricos que desean maximizar su vida útil. Teniendo en cuenta la importancia de la eficiencia energética, se proponen técnicas de acceso al medio basadas en teoría de juegos dónde las funciones objetivo están motivadas por el consumo energético. Además, se adopta la codificación de red lineal y aleatoria (Random Linear NC - RLNC) para eliminar la necesidad de un intercambio excesivo de paquetes de control y se utiliza la codificación de red analógica (Analog NC - ANC) para cancelar el impacto de las colisiones de paquetes.

De la realización de esta tesis se extraen dos conclusiones principales. En primer lugar, existe la necesidad del diseño e implementación de nuevos protocolos MAC para explotar técnicas de comunicación modernas que permiten mejorar el rendimiento y la eficiencia energética de la red. En segundo lugar, se destaca la importancia de diseñar nuevos protocolos MAC de eficiencia energética, dado que los enfoques tradicionales, que han sido diseñados principalmente para la prevención de colisiones en redes inalámbricas, podrían quedar obsoletos.

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Próxima Parada: Castelldefels. Four years have already passed since the first time I heard this announcement, which later on became part of my everyday life. I could write another "thesis", just to express my gratitude to those who helped me during these years, making this journey a pleasant experience. However, since this is not feasible, I would like to apologize in advance to all those I will not explicitly mention.

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proofreading of the document, I will not forget that you gave me the trigger for this trip (both figuratively and literally). Maria and Pol, without you the Spanish version of the abstract would describe a "novela de Carolina del Norte" rather than a contribution on Network Coding. Konstantinos and Marco, thanks for shedding light on the not-so-familiar world of physical layer. I would also like to thank Ferran and John who reviewed the dissertation before the final deposit.

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Finally, I would like to dedicate this thesis to Angeliki, who stood by me all this time, always being supportive and smiling, especially in the difficult moments. This thesis is also yours.

Angelos Antonopoulos
Barcelona, Spain
November, 2012

List of Publications

Journals

[J1] E. Kartsakli, A. Lalos, **A. Antonopoulos**, S. Tennina, M. Di Renzo and C. Verikoukis, "A Survey on M2M Systems for e-Health: A Wireless Communications Perspective", *IEEE Surveys & Tutorials* (submitted).

[J2] **A. Antonopoulos**, M. Di Renzo and C. Verikoukis, "Impact of Realistic PHY and Correlated Shadowing on the Performance of Network Coding-aided Cooperative MAC Protocols", *IEEE Communications Magazine* (submitted).

[J3] **A. Antonopoulos** and C. Verikoukis, "Multi-player Game Theoretic MAC Strategies for Energy Efficient Data Dissemination", *IEEE Transactions on Wireless Communications* (submitted).

[J4] E. Ibarra, **A. Antonopoulos**, E. Kartsakli and C. Verikoukis, "HEH-BMAC: Hybrid Polling MAC Protocol for Wireless Body Area Networks Operated by Human Energy Harvesting", *Springer Telecommunications Systems Journal (SI on Research Advances in Energy-Efficient MAC Protocols for WBANs)* (submitted).

[J5] **A. Antonopoulos**, C. Verikoukis, C. Skianis and O.B. Akan, "Energy Efficient Network Coding-based MAC for Cooperative ARQ Wireless Networks", *Ad Hoc Networks (Elsevier)*, available online 31 May 2012, ISSN 1570-8705, 10.1016/j.adhoc.2012.05.003.

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List of acronyms

3G	Third Generation
ACK	Acknowledgement
AF	Amplify-and-Forward
AMC	Adaptive Modulation and Coding
ANC	Analog NC
AP	Access Point
APER	Average PER
ARQ	Automatic Repeat reQuest
BS	Base Station
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CSMA	Carrier Sense Multiple Access
CW	Contention Window
DCF	Distributed Coordination Function
DF	Decode-and-Forward
DIFS	DCF Interframe Space
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
GF	Galois Field
ICT	Information and Communications Technology
ISO	International Organization for Standardization

ITU	International Telecommunication Union
LIFS	Long Interframe Space
LLC	Logical Link Control
MAC	Medium Access Control
MIMO	Multiple-Input Multiple-Output
NACK	Negative Acknowledgement
NC	Network Coding
NE	Nash Equilibrium
OPER	Outage PER
OSI	Open Systems Interconnection
P2P	Peer-to-Peer
PDA	Personal Digital Agenda
PER	Packet Error Rate
PHY	Physical
PNC	PHY-layer Network Coding
QoS	Quality of Service
RFC	Request for Cooperation
RLNC	Random Linear NC
SIFS	Short Interframe Space
SNR	Signal-to-Noise-Ratio
TDMA	Time Division Multiple Access
Tx/Rx	Transmission/Reception
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

Notation

$\mathbf{x}$	Vector
$\mathbf{x}^T$	Transpose vector
$\mathcal{X}$	Set
$\sum$	Summation
x^*	Target value of x
$\overline{x}$	Average value of x
$\mathbf{x}^*$	Nash Equilibrium strategy
$x \oplus y$	Exclusive disjunction of x and y
$\mathbf{E}[\cdot]$	Expected value
$PER(X)$	Packet Error Rate as a function of X
$PER_{x \to y}$	Packet Error Rate in the x to y link
$\mathbf{E}_X\{\cdot\}$	Statistical expectation computed over X
$Pr_X\{\cdot\}$	Probability computed over X
$f^{-1}(x)$	Inverse expression of $f(x)$
$b_{i,k}$	Steady state probability of state (i, k)
$p_{x\|y}$	Probability of x conditioned on y
$\overline{p}$	Complementary probability of p
$\begin{pmatrix} n \\ k \end{pmatrix}$	k-combinations of n elements
$\frac{\partial f(x,y)}{\partial x}$	Partial derivative of $f\left(x, y\right)$ with respect to x
$\lceil x \rceil$	Ceiling function of x

Chapter 1

Introduction

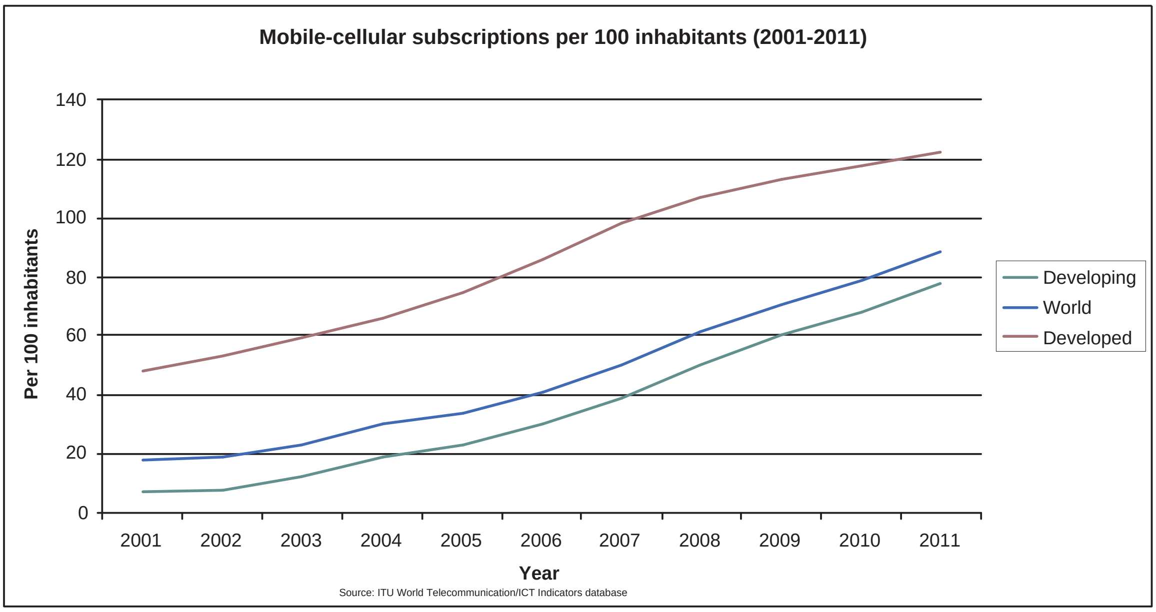
"It has to start somewhere, it has to start sometime, what better place than here? What better time than now?" **Zack de la Rocha**

Contents

1.1 Timeliness

Higher energy efficiency or better Quality of Service (QoS)? This is a question that is becoming more and more difficult to answer. On one hand, the European Union (EU) and standardization organizations constantly pose new targets and constraints with regard to the energy consumption of Information and Communications Technology (ICT) industry. On the other hand, the proliferation of wireless/mobile communication networks generates the need for high level network performance, which is achieved by putting stringent restrictions on specific metrics, such as the packet delay and the network throughput. Hence, the two above-mentioned aspects are often in contradiction, since it is not straightforward to achieve a win-win situation by fulfilling one of them without compromising the other.

Nowadays, mobile devices have become extension of our bodies and part of our daily lives. According to the International Telecommunication Union (ITU), by the end of 2011, the total mobile-cellular subscriptions reached almost six billion, corresponding to a global penetration of 86%, while at the same time the penetration in developed[1] countries surpassed 120% (Figure 1.1). In addition, Cisco foresees that the number of mobile-connected devices will exceed the world's population in 2012 [1]. The introduction of new technologies along with the spread of social networks have played a key role for this tremendous growth. In particular, users crave an "any-time-any-place" connectivity, using state-of-the-art devices such as smartphones, tablets, Personal Digital Agendas (PDAs), e-book readers and netbooks, among others. These high-end devices have bridged the gap between performance and hand-held size mobility, enabling the "on-the-move" use of bandwidth-hungry applications (Figure 1.2) that were traditionally present only in desktop workstations.



Source: ITU World Telecommunication/ICT Indicators database

Figure 1.1: Mobile/cellular subscriptions penetration rate

Social networking constitutes, undoubtedly, the most current trend of today. Initially, social networks were set up focusing on friendly ties between users. Lately however, business-oriented social networks, such as LinkedIn[2], where users seek for job opportunities or try to expand their business cycle, experience major growth. The idea of social networking has also

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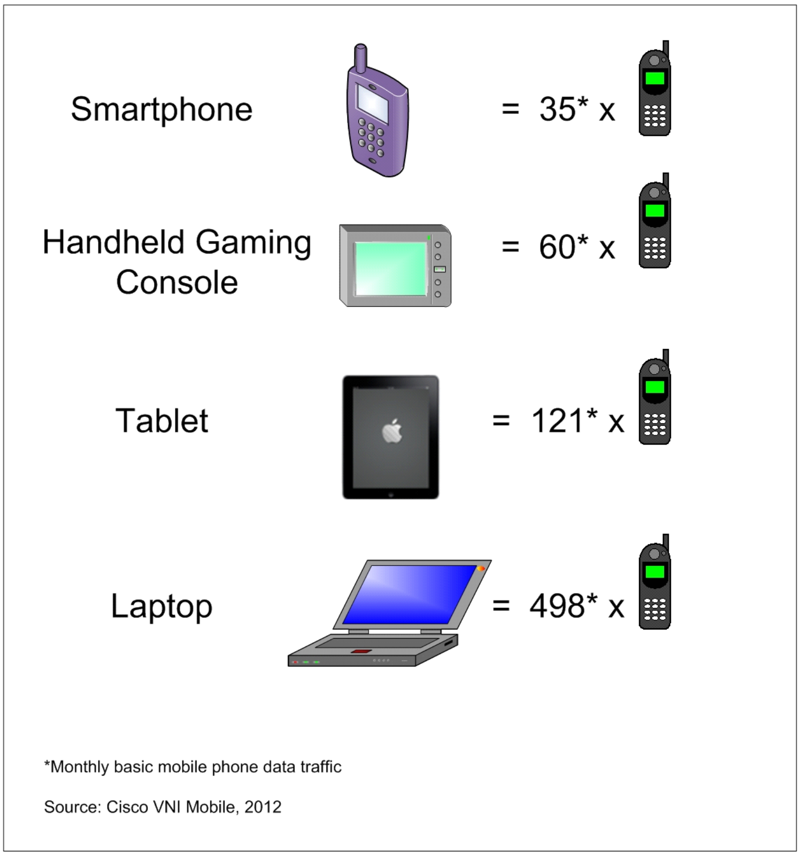
[1] The developed/developing country classifications are based on the United Nations M49, available at: http://www.itu.int/ITU-D/ict/definitions/regions/index.html

[2] http://www.linkedin.com

been infused directly to the mobile world, since today's high-end smartphones enable the interfacing of devices - and therefore their users - based on the criterion of close proximity [2]. In social mobile networks, users can detect other people in their nearby area and interact with them by chatting, exchanging multimedia files and/or playing online games.



*Monthly basic mobile phone data traffic

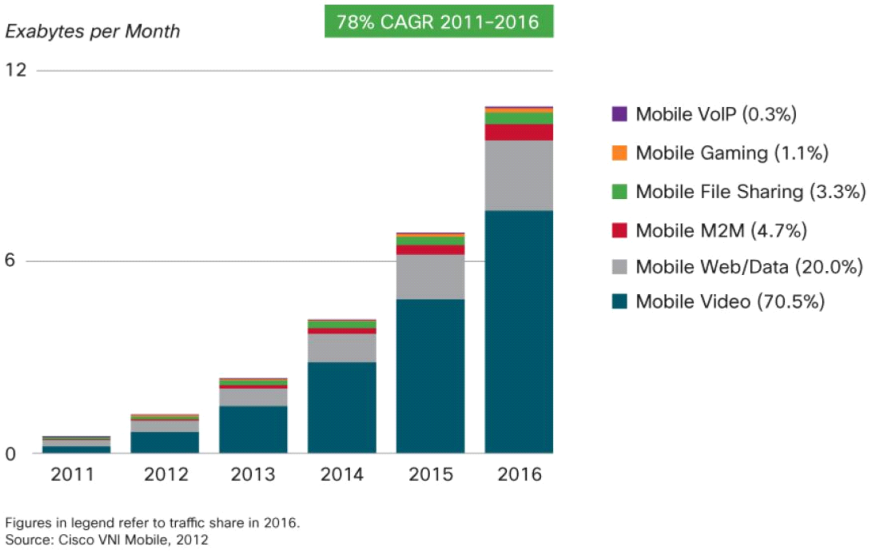
Source: Cisco VNI Mobile, 2012

Figure 1.2: Traffic correspondence between high-end devices and conventional mobile phones

The necessity and the desire for interaction with other people have motivated the development of peer-to-peer (P2P) networks, where distributed communication replaces the centralized infrastructure. In P2P networks, users are able to communicate amongst each other without the intervention of central servers, Base Stations (BSs) or any other kind of (usually paid subscription) network service. However, network operators might consider P2P networking more as an opportunity to enhance their offered services rather than a threat for their existence. In the following section, we deepen our understanding in these concepts by setting a framework for the issues that arise.

1.2 Problem Statement

The introduction of third generation (3G) systems has caused a shift from voice-oriented applications to mobile broadband internet. In particular, Cisco reports that mobile video traffic exceeded for the first time 50% of the total traffic at the end of 2011 [1], while it is expected that video, web and file sharing will reach 95% of traffic by the end of 2016 (Figure 1.3). This paradigm shift along with the craving for omnipresent communication have motivated the development of mesh P2P networks, where users communicate in a cooperative ad hoc manner to exchange information.



Figures in legend refer to traffic share in 2016.
Source: Cisco VNI Mobile, 2012

Figure 1.3: Traffic share prediction (CAGR: Compound Annual Growth Rate)

Sharing is a strong component of cooperation. The introduction of P2P networking enables users to share their personal content (e.g., photos, music, video) with other users in their proximity, eliminating the need of central coordination. Hence, over the last few years, the concept of data dissemination has been gaining great attention in the research community. In data dissemination scenarios, the digital content is spread among a group of interested users via cooperation. Hereafter, we provide two potential applications of data dissemination in order to refine how cooperation can significantly boost the system performance:

- *Cooperative Web Browsing:* The main idea behind cooperative web browsing [3] is the exploitation of multiple cellular air interfaces at the same time, since the time for reading is much longer than the web site download phase. In particular, a mobile device that wants to access a web page, contacts the inactive devices in its proximity to download the web content in a cooperative manner. Thus, the downloading time is reduced, while all devices benefit from the cooperation by preserving valuable energy resources.

- *Cooperative File Download:* Let us consider the network topology of Figure 1.4, where the nodes inside the cloud (PDAs, mobile phones, laptops) could correspond to a group of colleagues located in the same floor of a company's building, having though different connectivity to the central macrocell BS. Assuming that all users are interested in the same content, such as a particular video/audio file, it is possible that the users with better connectivity download the content from the server and, then, the data are disseminated in the network using short range connection links.

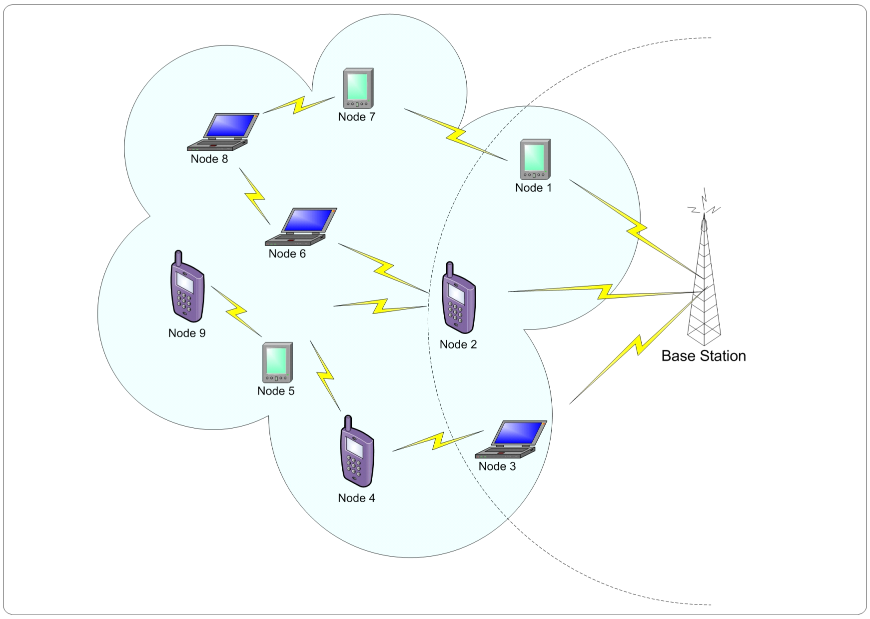


Figure 1.4: Cooperative file download

The two aforementioned exemplary cases give an insight to address common problems in wireless networks (e.g., low data rates, poor connectivity to the central BS) via user cooperation. Beyond its apparent advantages, short range cooperation is an effective countermeasure to energy consumption issues which are currently placed on the top of the research interest in the scientific community. Evidently, high-end devices carry more energy demanding functionalities that lead in fast battery drainage. In this point, it is worth noticing that the current technological achievements with regard to the battery capacity [4] are much slower than the computational power evolution which follows Moore's law, thus making new devices less autonomous, while restricting their mobility. Hence, the terminals can save energy and increase their battery lifetime by avoiding the direct links to the BS, exchanging information using low-power short range communication.

The discussion about energy saving is not confined in the battery level. The use of ICT products across wide ranging applications currently accounts for 5.7% of the world's electricity consumption and 1.8% of global carbon emissions [5]. However, ongoing "green"[3] innovative technology is expected to be released in the market in order to improve the energy efficiency of the ICT sector by the end of 2015, thus being in compliance with EU rules that command a reduction of 20% to the carbon emissions by the end of 2020. According to [5], the global value created through energy efficiency gains enabled by energy-smart ICT products and solutions across all sectors is projected to grow from \$170 billion in 2010 to \$478 billion in 2015. Towards this direction, a plethora of research studies has been published in the literature during the last few years [6–20], covering a wide range of research areas including, among others, cellular networking [10–12], cognitive radio [13–15], Multiple-Input Multiple-Output (MIMO) techniques [16, 17] and cooperative communications [18–20], among others. In addition, this trend has stimulated many European research projects including GREENET[4], EARTH[5] and Green-T[6], as well as important initiatives such as ICT4EE [21] and GreenTouch [22] comprising of influential ICT consortia.

In this context, taking into account the recent advances in cooperative mobile communications, our work is focused on studying energy efficient cooperative techniques. In the following section, our motivation and the scope of this dissertation are analyzed in detail.

1.3 Motivation and Scope

We are going through an era where the main tendency is twofold: on one side, the need for data dissemination, bidirectional communication and better QoS and, on the other side, the requirement for energy preservation. With energy consumption becoming an increasingly important design criterion, novel energy-aware techniques have been introduced in the literature.

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[3] Throughout this thesis, the term "green" refers to all environment-aware methods.

[4] http://www.fp7-greenet.eu

[5] https://www.ict-earth.eu

[6] http://greent.av.it.pt

Apart from their inherent benefits, these innovative techniques require new protocols and algorithms to optimize the trade-off between energy consumption and system performance. The design of these algorithms is further complicated due to the distributed nature of modern wireless networks. Some of the intrinsic treats of wireless ad hoc networks, which make their management a very interesting challenge, are the following:

- The lack of any centralized infrastructure imposes severe restrictions to the protocols design.
- The user mobility implies an unpredictable, volatile network topology.
- The portability of the mobile battery-powered terminals requires energy efficient protocols that guarantee the autonomy of the devices.

The aforementioned characteristics stress the need of research in various aspects of the wireless communications, such as resource allocation, scheduling and channel access, typically handled by protocols in the Medium Access Control (MAC) layer. MAC protocols essentially specify the rules of operation that the users should comply to, in order to achieve an efficient and fair use of the available system bandwidth.

This thesis constitutes a contribution to the MAC layer protocol design for decentralized ad hoc cooperative networks. Motivated by the recent advances in wireless communications, we introduce novel medium access techniques, aiming at providing higher network energy efficiency, without compromising the offered QoS. To this direction, we exploit state-of-the-art techniques such as digital and analog Network Coding (NC), while we adopt proper tools, such as non-cooperative game theory, to model and predict the behavior of entities that make interactive decisions, forming distributed infrastructureless networks. The main contributions and the structure of this dissertation will be discussed in detail in the following section.

1.4 Structure of the Dissertation and Main Contributions

This dissertation deals with MAC issues in cooperative wireless networks. We propose and evaluate novel advanced energy-aware NC-aided MAC protocols that provide enhanced QoS. The contributions of our work are divided into two main parts:

I. The first part is confined in Chapter 3, where we present an NC-assisted MAC protocol for cooperative wireless networks. It is proven that NC along with error correction mechanisms such as Automatic Repeat reQuest (ARQ) can significantly improve the system performance in terms of both throughput and energy efficiency.

II. The second part consists of Chapters 4 and 5, where we apply game theory in the design of distributed MAC protocols. It is particularly shown how energy aspects can be taken into account in the design of energy efficient MAC protocols, while NC can further boost the network performance.

The remainder of the thesis consists of five chapters, where the contents and the contributions of each chapter are described in detail as follows:

- **Chapter 2.** The second chapter introduces the basic background for the main concepts employed in this thesis. First, we briefly overview the MAC layer and the importance of MAC protocols in Wireless Local Area Networks (WLANs). Next, we introduce the concept of cooperative networking, while we classify the most important cooperative techniques from the MAC layer point of view. Subsequently, we present the NC concept in general, focusing on the description of particular NC techniques applied in our work. Finally, the last part of this chapter constitutes a preliminary guide to game theory, explaining the basic concepts and notations adopted in our work.
- **Chapter 3.** This chapter contains our first major contribution, the **NC**-aided **C**ooperative **ARQ** (NCCARQ) MAC protocol for wireless networks. NCCARQ is a Carrier Sense Multiple Access (CSMA)-based scheme, backwards compatible with well known existing standards for medium and short range wireless communication. In this chapter, we present two variants of our protocol: i) one version for WLANs, named NCCARQ-WLAN, backwards compatible with IEEE 802.11, and ii) one version for Wireless Sensor Networks (WSNs), named NCCARQ-WSN, backwards compatible with IEEE 802.15.4. For both approaches, the frame structure and sequence are described in detail, while comprehensive operational examples are given. In addition, a thorough analysis along with extensive simulation results are provided to evaluate both protocol versions. In the last part of this chapter, we consider practical Physical (PHY) layer issues and limitations on the design and performance of NCCARQ. In particular, the impact of correlated shad-

owing on the system performance is studied and the importance of PHY layer aspects is highlighted.

The contributions of this chapter have been published/submitted in part in four international journals and four peer-reviewed conferences:

- **A. Antonopoulos**, M. Di Renzo and C. Verikoukis, "Impact of Realistic PHY and Correlated Shadowing on the Performance of Network Coding-aided Cooperative MAC Protocols", *IEEE Communications Magazine* (submitted).
- **A. Antonopoulos**, C. Verikoukis, C. Skianis, O.B. Akan, "Energy Efficient Network Coding-based MAC for Cooperative ARQ Wireless Networks", *Ad Hoc Networks (Elsevier)*, available online 31 May 2012, ISSN 1570-8705.
- **A. Antonopoulos**, C. Skianis, C. Verikoukis, "Network Coding-based Cooperative ARQ Scheme for VANETs", *Journal of Network and Computer Applications* (2012), ISSN 1084-8045, 10.1016/j.jnca.2012.03.012.
- **A. Antonopoulos** and C. Verikoukis, "Network Coding-based Cooperative ARQ Medium Access Control Protocol for Wireless Sensor Networks", *International Journal of Distributed Sensor Networks*, vol. 2012, Article ID 601321, 9 pages, 2012. doi:10.1155/2012/601321.
- **A. Antonopoulos**, J. Bas, M. Katz, H. Lundqvist, T. Moreira, K. Ntontin, F. Vasquez and N. Zorba, "Green-T: Enabling Techniques for Energy Efficient Mobile Terminals", *IEEE CAMAD*, September 2012, Barcelona, Spain.
- **A. Antonopoulos**, C. Skianis and C. Verikoukis, "Network Coding-based Medium Access Control Protocol for Cooperative Wireless Networks", *IEEE ICC*, June 2012, Ottawa, Canada.
- **A. Antonopoulos** and C. Verikoukis, "Energy Efficient Network Coding-based Cooperative ARQ Scheme for Wireless Networks", *ICST Mobilight*, 9-11 May 2011, Bilbao, Spain.
- **A. Antonopoulos** and C. Verikoukis, "Network Coding-based Cooperative ARQ Scheme", *IEEE ICC*, June 2011, Kyoto, Japan.

- **Chapter 4.** This chapter introduces a multiplayer game theoretic MAC scheme for energy efficient data dissemination in wireless networks. Taking into account the selfish behavior of wireless nodes which contradicts with the need for cooperation, we come up with a game formulation in order to estimate the channel access probabilities for the source nodes in a wireless network where the upper goal is the data dissemination. Two different variations of the MAC protocol are proposed: i) a distributed approach for decentralized ad hoc networks, and ii) a centralized approach, where a central controller occasionally intervenes to expedite the data dissemination. Our proposed solutions are substantially evaluated by both analytical and simulation results, demonstrating their outperformance over existing widespread protocols.

The contributions of this chapter have been published/submitted in part in one journal and three international conferences:

  - **A. Antonopoulos** and C. Verikoukis, "Multi-player Game Theoretic MAC Strategies for Energy Efficient Data Dissemination", *IEEE Transactions on Wireless Communications* (submitted).
  - **A. Antonopoulos** and C. Verikoukis, "Energy Efficient Medium Access Strategies for Data Dissemination: A Game Theoretic Approach", *IEEE INFOCOM 2013* (submitted).
  - **A. Antonopoulos** and C. Verikoukis, "N-player Medium Access Game for Wireless Data Dissemination", *IEEE GLOBECOM*, December 2012, Anaheim, California, USA.
  - **A. Antonopoulos** and C. Verikoukis, "Game Theoretic Network Coding-aided MAC for Data Dissemination towards Energy Efficiency", *Workshop COCONET co-located with IEEE ICC*, June 2012, Ottawa, Canada.

- **Chapter 5.** This chapter presents ANGEL, an **A**nalog-**N**C-aided **G**ame theoretic **E**nergy efficient **L**ayout for data dissemination. Leveraging the latest developments in Analog NC (ANC) field, we propose a new MAC protocol that exploits to the maximum the collisions in the network, using advanced ZigZag decoding techniques. Analytical and simulation results prove that the combination of digital and analog NC can yield significant benefits to the network performance.

  The contributions of this chapter have been published in part in one international conference:

  - **A. Antonopoulos**, C. Skianis and C. Verikoukis, “ANGEL: Analog Network-Coded Game Theoretic Energy Efficient Layout for Data Dissemination”, *IEEE GLOBECOM*, December 2012, Anaheim, California, USA.

- **Chapter 6.** This chapter concludes the dissertation by providing a summary of our major contributions, together with some potential lines for future investigation.

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Chapter 2

Background

"When you know better, you do better." **Maya Angelou**

Contents

2.1 The Medium Access Control (MAC) Layer

2.1.1 MAC Layer Functionality

All computer networks, including wireless, are organized in a layered architecture. Open Systems Interconnection (OSI) [1] is the most widely used architecture model, developed by the International Organization for Standardization (ISO) to prevent the deployment of incompatible network architectures by different vendors.

The OSI reference model can be represented by a vertical stack composed of seven virtual independent layers as it is depicted in Figure 2.1. In this particular structure, the four upper layers (*Application, Presentation, Session, Transport*) are related to user applications, while the three lower layers (*Network, Data Link, Physical*) deal with data transmissions and computer communications. Each layer has different functionalities and is able to exploit the services offered by the next lower layer. These services are provided by procedures defined in the interconnection among layers, while the communication is restricted only between adjacent layers.

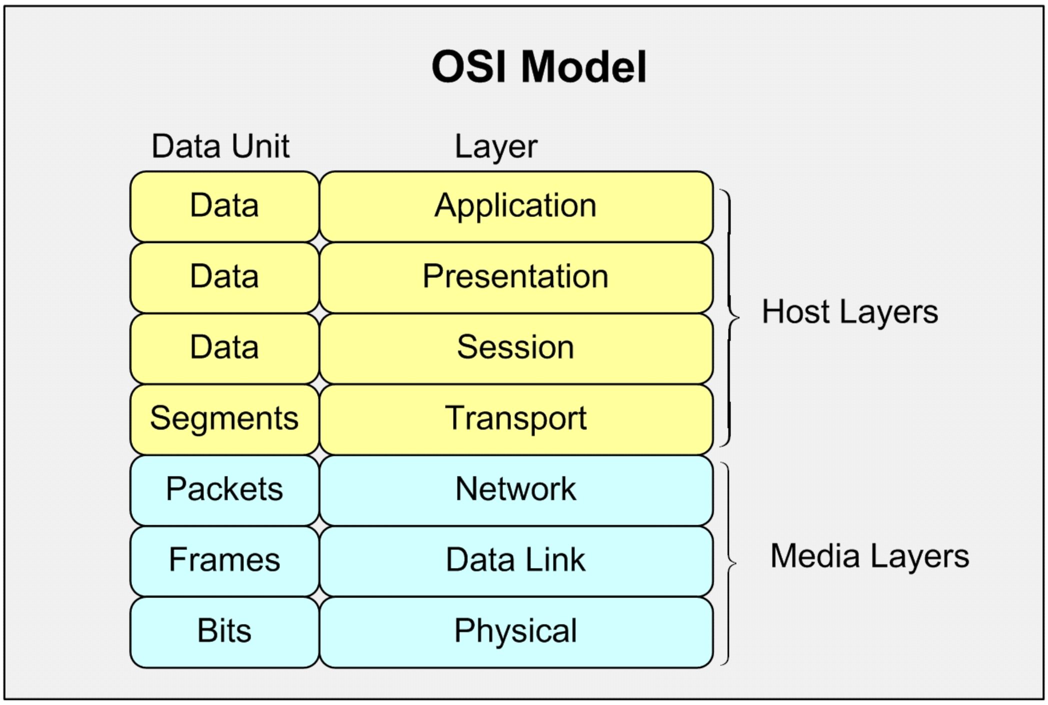

Figure 2.1: OSI reference model

The Data Link layer is further divided into two different sublayers, namely the Logical Link Control (LLC) and the MAC sublayer which is the focus of the present dissertation. The most important functions of the MAC layer can be summarized in the following:

1. *Channel Access Control:* The MAC layer defines the rules that the network nodes have to follow in order to access the shared medium. Moreover, it provides advanced mechanisms for collision resolution and coordinates both the data and control plane. The nodes can communicate either in an ad hoc manner or via a central Access Point (AP) with respect to the network topology (distributed or infrastructure-based, respectively).

2. *Scheduling:* The MAC layer is also responsible for scheduling the transmissions in the network. The scheduling optimization can yield significant improvements in the network performance, such as throughput maximization, fairness among users and energy efficiency enhancement, among others.

3. *Data Framing:* The data encapsulation into particular frames takes place in the MAC layer prior to any (inter-layer) data exchange. Framing organizes the data to be transferred by adding a header with descriptive information (e.g., source and destination MAC address), so they can be handled by the network devices.

4. *Error Control and Handling:* In the MAC layer, a Cyclic Redundancy Check (CRC) field for error detection is appended to each frame. This CRC is checked at the receiver's side to verify the correct reception of the packet. In case of errors, the packet is discarded and retransmission might be requested according to the MAC protocol rules.

2.1.2 MAC Protocols for WLANs

The study of MAC protocols constitutes a major issue for the scientific research community. Although a vast number of protocols has been proposed in the literature, the aim of this section is mainly to discuss some representative examples related to the main contribution of this thesis and not to provide an exhaustive review of the existing MAC protocols[1].

Figure 2.2 depicts a preliminary categorization of MAC protocols with respect to the way that the system resources are shared among the users. In particular, there are two main categories: i) the protocols that provide *deterministic* channel access, and ii) the protocols that provide *random* channel access. The protocols of the former class are applicable in infrastructure networks, where a central controller coordinates the channel access and, typically, resource

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[1] A comprehensive overview of wireless MAC protocols can be found in [2] and [3].

allocation takes place before transmissions. On the other hand, the protocols of the latter category coordinate all data transmissions in non-centralized or ad hoc networks, where users independently compete for channel access and, as a result, a potential of collisions exists in the network. Examples of deterministic MAC protocols are the following:

- Polling-based schemes: The users must receive a polling request by the central controller in order to attempt transmission.
- Time Division Multiple Access (TDMA): The users transmit in different portion of time (time slots) using the whole frequency bandwidth.
- Frequency Division Multiple Access (FDMA): The users transmit at the same time in different frequency channels of the available bandwidth.
- Code Division Multiple Access (CDMA): The users are assigned different unique codes that allow them to transmit at the same time and channel.

The random access MAC protocols are further divided into two sub-categories according to whether or not the nodes sense the channel before transmitting their data. ALOHA [4] and CSMA [6] are the two most fundamental archetypes for random access protocols in wireless networks. ALOHA was the first protocol introduced to realize uncoordinated channel access of multiple users in a common shared medium for packet-based computer communication. In pure ALOHA, users attempt transmissions as soon as they have packets to be transmitted in their buffers. In case of simultaneous or overlapping transmissions, the nodes retransmit their data after a random time in order to reduce the probability of having the same packet suffering of multiple consecutive collisions. An evolution of pure ALOHA, called slotted ALOHA [5], was later proposed to enhance the system performance and increase the medium utilization efficiency. In slotted ALOHA, the time is divided into slots, while the transmission attempts are restricted in the beginning of a time slot. The proposed game theoretic MAC protocol in the second part of this dissertation constitutes a variant of slotted ALOHA, where the nodes estimate the probabilities of transmission in each slot in order to maximize their battery lifetime.

Carrier sensing is a more sophisticated approach that dominates the medium access methods in WLANs, overcoming the limitations of ALOHA. In CSMA protocols, the user terminals listen to the channel and transmit only if the medium is sensed idle. On the contrary, if the chan-

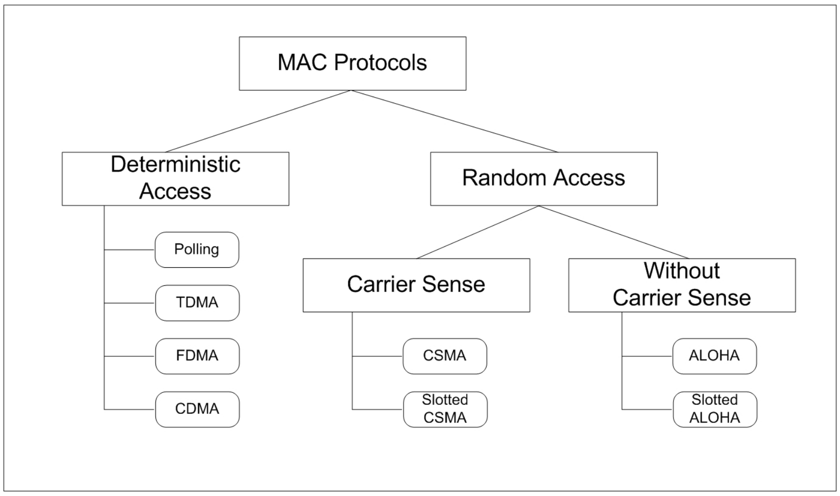

Figure 2.2: MAC protocols classification

nel is sensed occupied, several variations of the technique exist, defining the way that the users act:

- ***non-persistent CSMA:*** Users refrain from sensing the channel for a random backoff period. After this period elapses, they sense again the channel and the same procedure is repeated until the medium is sensed idle.
- ***1-persistent CSMA:*** Users persistently sense the channel and the transmission initiates with probability 1 when the medium is sensed idle.
- ***p-persistent CSMA:*** Users persistently sense the channel and the transmission initiates with probability p when the medium is sensed idle.

The operation of the widely used IEEE 802.11 Standard [7] is based on the CSMA, while the proposed NCCARQ MAC protocol in the first part of this dissertation is also subject to the CSMA rules.

2.2 Cooperative Networking

2.2.1 The Importance of Diversity

Diversity combining is a well-known concept, widely used in many current wireless technologies to improve the overall system performance, as it allows for the mitigation of multipath fading due to the wireless medium [8]. The rationale behind diversity combining consists in transmitting the same carrier signal by two or more antennas, and combining these multiple replicas at the receiver to increase the end-to-end system performance. In particular, over the last years, spatial diversity has been proven to be a very effective approach to boost channel capacity and improve the error performance over fading channels. However, the exploitation of multi-antenna technology is limited by two technological and practical issues: i) besides cost and performance issues imposed by increased power and processing requirements, the insertion of multiple antennas to mobile terminals constitutes at times an infeasible task due to strict space restrictions dictated by consumer trends; and ii) multi-antenna technology relies on the principle that the signals received by different antennas experience independent fading, which is a hard assumption for small-size devices.

2.2.2 Cooperative Diversity

To overcome the above-mentioned practical limitations, a new concept of spatial diversity has gained significant attention over the last years in the research community: cooperative diversity [9, 10]. This concept, was initially introduced by Van der Meulen [11] and later on investigated by Cover and El Gamal [12] who analyzed the capacity of the three-node network consisting of a transmitter, a receiver and a relay. The basic premise and main idea of cooperative diversity (also known as antenna sharing, user cooperation or virtual antenna array) is to achieve and exploit the benefits of spatial diversity without requiring each mobile node to be equipped with multiple co-located antennas. Instead, each mobile node in a cooperative diversity system becomes part of a large distributed array and shares its single antenna (as well as hardware, processing and energy resources) to assist the communication between two nodes (source and destination) by performing relayed transmissions. This becomes possible due to the broadcast nature of wireless communications, which enables the neighboring stations of a transmitter to overhear its transmissions. As a result, these adjacent stations (*relays*, *helpers* or *partners*) can actively contribute to the wireless communication, by forwarding the message from the source to other neighboring nodes or to the final destination, thus providing the latter with multiple copies of the same message, which can be locally combined using classical combining techniques to improve the reliability of the transmission. As a consequence, distributed cooperation takes advantage of two important and well-known wireless technniques: i) multi-hop relayed transmission, which is a well-established technology in both wireless and wired networks for radio range extension, and ii) spatial diversity, which allows the system to boost channel capacity and throughput. Consequently, distributed cooperation profitably exploits the benefits of both techniques, by potentially providing: i) higher spatial diversity, ii) better system performance, iii) lower energy consumption, iv) extended coverage, and v) adaptability to network conditions.

2.2.3 Cooperative Techniques

Relaying systems are classified as Amplify-and-Forward (AF) or Decode-and-Forward (DF). In the former, the relays amplify the received signal and forward it without decoding it, while in the latter, the signal is fully decoded and re-encoded before retransmission. From the MAC layer point of view, which is the scope of this thesis, there are two main cooperative techniques [13, 14]:

i) ***Proactive Cooperation (Cooperative Routing):*** Using Adaptive Modulation and Coding (AMC) [15], mobile stations in multi-rate wireless networks assign the modulation scheme and the transmission rate according to the detected Signal-to-Noise-Ratio (SNR) and the required transmission quality. Each modulation scheme could be further mapped to a range of SNRs in a given transmission power. Hence, stations select the highest available data rate according to the detected SNR to achieve high transmission efficiency in wireless systems. In cooperative (or opportunistic) routing, the routing of the packets takes place by taking into account the channel quality between the source, the relay and the destination. Therefore, a multi-hop transmission may be preferred instead of the direct one (Figure 2.3a).

ii) ***Reactive Cooperation (Incremental Relaying):*** ARQ is one of the main error control methods for data communications [16]. ARQ techniques have received considerable attention for data transmission due to their simplicity and reliability compared to alternative solutions such as Forward Error Correction (FEC) mechanisms. In cooperative ARQ schemes (incremental relaying), the relays persistently overhear every ongoing transmission, thus becoming capable of participating in any subsequent retransmission phase in case a message has not been correctly decoded at the destination. A retransmission phase is initiated when any overhearing neighboring stations receive a special control packet, usually referred as Request For Cooperation (RFC) or Negative Acknowledgement (NACK), broadcasted by the destination that experienced a decoding failure (Figure 2.3b).

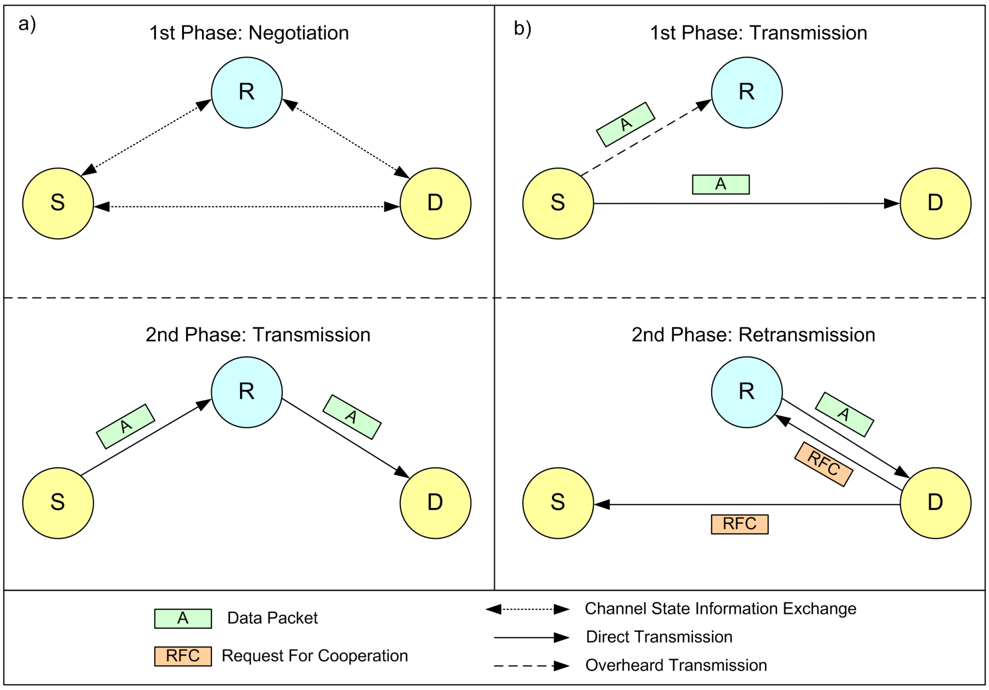

Figure 2.3: Cooperative techniques: a) Proactive cooperation b) Reactive cooperation

The concept of cooperation is used throughout this dissertation. In the first part (Chapter 3), an NC-aided reactive cooperative protocol is proposed, while in the second part (Chapters 4 and 5), the concept of cooperative routing is adopted to extend the radio coverage of a BS.

2.3 Network Coding (NC)

NC was introduced in 2000 [17] to improve network throughput and performance. In traditional communication networks, the intermediate nodes simply forward the received packets to output links (*store-and-forward* method) in order to assist the communication between two nodes. However, NC has come into play to enable the intermediate nodes not only to forward, but also to process the incoming information flows, thus achieving significant enhancements in system throughput, robustness, security and energy efficiency.

The broadcast properties alongside the idiosyncratic nature of the wireless medium offer offer fertile ground for NC applications. Random Linear NC (RLNC) [18, 19] was introduced to overcome the limitations of the initial NC approach that adopted a simple bitwise XOR operation. Recently, the concept of NC was extended to the signal domain by the introduction of advanced techniques such as PHY layer NC (PNC) [20] that further enhance the wireless network performance. The scope of this section is to provide a general background for NC techniques and discuss the NC types employed in this dissertation.

2.3.1 Wireless NC (Bitwise XOR)

The exclusive-OR (XOR) operation constitutes the initial attempt and the base for the digital NC. In particular, the nodes are able to perform the logical XOR function on each pair of corresponding bits of same size packets. Hence, they create a new packet whose every bit is either 0 or 1 depending on whether the bits of the incoming packets in the corresponding position were the same or opposite. To clarify this concept, let us study the scenario depicted in Figure 2.4, where nodes C and D want to exchange their respective packets c and d, through an intermediate node R. To accomplish the packets' relay following the traditional routing approach, node C transmits packet c to R in the $1st$ slot, node D transmits packet d to R in the $2nd$ slot and, in the $3rd$ and $4th$ time slots, node R forwards the packets c and d to the nodes D and C, respectively. However, by applying NC to this procedure the number of total required time slots is reduced by 25$\%$, since node R is able to code the received packets and transmit their XOR combination in a single time slot.

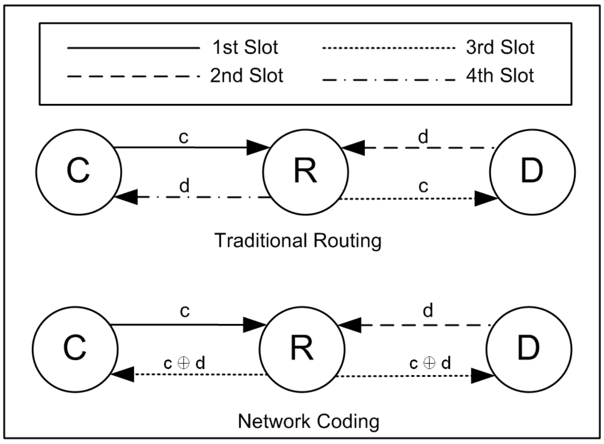

Figure 2.4: Traditional routing vs. NC

The application of wireless NC is not restricted only in two packets. The bitwise XOR can be also applied in n packets, but the decoding process presupposes that the destination node has received $n-1$ uncoded (or native) data packets. This limitation has motivated many researchers to study optimal ways of combining the native packets, thus leading to the development of particular research areas such as the *opportunistic listening* and the *opportunistic coding* [21, 22].

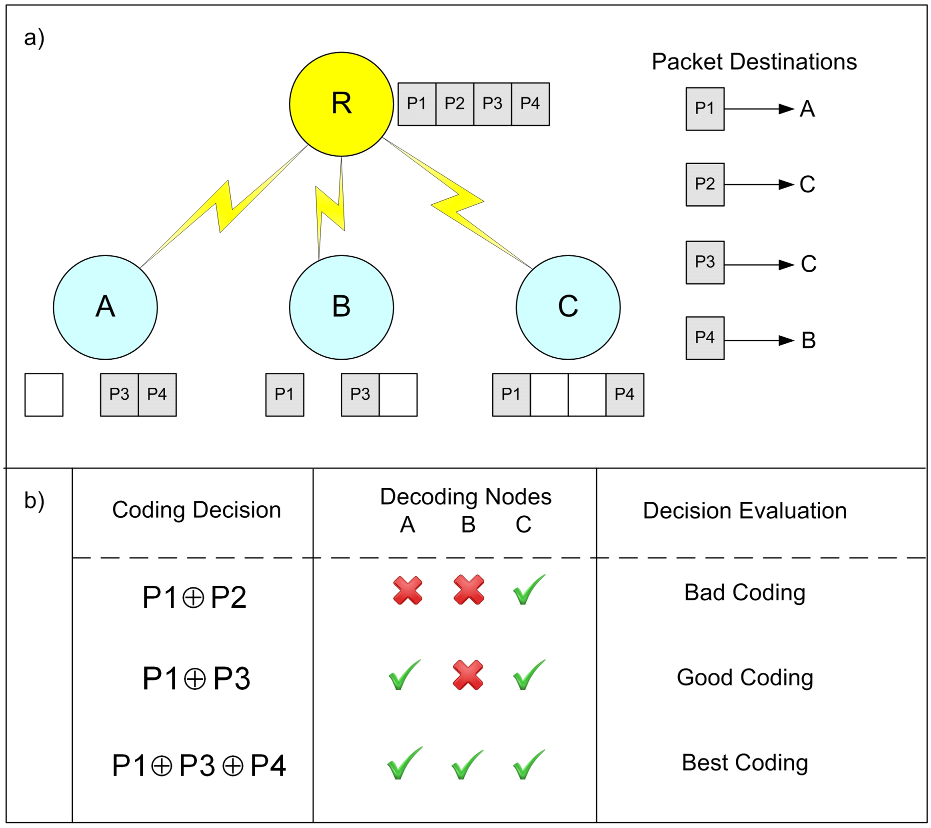

Figure 2.5: Opportunistic coding a) Scenario b) Evaluation of coding options

Figure 2.5 depicts an example regarding the importance of exercising opportunistic techniques. In Figure 2.5a node R has a set of packets ($P1, P2, P3, P4$) destined to its neighbor nodes A, B and C as it is denoted in the figure's legend, while the box under each node represents its packet buffer. The evaluation of the coding options of node R is presented in Figure 2.5b. The first case ($P1 \oplus P2$) is a bad coding decision, since only node C is able to retrieve a novel native packet destined to it. The second option ($P1 \oplus P3$) is a better coding decision, since both nodes A and C can benefit from this transmission. However, the best coding decision is the third one ($P1 \oplus P3 \oplus P4$) that would allow all three network nodes to decode their respective native packets in one transmission.

In the first part of this thesis (Chapter 3), the bitwise XOR NC is applied to the proposed cooperative MAC protocol for wireless networks. In particular, it is demonstrated how NC together with cooperation can significantly improve the system performance in terms of throughput, delay and energy efficiency.

2.3.2 Random Linear NC (RLNC)

RLNC [18,19] is an advanced form of NC which has been introduced to overcome the practical limitations of the simple XOR. Although beneficial for the network, the bitwise XOR operation faces inherent constraints due to its nature, since an excessive amount of uncoded information is required during the decoding process. Moreover, the advantage of being opportunistic comes at the cost of packet overhead, since a vast number of control information is required to provide the network nodes with the necessary context information. On the other hand, RLNC is a totally distributed NC paradigm, applicable in wireless networks without any other additional knowledge. In RLNC, the intermediate nodes in a network are able to code the incoming packets (either coded or native) by creating linear combinations before forwarding them to the next hop. Hence, a destination node is able to decode the total information as soon as it receives a sufficient number of independent linear packet combinations.

Figure 2.6 illustrates the coding/decoding process in RLNC, where $x_1, x_2, ..., x_n$ are the original packets to be transmitted. Each transmitting node selects a random vector $\boldsymbol{\alpha}_j = [a_{j1}, ..., a_{jn}]$ of coding coefficients from a finite Galois Field (GF) F_q of q elements and creates a coded packet:

$$y_j = \boldsymbol{\alpha}_j \cdot \mathbf{x}^T = \sum_{i=1}^{n} a_{ji} \cdot x_i \tag{2.1}$$

where $\mathbf{x}$ is a vector composed of the native packets.

It is worth noting that the encoding procedure can be applied in every intermediate node, without affecting the decoding process. However, the random selection of coding coefficients in the different network nodes requires a GF of sufficient size to ensure the linear independence among them. Regarding the decoding procedure, at least n independent packet combinations along with the respective coding vectors are required at the destination's side. In particular, each destination node stores the received coding vectors in a decoding matrix A. A new packet

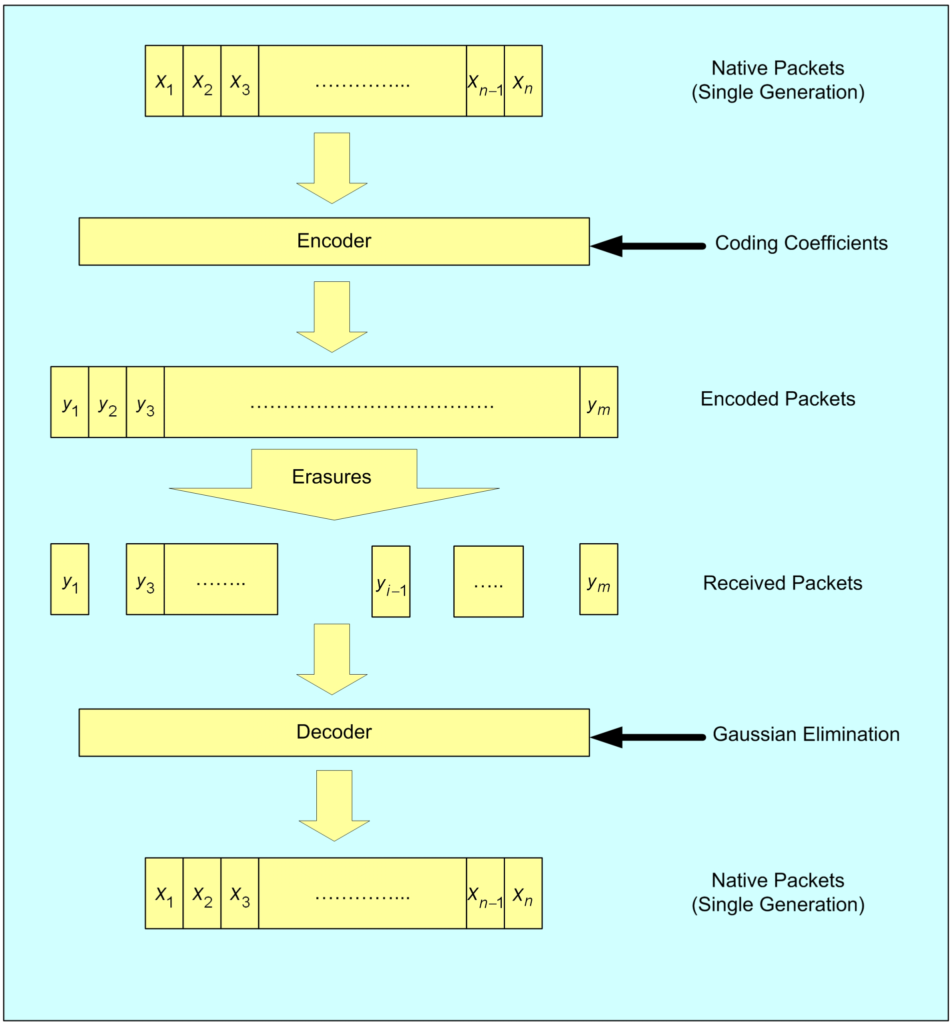

Figure 2.6: RLNC operation

is defined as innovative if its vector increases the rank of matrix A, while the reception of non-innovative packets is simply ignored. Once a node has received n linear independent combinations, i.e., the matrix A has full rank, it is able to decode the packets by applying standard Gaussian elimination, thus retrieving the original information $x_1, x_2, ..., x_n$.

Apparently, the price to be paid for this distributed transmission scheme is the overhead associated to the coding vectors $\boldsymbol{\alpha}_j$. To reduce this overhead, it is possible to fragment the original data packet/file to be transmitted into various segments of smaller size, known as *generations*. Hence, only packets that belong to the same generation can be encoded together, while the impact of the generation size has been extensively studied in the literature [23–27].

Apart from the straightforward gains of RLNC with regard to throughput and energy efficiency of the system, there are also several collateral benefits in its applications. First, RLNC eliminates the need of exchanging control packets, i.e., acknowledgements (ACK), in the network, since it is sufficient for a node to obtain a satisfactory number of independent linear packet combinations in order to extract the original information. This is, indeed, beneficial for broadcasting schemes, where the simultaneous transmission of multiple ACK packets to the central node constitutes a critical issue. Another important beneficial “side-effect” of RLNC is the robustness against channel impairments, as it is shown in the example of Figure 2.7. In this particular example, we assume a communication between two nodes where statistically half of the transmissions fail, i.e., the Packet Error Rate (PER) between the source and the destination is equal to 0.5. We further assume that the source wants to transmit two packets ($x = 1$ and $y = 4$) to the destination. In the conventional approach, the source can transmit twice each native packet but, still, there exists a high probability of failure, since the success of the transmissions depends on the erroneous links. On the other hand, RLNC enables the destination to decode both packets, independently of which particular transmissions have failed.

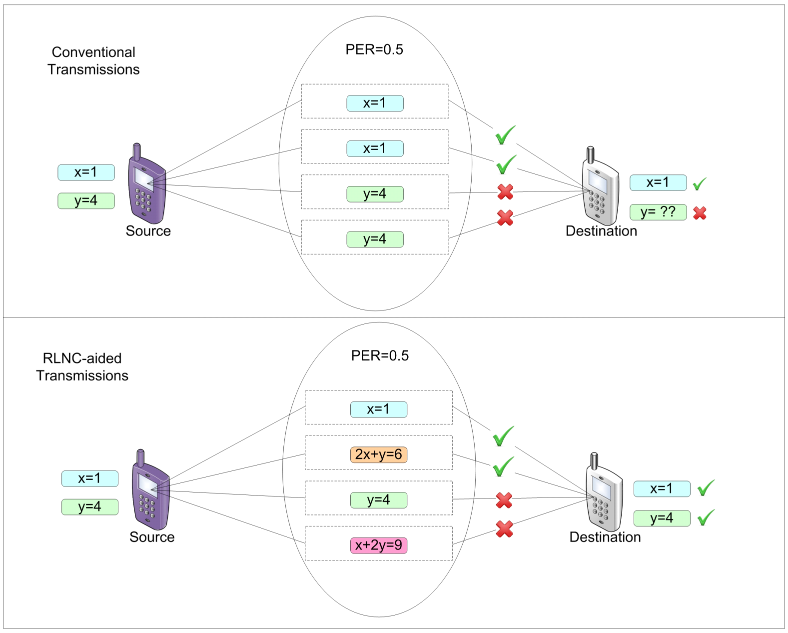

Figure 2.7: Channel error robustness (Traditional transmissions vs. RLNC)

In the second part of this dissertation (Chapters 4 and 5), RLNC is adopted in our proposed game theoretic MAC protocols for data dissemination. In particular, we exploit the benefits of RLNC techniques to reduce the data dissemination completion time and enhance the energy efficiency in the network.

2.3.3 Analog NC (ANC)

The basic concepts of NC have been adjusted to the analog domain, thus creating new schemes such as PNC [20], MIMO-NC [28] and ZigZag decoding [29]. All these schemes, branches of a broader notion known as ANC [30], deal with the electromagnetic signal reception, modulation and processing, hence boosting further the system performance.

ANC was initially introduced as an effective countermeasure against interference in wireless networks. Compared to digital NC, ANC can further reduce the number of required time slots for a bidirectional communication, as it is shown in Figure 2.8. In particular, C and D can simultaneously transmit to the router their packets c and b, respectively. Although the router experiences a collision by the concurrent reception of two signals, it can simply amplify and forward the received interfered signal without decoding it, in a single time slot. Since the two nodes already know the signals they have transmitted in the first slot, they are able to subtract them from the received interfered signal in order to decode the packets.

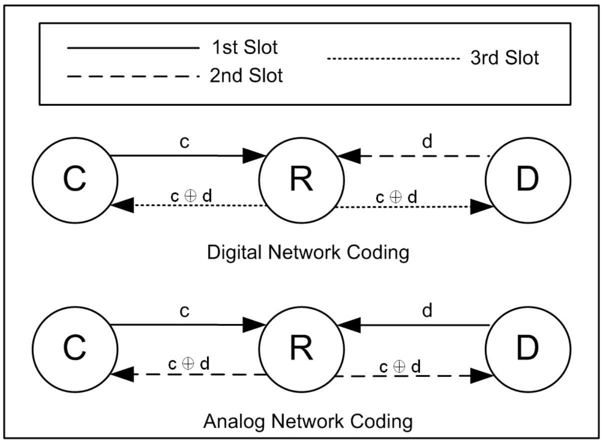

Figure 2.8: Digital vs. Analog NC

In addition, ANC finds application in new scenarios, where the broadcasting and the bidirectional flows are not a prerequisite to employ coding. For illustrative purposes, let us consider the topology in Figure 2.9 where a single flow has to travel 3 hops from source (A) to destination (D) via the intermediate nodes B and C. In this particular case, digital NC cannot reduce the number of time slots for the delivery of one packet. On the other hand, ANC is able to expedite the transmissions by allowing nodes A and C to transmit simultaneously, although node B is located in the intersection of the radio ranges of these nodes. To clarify, let us provide an example where node A has two packets (a and b) destined to node D. In the beginning, A

transmits packet a to B, which further forwards the packet to C. According to the traditional routing approach, node C should transmit packet a to D before A starts the transmission of packet b. However, the application of ANC in the system allows for the concurrent transmission of packets a and b, since node B is able to retrieve packet b by exploiting the fact that it already knows the transmitted interfered signal of packet a.

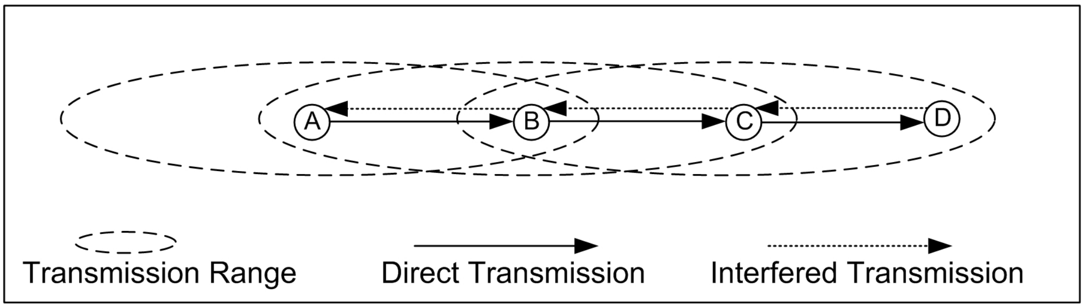

Figure 2.9: Interference cancelation

ZigZag Decoding

Similar to ANC, ZigZag was introduced to combat the hidden terminal problem in wireless networks, providing another advanced interference cancelation mechanism. However, unlike ANC, ZigZag requires no *a priori* knowledge for the signals involved in a collision, but enables a receiver to decode pairs of collisions that contain the same packets. The operation of ZigZag is based on the signal propagation characteristics that cause a lack of synchronization across successive collisions. Hence, ZigZag exploits the different interference-free offsets at the start of these collisions in order to decode the involved packets.

Figure 2.10 provides an illustrative example for the ZigZag decoding procedure in two different successive collision sets that contain the same packets (A and B), having though different interference-free offsets, i.e., $\Delta_1 \neq \Delta_2$. In the first place, the receiver identifies a part that experiences interference in one collision, while it is interference-free in the other, i.e., chunk *2* in Figure 2.10. Having a “clear” part of a packet, the receiver can subtract it from the interfered signal of the second collision to retrieve chunk *a*. Then, it uses chunk *a* to the first collision set to extract chunk *3* and this procedure is iteratively repeated until the receiver decodes both collided packets.

In Chapter 5 of this dissertation, ZigZag decoding techniques are exploited in the design of an ANC-aided MAC protocol for data dissemination. In particular, we introduce a game

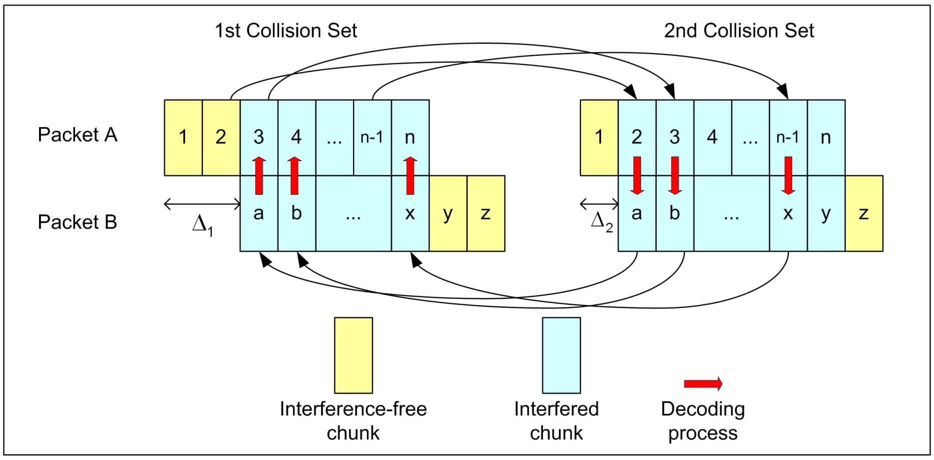

Figure 2.10: ZigZag decoding process

theoretic MAC protocol that exploits to the maximum the collisions in a wireless network where the global upper goal is the data dissemination.

2.4 Game Theory

2.4.1 Introduction to Game Theory

Game theory [31] is a field of mathematics that provides an analytical framework suitable for modeling and analyzing the interactive decision-making process involving several entities with partially or totally conflicting interests. Although the roots of game theory can be placed hundreds of years ago, it was extensively studied and applied in 1950's, initially in the areas of economics, management, politics and sociology. However, the list of its applied areas is continuously increasing, with computer science and engineering being the most prominent addition in the last twenty years.

A game consists of three fundamental concepts: the players[2], the actions (strategies)[3] and the utility/payoff functions[4]. In the most straightforward approach, the decision-making entities, defined as players, choose their strategies from a predefined set. Since the players have conflicting interests, the action of each player has an influence in the payoff of the other

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[2] Please note that the terms “players”, “nodes” and “clients” are used interchangeably in the second part of this thesis.

[3] Although slightly different, the terms “actions” and “strategies” are used interchangeably in this thesis.

[4] The function that determines the player's reward with regard to the actions chosen by the players.

players, thus affecting their resulting outcome. Formally, a game can be represented by a tuple $\Gamma = \langle \mathcal{N}, \mathcal{A}, U \rangle$, where $\mathcal{N} = \{1, 2...., n\}$ is the set of the players, $\mathcal{A} = \mathcal{A}_1 \times \mathcal{A}_2 \times ...... \times \mathcal{A}_n$ is the Cartesian product of the action sets of each player where $\mathcal{A}_i$ is the action set for player i, and $U = \{U_1, U_2....., U_n\}$ is the set of the utility functions that each player wants to maximize.

The utility function of player i depends both on the strategy chosen by player i, denoted as α_i and the strategies of the other players, represented by the vector $\boldsymbol{\alpha}_{-i} = (\alpha_1, ..\alpha_{i-1}, \alpha_{i+1}, ..\alpha_n)$. Hence, the vector $\boldsymbol{\alpha}$ derives by the union of α_i with the vector $\boldsymbol{\alpha}_{-i}$ and represents a complete combination strategy. Using this notation, we can define the *best response* of a player as the strategy that maximizes her utility function for a given strategy combination of the other players.

The majority of the games found in real world can be classified in the following categories:

i) **Static vs. Dynamic:** In *static games*, the players choose their actions simultaneously, while in *dynamic games* one player determines her action by observing the other players' moves.

ii) **Cooperative vs. Non-Cooperative:** In *cooperative games*, the players have the possibility of forming coalitions, making common decisions, while in *non-cooperative games* each player acts individually.

iii) **Complete vs. Non-Complete Information:** In *games with complete information*, each player's payoff function is common knowledge among all players, while in *games with non-complete information* (or *Bayesian games*), at least one player is uncertain about another player's payoff function.

Nonetheless, the scope of this section is not to provide an extensive guide to game theory. We will discuss the main concepts that are used throughout this dissertation, mainly focusing on *static non-cooperative games with complete information*. In this point, it is worth noting that the term *non-cooperative* does not necessarily imply that the players do not cooperate in the network, but indicates the lack of coordination of the strategic choices among the players. Hence, it is possible to model a cooperative network with non-cooperative game theory as long as sufficient justifications for this choice are provided.

2.4.2 Nash Equilibrium and Pareto Efficiency

Nash Equilibrium (NE), introduced by John Nash in his pioneer work [32], is one of the most accepted solution concepts for non-cooperative games. NE can be defined as a steady-state condition that corresponds to the mutual best response of all players. In other words, a strategy combination $\boldsymbol{\alpha}^* = (\alpha_1^*, ...\alpha_i^*, ...\alpha_n^*)$ achieves the NE if no player can improve her utility by unilaterally deviating from her own strategy. This could be mathematically expressed as:

$$U_i(\alpha_1^*, ...\alpha_i^*, ...\alpha_n^*) \geq U_i(\alpha_1^*, ...\alpha_i, ...\alpha_n^*), \forall \alpha_i \in \mathcal{A}_i, i \in \mathcal{N} \tag{2.2}$$

In addition to the pure strategies $\mathcal{A}_i$, players can also choose a probability distribution over their pure strategies. This is described as *mixed strategies* and we will denote by $\sigma_i(\alpha_i)$ the probability that player i chooses her pure strategy $\alpha_i \in \mathcal{A}_i, \forall i \in \mathcal{N}$. Accordingly, we can define the concept of a *mixed-strategy* NE as follows:

$$U_i(\sigma_i^*, ...\sigma_i^*, ...\sigma_n^*) \geq U_i(\sigma_1^*, ...\sigma_i, ...\sigma_n^*), \forall i \in \mathcal{N} \tag{2.3}$$

Although widespread, the NE is not always the optimal steady state for a system. A given solution can be characterized optimum, if and only if it satisfies the "Pareto efficiency" rule. In particular, given an initial allocation of goods among a set of individuals, a change to a different allocation that makes at least one individual better off without making any other individual worse off is called a Pareto improvement. An allocation is defined as "Pareto efficient" or "Pareto optimal" when no further Pareto improvements can be made.

From the above definitions, we conclude that each Pareto efficient solution does not necessarily constitute a NE, and vice versa. Nevertheless, both NE and Pareto optimality are milestone notions in game theory and necessary background for our research.

2.4.3 An Illustrative Example

In this section, we provide an application example of game theory in wireless networks[5] in order to clarify the introduced concepts and study the matrix representation of a game. Hence, let us consider a P2P file sharing network of 3 nodes, where the users experience a tradeoff in

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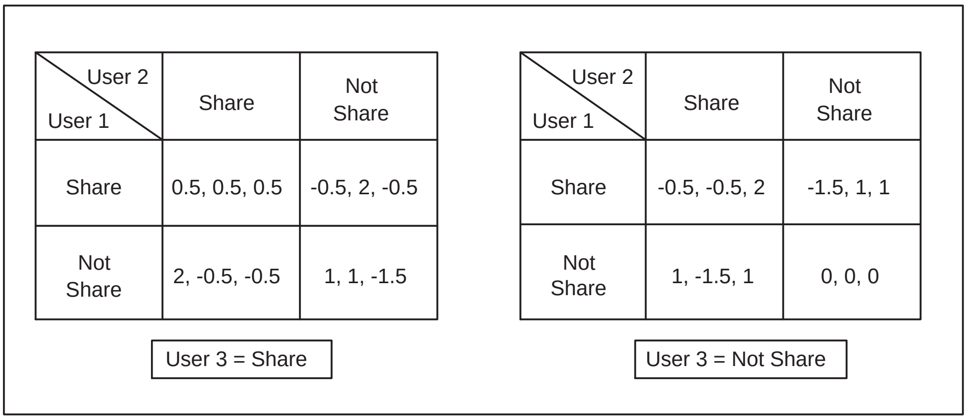
[5] This example can be considered as an equivalent 3-person version of the well-known Prisoner's Dilemma problem.

sharing their files with others. Each player has the option of sharing or not sharing her files and, thus, the action set is defined as $\mathcal{A}$=$\{$*Share, Not Share*$\}$. Regarding the payoffs, we assume that each player benefits by 1 unit for each set of files that any other player shares and incurs a cost of 1.5 units in sharing her own files.



User 2 User 1	Share	Not Share
Share	0.5, 0.5, 0.5	-0.5, 2, -0.5
Not Share	2, -0.5, -0.5	1, 1, -1.5

User 3 = Share

User 2 User 1	Share	Not Share
Share	-0.5, -0.5, 2	-1.5, 1, 1
Not Share	1, -1.5, 1	0, 0, 0

User 3 = Not Share

Figure 2.11: Payoff matrix

To clearly specify the problem structure, we adopt a matrix representation as it is shown in Figure 2.11. The possible actions correspond to the rows and the columns of the table, while each cell contains the respective payoffs for the three players, separated by commas. The unique NE is the action vector $(\alpha_1, \alpha_2, \alpha_3)$=(*Not Share, Not Share, Not Share*), since no user benefits from unilaterally deviating and sharing her files. However, it is evident that the NE solution is not Pareto optimal in this case, as the strategy combination $\boldsymbol{\alpha}$=(*Share, Share, Share*) would serve all the players.

In the second part of this dissertation, we introduce two novel MAC protocols for data dissemination, using game theoretic techniques to resolve the medium access conflicts among the wireless network nodes. It is proven that game theory can provide state-of-the-art solutions that significantly reduce the dissemination completion time and enhance the energy efficiency of the network.

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Chapter 3

NCCARQ MAC for Wireless Networks

"In union there is strength." **Aesop**

Contents

3.1 Introduction

Although the need for communication has always been the driving force for the development of wireless networks, the introduction of P2P and social networking was an extra incentive for bidirectional communication among wireless users. In particular, new ways of direct contact, such as video exchange and music sharing, have been added to the existing traditional ones (e.g., phone calling or message texting). This trend, along with the huge penetration of portable devices which facilitates the formation of cooperative clusters around any mobile device, have been our motivation for the first main part of this thesis.

More precisely, despite the advantages offered by the existence of several potential relays in the network, there is a need for coordinating these devices in the MAC layer. In this context, several schemes focused on the MAC layer have been already proposed in the literature [1–10]. The classification of these works can be made into two main categories (see Section 2.2.3), with respect to the time that the cooperation is triggered: i) *proactive* cooperative protocols and ii) *reactive* cooperative protocols.

Applying AMC, the protocols of the former class [1–5] determine the cooperation *a priori*, according to the detected channel conditions. Specifically, the packet routing procedure takes into account the channel state between the source, the relay and the destination and, therefore, a multi-hop transmission may be preferred instead of the direct one.

Regarding the reactive protocols [6–10], the retransmissions are initiated by the destination (*a posteriori*) after an erroneous packet reception. The helpers in a network are enabled to relay the original packets to the destination, as ARQ defines, using higher data rates or better channel conditions compared to the direct source-to-destination link.

Lately, the introduction of NC along with its inherent characteristics have generated a trend towards incorporating NC techniques in cooperative communications. The initial attempts for developing NC-based cooperative communications were focused on the PHY layer [11–14], studying the system mainly from an information theoretic perspective. These approaches refer to the coding gain and optimal power allocation in simple cooperative topologies, usually considering one relay node or cooperation between two users.

However, the applications of NC in cooperative communications are not confined only within the PHY layer. With respect to the MAC layer, which is the scope of this thesis, several researchers have proposed cooperative MAC schemes, exploiting the NC benefits. A pioneer work that deals with the MAC layer of NC-based cooperative communication was presented by Tan *et al.* [15]. Their proposed protocol, called CODE, exploits the benefits of NC in conjunction with the multi-rate capabilities of IEEE 802.11 Standard. Specifically, the coding of the packets takes place at the relay nodes, under two basic conditions: i) the direct link between the sender and the receiver is poor and exists one or more relay candidates that experience better link conditions, and ii) the traffic is bidirectional. Another similar NC-based MAC protocol has been recently introduced by An *et al.* [16]. Their proposed scheme, called Enhanced Cooperative Communication MAC (ECCMAC), adopts a best relay approach, taking into account NC parameters during the relay selection process.

Argyriou [17] introduced an opportunistic NC-based cooperative protocol by enabling the nodes to transmit opportunistic ACK packets that confirm the correct reception of overheard transmissions. However, the proposed opportunistic protocol suffers from excessive overhead and collisions among the control packets. In a more theoretical work, Umehara *et al.* [18] developed throughput and delay analytical models for slotted ALOHA with NC (S-ALOHA/NC) for single-relay multi-user wireless networks with bidirectional data flows. Their proposed models have been validated under both saturation and non-saturation conditions for the relay buffers.

MIMO-NC is a fresh idea that is already employed in cooperative wireless scenarios. In this context, Munari *et al.* [19] introduced PHOENIX, a MAC protocol that exploits the advanced MIMO-NC principle to enable the relay nodes to code their own data packets along with noisy versions of packets received from other nodes. Thereby, additional incentives are provided to the relays for taking part in the cooperation phase, thus increasing the overall network performance. The idea of PHOENIX has been extended by Want *et al.* in [20]. In their work, the authors proposed an NC-Aware Cooperative MAC (NCAC-MAC) protocol that takes into account the packet queuing conditions at different relay candidates, hence exploiting the coding opportunities.

The impact of NC in "green" communications is currently an active research subject, especially in broadcast and multicast scenarios [21–24]. The recent research work that investigates the energy aspect of NC applications deals mostly with the network layer. Cui *et al.* [25] introduced CORP by using a suboptimal scheduling algorithm that exploits NC opportunities, thus achieving a significant power saving over pure routing. More recently, Miao *et al.* [26] proposed an energy efficient broadcast algorithm using NC for gradient-based routing (GBR) in wireless networks. Their proposed algorithm aims to reduce the network traffic and, consequently, the energy consumption in order to prolong the network lifetime.

In this chapter, considering the research carried out in the related fields, we present an NC-aided Cooperative ARQ (NCCARQ) MAC protocol, specially designed for cooperative wireless networks. In particular, the main contribution of this chapter lies on the following:

1. We introduce a MAC protocol (NCCARQ) that exploits the benefits of both NC and ARQ in bidirectional communication scenarios without any additional overhead.
2. The proposed protocol is able to coordinate multiple relays during the retransmission phase, whilst also being compatible with widespread existing technologies and standards.
3. The performance of NCCARQ is validated through precise analytical models, that provide detailed insight on throughput, delay and energy efficiency from the MAC layer perspective.
4. Unlike the majority of the related research works in the MAC layer, we study PHY layer aspects in the MAC protocol design, while we evaluate the NCCARQ performance under realistic correlated shadowed channel conditions.

The remainder of the chapter is organized as follows. Section 3.2 presents the system model and the network topology. The backwards compatibility with CSMA and the motivation for the design of different protocol variants are discussed in Section 3.3. Section 3.4 introduces two versions of NCCARQ MAC, providing explanatory details and illustrative operation examples. Section 3.5 comprises the analytical models along with the protocol performance evaluation. The PHY layer aspects in the protocol design and operation are discussed in detail in Section 3.6, taking into account correlated shadowing effects among different wireless links. Finally, Section 3.7 concludes the chapter.

3.2 System Model

Figure 3.1 depicts the considered network, consisting of two nodes (S and D) that have data packets to exchange in a bidirectional communication, and a set of n nodes ($R_1, R_2, ..., R_n$)

that act as relays in this particular network setup. We further assume that node D is located marginally in the transmission range of node S, and vice versa, resulting in a weak direct link with high PER. However, the erroneous direct transmissions are compensated by employing network cooperation after the transmission of special control packets (i.e., RFC) either by S or D.

In our system model, all nodes in the network operate in a promiscuous mode in order to be able to listen to every ongoing transmission and cooperate if requested, while the relays always store a copy of any captured data packet (regardless of its destination address) until it is acknowledged by the intended destination. In addition, all relays are equipped with NC capabilities, thus being able to apply XOR techniques to the packets before any further forwarding takes place. Apparently, the existence of many relay nodes in the cooperation phase causes conflicting situations that need to be handled by novel MAC protocols. To this end, NCCARQ MAC has been designed to coordinate the retransmissions among the relay set in the network.

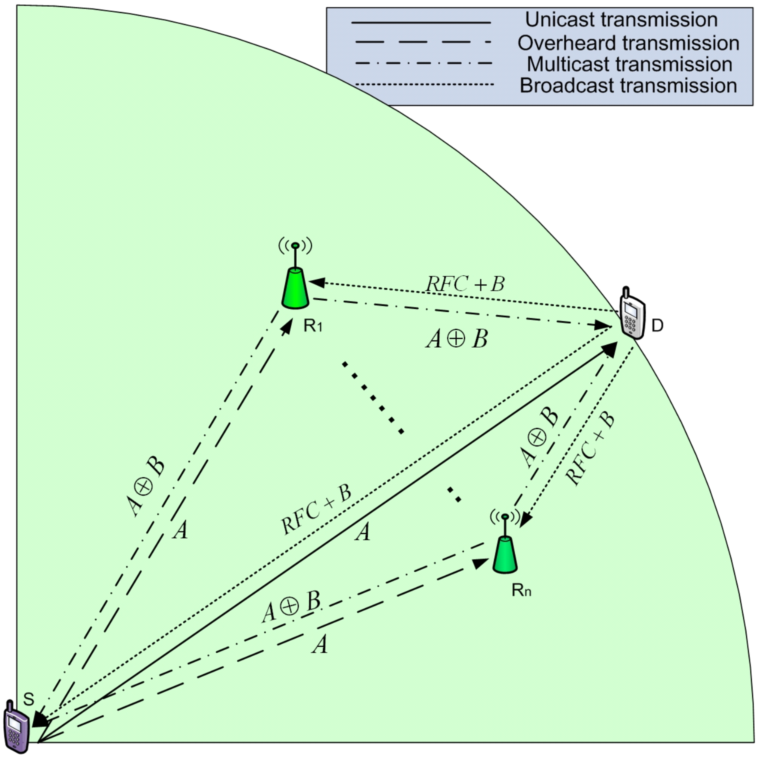

Figure 3.1: System model

3.3 Backwards Compatibility

Backwards compatibility constitutes a very important parameter for the design of new schemes, considering the already widespread deployed wireless infrastructure. In Data Link layer, particularly, one major challenge is the implementation of novel MAC protocols, applicable in existing technologies by slightly modifying the controller of the wireless interface.

Contemporary ad hoc communications are dominated by CSMA techniques. However, despite their common operation principles, each standard defines its own framing structure and timing operations. For instance, the IEEE 802.11 Distributed Coordination Function (DCF) [28] is the dominant channel access method for medium range ad hoc wireless communications. In DCF, a station is required to sense the channel idle for a DIFS (DCF Interframe Space) interval before starting a data transmission. If the channel is sensed busy during this interval, the transmission is postponed until the medium is sensed free. In addition, when the DIFS time elapses, the station defers its transmission for an additional random backoff time, selected by a predefined Contention Window (CW), in order to minimize the probability of collision. With regard to the control packets, the transmission takes place after the node has sensed the channel idle for a SIFS (Short Interframe Space) period of time, in order to distinguish the priorities between data and control plane. Last but not least, it is worth noting that the control packets are usually transmitted at a lower bit rate compared to data packets, to decrease the loss probability in the wireless medium.

Regarding the Personal Area Networks (PANs), which experience an impressive growth during the last few years, IEEE 802.15.4 [29] is the most widely used standard. The MAC layer of the IEEE 802.15.4 has two modes of operation: i) the beacon-enabled mode (combination of TDMA and CSMA) and ii) the non-beacon-enabled mode (CSMA). In our work, we focus on the latter, since it is of crucial importance to provide techniques that ensure the efficient use of the energy and system resources. In non-beacon mode, the stations maintain backoff counters and sense the channel for a Clear Channel Assessment (CCA) period before transmitting their data. In addition, the transmission of ACK packets commences a turnaround time (T_{ACK}) which enables the station to switch mode between reception and transmission. It is also worth mentioning that long frames are followed by a Long Interframe Space (LIFS), while short frames are followed by a SIFS period of time. Moreover, unlike IEEE 802.11, there is a common transmission bit rate for both data and control packets.

The key differences between IEEE 802.11 and 802.15.4 described above have motivated us to adapt NCCARQ in both standards, in order to achieve a more integrated and comprehensive evaluation of our scheme. Hence, in the following section, we present two variants of the proposed protocol, which have been made in order to be compatible with different CSMA-based wireless standards: i) NCCARQ MAC for WLAN, and ii) NCCARQ MAC for WSN. Both protocols have been designed to coordinate the retransmissions among a set of relays compliant to the respective standards rules (i.e., IEEE 802.11 and IEEE 802.15.4), thus using the same frame structure and following the same principles with the standards.

3.4 NCCARQ MAC

In NCCARQ MAC, a cooperation phase is initiated once a data packet is not received correctly by the destination[1]. Various error detection mechanisms such as CRC [27] can be applied to perform error control to the received messages. Therefore, the destination station initiates the retransmission phase by broadcasting an RFC packet to the network, indicating the need for cooperation. Furthermore, in case of bidirectional traffic, i.e., when the destination has data for the source, the data packet is broadcasted piggy-backed on the RFC message.

The stations that receive the RFC packet are potential candidates to become active relays for the communication process. Therefore, the relay set is formed upon the reception of the RFC and the participants (helpers) get ready to forward their information. Since the helpers have already stored the packets addressed both to the destination (so called cooperative packet) and to the source (so called piggy-backed packet), they create a new coded packet by combining the two native data packets, using the XOR method. Accordingly, the active relays will try to gain access to the channel in order to persistently transmit the network coded packet. Once the source and the destination receive the network coded packet from the relays, they are able to decode it (by applying again the XOR operation to their respective native packet and the received network coded packet) and extract the original data packets. Subsequently, they confirm the received data packet by transmitting the respective ACK packets, thus terminating the cooperation phase. Upon successful ACK reception, the relays are informed that the particular communication has been completed, hence becoming able to erase the respective packets from

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[1] The terms “source” and “destination” are used with regard to the initial transmission. Throughout the communication, both nodes can act as source or destination of data flows.

their buffers. In case that either one or both of the received coded packets can not be decoded after a certain maximum cooperation timeout due to transmission errors, the relays are obliged to forward again the coded packet following the same rules.

Despite the backwards compatibility with the CSMA-based standards, our protocols have undergone some modifications in order to efficiently exploit the advantages of both cooperative and NC techniques:

1. A reliable multicast communication scheme is guaranteed by employing ACK packets for the reception of the network coded data.
2. For bidirectional traffic, the data packets are transmitted along with the RFC packets, without taking part in the contention phase.
3. Since the subnetwork formed by the relay set operates in saturated conditions as the relays store the packets of the overheard transmissions, it is necessary to execute a backoff mechanism at the beginning of the cooperation phase to minimize the probability of a certain initial collision.

The two following sections present two illustrative operation examples for NCCARQ-WLAN and NCCARQ-WSN, respectively, that assist in further clarifying the operation of the proposed scheme. In both examples, a simple network topology with four stations is considered, all of them residing within the transmission range of each other. A source station (S) transmits a data packet (A) to a destination station (D) that also has a packet (B) destined to S. Furthermore, there are two relay nodes (R_1 and R_2) that support this particular bidirectional communication[2].

3.4.1 Case 1: WLAN

NCCARQ-WLAN is the first version of the proposed MAC, particularly designed for cooperative medium range wireless communications. It adopts the IEEE 802.11 frame structure and the interframe spaces are backwards compatible with the DCF. To further clarify the protocol operation, let us provide a more accurate step-by-step description of the frame exchange in NCCARQ-WLAN for the network scenario in Figure 3.1.

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[2] NCCARQ has been designed to handle an arbitrary number of relays and, hence, the two-relay network topology in this example is given only for illustrative purposes.

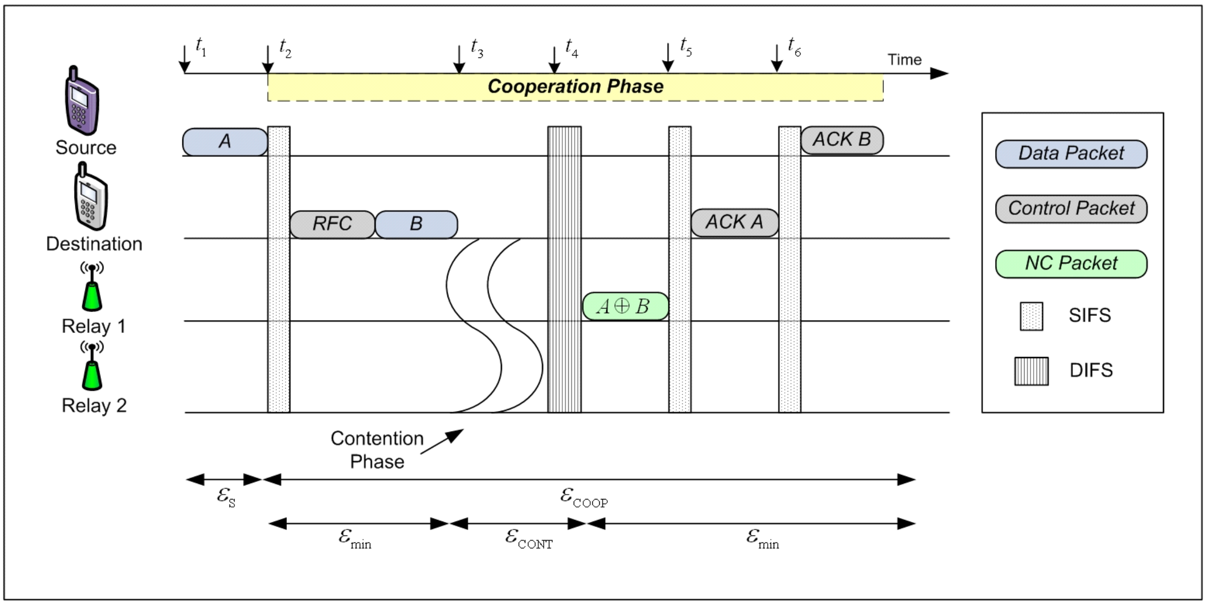

Figure 3.2: NCCARQ-WLAN example of frame sequence

In detail, the protocol works as follows (see Figure 3.2):

1. At instant t_1, station S sends the data packet A to station D.

2. Upon the erroneous reception of packet A, at instant t_2, station D broadcasts an RFC packet asking for cooperation by the neighboring stations (R_1 and R_2 in this example) along with the data packet B, addressed to station S. The transmission of both packets takes place after sensing the channel idle for SIFS period of time, thus having higher priority over regular data traffic.

3. The reception of the RFC packet at the time instant t_3 triggers the stations R_1 and R_2 to become active relays and set up their backoff counters (CW_1 and CW_2, respectively) in order to participate in the contention phase. In addition, the reception of packet B enables the relays to apply network coding to the packets before further forwarding them.

4. At instant t_4, the backoff counter of R_1 expires, and R_1 transmits the coded packet $A \oplus B$ to the nodes S and D simultaneously after sensing the channel idle for DIFS time.

5. At instant $t_5(t_6)$, the station $D(S)$ decodes properly the network coded packet $A \oplus B$ and confirms the correct reception of the original packet $A(B)$ by transmitting an ACK packet. The priority in the ACK transmission is determined by the temporal order that the transmissions of the native packets took place.

3.4.2 Case 2: WSN

NCCARQ-WSN is the second version of the proposed protocol, appropriate for short range wireless communications. It is backwards compatible with the non-beacon access mode of IEEE 802.15.4, using the same frame structure and timing with the standard.

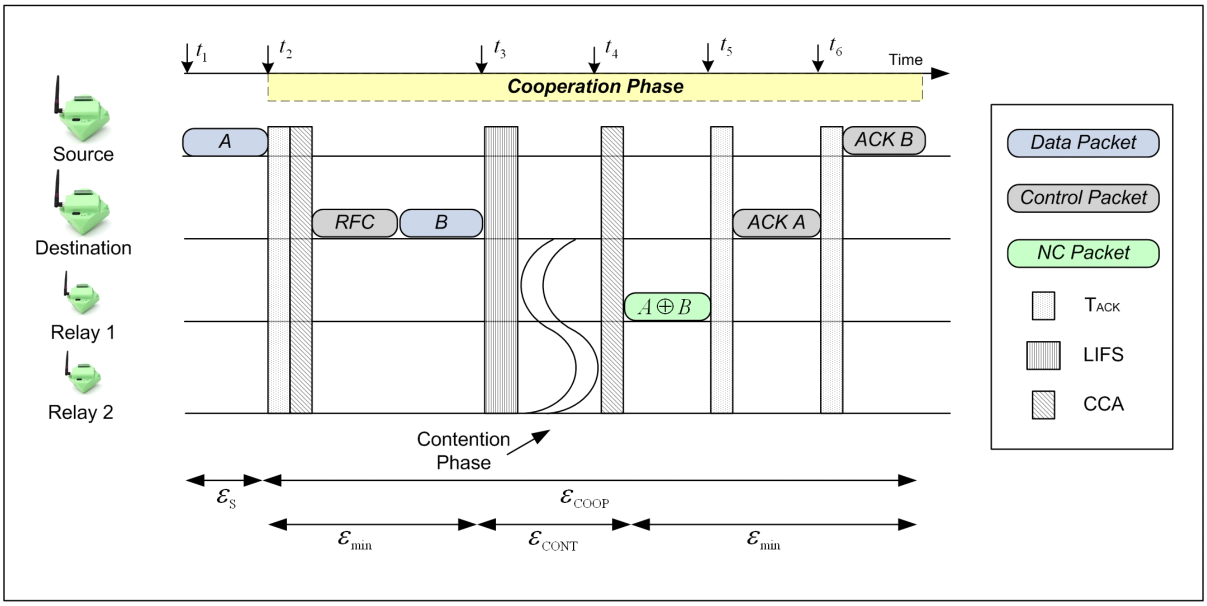

Figure 3.3: NCCARQ-WSN example of frame sequence

Figure 3.3 presents a frame exchange example in NCCARQ-WSN for the network topology in Figure 3.1 with two relay nodes. The protocol operates as follows:

1. At instant t_1, node S transmits the data packet A to node D.

2. At instant t_2, node D fails to demodulate the received data packet. Hence, it waits for T_{ACK} to switch mode in order to broadcast an RFC message asking for cooperation by the neighboring sensor nodes (R_1 and R_2 in this example) along with the data packet B, destined to node S. It is worth mentioning that the transmission takes place after a CCA time, while the LIFS time is omitted to provide the cooperation phase with higher priority.

3. The reception of both RFC and B (t_3) triggers the stations R_1 and R_2 to become active relays and set up their backoff counters (CW_1 and CW_2, respectively) in order to participate in the contention phase for the transmission of the network coded packet $A \oplus B$.

Moreover, before starting the transmission, they have to sense the channel idle for LIFS time, as the standard dictates.

4. At instant t_4, CW_1 expires and R_1 transmits the coded packet $A \oplus B$ to the nodes S and D simultaneously.

5. At instant $t_5(t_6)$, the station $D(S)$ decodes properly the XOR-ed packet and transmits an ACK packet to verify the correct reception of packet $A(B)$.

3.5 Performance Analysis

In this section, taking into account the NCCARQ MAC operation, we develop theoretical probabilistic models to analytically evaluate the protocol performance, in both WLAN and WSN scenarios. The design of these models lead to closed-form expressions for the packet delay, the system throughput and the energy consumption in the network. In this point, we have to clarify that, although the main analysis of both NCCARQ MAC versions is similar, we need to explicitly distinguish between the different cases when necessary.

3.5.1 Delay

The NC techniques applied in NCCARQ MAC imply the simultaneous transmission of more than one packet in the network. Therefore, we analytically estimate the expected time needed for two packets to be exchanged in our protocol.

The total time elapsed from the initial transmission from the source until the correct reception of the coded packet at the destinations (S and D) can be defined as:

$$\mathbf{E}[T_{total}] = \mathbf{E}[T_S] + \mathbf{E}[T_{COOP}] \tag{3.1}$$

where $\mathbf{E}[T_S]$ represents the average time for the direct transmission of a single data packet from the source to the destination, and $\mathbf{E}[T_{COOP}]$ corresponds to the average time required for a cooperative transmission via relays to be completed.

Since the estimation of $\mathbf{E}[T_S]$ is straightforward depending on the network configuration (i.e., packet length and transmission data rate), our analysis is focused on the term $\mathbf{E}[T_{COOP}]$ in order to derive a closed-form expression for the packet delay. The average time spent during the cooperation phase can be defined as:

$$\mathbf{E}[T_{COOP}] = \mathbf{E}[T_{min}] + \mathbf{E}[T_{CONT}] \tag{3.2}$$

where $\mathbf{E}[T_{min}]$ is the minimum average delay in case of perfect scheduling among the relays, i.e., when no contention takes place, while the term $\mathbf{E}[T_{CONT}]$ is used to denote the additional delay caused due to the contention phase.

The term $\mathbf{E}[T_{min}]$ for WLAN and WSN can be respectively calculated as:

WLAN:

$$\mathbf{E}[T_{min}] = T_{SIFS} + T_{RFC} + T_B + T_{ONC} + \mathbf{E}[r] \cdot (T_{DIFS} + T_{A\oplus B} + T_{SIFS}) + T_{ACK} + T_{SIFS} + T_{ACK} \tag{3.3}$$

WSN:

$$\begin{aligned} \mathbf{E}[T_{min}] &= T_{T_{ACK}} + T_{CCA} + T_{RFC} + T_B + T_{ONC} + \mathbf{E}[r] \cdot (T_{LIFS} + T_{CCA} + T_{A\oplus B} + T_{T_{ACK}}) \\ &+ T_{ACK} + T_{T_{ACK}} + T_{ACK} \end{aligned} \tag{3.4}$$

where $\mathbf{E}[r]$ corresponds to the expected number of retransmissions until the correct reception of the network coded packet by S and D. T_{RFC}, T_{ACK} and T_B represent the transmission times for the RFC, ACK and B packet, respectively. Furthermore, $T_{A\oplus B}$ is the time required to retransmit a coded packet, while T_{ONC} is the time that a relay needs for applying NC techniques in the two native packets. Finally, T_{SIFS} and T_{DIFS} is the duration of a $SIFS$ and a $DIFS$ sensing period in IEEE 802.11, while T_{LIFS}, $T_{T_{ACK}}$ and T_{CCA} is the duration of a $LIFS$ silence period, a T_{ACK} period and a CCA period in IEEE 802.15.4.

In general, the expected number of retransmissions ($\mathbf{E}[r]$) required to properly demodulate the coded packet at the destination nodes is directly connected with the PER of the link between the relays and the destination ($PER_{R\to D}$). However, in our scheme, two packets are sent at the same time via different channels (relay-to-source and relay-to-destination) and, as a result, the number of retransmissions can be expressed as[3]:

$$\mathbf{E}[r] = \frac{1 + \frac{(1-PER_{R\to S})\cdot PER_{R\to D}}{1-PER_{R\to D}} + \frac{(1-PER_{R\to D})\cdot PER_{R\to S}}{1-PER_{R\to S}}}{1 - PER_{R\to S} \cdot PER_{R\to D}} \tag{3.5}$$

Regarding the contention time overhead, the term $\mathbf{E}[T_{CONT}]$ in equation (3.2) can be defined as:

$$\mathbf{E}[T_{CONT}] = \mathbf{E}[r] \cdot \mathbf{E}[T_c] \tag{3.6}$$

---

[3] The derivation of the formula (3.5) is given in the Appendix 3.A.1.

where $\mathbf{E}[T_c]$ represents the average time required to transmit a network coded packet during the contention phase. The theoretical estimation of $\mathbf{E}[T_c]$ is associated to Appendix 3.A.2. Applying this analysis, the formula (3.6) can be rewritten as:

$$\mathbf{E}[T_{CONT}] = \mathbf{E}[r] \cdot (\frac{1}{p_s} - 1)[(\frac{p_i}{1-p_s})\sigma + (\frac{p_c}{1-p_s})T_{col}] \tag{3.7}$$

where p_s, p_c and p_i represent the probability of a successful, collided and idle slot, respectively, σ is the idle slot duration, and T_{col} corresponds to the time of a collision in NCCARQ MAC, and is equal to:

WLAN:

$$T_{col} = T_{DIFS} + T_{A\oplus B} + T_{SIFS} \tag{3.8}$$

WSN:

$$T_{col} = T_{LIFS} + T_{A\oplus B} + T_{CCA} \tag{3.9}$$

Hence, we are able to derive a closed-form formula of the total delay for two packets to be exchanged in the system by exploiting the equations (3.1), (3.2), (3.3) and (3.7).

3.5.2 Throughput

The total throughput of the network (S_{total}) can be defined as the sum of the throughput produced by the successful direct transmissions from the source (S_S)plus the throughput during the cooperation phase after erroneous initial transmissions (S_{COOP}). This can be mathematically expressed as:

$$\mathbf{E}[S_{total}] = \mathbf{E}[S_S] + \mathbf{E}[S_{COOP}] \tag{3.10}$$

where

$$\mathbf{E}[S_S] = (1 - PER_{S\to D}) \cdot \frac{\mathbf{E}[P]}{\mathbf{E}[T_S]} \tag{3.11}$$

and

$$\mathbf{E}[S_{COOP}] = PER_{S\to D} \cdot \frac{2 \cdot \mathbf{E}[P]}{\mathbf{E}[T_{total}]} \tag{3.12}$$

In the above expressions, the parameters $\mathbf{E}[T_S]$ represents the average time needed for a correct direct transmission, while $\mathbf{E}[T_{total}]$ corresponds to a correct transmission that is completed via relays (both values have already been defined in Section 3.5.1). Furthermore, the

PER in the link between the source and the destination is given by $PER_{S \to D}$, while $\mathbf{E}[P]$ denotes the average packet payload. In this point, it must be clarified that the use of the coefficient 2 in formula (3.12) is mandatory, since two native packets are delivered in each particular successful retransmission during the cooperation phase.

Thus, having obtained a closed-form expression for $\mathbf{E}[T_{total}]$ and since $\mathbf{E}[P]$, $\mathbf{E}[T_S]$ and $PER_{S \to D}$ are known network parameters, we are able to theoretically compute the system throughput.

3.5.3 Energy Consumption

Following the same line of thought as in the throughput calculation, the average total energy consumption in the network is described by the following expression:

$$\mathbf{E}[\mathcal{E}_{total}] = \mathbf{E}[\mathcal{E}_S] + \mathbf{E}[\mathcal{E}_{COOP}] \tag{3.13}$$

where $\mathbf{E}[\mathcal{E}_{COOP}]$ and $\mathbf{E}[\mathcal{E}_S]$ represent the average energy consumption during the cooperative phase and the initial transmission from the source, respectively.

In our attempt to clarify the above equation, we consider three discrete power modes:

1. **Transmission mode**, when the node is transmitting data/control packets.
2. **Reception mode**, when the node is receiving data/control packets.
3. **Idle mode**, when the node is sensing the medium without performing any action.

The power levels associated to each mode are P_T, P_R and P_I, respectively. Furthermore, the relationship between energy and power is given by $\mathcal{E} = P \cdot t$, where the terms $\mathcal{E}$, P and t represent the energy, the power and the time, respectively. Let us recall that the network consists of a source, a destination and a set of n relays. Therefore, taking into account the network topology, we have:

$$\mathbf{E}[\mathcal{E}_S] = P_T \cdot T_A + (n+1) \cdot P_R \cdot T_A \tag{3.14}$$

where T_A corresponds to the transmission time for packet A. On the other hand, the term $\mathbf{E}[\mathcal{E}_{COOP}]$ could be further expressed as:

$$\mathbf{E}[\mathcal{E}_{COOP}] = \mathbf{E}[\mathcal{E}_{min}] + \mathbf{E}[\mathcal{E}_{CONT}] \tag{3.15}$$

where $\mathbf{E}[\mathcal{E}_{min}]$ denotes the energy consumption in a perfectly scheduled cooperative phase and $\mathbf{E}[\mathcal{E}_{CONT}]$ is the energy consumed during the contention phase (i.e., idle slot and collisions). For illustrative purposes, the particular energy consumptions for WLAN and WSN are depicted in Figures 3.2 and 3.3, respectively. Bearing in mind the characteristics of the different standards, the minimum time is computed as follows:

WLAN:

$$\begin{aligned}
&\mathbf{E}[\mathcal{E}_{min}] = (n+2) \cdot P_I \cdot T_{SIFS} + P_T \cdot (T_{RFC} + T_B) + (n+1) \cdot P_R \cdot (T_{RFC} + T_B) + (n+2) \cdot P_I \cdot T_{ONC} + \\
&+ \mathbf{E}[r] \cdot ((n+2) \cdot P_I \cdot T_{DIFS} + P_T \cdot T_{A \oplus B} + 2 \cdot P_R \cdot T_{A \oplus B} + (n-1) \cdot P_I \cdot T_{A \oplus B} + (n+2) \cdot P_I \cdot T_{SIFS}) + \\
&+ 2 \cdot P_T \cdot T_{ACK} + 2 \cdot (n+1) \cdot P_R \cdot T_{ACK} + (n+2) \cdot P_I \cdot T_{SIFS}
\end{aligned} \tag{3.16}$$

WSN:

$$\begin{aligned}
&\mathbf{E}[\mathcal{E}_{min}] = (n+2) \cdot P_I \cdot (T_{T_{ACK}} + T_{CCA}) + P_T \cdot (T_{RFC} + T_B) + (n+1) \cdot P_R \cdot (T_{RFC} + T_B) + \\
&+ (n+2) \cdot P_I \cdot T_{ONC} + \mathbf{E}[r] \cdot ((n+2) \cdot P_I \cdot (T_{LIFS} + T_{CCA}) + P_T \cdot T_{A \oplus B} + 2 \cdot P_R \cdot T_{A \oplus B} + \\
&+ (n-1) \cdot P_I \cdot T_{A \oplus B} + (n+2) \cdot P_I \cdot T_{T_{ACK}}) + 2 \cdot P_T \cdot T_{ACK} + (n+2) \cdot P_I \cdot T_{T_{ACK}} + \\
&+ 2 \cdot (n+1) \cdot P_R \cdot T_{ACK}
\end{aligned} \tag{3.17}$$

The equations (3.16)-(3.17) are based on the following principles:

- All stations remain idle during the $SIFS$, $DIFS$, $LIFS$, CCA, T_{ACK} and T_{ONC} times.
- The relays that lose in the contention phase turn into idle mode.
- When the source/destination transmits a packet (control or data), the relays are in promiscuous mode in order to capture the transmission.

The total energy consumption during the contention phase derives from the energy spent during both idle and collided slots. Hence, formulating an analytical model for the energy consumed during this phase constitutes a very challenging task, mainly due to the uncertainty of the average number of nodes involved in a collision. Let us start by defining that:

$$\mathbf{E}[\mathcal{E}_{CONT}] = \mathbf{E}[r] \cdot \mathbf{E}[\mathcal{E}_C] \tag{3.18}$$

where $\mathbf{E}[\mathcal{E}_C]$ represents the average energy required to transmit a network coded packet during the contention phase among all the relays. In order to calculate the energy consumed during the collisions, we have to estimate the average number of stations that transmit a packet simultaneously. The probability p_k that exactly k stations are involved in a collision is:

$$p_k = \frac{\binom{n}{k}\tau^k(1-\tau)^{n-k}}{p_c} \tag{3.19}$$

where τ and p_c are defined in Appendix 3.A.2.

Therefore, the expected number $\mathbf{E}[K]$ of stations that are involved in a collision is:

$$\mathbf{E}[K] = \sum_{k=2}^{n} k \cdot p_k = \sum_{k=2}^{n} k \cdot \frac{\binom{n}{k}\tau^k(1-\tau)^{n-k}}{p_c}. \tag{3.20}$$

During the idle slots, all the stations in the network remain idle. On the other hand, during the collisions, more than one relay is in transmission mode, two stations (the source and the destination) are in reception mode, while the rest of the relays remain idle. Considering the probabilities that we have derived in Appendix 3.A.2 regarding the contention phase (p_c, p_i), the above assumptions can be mathematically expressed as:

$$\mathbf{E}[\mathcal{E}_C] = p_i \cdot ((n+2) \cdot P_I \cdot \sigma) + p_c \cdot (\mathbf{E}[K] \cdot P_T \cdot T_{col} + 2 \cdot P_R \cdot T_{col} + (n - \mathbf{E}[K]) \cdot P_I \cdot T_{col}) \tag{3.21}$$

where all parameters have already been defined. Thus, combining the equations (3.13)-(3.21), we are able to estimate the total energy consumption in the network.

3.5.4 Performance Evaluation

In order to validate our analysis and further evaluate the performance of both NCCARQ MAC versions, we have developed time-driven C++ simulators that execute the rules of the proposed protocols. In the following sections, we present the simulation setup along with the results of our experiments.

Simulation Scenario

In our experiments, we consider two different networks (i.e., a WLAN and a WSN) of the same topology. In particular, the networks under simulation consist of a transmitter-receiver pair (both nodes transmit and receive data) and a set of relay nodes that facilitate the communication, all of them residing in the transmission range of each other. The relays operate in promiscuous mode in order to overhear the ongoing transmissions in order to store the data packets in their buffers.

Unless differently stated, the relay set includes five nodes ($n = 5$), each of them implementing a backoff counter starting with a contention window (CW_{min}) equal either to 32 or 8 for WLAN and WSN, respectively. Additionally, the relay nodes are capable of performing NC techniques to their buffered packets before relaying them. In order to focus on the impact of both NC and cooperative communication, we have made the following assumptions:

1. The traffic is bidirectional, i.e., the destination node has always a packet to transmit back to the source node.
2. Original transmissions from source to destination are always received with errors, as we consider a highly noisy channel with $PER_{S \to D} = 1$.
3. The channel between the source and the destination is error symmetric, i.e., $PER_{S \to D} = PER_{D \to S}$.
4. The channel between the source and the relays is error free, i.e., $PER_{S \to R} = 0$.
5. The relay nodes transmit employing a common transmission rate.

The configuration parameters for the WLAN and the WSN have been selected according to the IEEE 802.11g [30] and the IEEE 802.15.4 PHY layer [29], respectively. In both approaches, the time for applying NC (T_{ONC}) to the data packets is considered to be negligible, since the coding takes place between only two packets.

With regard to the power consumption of a wireless interface, Ebert *et al.* [31] have conducted experimental measurements to estimate the power consumption during the transmission and reception phase of a WLAN interface. Based on their work, we have chosen the following power levels for our medium range experiments: $P_T = 1900mW$, $P_R = P_I = 1340mW$[4]. On the other hand, based on hardware specifications and since different power modes are allowed in WSN, we have chosen the following power levels for our short range experiments: $P_T = 15mW$[5], $P_R = 35mW$ and $P_I = 712\mu W$ [32]. The simulation parameters for NCCARQ-WLAN and NCCARQ-WSN are summarized in Table 3.1 and 3.2, respectively.

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[4] The value of P_T has been selected as an average value of transmission consumed power, since it varies according to the Radio Frequency (RF) power level.

[5] We use the maximum of the transmission power levels that are offered in IEEE 802.15.4.

Table 3.1: System parameters (WLAN case)

Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
Data Packet	1500 bytes	RFC	14 bytes	Time Slot	20 μs
MAC Header	34 bytes	ACK	14 bytes	P_T	1900 mW
PHY Header	96 μs	$SIFS$	10 μs	P_R	1340 mW
CW_{min}	32	$DIFS$	50 μs	P_I	1340 mW

Table 3.2: System parameters (WSN case)

Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
Data Packet	100 bytes	*Data Rate*	256 kb/s	Time Slot	320 μs
MAC Header	9 bytes	T_{ACK}	192 μs	P_T	15 mW
PHY Header	6 bytes	*CCA*	128 μs	P_R	35 mW
ACK, RFC	11 bytes	*LIFS*	640 μs	P_I	712μW

Furthermore, since IEEE 802.11g offers various data rates supporting AMC, we consider three different scenarios with regard to the SNR between the original source and the destination (Table 3.3). In particular, the transmission rate for the data packets is 6, 24 and 54 Mb/s for *low*, *medium* and *high* SNR values, respectively, while the control packets are always transmitted at the rate of 6 Mb/s. On the other hand, assuming that the relays are located between the source and the destination, the transmission rates in all scenarios are equal to 6 and 54 Mb/s for control and data packets, respectively. Furthermore, the network operates under saturated conditions, since the nodes have always packets to send in their buffers.

In order to evaluate our approach, we compare our schemes with a simple cooperative ARQ scheme (CARQ), where the bidirectional communication takes place in two phases. In the first phase, the source sends a packet to the destination and, upon the erroneous reception, the destination broadcasts the RFC packet, thus triggering the relays to retransmit the packet. In the second phase, the destination transmits its own packet to the source and the same procedure as in the first phase is repeated, hence consuming valuable network resources. In both phases, the relays take part in the contention phase in order to access the medium and transmit the

Table 3.3: Simulation scenarios (WLAN case)

SNR (S-D)	**Source Control Rate**	**Source Data Rate**	**Relay Control Rate**	**Relay Data Rate**
Low	6 Mb/s	6 Mb/s	6 Mb/s	54 Mb/s
Medium	6 Mb/s	24 Mb/s	6 Mb/s	54 Mb/s
High	6 Mb/s	54 Mb/s	6 Mb/s	54 Mb/s

respective packets.

The metrics we considered to evaluate the QoS performance of our protocol are delay and throughput, as they have been defined in Sections 3.5.1 and 3.5.2, respectively. Moreover, in order to evaluate the energy performance of our proposed protocol we use the energy efficiency metric [33] which provides sufficient information with regard to the useful payload bits transmitted per energy unit (Joule), overcoming the limited information provided by the energy consumption metric. Energy efficiency is usually denoted by η, defined as:

$$\eta = \frac{total\ amount\ of\ useful\ data\ delivered\ (bits)}{total\ energy\ consumed\ (Joule)} \tag{3.22}$$

Before proceeding to the simulation results, it is worth mentioning that the definition of equation (3.22) implies that NC inherently benefits the energy efficiency of a protocol, as the number of the delivered useful bits increases by combining multiple data packets.

Performance Results

This section presents the experimental results for the simulation setup described above. In order to distinguish the protocol assessment between the two different technologies, we demonstrate the results regarding the two protocol versions (i.e., NCCARQ-WLAN and NCCARQ-WSN) in the two following paragraphs, respectively.

NCCARQ-WLAN: Figure 3.4 presents the throughput performance for various values of $PER_{R\to D}$ in the three SNR scenarios described above. First, we can see that the simulation results verify our analysis, since they almost perfectly match the theoretical derivations. Comparing with simple cooperative schemes which have only the advantage of spatial diversity without any NC capabilities, a throughput enhancement up to 88% is achieved. This improvement can be rationally explained considering the operation of NCCARQ, where some data packets are sent to the relay attached to the RFC message, thus avoiding the weak direct link. Furthermore, in our proposed scheme, we manage to reduce the backoff phases by transmitting two packets simultaneously, while in simple cooperative protocols the relays have to participate in the contention phase for each packet that has to be retransmitted. The difference in the performance of the two schemes is higher in *low SNR scenarios*, since the packet transmission time increases dramatically and collisions have greater impact on the network. It is also worth noticing that NCCARQ eventually outperforms CARQ even for worse SNR scenarios. In particular, observing the achievable throughput in NCCARQ for the *medium SNR scenario* we can see that it clearly exceeds the performance of CARQ under the *high SNR scenario* with gain reaching up to 30%.

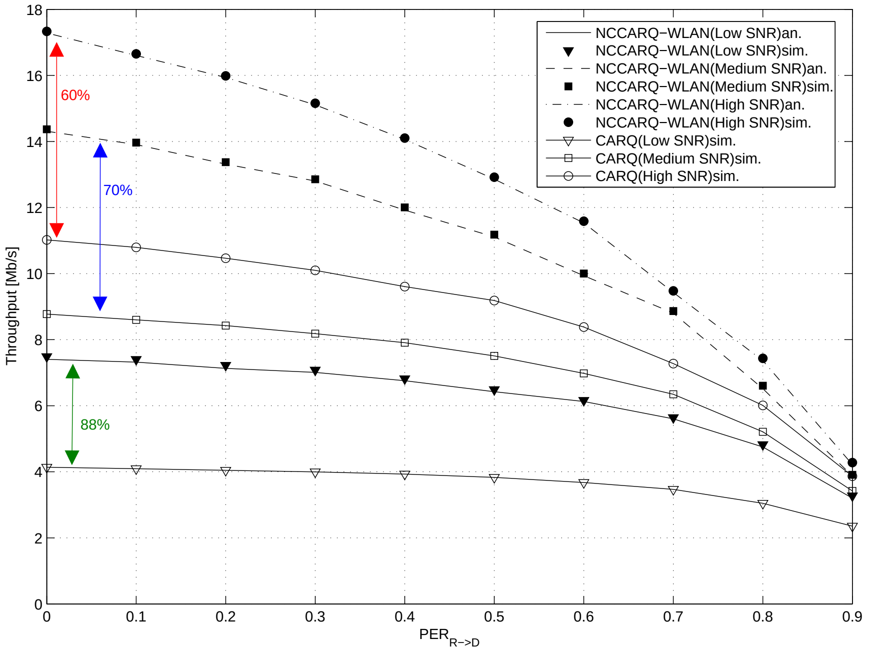

Figure 3.4: Network throughput (NCCARQ-WLAN vs. CARQ)

Figure 3.5 shows the throughput performance for the *low SNR scenario* with regard to CW_{min} of the wireless nodes. In this specific case, the network consists of a source (S), a destination (D) and ten relay nodes ($n = 10$), while we assume that $PER_{R \to D} = 0.5$, meaning that two retransmissions on average are needed for each network coded packet to be properly delivered (i.e., $\mathbf{E}[r] = 2$). As it was expected, the two curves exhibit similar behavior, achieving maximum throughput for $CWmin = 64$. However, a useful conclusion derived by this figure is that NCCARQ outperforms CARQ regardless of the initial CW. More specifically, the lowest NCCARQ throughput ($CWmin = 512$) is almost 52% better than the highest throughput achieved by CARQ ($CWmin = 64$).

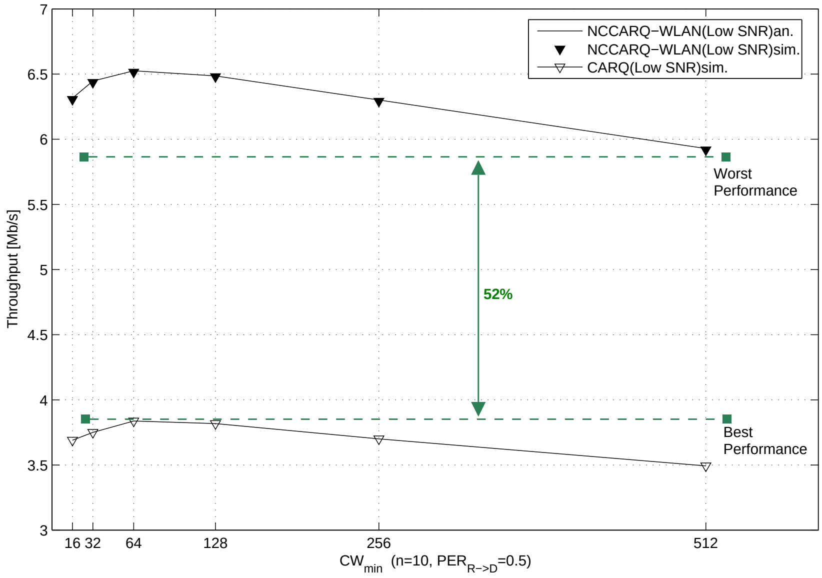

Figure 3.5: Network throughput (NCCARQ-WLAN vs. CARQ) (low SNR, n=10, $\mathbf{E}[r]$=2)

The packet delay in both NC-based and simple cooperative ARQ MAC protocols for WLANs is presented in Figure 3.6. In this point, we must recall that two packets are delivered to their respective destinations in each transmission cycle of NCCARQ. Hence, in order to be consistent, we compare the delay in NCCARQ with the time required for two packets to be exchanged in CARQ. As it can be observed, we can achieve significantly lower packet delay by applying NC techniques. For example, considering the *low SNR scenario*, the average time that is required for two packets to be transmitted using CARQ is 5.9 ms in error-free source-to-destination channels where one retransmission is necessary, reaching up to 7.9 ms when $PER_{R\to D}$=0.8, i.e., $\mathbf{E}[r] = 5$. On the other hand, the delay values in NCCARQ are 3.3 and 5 ms, for one and five expected retransmissions, respectively. This difference is again attributed to the NCCARQ operation, where the erroneous direct channel is avoided, while the number of contention is decreased. Therefore, we are able to reduce the packet delay, since the time spent in idle slots and collisions is significantly lower, especially as the PER between the

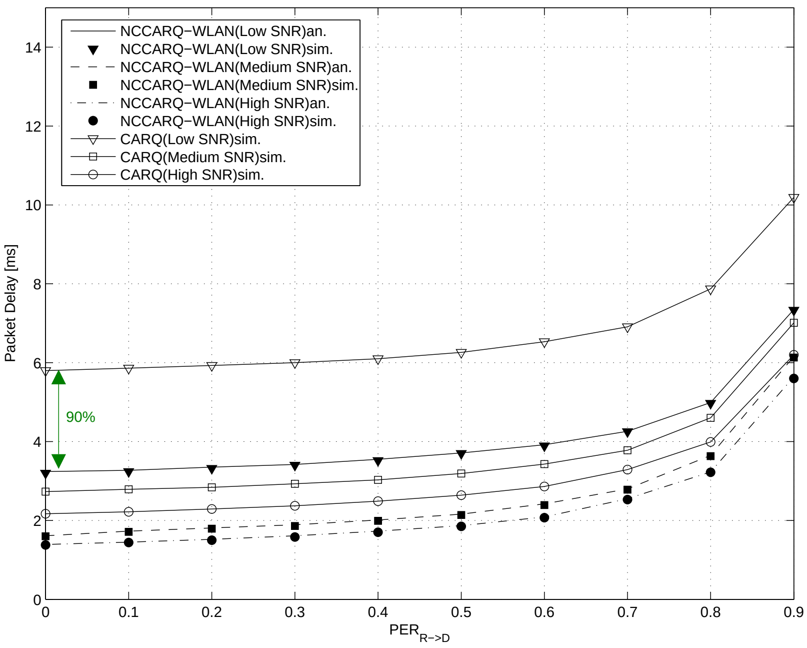

Figure 3.6: Packet delay (NCCARQ-WLAN vs. CARQ)

relays and the destination grows.

Figure 3.7 shows that the simulation results verify our analysis regarding the energy performance. Comparing our proposed NC-based scheme with simple cooperative protocols for different PER (and consequently different number of retransmissions) between the relays and the destination, we observe that our scheme is more energy efficient than CARQ, since more bits are delivered over the same amount of consumed energy. While keeping constant the data packet payload (1500 bytes), the energy efficiency of NCCARQ decreases as the PER between the relays and the destination grows. However, the gain compared to simple cooperative schemes remains steadily over 60% for reasonable values of PER (i.e., $PER_{R \to D} < 0.7$).

In addition, comparing the two protocols under the same channel conditions (i.e., when both schemes operate under similar SNR values), we observe that NCCARQ-WLAN outperforms CARQ in all cases. Furthermore, it is worth mentioning that NC is proved to be beneficial for the system when the communication takes place under bad channel conditions. By observing the energy performance of the NCCARQ for the *medium SNR scenario*, we can see that it clearly outperforms the CARQ-MAC under the *high SNR scenario*. This particular observation indicates NC as an appropriate tool to compensate the PHY layer impairments and enhance the network performance in bidirectional communication scenarios. However, in all cases, the gain

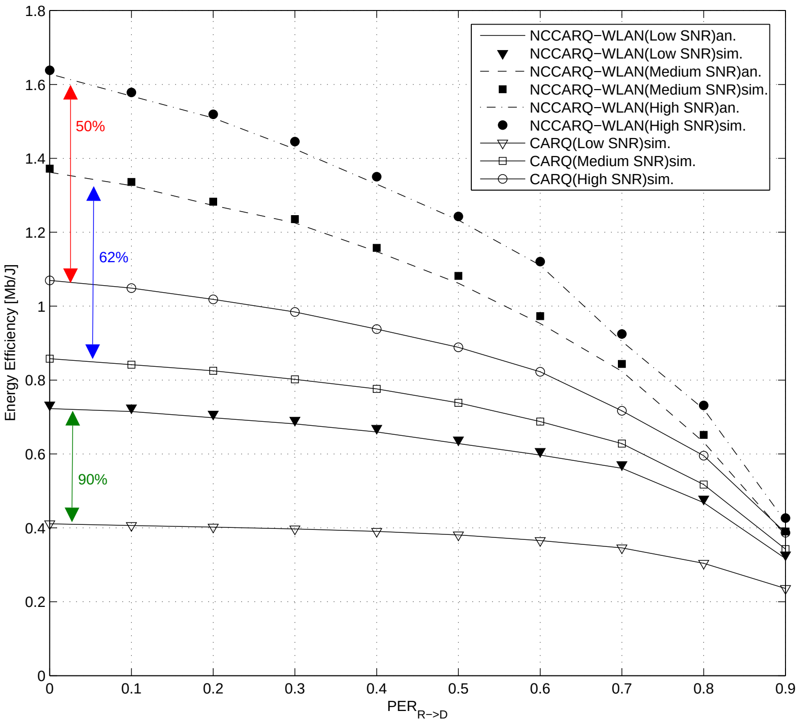

Figure 3.7: Energy efficiency (NCCARQ-WLAN vs. CARQ)

of NC becomes negligible as the channel PER asymptotically tends to zero ($PER_{R\rightarrow D} \rightarrow 1$).

NCCARQ-WSN: The performance results in the WSN case exhibit similar behavior to the WLAN case study. Figure 3.8 shows the throughput enhancement that NCCARQ-WSN achieves compared to simple cooperative protocols without NC capabilities. While, in the case of simple cooperative schemes, throughput values saturate around 66 kb/s, NCCARQ-WSN achieves 99 kb/s, exhibiting a 50% throughput increase. Evidently, it can be observed that as the number of required retransmissions (x-axis) grows due to channel impairments, the relative throughput gain increases as well, reaching a difference of 80% in networks where five retransmissions are expected in order for the packets to be properly delivered. This significant improvement makes sense for three main reasons: i) the total number of transmissions in NCCARQ-WSN protocol is lower compared to CARQ, ii) the number of RFC packets is also decreased, and iii) for bidirectional traffic, in NCCARQ-WSN the cooperation phase is initiated only once, thus saving valuable time compared to other cooperative schemes where the cooperation takes place upon every erroneous packet reception.

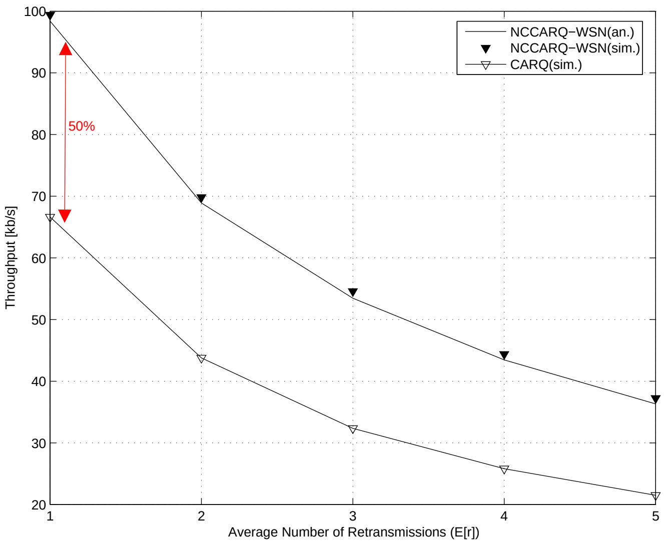

Figure 3.8: Network throughput (NCCARQ-WSN vs. CARQ)

Figure 3.9 presents the packet delay in both NC-based and simple cooperative ARQ MAC protocols. As it can be observed, we can achieve significantly lower packet delay by using NC techniques. Specifically, the average time required for two packets to be transmitted using CARQ is 0.024 s when one retransmission is necessary due to channel conditions. Applying NC, we reduce this time to 0.016 s, yielding an enhancement of 50%. With respect to the case where five retransmissions are required for a correct packet reception, the relative gain of NCCARQ-WSN over simple cooperative techniques increases up to 70%.

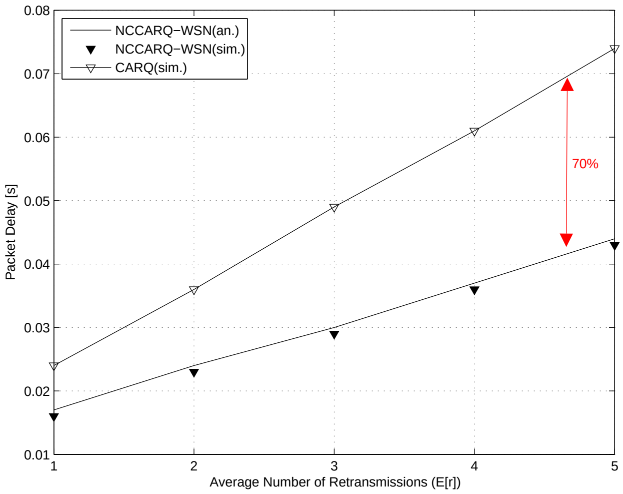

Figure 3.9: Packet delay (NCCARQ-WSN vs. CARQ)

Figure 3.10 shows that our analysis verifies the simulation results with regard to the energy performance. Comparing our proposed NC-based scheme with simple cooperative protocols for various expected number of retransmissions, we observe that our scheme is more energy efficient than non-NC-based schemes, since the amount of bits delivered over the same energy consumption is higher. As it was expected, for a constant packet length of 100 bytes, the energy efficiency of NCCARQ-WSN decreases as the number of relay retransmissions grows. However, the difference with simple cooperative schemes remains steadily over 30%.

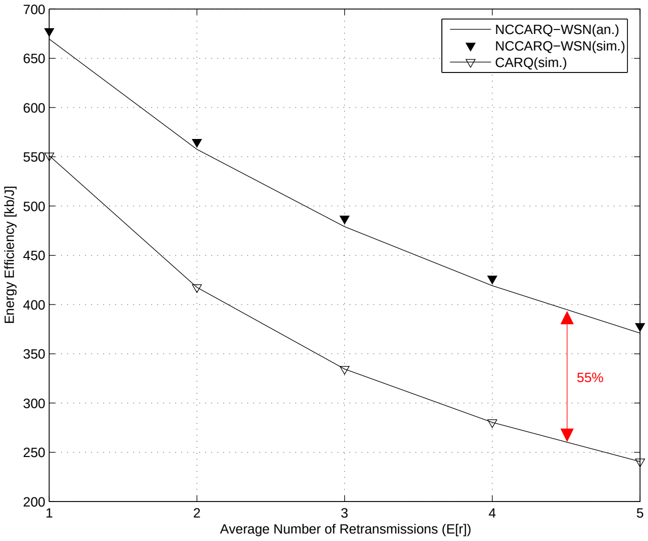

Figure 3.10: Energy efficiency (NCCARQ-WSN vs. CARQ)

Even though the evaluation of the proposed schemes was conducted under various scenarios and assumptions, there are many practical restrictions in real life that have not been taken into consideration. The scope of the following section is to overcome these limitations by studying the performance of the proposed protocol under realistic PHY layer implementations in the presence of correlated shadowing in the network.

3.6 PHY Layer Impact on NCCARQ MAC Protocol

The accurate PHY layer and wireless channel modeling plays a crucial role in the design and optimization process of MAC protocols for cooperative wireless networks. However, a fundamental limitation affecting the vast majority of these works is that design and analysis are usually conducted by considering very simplified PHY layer and channel models, which significantly affect the actual performance of any protocol [34]. Most cooperative protocols are evaluated by taking into account either the transmission distance or the fast fading effect, but not both simultaneously, even though many experimental activities have highlighted the importance of long-term shadowing on the performance of cooperative and distributed wireless systems [35–38]. In particular, spatially-close network nodes might experience similar signal attenuation and, hence, the spatial-correlation of shadowing might severely affect the system performance. Furthermore, the non-ergodic nature of long-term shadowing should be properly taken into account for accurate system analysis and design. Specifically, three fundamental issues deserve special consideration (see [34, 37], and references therein):

- **Non-ergodicity**: Unlike fast fading, shadowing is a non-ergodic process for the transmission of multiple packets. In other words, shadowing might change during the duration of a communication, but its fluctuations are, in general, not fast enough to cover all the possible states of the distribution. Figure 3.11 provides an illustrative example of the normalized received signal strength in dB during a particular communication duration for the combined effects of fast fading and shadowing. This figure clearly illustrates that, in the presence of shadowing, the most suitable metric for the analysis of communication protocols is the Outage PER (OPER), which is defined as the probability that the Average (over fast fading) PER (APER) exceeds a pre-determined value that depends on the QoS requested by the application layer (see Table 3.4). In fact, this metric has a direct impact on the achievable throughput [34].

- **Mobility**: Unlike conventional cellular systems, in cooperative wireless networks all nodes might be in motion. As a result, different propagation channel models should be taken into account [37]. Thus, shadowing time-correlation plays an important role to assess the performance of multi-hop mobile networks, as several consecutive packets might experience the same attenuation and, therefore, might be in outage for a long period of time. In this context, it is crucial to characterize second-order statistics for a sound system design.

- **Spatial topology**: Unlike non-cooperative protocols, when spatially-close neighboring nodes are willing to collaborate, it is important to consider that their wireless links often experience similar environmental shadowing effects (e.g., due to the same objects and scatterers hindering different links), thus possibly suffering from correlated shadowing.

In these scenarios, neglecting the correlation among the cooperative links might result in overestimating the end-to-end performance and the benefits of cooperation.

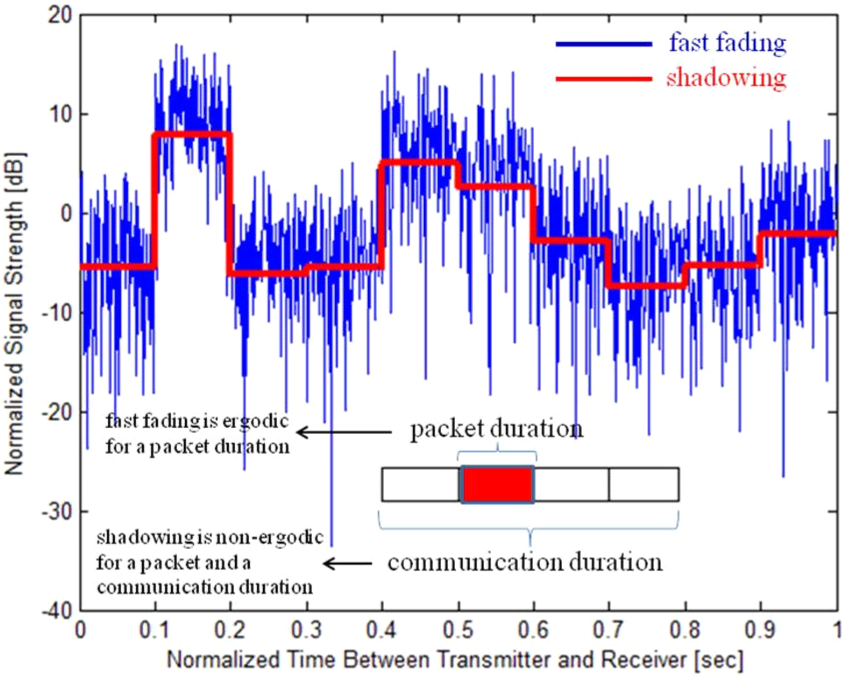

Figure 3.11: Fast fading ergodicity vs. shadowing non-ergodicity during a packet and a communication duration

In this section, we study the effect of correlated shadowing on the design and performance of the NCCARQ MAC scheme. Motivated by the above considerations, the aim of this section is twofold: i) to explicitly include realistic PHY layer parameters, channel characteristics and QoS guarantees in the relay selection policy, and ii) to study the impact of correlated shadowing on the performance of MAC protocols and relay selection mechanisms in order to highlight the major challenges that arise in designing effective cooperative protocols.

3.6.1 PHY Layer Impact on MAC Protocol Design

There are two key aspects that play a crucial role in the correct operation and optimization of MAC protocols under realistic PHY layer and fading channels. The first issue consists in distinguishing between correctly received and corrupted packets. In particular, a packet is deemed either correct or corrupted depending on whether it satisfies a given QoS level requested by the application layer. This issue is of major importance in cooperative wireless networks, where the estimation of packet integrity determines the initialization of a cooperation phase as well as the set of relays that have an active role during the retransmission phase. In this context, special attention should be paid to the shadowing non-ergodicity, in order to choose the most appropriate QoS metric for protocol analysis (see Table 3.4).

The second key issue lies on realistically analyzing the impact of distributed cooperation on the achievable performance, which requires adequate spatial propagation models that take into account the fact that adjacent relay nodes may receive packets that have undergone similar channel conditions. Hence, the investigation of shadowing correlation is of paramount importance in order to assess and compare the potential benefits of cooperative and non-cooperative protocols. The aforementioned two key issues are extensively analyzed in the following sections.

Impact of PHY Layer and Shadowing Non-Ergodicity on Packet Reception for Guaranteed QoS

In wireless communications, efficient mechanisms have to be put in place to determine whether a packet can be accepted by the MAC layer for a given QoS specified at the application layer. To this end, the key point is to provide a reliable mechanism, which explicitly takes into account actual transmission/reception (Tx/Rx) schemes, along with system parameters (e.g., modulation, coding, packet length) and channel models. More specifically, the minimum requirement on the received power for the target QoS specified at the application layer may vary with the adopted Tx/Rx method. In particular, advanced Tx/Rx techniques (e.g., MIMO-based schemes, turbo coding, etc.) might enable the MAC layer to accept packets of lower quality than simpler Tx/Rx schemes (e.g., uncoded single-antenna transmissions). Hence, it is instrumental to develop advanced communication-theoretic frameworks that can accurately map the PHY layer parameters into achievable QoS requirements and use them for protocol design and optimization. In addition, the characteristics of the wireless channel ultimately determine the performance of MAC protocols. Due to the non-deterministic nature of wireless propagation, protocol analysis and design can be made only statistically, i.e., by using proper QoS requirements that account for the statistical distribution of the wireless channel. To make the discussion more concrete, as an illustrative example, the PER[6] is employed as a metric for QoS provisioning, demanding that it has to be below a given threshold to guarantee a reliable data transmission and packet reception.

Table 3.4 summarizes three different PER metrics that can be used with respect to the possible statistical distributions of the wireless channel over the duration of a communication round (as it is shown in Figure 3.11). It is worth mentioning that, for each case study, the PER depends on the adopted transmission scheme at the PHY layer. More specifically, the metrics in the second column of Table 3.4[7] provide the probability that a received packet is acceptable at the MAC layer, i.e., the QoS requested by the application layer is satisfied. On the other hand, the reliability criteria summarized in the third column of Table 3.4 provide expressions for the minimum required received power in order for the packet to be accepted at the MAC layer, which depends on the PHY layer setup and the target QoS specified at the application layer. The inversion of the PER function is crucial for the application of these criteria, while practical ways to deal with this issue for some advanced PHY layer transmission schemes and channel models are described in [34, 39], and references therein.

Impact of Shadowing Spatial-Correlation

As already mentioned, the importance of accurately modeling the effect of shadowing has been acknowledged by many experimental measurements, which have indicated that typical channel models used in many simulations and analytical studies are, in practice, not sufficiently realistic [35]. As far as cooperative MAC protocols are concerned, shadowing spatial-correlation is the most important aspect to be considered for an accurate performance assessment [34–38], since it directly affects: i) the received signal power at each network node, which determines the need for cooperation, and ii) the most suitable number of cooperative relays for a given QoS

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[6] The same concepts can be applied to other performance metrics of interest, such as delay, fairness, throughput, outage probability or energy consumption. For example, video transmission requires stringent QoS requirements in terms of delay, PER and video quality.

[7] Notation: i) $PER(X)$ = PER as a function of X ii) $\mathbf{E}_X\{.\}$ statistical expectation computed over X iii) $Pr_X\{.\}$ probability computed over X; vi) QoS^* is the target QoS (PER) requested by the application layer iv) P^*_{Rx} is the deterministic received power, which depends on the distance between transmitter and receiver and is independent of the wireless channel v) $P_{Rx,Measured}$ is the received power that is actually measured at the receiver node, which accounts for the transmit power, the transmission distance and the wireless channel vi) PER^{-1} and $APER^{-1}$ denote the inverse expressions of PER and $APER$, respectively.

Table 3.4: Relation between channel fading characteristics and QoS performance metrics

Channel Model	**Most Appropriate Metric to Compute**	**Reliability Criterion for Received Packets**
Fast Fading (F)	Due to channel ergodicity, “average” metrics are appropriate (note: F=Fast Fading) $QoS^* = APER(P^*_{Rx}; PHY) = \mathbf{E}_F\{PER(P^*_{Rx}; PHY; F)\}$	A received packet is accepted by the MAC if $P_{Rx,Measured} > P^*_{Rx} = APER^{-1}(QoS^*; PHY)$
Shadowing (S)	Due to channel non-ergodicity, “outage” metrics are appropriate (note: S=Shadowing) $OPER(P^*_{Rx}; PHY) = Pr_S\{PER(P^*_{Rx}; PHY; S) > QoS^*\}$	A received packet is accepted by the MAC if $P_{Rx,Measured} > (P_{Rx} \cdot S)^* = PER^{-1}(QoS^*; PHY)$
Fast Fading (F) Shadowing (S)	Due to the composite nature of the channel statistics, a combination of “average” and “outage” metrics is appropriate (note: F=Fast Fading, S=Shadowing) $APER(P^*_{Rx}; S; PHY) = \mathbf{E}_F\{PER(P^*_{Rx}; PHY; S; F)\}$ $OPER(P^*_{Rx}; PHY) = Pr_S\{APER(P^*_{Rx}; PHY; S) > QoS^*\}$	A received packet is accepted by the MAC if $P_{Rx,Measured} > (P_{Rx} \cdot S)^* = APER^{-1}(QoS^*; PHY)$

requirement, which affects the overhead associated with the cooperation.

To further clarify, let us consider two simple examples:

1. The main reason for introducing cooperative networks is the possibility of providing multiple paths for the same packet to reach a given node. For example, in Figure 3.12 each transmission path is determined by a relay node, which overhears a transmitted packet, and is willing to apply NC in order to forward the coded packet on behalf of the transmitter. If all relays involved in the cooperative phase receive packets through uncorrelated shadowing channels, then the probability that some of them satisfy the QoS requirement is proportionally higher. However, in real network deployments, as measurements have confirmed, geographically-close relays can experience correlated shadowing conditions [35], which lead to potential performance degradation.

2. Cooperative ARQ protocols have been introduced to overcome the inherent limitations of ARQ protocols in low-mobility applications, where packets retransmitted in subsequent time slots from the same relay may experience similar, time correlated bad channel conditions, thus leading to many successive failures [34, 37]. The main idea is to exploit diversity by enabling the retransmission of the same packets by different relay nodes through diverse spatial channels, instead of having multiple retransmissions of the

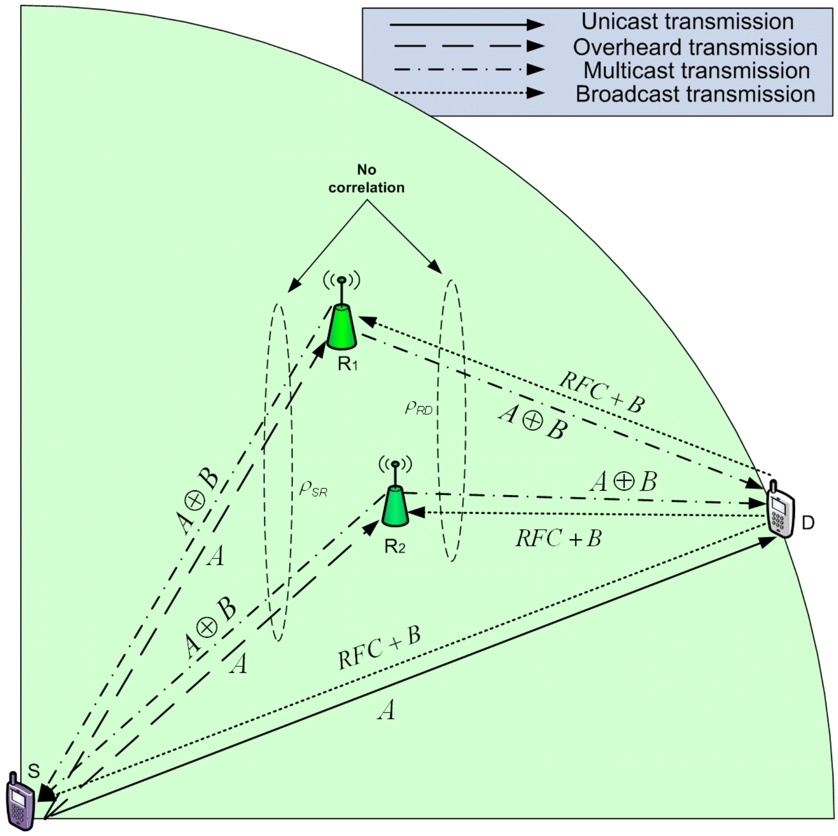

Figure 3.12: NCCARQ MAC with shadowing spatial correlation among different links

same packet by a single node over the same wireless link. The main motivation is to take advantage of the spatial diversity benefits: since the nodes occupy different spatial positions, it is expected that the retransmitted packets experience different channel conditions. However, as in the first example, the presence of shadowing spatial-correlation may limit the benefit of this approach, since, even though the relays have different spatial locations, they may experience correlated failures. As a consequence, the thorough comprehension of the impact of shadowing spatial-correlation seems to be very relevant in such a context.

3.6.2 Incorporating PHY Layer Features in the Design of NCCARQ

In this section, we examine how the realistic PHY layer characteristics affect the design of the proposed NCCARQ MAC protocol during different phases of the wireless communication. In particular, we study how the illustrative example in Figure 3.2 is altered in order to effectively adopt the PHY parameters. Let us recall that node S has to transmit a data packet A to node

D, and node D has to transmit a data packet B to node S, while there are two relay nodes (R_1 and R_2) helping S and D to deliver their packets satisfying a given QoS requirement. Even though all nodes are assumed to be in the communication range of each other, some received packets might be discarded by the MAC layer due to fading, shadowing and path-loss. The packet acceptance criteria for three different wireless channel models are given in Table 3.4.

In this particular example, we consider the wireless channel model for fast fading and shadowing depicted in Figure 3.11 and, hence, the reliability criterion of the third case study in Table 3.4 (third column) can be used to accept or discard the packets. More specifically, for a given PHY setup and target QoS^*, each relay measures the average power of the received packets ($P_{Rx,Measured}$) and compares it with the threshold $APER^{-1}(QoS^*; PHY)$. If the actual measured value is higher than this threshold at the receiver, the packet is accepted as correctly received by the MAC. If the node is a relay, it is included in the set of possible "active" relays during the cooperation phase (active relay set). On the other hand, if the measured power value is lower than the required threshold, the packet is discarded and the link is declared to be in outage. Accordingly, if the node is a relay, it is not included in the active relay set. The probability that a node discards a packet is given by the $OPER$, as presented in the second column of Table 3.4.

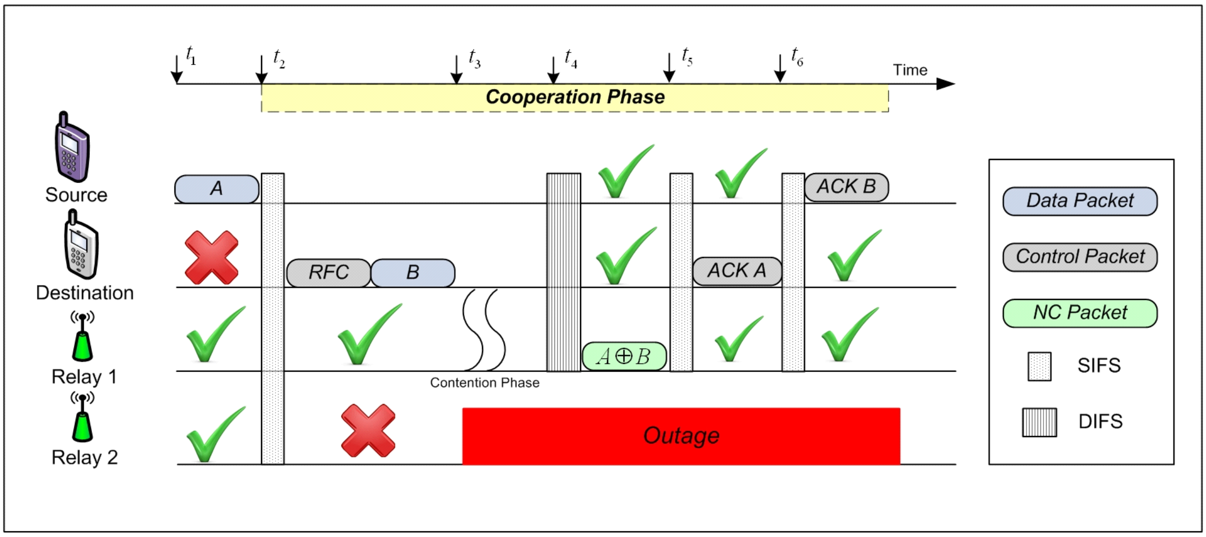

Figure 3.13: NCCARQ-WLAN example of frame sequence (under correlated-shadowing conditions)

Hence, the operation of the protocol under realistic PHY layers conditions is adapted as follows (see Figure 3.13):

1. At time instant t_1, S sends packet A to D, while the relays R_1 and R_2 overhear this transmission. Upon reception, each node (D, R_1, R_2) verifies whether the received packet satisfies the QoS specified at the application layer, as described above. For illustrative purposes, let us assume that both R_1 and R_2 accept packet A, while the same packet received by D is discarded, since it does not meet the QoS requirement (this link is in outage). This might happen due to the different propagation conditions in each link. In a different case, where node D receives an acceptable packet, the relays may drop this packet and the transmission sequence is completed.

2. Since, at time instant t_2, D receives a corrupted packet, it broadcasts an RFC packet to the relays R_1 and R_2, notifying them the need for cooperation. In our protocol, D sends the RFC packet along with its own data packet B, which should be delivered to S. In this example, let us assume that R_1 receives a copy of B that is accepted by the MAC layer, i.e., $P_{Rx,Measured} > APER^{-1}(QoS^*; PHY)$, while the reception of the packet at R_2 does not satisfy the QoS requirement.

3. The reception, at time instant t_3, of the RFC packet at the relay nodes initiates the cooperation phase. Since, in this example, only the relay R_1 has accepted both packets A and B, it is the only node included in the active relay set. Hence, R_1 sets up its backoff counter (CW_1) to participate in the contention phase to forward a network coded version of packets A and B. On the other hand, the relay R_2 is declared to be in outage, since it is not able to apply NC during the cooperation phase, as it has received only one out of the two native packets. It is worth mentioning that if none of the available relays receives both A and B with sufficient quality, then S or D (depending on which gains first access to the channel) starts a new transmission.

4. Let us assume that, at time instant t_4, the backoff counter of R_1 expires, and R_1 transmits the network coded packet $A \oplus B$ to S and D simultaneously. Also in this case, S and D check whether the received network coded packet fulfills the QoS requirement of interest. If both S and D receive acceptable packets, then D can retrieve A, and S can retrieve B, as they have a copy of their own packets already. So, at time instants t_5 and t_6, D and S, respectively, transmit ACK packets to complete the particular communication. If, on the other hand, either S or D have not received a good $A \oplus B$ packet, then the "active" relays compete again to have access to the channel in order to transmit another copy of the same

$A \oplus B$ packet. The process is iterated until both S and D can decode the packets or a timeout has elapsed.

3.6.3 Performance Evaluation

In this section, we provide some numerical examples to assess the performance of the NCCARQ MAC protocol with a practical PHY layer setup and correlated shadowing. The results have been obtained using a time-driven C++ simulator that implements the rules of the NCCARQ MAC protocol, along with the realistic fading channel model shown in Figure 3.11. All MAC parameters have been chosen according to the specifications of the IEEE 802.11g standard, summarized in Table 3.1. The simulation scenario used for our investigation is given in Figure 3.12, where we highlight the impact of the shadowing correlation (ρ) on the different links [35]. In particular, for illustrative purposes, we assume that: i) all S-to-R links have the same correlation coefficient (ρ_{SR}), ii) all D-to-R links have the same correlation coefficient (ρ_{DR}), and iii) there is no correlation between S-to-R and D-to-R links, since measurements in [35] have shown that this is a reasonable assumption. Furthermore, we consider a symmetric network topology with $\rho_{SR} = \rho_{DR} = \rho$.

Regarding the PHY layer parameters, we define as γ^* the normalized reliability criterion, used by the nodes to accept or to discard the packets according to the chosen Tx/Rx scheme, the channel model, the PHY layer and the QoS requested at the application layer. In our simulations we have set $\gamma^* = 10log_{10}(APER^{-1}(QoS^*; PHY)/\sigma^2_{Noise}) = 16.14\ dB$, where $(APER^{-1}(QoS^*; PHY)$ is the reliability threshold introduced in Table 3.4 and σ^2_{Noise} is the noise variance at the receiver. If the actual (measured) value of the SNR, which depends on the transmit power, the transmission distance, the shadowing and the noise power, is greater than the threshold (i.e., $\gamma = 10log_{10}(P_{Rx,Measured}/\sigma^2_{Noise}) > 16.14\ dB$), then the packet is accepted at the MAC layer for further processing, otherwise, the packet is discarded. Hence, γ^* and γ denote the target and the actual received SNR, respectively, while the analytical computation of γ^* threshold is out of the scope of this thesis[8]. Furthermore, we realistically assume that the direct (S-to-D) link with SNR $\bar{\gamma}_{SD}$ is relatively weak with respect to the SNR threshold (γ^*).

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[8] The interested reader is referred to [34] for further details about the PHY layer parameters as well as for advanced techniques to analytically compute $APER^{-1}(\cdot)$, and, thus, γ^*, for a given PHY layer setup and channel model.

We are interested in studying the throughput achieved by the NCCARQ MAC protocol for different shadowing parameters, such as: i) the average SNR on the S-to-R and D-to-R links ($\bar{\gamma}_{SR}$ and $\bar{\gamma}_{DR}$), ii) the shadowing spatial-correlation coefficient ρ, and iii) the shadowing standard deviation σ. In addition, without loss of generality, let these parameters be identical for all wireless links. Furthermore, we are interested in studying the gain of cooperation when multiple relays (N) are available in the network. Let us emphasize that N is the number of potential relay nodes, while the set of "active" relays depends on the number of nodes that receive both packets correctly, i.e., both packets satisfy the QoS requirement $\gamma > 10log_{10}(APER^{-1}(QoS^*; PHY)/\sigma^2_{Noise}) = 16.14\ dB$. Finally, we consider a low-mobility scenario, where we can assume that shadowing is quasi-static over time, meaning that, in both uplink (R-to-S and R-to-D) and downlink (S-to-R and D-to-R), the shadowing gain is the same.

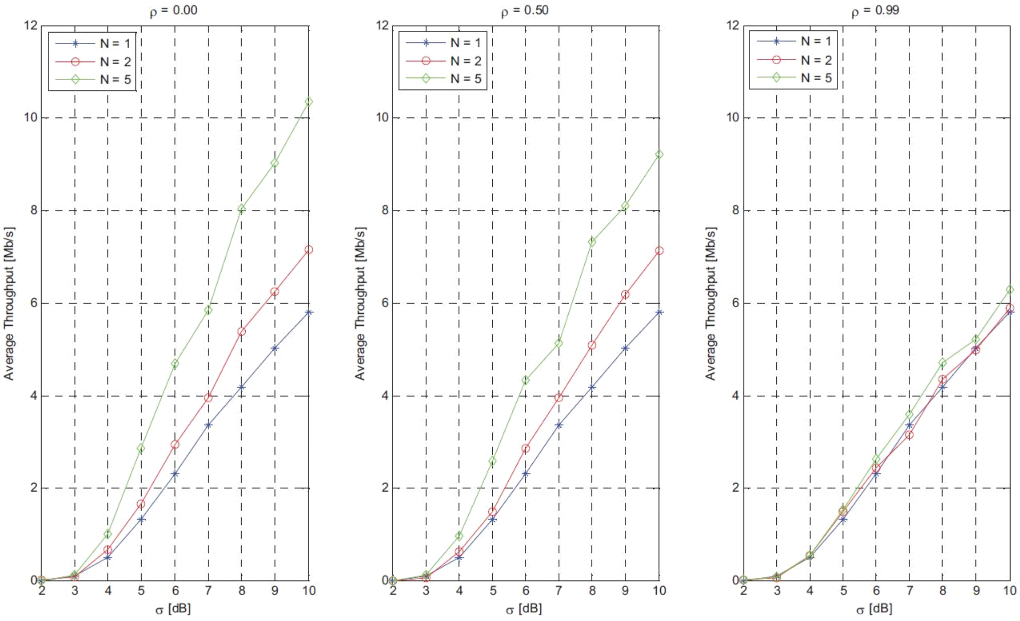

Figure 3.14: Network throughput for $\bar{\gamma}_{SR} = \bar{\gamma}_{DR} = 10\ dB$

Figures 3.14 and 3.15 provide some selected results for $\bar{\gamma}_{SR} = \bar{\gamma}_{DR} = 10\ dB$ and $\bar{\gamma}_{SR} = \bar{\gamma}_{DR} = 20\ dB$, respectively. These figures depict two important case studies, since the average SNR $\bar{\gamma}_{SR} = \bar{\gamma}_{DR}$ is below and above the SNR reliability threshold γ^*, respectively. In these figures, we can notice a very different behavior. In Figure 3.14, the throughput increases with the shadowing standard deviation σ. On the contrary, in Figure 3.15, the throughput decreases with σ. This counter-intuitive behavior has a simple explanation. In case of $\bar{\gamma}_{SR} = \bar{\gamma}_{DR} < \gamma^*$, it is not possible to achieve a successful communication without the random fluctuations introduced by shadowing, since the SNR on the relay links is below the minimum SNR reliability requirement. Thus, shadowing is beneficial, and the larger the shadowing fluctuations are, the higher the throughput is. On the other hand, if $\bar{\gamma}_{SR} = \bar{\gamma}_{DR} \geq \gamma^*$, communication would always be successful without shadowing random fluctuations. In this case, shadowing is particularly harmful, as it introduces many events where the received SNR is below the threshold γ^*. Consequently, the larger the shadowing fluctuations (σ) are, the lower the throughput is. The reason is that, in this case, the throughput is dominated by low SNRs, which occur more often for larger values of σ.

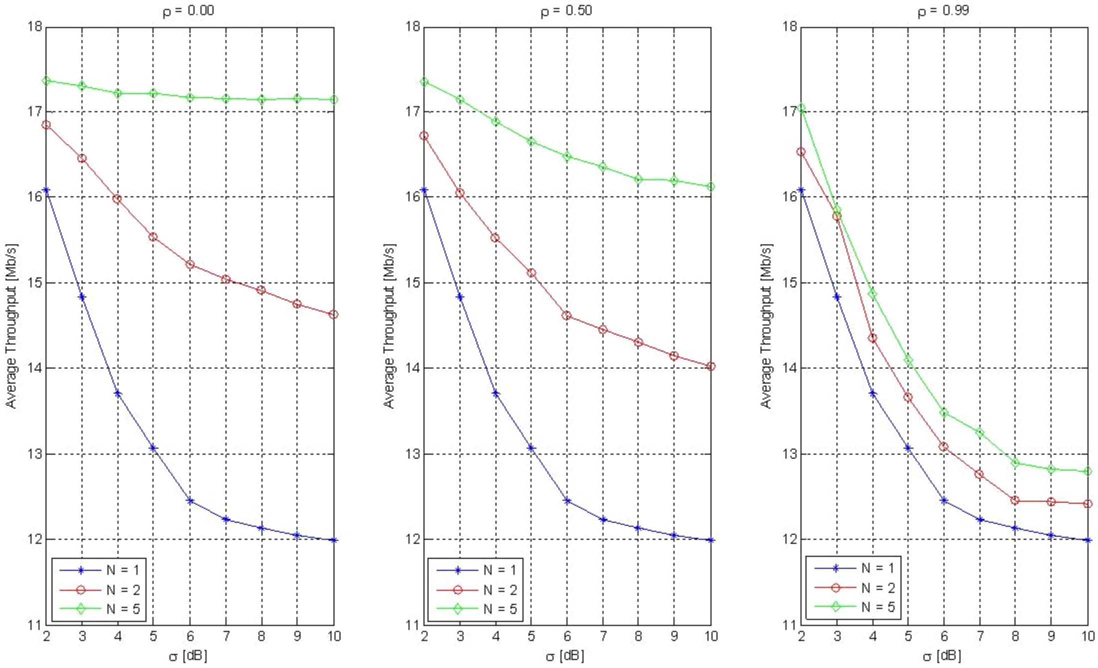

Figure 3.15: Network throughput for $\bar{\gamma}_{SR} = \bar{\gamma}_{DR} = 20\ dB$

In both case studies, we notice two important trends. First, distributed cooperation is beneficial, as the throughput increases with the number of available relays N. In particular, in Figure 3.15 the gain of cooperation is significant. Second, the shadowing correlation is detrimental to the potential gain introduced by cooperation. Specifically, as the correlation grows ($\rho \to 1$), distributed cooperation is useless, since all relays experience very similar shadowing attenuations and, consequently, the throughput is reduced to that of a single-relay network. This result is important for network design, where the deployment cost of many relays can not be neglected. Therefore, by taking into account the actual propagation conditions where the network is supposed to be deployed and operate (i.e., having an estimation, based on measurements, of the shadowing parameters ρ and σ), we are able to choose the best (minimum) number of relays to achieve the desired performance, as well as the most appropriate placement of the relays in network topologies with fixed relay stations.

3.7 Chapter Summary and Conclusions

This chapter, which constitutes the first part of the thesis, has presented the NCCARQ scheme, a novel CSMA-based distributed MAC protocol for cooperative wireless networks. The novelty of the proposed scheme lies on exploiting the NC capabilities along with the cooperative ARQ benefits in modern wireless networks. By allowing users to cooperate among them and enabling the nodes to perform NC, significant diversity and performance gains can be achieved. In addition, it has been proven that NCCARQ can be adapted in various technologies in order to be compatible with existing standards such as IEEE 802.11 and 802.15.4. In this chapter, we have also focused on the impact of realistic PHY layer models and channel conditions on the actual performance of NC-aided cooperative MAC protocols. In particular, the performance of NCCARQ has been evaluated in the presence of correlated shadowing in the network. The key conclusions of this chapter can be summarized in the following:

- The introduction of NCCARQ MAC protocol yields significant performance gains in terms of network throughput and packet delay in cooperative bidirectional scenarios for both short and medium range wireless communications. In particular, compared to simple cooperative schemes (CARQ) which have only the advantage of spatial diversity without any NC capabilities, NCCARQ can achieve a throughput and delay improvement up to 90%. This tremendous enhancement can be rationally explained considering that some data packets in NCCARQ are transmitted to the relays attached to the RFC message, thus avoiding the unreliable source-to-destination channel. Moreover, in the proposed scheme, the number of backoff phases is significantly reduced by sending two packets simultaneously, while in simple cooperative protocols the relays have to participate in the contention phase for each packet that has to be retransmitted.
- Network coding techniques can compensate the relatively worse channel states in the network. As our experiments have revealed, NCCARQ eventually outperforms conventional cooperative schemes even for unfair comparison cases. For instance, the application of

NCCARQ in a network where the source transmits data to the destination with a rate of 24 Mb/s can achieve an enhancement of up to 30% with respect to the performance of CARQ schemes where the transmission data rate between the source and the destination is 54 Mb/s.

- Regarding the energy efficiency, the adoption of NC enables the transmission of more bits in NCCARQ compared to CARQ over the same amount of consumed energy. Hence, the energy efficiency is enhanced, following the trend of throughput performance. In the context of this thesis, precise analytical models for the energy consumption in the network have been designed, verified by extensive simulations to demonstrate this advancement.
- The impact of realistic PHY layer and channel conditions on the performance of NCCARQ was thoroughly discussed and investigated. The packet reliability threshold was determined by taking into account realistic PHY layer parameters, while the protocol performance was assessed under correlated shadowing channel conditions. In our experiments, two different cases were analyzed: i) one scenario where the average source-to-relays and relays-to-destination SNR ($\bar{\gamma}_{SR} = \bar{\gamma}_{DR}$) is below the reliability threshold γ^*, and ii) one scenario where $\bar{\gamma}_{SR} = \bar{\gamma}_{DR}$ is above γ^*. In both case studies, distributed cooperation is beneficial, as the throughput increases with the number of available relays N. On the other hand, shadowing correlation is proven to be detrimental to the potential gain introduced by cooperation, since asymptotically ($\rho \rightarrow 1$) distributed cooperation is useless, as all the relays experience very similar shadowing attenuations. Our results clearly showcase the need for considering realistic non-ergodic spatial-correlated shadowing models towards a sound design, analysis and optimization of cooperative MAC protocols.

This chapter has provided interesting insights for novel cooperative wireless systems, drawing potential future research lines. The next chapter commences the second part of this thesis, which is dedicated to the research of MAC issues in data dissemination scenarios.

3.A Appendix

3.A.1 $\mathrm{E}[r]$ Analysis

In cooperative ARQ schemes, the expected number of retransmissions required in order for the destination to properly demodulate the data packet is a geometric random variable, directly connected to the PER in the channel between the relay and the destination ($PER_{R\to D}$). Hence, the expected value $\mathbf{E}[r]$ of the number of retransmissions can be calculated as:

$$\mathbf{E}[r] = \sum_{i=0}^{\infty}(i+1)\cdot PER_{R\to D}^{i}\cdot(1-PER_{R\to D}) = \frac{1}{1-PER_{R\to D}} \tag{3.23}$$

In our scheme, however, two coded packets are simultaneously transmitted by the relay via different channels to the source and to the destination, respectively. Hence, in order to estimate the expected number of retransmissions, we model the decoding procedure as a Markov process (Figure 3.16), where the transition probabilities a and β represent the $PER_{R\to S}$ and $PER_{R\to D}$, respectively. Moreover, the states of the chain correspond to the following cases:

- **State $\{\mathbf{0}\}$:** None of the packets has been decoded successfully.
- **State $\{\mathbf{S}\}$:** Only the source has decoded the packet successfully.
- **State $\{\mathbf{D}\}$:** Only the destination has decoded the packet successfully.
- **State $\{\mathbf{2}\}$:** Both packets have been decoded successfully.

To estimate the average number or retransmissions required until the correct decoding of both packets, we need to estimate the mean time needed to reach state $\{2\}$, given that $\{0\}$ is the initial state. The mean absorption time is given by the relationship

$$X_{ij} = 1 + \sum_{k\neq j} P_{ik}\cdot X_{kj} \tag{3.24}$$

where i and j represent the starting and the absorbing state, respectively, k corresponds to all intermediate states and P_{ik} denotes the transition probability from state i to state k. Applying this formula to our Markov chain, we form a system of four equations, as follows:

$$X_{02} = 1 + a\cdot\beta\cdot X_{02} + (1-a)\cdot\beta\cdot X_{S2} + (1-\beta)\cdot a\cdot X_{D2} + (1-\beta)\cdot(1-a)\cdot X_{22} \tag{3.25}$$

$$X_{S2} = 1 + \beta\cdot X_{S2} + (1-\beta)\cdot X_{22} \tag{3.26}$$

$$X_{D2} = 1 + a \cdot X_{D2} + (1 - a) \cdot X_{22} \tag{3.27}$$

$$X_{22} = 0 \tag{3.28}$$

Solving the system, we derive the expected number of retransmissions as:

$$\mathbf{E}[r] = X_{02} = \frac{1 + \frac{(1-a)\cdot\beta}{1-\beta} + \frac{(1-\beta)\cdot a}{1-a}}{1 - a \cdot \beta} \tag{3.29}$$

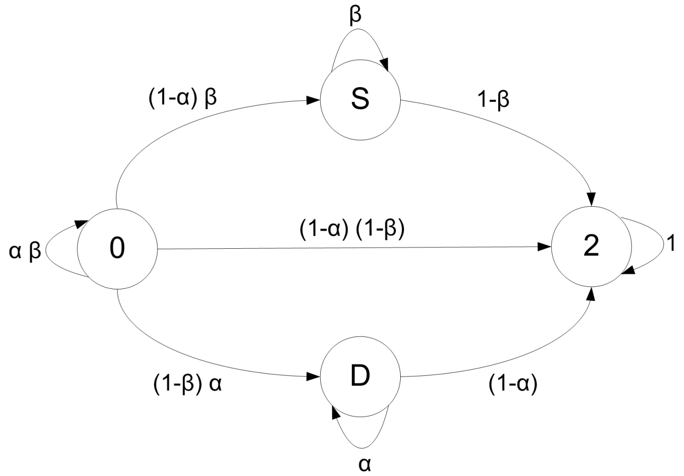

Figure 3.16: Markov model for the estimation of $\mathbf{E}[r]$

3.A.2 $\mathbf{E}[T_c]$ Analysis

In order to analytically compute the $\mathbf{E}[T_c]$ value, we need to model the backoff counter of each of the relays with the Markov chain introduced by Bianchi in [40] (Figure 3.17), since the formed subnetwork behaves as a saturated IEEE 802.11 ad hoc network despite the modifications in the access rules. According to this model, the probability τ that a station transmits in a randomly chosen slot, is given by:

$$\tau = \sum_{i=1}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \tag{3.30}$$

where

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \tag{3.31}$$

and the probability of a collision p as a function of τ is given by:

$$p = 1 - (1-\tau)^{n-1} \tag{3.32}$$

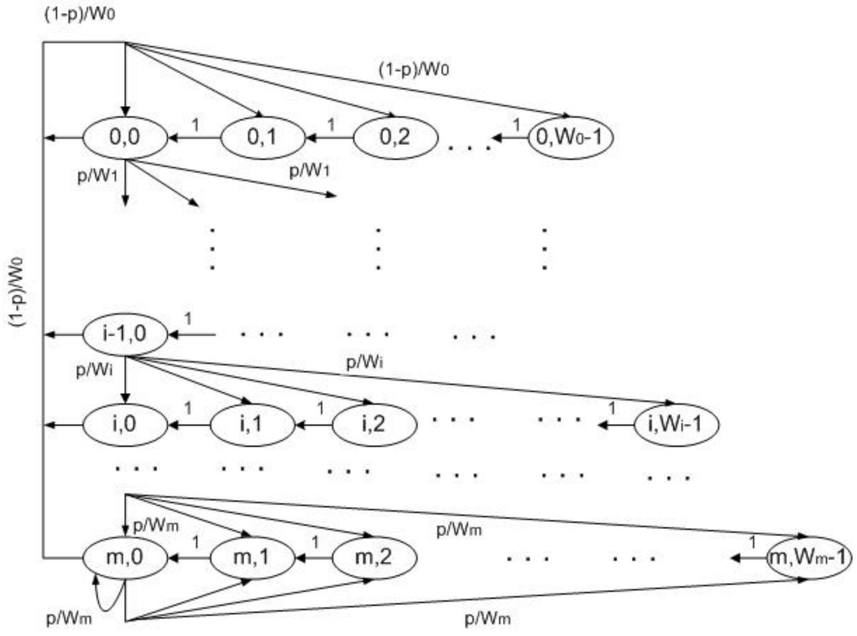

Figure 3.17: Markov model for the backoff operation

In the formulas (3.30)-(3.31), $b_{i,k}$ represents the steady state probability of the state $\{i, k\}$, W is the size of the contention window, m denotes the number of the backoff stages and n corresponds to the number of the relays in the network.

Furthermore, the probability that at least one relay attempts to transmit can be expressed as:

$$p_{tr} = 1 - (1 - \tau)^n \tag{3.33}$$

and the probability of a successful transmission, i.e., exactly one station transmits conditioned on the fact that at least one station transmits, is given by:

$$p_{s|tr} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{3.34}$$

In addition, the probabilities of having an idle (p_i), successful (p_s) or collided (p_c) slot can be written as:

$$p_i = 1 - p_{tr} \tag{3.35}$$

$$p_s = p_{tr} \cdot p_{s|tr} \tag{3.36}$$

$$p_c = p_{tr} \cdot (1 - p_{s|tr}) \tag{3.37}$$

Considering the above probabilities, and given that the average number of slots we have to wait before achieving a successful transmission can be represented as:

$$\mathbf{E}[N] = \sum_{k=0}^{\infty} k(1-p_s)^k p_s = \frac{1}{p_s} - 1, \tag{3.38}$$

the total contention time can be written as:

$$\mathbf{E}[T_c] = \mathbf{E}[N] \cdot \mathbf{E}[T_{slot|non\_successful\_slot}]. \tag{3.39}$$

Applying Bayes' theorem we are able to estimate the average duration of a slot, given that the specific slot is either idle or collided:

$$\mathbf{E}[T_{slot|non\_successful\_slot}] = (\frac{p_i}{1-p_s})\sigma + (\frac{p_c}{1-p_s})T_{col} \tag{3.40}$$

with σ representing the duration of an idle slot, while T_{col} corresponds to the collision duration, usually equal to the packet transmission time, since the collision detection takes place at the receiver's side.

Hence, the equation (3.39) is written as:

$$\mathbf{E}[T_c] = (\frac{1}{p_s} - 1) \cdot [(\frac{p_i}{1-p_s})\sigma + (\frac{p_c}{1-p_s})T_{col}]. \tag{3.41}$$

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Chapter 4

Game Theoretic Medium Access Strategies for Wireless Data Dissemination

"You have to learn the rules of the game. And then you have to play better than anyone else." **Albert Einstein.**

Contents

4.1 Introduction

The introduction of 3G technologies caused a shift from voice-centric applications to the mobile Internet, thus posing major challenges to the design of future communication systems. Recent reports have highlighted the importance of non-voice traffic in future wireless networks [1]. In particular, video and file sharing are increasingly dominating the mobile data traffic, and it is forecasted to account for more than 95% of total data traffic by 2015. This trend, along with the growth of P2P networking, have reinforced the need of distributing the digital information, such as video conferencing, live streaming, etc., among multiple end users. Hence, the concept of data dissemination has lately attracted great attention, especially in the context of wireless networks [2–4].

The problem of data dissemination becomes even harsher in wireless networks due to the energy constraints of battery-operated mobile terminals. These limitations are just an additional component to the general issue of energy consumption, which has become a key factor for the design and implementation of "green" networks, protocols and algorithms. Several works that deal with energy consumption issues in data dissemination scenarios have been proposed during the last few years [5–7]. Yilmaz *et al.* [5] proposed an innovative decentralized shortest hop multi-path algorithm for WSNs in order to generate energy efficient paths for data dissemination. Their algorithm generates shortest hop braided multipaths to be used for fault-tolerance or load-balancing, while guaranteeing low time and message complexity. Visvanathan *et al.* [6] introduced three hierarchical data dissemination schemes that prolong the lifetime of battery-driven sensor nodes by reducing the amount of information exchanged. The three proposed schemes create different hierarchical dissemination structures from the source to the sink nodes in order to achieve reduced data redundancy and communication overhead. In the same context, Xing *et al.* [7] presented the Minimum Incremental Dissemination Tree (MIDT) to minimize the total energy consumption in data dissemination by jointly considering: i) the quality of the links, ii) the power of all active radio modes (transmission, reception, idle), and iii) the data rates of different service requests. However, despite the reduction of the network's energy consumption, the aforementioned works either assume perfect coordination in the MAC layer [5] or sacrifice the QoS by deteriorating the end-to-end delay [6], [7]. Therefore, a challenging task to overcome these limitations is the design of realistic energy efficient MAC protocols that respect the QoS constraints set by different applications in data dissemination scenarios.

The common global goal of all nodes in wireless data dissemination schemes is twofold: i) the completion of the dissemination in a reasonable time that satisfies the QoS restrictions and ii) the least possible energy consumption that maximizes the nodes' lifetime. However, in such scenarios, the selfish nature of the nodes may cause conflicting situations, since all nodes have revenue by the dissemination completion, but at the same time, they aim at preserving their individual energy status. To this end, game theory has come into play to study mathematical models of conflict and cooperation between intelligent rational decision-makers [8]. In particular, during the last decade, game theoretic frameworks have been broadly proposed to investigate and model the medium access contention problem in wireless networks. The vast majority of these works focus on estimating the NE [9] point of a given game, which can be defined as a steady-state condition that corresponds to the mutual best response of all players.

MacKenzie and Wicker [10] proposed a pioneer game theoretic model to study the behavior of selfish nodes in slotted ALOHA systems. In [11], the same authors extended their former work by proving the existence of equilibria in multi-packet reception models. Altman *et al.* [12] introduced a non-cooperative game, where ALOHA nodes aim at maximizing their throughput under non-saturation conditions. Inaltekin and Wicker [13] analyzed the asymmetric NE for heterogeneous networks, where nodes are non-identical, having different perceived utilities. More recently, Cho *et al.* [14] proposed robust random-access protocols for wireless networks in fading environments, where the terminal nodes estimate the NE of a random-access game. Their game formulation provides higher access probabilities to the nodes with better channel states, thus guaranteeing the multiuser diversity. In the same context, Wang *et al.* [15] introduced a game theoretic model in order to design a NE threshold associated to the statistical channel characteristics.

Several game theoretic works have been also conducted regarding the IEEE 802.11 DCF [16–18]. In [16], Fang and Bensaou dealt with the problem of fair bandwidth sharing among the wireless nodes in ad hoc networks. They proposed two different game formulations for the specific problem, where the solutions are provided without the need for global knowledge. Zhao *et al.* [17] presented an incompletely cooperative game to enhance the performance of MAC protocols in wireless mesh networks. In their game, the nodes first estimate the number of competing stations, and they adapt their individual equilibrium strategies by adjusting their local contention parameters, i.e., the minimum CW. Tinnirello *et al.* [18] proposed a game theoretic analysis of persistent access schemes for wireless infrastructure networks, where the nodes are interested in both upload and download traffic. The authors proved the existence of NE, while they used the AP as an arbitrator to improve the global network performance.

In the same context, this chapter introduces multi-player game theoretic channel access strategies for wireless data dissemination schemes, where multiple source nodes have conflicting interests. We propose strategic game formulations, where each player identifies a steady state condition (NE) in order to balance a trade-off between saving energy and completing the data dissemination. In addition, RLNC techniques are employed to eliminate the need of exchanging ACK control packets in the network. The particular contribution of this chapter is twofold:

1. Taking into account the importance of energy efficiency in wireless communications, we present two different game theoretic MAC strategies: i) a distributed approach for infrastructureless ad hoc networks where the wireless nodes individually estimate the NE transmission probabilities according to energy-based utility functions, and ii) a centralized approach for infrastructure networks, where the nodes also act individually to achieve the NE, while a central controller is occasionally used to facilitate the dissemination procedure. The proposed game formulations can be applied to realistic wireless networks, where multiple sources compete for channel access.
2. We present an analytical probabilistic framework to evaluate the network performance in terms of energy efficiency and completion time in the NE state, taking into account the RLNC packet overhead. The proposed analytical model further demonstrates the scalability of both approaches, while proving that our game theoretic strategies outperform other standardized approaches.

The remainder of the chapter is organized as follows. Section 4.2 presents our system model along with the game formulation. Sections 4.3 and 4.4 introduce the distributed and the centralized game theoretic medium access approaches, respectively. Section 4.5 quantifies the derived formulas by providing medium access probabilities for both schemes in the NE state. The analytical models for the completion time and the energy efficiency performance of the proposed schemes are designed in Section 4.7, while the models validation along with experimental results are provided in Section 4.8. Finally, Section 4.9 summarizes the chapter, highlighting the most important conclusions.

4.2 System Model and Game Formulation

Figure 4.1 depicts the considered network, consisting of: i) a BS that initially holds and broadcasts the digital information, ii) a set of n nodes (so called source nodes) located inside the transmission range of the BS, and iii) a set of l nodes (so called sink nodes) placed outside the transmission range of the BS, but inside the transmission range of at least one source node. In our system, the source nodes have the same impact[1] on the network, affecting the same number of sink nodes. The data dissemination is carried out in two phases. During the first phase, the BS transmits the information to the n source nodes in its coverage area, while, in the second phase, the source nodes disseminate the data to the rest l sink nodes. It is worth mentioning that our proposal can be adaptively employed in large-scale networks, by considering a layered architecture consisting of distinct phases, where the sink nodes of each phase constitute the source nodes of the following phase. This is, though, out of the scope of this thesis.

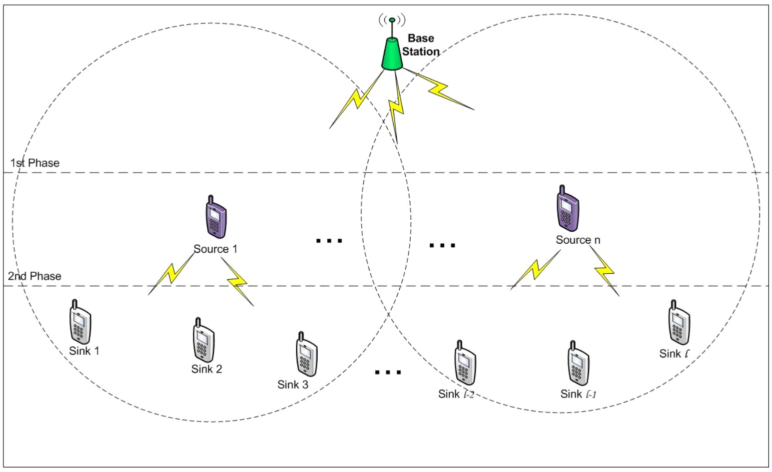

Figure 4.1: System model

Our study is particularly focused on the second phase of the dissemination. We assume a slotted system where the node with the greatest impact on the network gains the channel access to transmit in every slot, since this technique has been recently proven to expedite the dissemination procedure [19]. However, the mutual interference among the transmitting radio

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[1] Impact is defined as the number of innovative packets delivered in each transmission

signals allows for only one transmission in every slot, thus hindering the realization of multiple parallel transmissions. Hence, the transmissions have to be coordinated by MAC mechanisms that will be applied to resolve the contention caused by the existence of several source nodes with the greatest impact on the network.

Regarding the data transmissions, the network operates under saturated conditions, since the source nodes already hold the total information, thus having packets to send in their buffers. Furthermore, RLNC techniques are used to assist the dissemination progress. Specifically, since data collection is an equivalent situation to the coupon collector's problem [20], NC can significantly simplify the complexity of the solution [21]. In particular, the transmission of linear packet combinations instead of just forwarding the information flows eliminates the necessity of exchanging ACKs. Hence, it is sufficient for a network node to receive enough linearly independent combinations in order to decode the entire data set. On the other hand, NC comes with an additional cost, since the data packets are charged with an extra overhead due to the NC header. The specific header contains essential information for the decoding process, such as the coding vector, the generation size and the generation index [22].

In our scenario, the global goal of all nodes is the successful completion of the data dissemination. However, the sender's role implies energy wasting, hence particular incentives should be provided to a particular player in order to take up this role. On the other hand, if no one transmits, the nodes will waste all their energy in idle state, thus hindering the data dissemination. To analyze this conflicting situation, we model the access scenario as a *static non-cooperative game with complete information* [8], where each player selects the strategy that maximizes their own utility.

In game theory, a game Γ is represented by a tuple $\Gamma = (\mathcal{N}, (\mathcal{A}_i)_{i \in \mathcal{N}}, (U_i)_{i \in \mathcal{N}})$, where $\mathcal{N} = \{1, ..., n\}$ is the set of players. For each player $i \in \mathcal{N}$, $\mathcal{A}_i$ is a finite set of actions, while U_i is a *utility* (or *payoff*) function, given a set of actions. Our game consists of n players (*source* nodes) who decide if they transmit or not in each slot. Therefore, we use the following notations to be compatible with the game theory rules: $\mathcal{N} = \{1, ..., n\}$ and $\mathcal{A} = \{Transmit(T), Wait(W)\}$. Furthermore, in order to focus on the energy aspect of the problem, the utility function is chosen such that to quantify the lifetime of the nodes. Defining $\mathcal{E}_{TOTAL_i}$ as the total energy amount available to each node i, and $\mathbf{E}[\mathcal{E}_i]$ as the average amount of energy consumed by node i in each slot, the utility function of player i is given by:

$$U_i = \frac{\mathcal{E}_{TOTAL_i}}{\mathbf{E}[\mathcal{E}_i]}. \tag{4.1}$$

The strategic form of the proposed game is presented in Table 4.1. We have formulated our problem as a game with 2 players, where Player 1 represents node i, while Player 2 includes the rest $n-1$ nodes except for node i. The table's contents correspond to the Player's 1 energy costs with regard to the different contingencies in Player's 2 set. In particular, the values $\mathcal{E}_T$ and $\mathcal{E}_W$ represent the energy amounts consumed during transmission and idle mode, respectively, while $\mathcal{E}_C$ corresponds to the cost in case that the dissemination does not proceed either due to collisions or idle slots.

Table 4.1: Game model

	Player 2 (all the other n-1 nodes)			
Player 1 (node i)		**T**		**W**
	T	$\mathcal{E}_T + \mathcal{E}_C$		$\mathcal{E}_T$
	W	*Successful Transmission*	*Failed Transmission*	$\mathcal{E}_W + \mathcal{E}_C$
		$\mathcal{E}_W$	$\mathcal{E}_W + \mathcal{E}_C$	

Having formulate our problem in a strategic form, in the following sections we introduce our game theoretic medium access policies: i) a distributed approach where the wireless nodes individually estimate the NE channel access probabilities according to the aforementioned energy-based utility function, and ii) a centralized approach for infrastructure networks, where the nodes act individually to achieve the NE, while a central controller is occasionally used to facilitate the dissemination procedure.

4.3 Distributed Approach

In the distributed access strategy, the nodes estimate their transmission probabilities in a totally decentralized manner, by calculating the NE with regard to the global utility function. The lack of efficient equilibriums in pure strategies (as it has been explained in Section 4.2) enables each source node (Player 1) to select a transmission probability, s_i, independently of the other $n-1$ nodes, which transmit with probability s_j. Given the system model, there are five possible outcomes for each slot. Two of them result in successful transmissions, while the rest three lead in unsuccessful/failed slots, either idle or collided. In particular:

$s1$: Player 1 transmits - All nodes in Player 2 wait ⇒ Successful transmission.

$s2$: Player 1 waits - Exactly one node of Player 2 transmits ⇒ Successful transmission.

$f1$: Player 1 transmits - At least one node of Player 2 transmits ⇒ Collision.

$f2$: Player 1 waits - At least two nodes of Player 2 transmit ⇒ Collision.

$f3$: Player 1 waits - All nodes in Player 2 wait ⇒ Idle slot.

Therefore, considering the energy costs in the strategic form of the proposed game (Table 4.1), the expected consumed energy for node i, $\forall i \in \mathcal{N}$ is given by:

$$\mathbf{E}[\mathcal{E}_i] = p_{s1} \cdot \mathcal{E}_T + p_{s2} \cdot \mathcal{E}_W + p_{f1} \cdot (\mathcal{E}_T + \mathcal{E}_C) + p_{f2} \cdot (\mathcal{E}_W + \mathcal{E}_C) + p_{f3} \cdot (\mathcal{E}_W + \mathcal{E}_C) \quad (4.2)$$

where the probabilities $p_{s1}, p_{s2}, p_{f1}, p_{f2}$ and p_{f3} correspond to the respective above contingencies and can be mathematically expressed as[2]:

$$p_{s1} = s_i \cdot (\bar{s}_j)^{n-1}, \forall i, j \in \mathcal{N}, n \in \mathbb{Z}, n \geq 2 \quad (4.3)$$

$$p_{s2} = \bar{s}_i \cdot (n-1) \cdot s_j \cdot (\bar{s}_j)^{n-2}, \forall i, j \in \mathcal{N}, n \in \mathbb{Z}, n \geq 2 \quad (4.4)$$

$$p_{f1} = s_i \cdot (1 - (\bar{s}_j)^{n-1}), \forall i, j \in \mathcal{N}, n \in \mathbb{Z}, n \geq 2 \quad (4.5)$$

$$p_{f2} = \bar{s}_i \cdot ((1 - (1 - s_j)^{n-1}) - (n-1) \cdot s_j \cdot (\bar{s}_j)^{n-2}), \forall i, j \in \mathcal{N}, n \in \mathbb{Z}, n \geq 2 \quad (4.6)$$

$$p_{f3} = \bar{s}_i \cdot (\bar{s}_j)^{n-1}, \forall i, j \in \mathcal{N}, n \in \mathbb{Z}, n \geq 2 \quad (4.7)$$

The best response of s_i to the strategy s_j - and consequently the NE s^* of the game - is given by setting $\frac{\partial U_i}{\partial s_i} = 0$. The partial derivative of the utility function $U_i = \frac{\mathcal{E}_{TOTAL}}{\mathbf{E}[\mathcal{E}_i]}$ with respect to s_i, is equal to:

$$\frac{\partial U_i}{\partial s_i} = -\frac{\mathcal{E}_{TOTAL}}{(\mathbf{E}[\mathcal{E}_i])^2} \cdot \frac{\partial(\mathbf{E}[\mathcal{E}_i])}{\partial s_i}. \quad (4.8)$$

Hence, as derived by equation (4.8), in order to estimate the NE of the proposed game, it is sufficient to solve the equation:

$$\frac{\partial(\mathbf{E}[\mathcal{E}_i])}{\partial s_i} = 0. \quad (4.9)$$

More details and numerical examples for the NE transmission probability under different scenarios are provided in Section 4.5.

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[2] We use the notation $\bar{s}_i$ to denote the complementary probability of s_i, i.e., $\bar{s}_i = 1 - s_i$.

4.4 Centralized Approach

In data dissemination scenarios, the delay metric constitutes a key QoS indicator, as well as a restrictive factor for the network performance. The application of the proposed game theoretic distributed channel access scheme to the system might potentially cause unsuccessful or empty slots in the network, either due to collisions or idle slots when the nodes mutually transmit or wait, respectively. Hence, in order to bound the time needed to complete the data dissemination, we also propose a game theoretic centralized channel access strategy, applicable in infrastructure networks.

In particular, in the centralized approach we adopt the use of a central controller that deterministically provides the source nodes with channel access in case of k_f consecutive unsuccessful slots. More specifically, the controller is able to distinguish between idle slots, successful transmissions and collisions by sensing the energy level in the channel [23] and, accordingly, to select the node to transmit in case of k_f successive failed slots in the network. It is worth noting that unlike pure centralized systems where the central controller schedules the total transmissions, in our proposed strategy the controller intervenes only occasionally by polling one station, hence eliminating the necessity of extra overhead and preserving valuable energy.

Despite being a very challenging research opportunity, the optimal selection of k_f is out of the scope of this thesis. In our work, we consider $k_f = 2$ in order to focus on the potential benefits that the centralized intervention can bring to the network performance. Given the operation of the game theoretic centralized medium access strategy, there are three possible cases before achieving a successful transmission of a packet:

i) The first attempt can be either successful or unsuccessful.

ii) Given that the first attempt failed, the second can be again either successful or unsuccessful.

iii) Given that the two previous attempts were unsuccessful, the central controller defines which node is going to transmit.

For the sake of clarity and comprehension, let us denote by Z the expected energy consumption of a node, as derived by the respective energy costs in Table 4.1:

$$Z = p_{s1} \cdot \mathcal{E}_T + p_{s2} \cdot \mathcal{E}_W + p_{f1} \cdot (\mathcal{E}_T + \mathcal{E}_C) + p_{f2} \cdot (\mathcal{E}_W + \mathcal{E}_C) + p_{f3} \cdot (\mathcal{E}_W + \mathcal{E}_C), \quad (4.10)$$

where the probabilities p_{s1}, p_{s2}, p_{f1}, p_{f2} and p_{f3} have been defined in Section 4.3. Therefore, the total expected consumed energy $\mathbf{E}[\mathcal{E}'_i]$ of node i until a correct packet transmission is given by:

$$\mathbf{E}[\mathcal{E}'_i] = [Z] + [(p_{f1}+p_{f2}+p_{f3}) \cdot Z] + [(p_{f1}^2+p_{f2}^2+p_{f3}^2+2 \cdot p_{f1} \cdot p_{f2}+2 \cdot p_{f1} \cdot p_{f3}+2 \cdot p_{f2} \cdot p_{f3}) \cdot p_{poll} \cdot \mathcal{E}_T] \quad (4.11)$$

where the three terms in brackets correspond to the expected values of energy consumption with regard to the three aforementioned possible cases, respectively. Furthermore the probability p_{poll} is considered constant, due to the scheduler's fairness.

To distinguish from the distributed access strategy, let us denote by $U'_i = \frac{\mathcal{E}_{TOTAL}}{\mathbf{E}[\mathcal{E}'_i]}$ the utility function in the centralized policy. Searching for equilibrium strategies, we differentiate the utility function with respect to s_i:

$$\frac{\partial U'_i}{\partial s_i} = -\frac{\mathcal{E}_{TOTAL}}{(\mathbf{E}[\mathcal{E}'_i])^2} \cdot \frac{\partial(\mathbf{E}[\mathcal{E}'_i])}{\partial s_i}. \quad (4.12)$$

The best response of s_i to the strategy s_j is given by setting $\frac{\partial U'_i}{\partial s_i} = 0$ or equivalently (from equation (4.12)):

$$\frac{\partial(\mathbf{E}[\mathcal{E}'_i])}{\partial s_i} = 0. \quad (4.13)$$

The following section provides numerical solutions for the proposed medium access strategies.

4.5 NE Numerical Results

Sections 4.3 and 4.4 were dedicated to the theoretical analysis of NE estimation under different medium access strategies. The present section evaluates the aforementioned analysis by providing NE numerical results for various scenarios and parameters.

Let us recall that the solutions of the equations (4.9) and (4.13) correspond to the NE transmission probabilities in the distributed and the centralized access strategy, respectively. Without loss of generality, let $\mathcal{E}_W = a \cdot \mathcal{E}_T$ and $\mathcal{E}_C = b \cdot \mathcal{E}_T$. Thus, the expected NE, s^*, for the distributed access strategy is given by:

$$a \cdot (s^* - 1) \cdot (\bar{s}^{*n} - s^* + 1) + b \cdot (n \cdot s^* + s^* - 2) \cdot \bar{s}^{*n} + (s^* - 1)^2 = 0. \qquad (4.14)$$

Considering as a use case the IEEE 802.11g Standard [24], where the power level of the reception (P_R) and idle state (P_I) is the 70% of the transmission power (P_T) [25], we set $a = 0.7$. Regarding the parameter b, which is the weight factor of the energy cost in case that the dissemination does not successfully proceed, we assume three different values ($b = 0.8$, $b = 1.0$ and $b = 1.2$), with respect to the impact of the dissemination standstill on the network. To this end, the NE transmission probabilities for different number of players (source nodes) in the network are presented in Table 4.2, where we observe that the NE transmission probability increases with b, as the nodes adopt an "aggressive" attitude to complete the process. Conversely, for fixed values of b, the transmission probability decreases as the number of competing source nodes increases in the network.

Table 4.2: NE transmission probabilities

	Distributed			Centralized		
n	$s^*(b = 0.8)$	$s^*(b = 1.0)$	$s^*(b = 1.2)$	$s^*(b = 0.8)$	$s^*(b = 1.0)$	$s^*(b = 1.2)$
2	0.312	0.350	0.375	0.423	0.432	0.439
3	0.180	0.207	0.225	0.259	0.268	0.275
4	0.127	0.147	0.161	0.185	0.193	0.199
5	0.097	0.113	0.125	0.144	0.150	0.156
6	0.080	0.092	0.102	0.117	0.123	0.128
7	0.067	0.078	0.086	0.099	0.104	0.108
15	0.030	0.035	0.038	0.044	0.046	0.048
17	0.026	0.030	0.034	0.039	0.041	0.043
19	0.023	0.027	0.030	0.034	0.036	0.038

The main advantage of the NE is the achievement of balance in the system. However, despite its popularity, the NE does not always reach the ideal state for a system, known as "Pareto efficient" state. To determine the optimal strategy in our problem, we substitute $s_1 = s_2 = s$ in the utility function. Figure 4.2 depicts the variation of the utility using identical access strategies ($s_1 = s_2 = s$), assuming $a = 0.7$, $b = 1.0$ and a varying number of source nodes. In this figure, it can be observed that NE transmission probabilities result in high utility values, but not the optimal ones, thus proving the Pareto inefficiency of the NE, which is a common phenomenon in non-cooperative games. In addition, it is worth noticing how the tendencies of the plots vary for different number of nodes. In particular, the presence of numerous nodes in the network restricts the range of high payoff probabilities, thus requiring the precise calculation of the NE in order to avoid undesirable low utility situations.

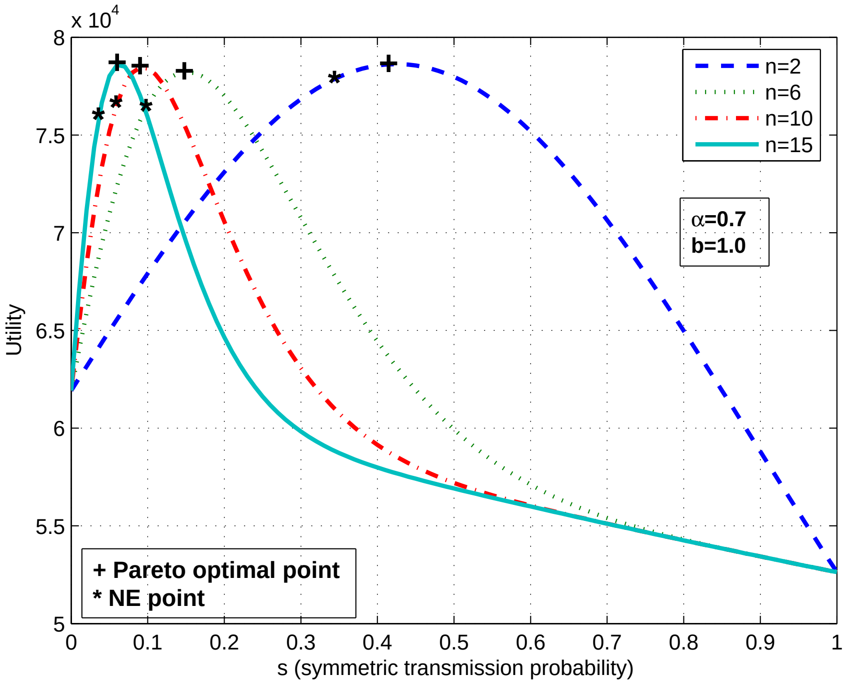


Figure 4.2: Utility vs. Symmetric strategies

With respect to the centralized channel access strategy, Figure 4.3 plots the results of equation (4.13) for various numbers of source nodes (n) in the particular case of having set $a = 0.7$ and $b = 1.0$. In this plot, it can be observed that for every n there is only one fixed-point solution in the strategy space ($s_i, s_j \in [0, 1]$), which is the unique equilibrium of the game according to the NE definition. Specifically, since the NE is defined as the mutual best response, we conclude that any fixed point in mixed strategies constitutes a NE [26].

More detailed results for different values of b are included in Table 4.2, where we can see that the estimated values of NE under the centralized access strategy are higher compared to the NE probabilities in the distributed strategy, under the same conditions and variables. This

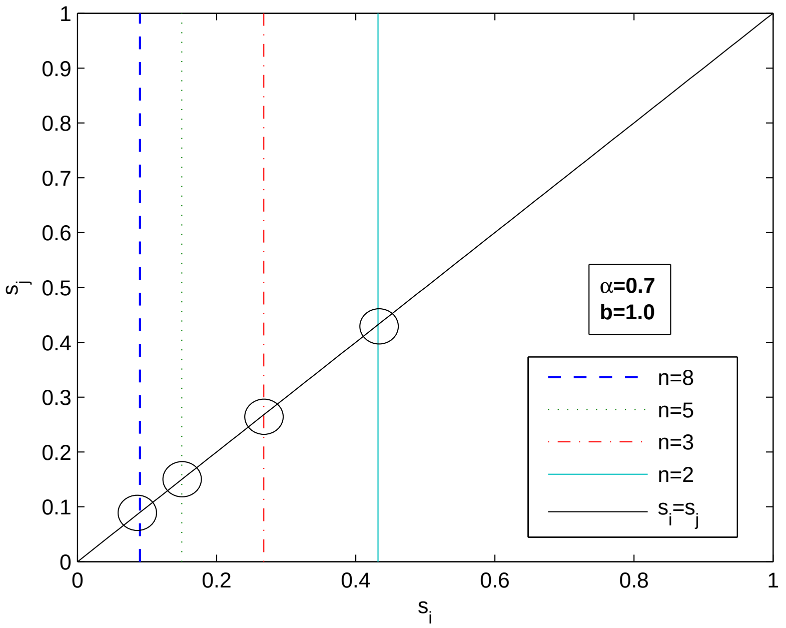


Figure 4.3: s_i vs. s_j and Fixed Point solutions for various number of source nodes

trend can be rationally justified by the presence of the central controller that acts as a safeguard to guarantee correct transmission after consecutive unsuccessful slots. Hence, the nodes are enabled to estimate higher transmission probabilities without taking into account the threat of collisions.

The next section presents two operational examples for the distributed and the centralized access strategy, respectively.

4.6 Operational Examples

A simple network topology is considered, consisting of a central controller, two source nodes and a single destination node in the transmission range of both sources. According to our system model, the source nodes transmit random linear packet combinations and, for this particular case, we assume that the destination needs to receive three packets to decode the total information.

Figure 4.4 depicts the frame sequence in the distributed game theoretic channel access strategy for the simple scenario described above. We recall that, in this scheme, the central controller is not involved in the procedure. In detail, the protocol operates as follows:

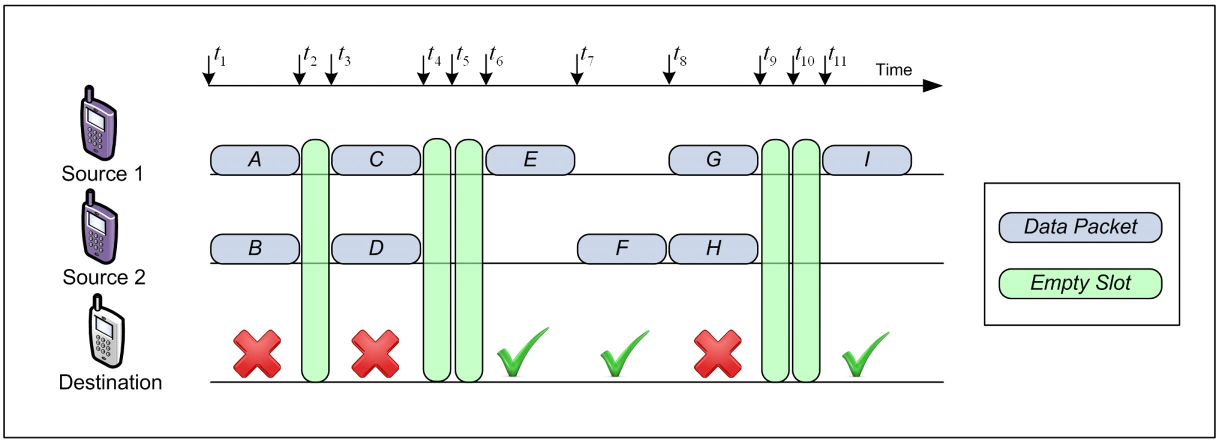


Figure 4.4: Example of frame sequence in the distributed MAC strategy

1. At instant t_1, both sources decide to transmit and, as a result, the destination experiences a collision.
2. At instant t_2, both sources remain idle, which results in an empty slot in the system.
3. At instant t_3, both sources decide to transmit and a collision takes place again in the network.
4. At instants t_4 and t_5, the sources remain silent, thus having two more idle slots in the network.
5. At instant t_6, source 1 decides to transmit the network-coded packet E, while source 2 decides to remain idle and, therefore, the destination is able to extract packet E.
6. At instant t_7, source 1 chooses not to transmit, while source 2 transmits the network-coded packet F and, hence, the destination receives the packet correctly.
7. At instant t_8, both sources transmit their packets and the transmitted packets collide at the destination.
8. At instant t_9 and t_{10}, both sources remain silent, having two consecutive idle slots in the network.
9. At instant t_{11}, source 1 decides to transmit the network-coded packet I, while source 2 decides to remain idle. The destination node is able to extract the transmitted packet I, thus collecting the three different packets required for the information decoding.

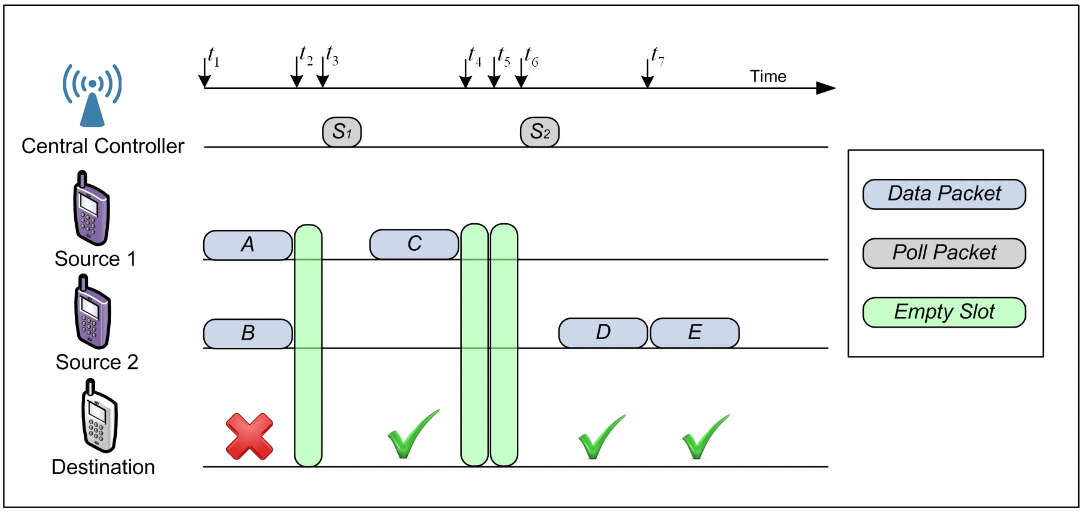


Figure 4.5: Example of frame sequence in the centralized MAC strategy

Figure 4.5 illustrates the frame sequence in the centralized medium access strategy. In this case, the central controller ensures the non-existence of more than two consecutive failed slots (either collided packets or idle slots) in the network by transmitting control polling packets. In this approach, the protocol operates as follows:

1. At instant t_1, both sources decide to transmit and, as a result, the destination experiences a collision.
2. At instant t_2, both sources remain idle, which results in an empty slot in the system.
3. At instant t_3, after two consecutive failed slots (one collision and one idle slot), the central controller intervenes by polling source 1 which, in turn, successfully transmits the network-coded packet C.
4. At instants t_4 and t_5, the sources remain silent, thus having two more idle slots in the network.
5. At instant t_6, after two successive idle slots, the central controller polls source 2 which, in turn, successfully transmits the network-coded packet D.
6. At instant t_7, source 1 decides to remain idle, while source 2 decides to transmits the network-coded packet E. Hence, the destination node is able to extract the transmitted packet correctly, thus compiling the total required information.

The two foregoing examples graphically depict the operation of both game theoretic strategies and, in particular, the enhancements that the existence of the central controller can bring in the network performance including among others completion time reduction and higher energy efficiency. Nevertheless, this improvement comes with the cost of transmitting extra control polling packets in the network, and also requires a rudimentary infrastructure and coordination. In the following section, we provide analytical models for the data dissemination completion time and the energy efficiency of both proposed protocols in generalized settings.

4.7 Performance Analysis

Until now, we have presented two different versions of the proposed game: i) a distributed and ii) a centralized medium access strategy. In this section we analytically estimate the data dissemination completion time and the energy efficiency performance of both schemes.

4.7.1 Completion Time

Although the data dissemination in our system model takes place in two distinct phases, we focus our analysis on the latter phase, where our game theoretic MAC techniques are applied. Therefore, the expected completion time for the dissemination is represented by:

$$\mathbf{E}[T_{total}] = \mathbf{E}[R] \cdot (p_s \cdot T_{tr} + p_i \cdot \sigma + p_c \cdot T_c) \tag{4.15}$$

where $\mathbf{E}[R]$ is the average number of slots needed in order for the data dissemination to be accomplished. The probabilities of having a successful transmission, an idle slot or a collision are given by p_s, p_i and p_c, respectively. Moreover, the terms T_{tr}, σ and T_c represent the duration of a transmission, an empty slot and a collision, respectively. The slot time σ is a system parameter, while T_{tr} depends on the packet length and the transmission data rate. Furthermore, we consider that $T_c = T_{tr}$, since the collision detection takes place at the receiver's side.

The term $\mathbf{E}[R]$ can be further analyzed as

$$\mathbf{E}[R] = \frac{R_{ideal}}{p_s}, \tag{4.16}$$

where R_{ideal} is the minimum number of slots in case of ideal scheduling among the nodes, i.e., contention-free scheme. As it has been already demonstrated in [19], it can be calculated as:

$$R_{ideal} = M \cdot \left\lceil \frac{l}{J} \right\rceil, \tag{4.17}$$

where M is the number of the information data packets, l is the number of the sink nodes, and J represents the impact of the source nodes on the network.

Therefore, the most challenging part is to derive closed-form formulas for the probabilities of successful transmissions (p_s), idle slots (p_i) and collisions (p_c) in our proposed access strategies. In the following subsections, we compute the theoretical values of p_s, p_i and p_c for both the distributed and the centralized access scheme.

Distributed Access Scheme In the distributed access scheme, given that the source nodes estimate a common transmission probability s^* according to the NE of the game, we are able to derive closed-form expressions for the probabilities p_s, p_i and p_c. The probability that at least one of the n sources attempts to transmit in a given slot can be expressed as:

$$p_{tr} = 1 - (1 - s^*)^n, \tag{4.18}$$

while the probability of a successful transmission, i.e., one station transmits conditioned on the fact that at least one station transmits, is given by:

$$p_{s|tr} = \frac{n \cdot s^* \cdot (1 - s^*)^{n-1}}{1 - (1 - s^*)^n}. \tag{4.19}$$

Therefore, the probabilities of having a successful (p_s), collided (p_c) or idle (p_i) slot can be written as:

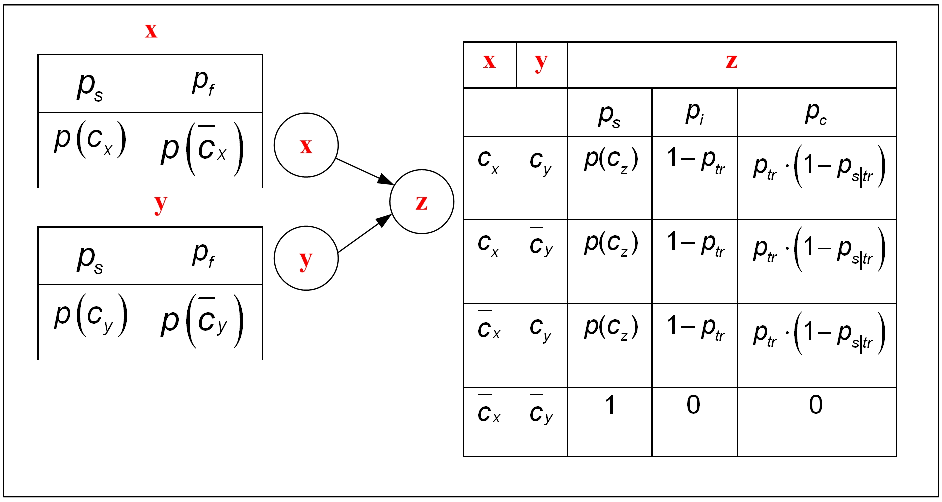
$$p_s = p_{tr} \cdot p_{s|tr} \tag{4.20}$$

$$p_c = p_{tr} \cdot (1 - p_{s|tr}) \tag{4.21}$$

$$p_i = 1 - p_{tr} \tag{4.22}$$

Hence, combining the equations (4.15) - (4.22), we are able to estimate the completion time for the dissemination under the distributed access policy.

Centralized Access Scheme The presence of the central controller modifies the analytical model for the dissemination completion time in the centralized access scheme. Let us recall that, under this scheme, the central controller schedules a transmission after two consecutive unsuccessful (idle or collided) slots in the network. Therefore, in order to model our strategy, we consider a Bayesian Network of three states - x, y, z - corresponding to the three consecutive slots, where the outcome of states x and y determines the outcome of state z.



x	y	z		
		p_s	p_i	p_c
c_x	c_y	$p(c_z)$	$1-p_{tr}$	$p_{tr}\cdot(1-p_{s\|tr})$
c_x	$\bar{c}_y$	$p(c_z)$	$1-p_{tr}$	$p_{tr}\cdot(1-p_{s\|tr})$
$\bar{c}_x$	c_y	$p(c_z)$	$1-p_{tr}$	$p_{tr}\cdot(1-p_{s\|tr})$
$\bar{c}_x$	$\bar{c}_y$	1	0	0

Figure 4.6: Bayesian Network of the centralized MAC strategy

Figure 4.6 depicts the associate probabilities to our game, where the probabilities p_s, p_c and p_i have been defined, and the term p_f denotes the probability of having a failed (either idle or collided) slot. Moreover, we use the notations c_i and $\bar{c}_i$ to denote that a transmission in the i^{th} slot is successful or unsuccessful, respectively. One transmission is considered successful if exactly one node is transmitting in the specific slot. For our particular game, we can write:

$$p(c_i) = p_{tr} \cdot p_{s|tr}, \forall i \in \mathbb{N} \tag{4.23}$$

$$p(\bar{c}_i) = 1 - p(c_i), \forall i \in \mathbb{N} \tag{4.24}$$

Since the success in one random slot depends on the status of the two previous slots, we use conditional probabilities to estimate the probabilities, p_s, p_i and p_c. Specifically, p_s can be calculated as:

$$p_s = \sum p(x, y, z = c_z), \forall x \in \{c_x, \bar{c}_x\}, y \in \{c_y, \bar{c}_y\} \tag{4.25}$$

The statistical independence of the events enables us to use the definition of conditional probability in order to simplify the above formula. Thus, we have:

$$p_s = \sum p(z = c_z|x, y) \cdot p(x) \cdot p(y), \forall x \in \{c_x, \bar{c}_x\}, y \in \{c_y, \bar{c}_y\} \tag{4.26}$$

Accordingly, we can calculate the probability of having an idle slot or a collision as:

$$p_i = \sum p(z = idle|x, y) \cdot p(x) \cdot p(y), \forall x \in \{c_x, \bar{c}_x\}, y \in \{c_y, \bar{c}_y\} \tag{4.27}$$

$$p_c = \sum p(z = col|x, y) \cdot p(x) \cdot p(y), \forall x \in \{c_x, \bar{c}_x\}, y \in \{c_y, \bar{c}_y\} \tag{4.28}$$

In the above equations, the probabilities $p(x)$ and $p(y)$ can be derived by the formulas (4.23) and (4.24), while the conditional probabilities can be found in Figure 4.6. Specifically, when there is at least one successful transmission in the last two slots, the probability of having a successful transmission p_s in the current slot is independent of the history, equal to $p(c_z)$. On the other hand, if the last two slots were unsuccessful (either idle or collided), the probability p_s on the current slot is equal to one, since the controller schedules the transmission. Consequently, the probabilities of having idle slot or collision are both equal to zero.

Therefore, we have derived closed-form formulas for the completion time of the two proposed medium access games for data dissemination.

4.7.2 Energy Efficiency

The detailed analysis for the operation of our proposed game theoretic policies enables us to derive a closed-form expression to describe the energy efficiency (η) in the network during the second phase of the dissemination:

$$\eta = \frac{D_{useful}}{\mathbf{E}[\mathcal{E}_{total}]} \tag{4.29}$$

where D_{useful} denotes the useful data delivered during the second phase of the dissemination, calculated as $D = M \cdot Payload \cdot l$, with $Payload$ corresponding to packet payload, while M and l represent the number of total packets and the number of sink nodes, respectively. On the other hand, the term $\mathbf{E}[\mathcal{E}_{total}]$ denotes the expected higher bound for the energy consumption in the radio part of the network, estimated as:

$$\mathbf{E}[\mathcal{E}_{total}] = \mathbf{E}[R] \cdot (\mathbf{E}[\mathcal{E}_{succ}] + \mathbf{E}[\mathcal{E}_{idle}] + \mathbf{E}[\mathcal{E}_{col}]) \tag{4.30}$$

where $\mathbf{E}[R]$ was defined in Section 4.7.1, while the terms $\mathbf{E}[\mathcal{E}_{succ}]$, $\mathbf{E}[\mathcal{E}_{idle}]$ and $\mathbf{E}[\mathcal{E}_{col}]$ correspond to the expected energy consumption during the successful transmissions, the idle slots and the collision periods, respectively. To compute these values, we consider three different modes for the wireless interface of each node, i.e., transmission, reception and idle.

The power levels associated to each mode are P_T, P_R and P_I, respectively, while the relationship between energy and power is given by $\mathcal{E} = P \cdot t$, where the terms $\mathcal{E}$, P and t represent the energy, the power and the time, respectively. Hence, taking into account the network topology, we have:

$$\mathbf{E}[\mathcal{E}_{succ}] = p_s \cdot (P_T + J \cdot P_R + (n-1)(J+1) \cdot P_I) \cdot T_{tr} \tag{4.31}$$

$$\mathbf{E}[\mathcal{E}_{idle}] = p_i \cdot (n+l) \cdot P_I \cdot \sigma \tag{4.32}$$

$$\mathbf{E}[\mathcal{E}_{col}] = p_c \cdot (\mathbf{E}[K] \cdot P_T + \mathbf{E}[K] \cdot J \cdot P_R + (n - \mathbf{E}[K])(J+1) \cdot P_I) \cdot T_c \tag{4.33}$$

where n and l correspond to the source and sink nodes, respectively, J is the impact of the source nodes in the network, and the term $\mathbf{E}[K]$ denotes the average number of source nodes involved in a collision, expressed as:

$$\mathbf{E}[K] = \sum_{k=2}^{n} k \cdot p_k \tag{4.34}$$

where p_k corresponds to the probability that exactly k stations are involved in a collision, computed as:

$$p_k = \frac{\binom{n}{k} {s^*}^k (1-s^*)^{n-k}}{p_c}. \tag{4.35}$$

Similarly to the completion time analysis, the probabilities of having successful (p_s), idle (p_i) or collided (p_c) slots in the second phase of the dissemination differ in the two proposed game theoretic schemes. Hence, in order to estimate the energy consumption in the distributed and the centralized medium access scheme, we use the values of the respective probabilities we derived in Section 4.7.1.

The evaluation of our analytical models, as well as an extensive assessment of the proposed MAC strategies are provided in the following section.

4.8 Performance Evaluation

We have developed a time-driven C++ simulator that executes the rules of the proposed game theoretic MAC schemes. Monte Carlo simulations have been carried out to validate our analysis and further evaluate the performance of the protocols. In this section, we present the simulation setup along with the experimental results.

4.8.1 Simulation Scenarios

Our experiments are focused on the second phase of the data dissemination, where the proposed game theoretic medium access techniques are applied to resolve the conflicts among the source nodes. We consider two different network topologies in order to assess the scalability and the flexibility of our schemes under different scenarios:

1. **Topology A:** There are n source nodes, each of them affecting 2 sink nodes ($J = 2$) in a network formulation similar to that illustrated in Figure 4.1.
2. **Topology B:** There are n source nodes, each of them affecting all l sink nodes in the network ($J = l$), as depicted in Figure 4.7.

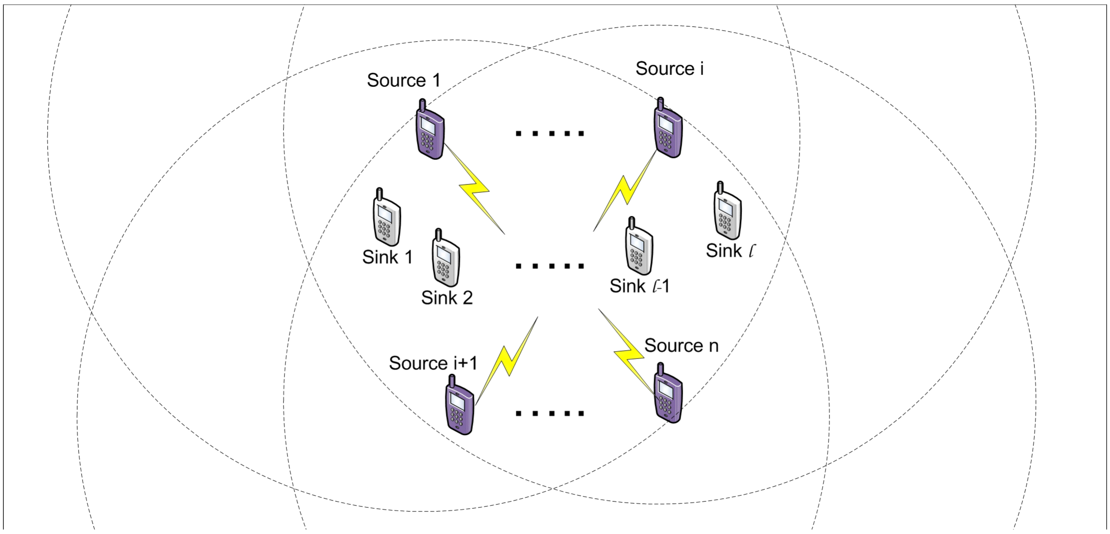


Figure 4.7: Simulation scenario: Topology B (All sink nodes inside the common transmission range of the sources)

Apparently, in both topologies, the source nodes have the same (highest) impact on the network during the data dissemination. In addition, as we have already mentioned, the nodes are capable of applying NC to the packets to be transmitted, before further forwarding them. The goal of our scenarios is the dissemination of a set of data packets that constitute an RGB[3]

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[3] The RGB color model is an additive color model in which red, green, and blue light are added together in various ways to reproduce a broad array of colors.

image of dimensions 256×256 (translated as 256 packets of 256 pixels). The resolution of the image and, consequently, the color "depth" of the pixels determine the packet length. In particular, a 2-bit "depth" (grey-scale) results in 64 bytes, while an RGBA[4] image (32-bit "depth") results in 1024 bytes packet payload. In our simulations we consider packet lengths of $PHY + MAC + NC_H + P$ bytes, where PHY and MAC are the physical and the MAC headers, respectively, with $PHY = 192$ bits and $MAC = 224$ bits. NC_H is the NC header, while P is the packet payload which varies between 128 and 1024 bytes with regard to the image resolution. Unless otherwise stated, the coding of the packets is performed over a finite GF2^8, since it has been proven to be sufficient for linear independence among the packets [27]. The specific field implies that the number of the encoding packets reflects to the number of the bytes in the encoding vector. If we use one generation of 256 packets, the extra overhead in each packet will be 256 bytes, which is a huge value, especially for small size payloads. Therefore, we have chosen to create 16 generations of 16 packets each, which results in NC_H of 17 bytes in total (16 bytes for the encoding vector, 4 bits for the generation size and 4 bits for the generation identifier).

Table 4.3: System parameters

Parameter	Value	Parameter	Value
Packet Payload	128-1024 bytes	σ	20 μs
MAC+PHY Header	52 bytes	*NC Header*	17 bytes
Data Tx.Rate	54 Mb/s	*Generation Size*	16
CW_{min}	32	*DIFS*	50μs
P_T	1900 mW	P_I, P_R	1340 mW

The time slot in our system has been selected equal to 20 μsec according to the IEEE 802.11g PHY layer [24], while the power level values have been chosen according to wireless interface power consumption measurements [25]: $P_T = 1900\ mW$[5], $P_R = P_I = 1340\ mW$.

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[4] RGBA (stands for "Red-Green-Blue-Alpha") is a use of the RGB color model with extra information.

[5] The value of P_T has been selected as an average value of transmission consumed power, since it varies according to the RF power level.

In order to evaluate our game theoretic approaches, we compare the proposed policies with the DCF of the legacy IEEE 802.11g [24] where backoff counters are used to reduce the probability of collisions among the source nodes. In our experiments we assume a minimum CW (CW_{min}) equal to 32. Furthermore, RLNC techniques are also adopted for the data transmissions and hence we consider the multicast operation of IEEE 802.11g, since there is no need for transmitting ACK packets. The simulation parameters are summarized in Table 4.3.

4.8.2 Performance Results

The application of our strategies in different scenarios aims at their comprehensive evaluation, studying different aspects of the proposed techniques such as scalability (Topology A) and flexibility (Topology B). We therefore present the performance results separately for the two topologies. However, before proceeding to the protocols assessment, we try to justify our choice to use a GF(2^8) for packet coding.

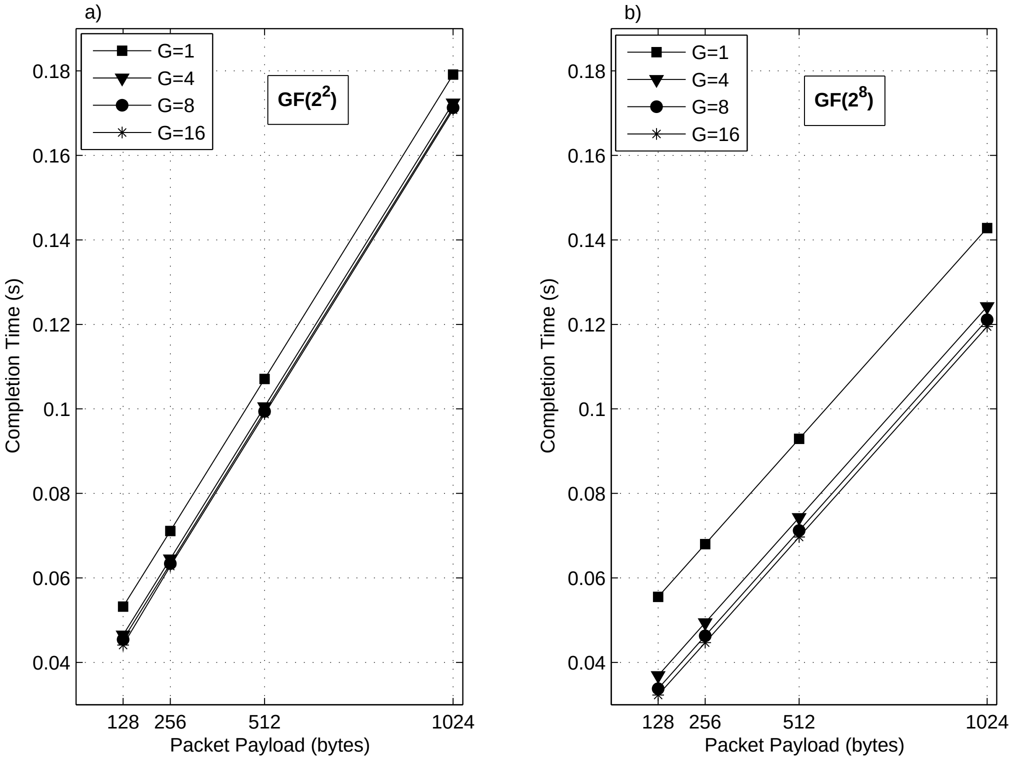

Figure 4.8: NC impact on the dissemination completion time for a) GF(2^2) and b) GF(2^8) ($b = 1.0, n = 3$, Topology A)

Figure 4.8 highlights the impact of NC on the system performance under the distributed access strategy. In particular, Figure 4.8a and Figure 4.8b present the completion time for different number of coding generations (G), selecting the coefficients from a finite GF equal to 2^2 or 2^8, respectively. In both cases, it can be clearly observed that the creation of various generations has a positive influence in the system performance. It is worth noting the tradeoff between the packet overhead and the decoding probability with respect to the selected GF. Although higher GF implies higher overhead, the linear independence (decoding) probability is significantly higher. Hence, the number of required transmissions is reduced, thus providing a better system performance.

Topology A: Figure 4.9 presents the data dissemination completion time under the proposed game theoretic policies in Topology A for different number of source nodes ($n = 3, 7, 15$), assuming $b = 1.0$. First, we can see that the numerical results almost perfectly match the analytical ones, thus verifying our theoretical derivations. In this figure, we can see that the centralized approach outperforms the distributed access policy, with the gain, though, coming at the expense of having a central controller in the network. It is also worth noticing that the relative gain grows as the number of source nodes in the network increases.

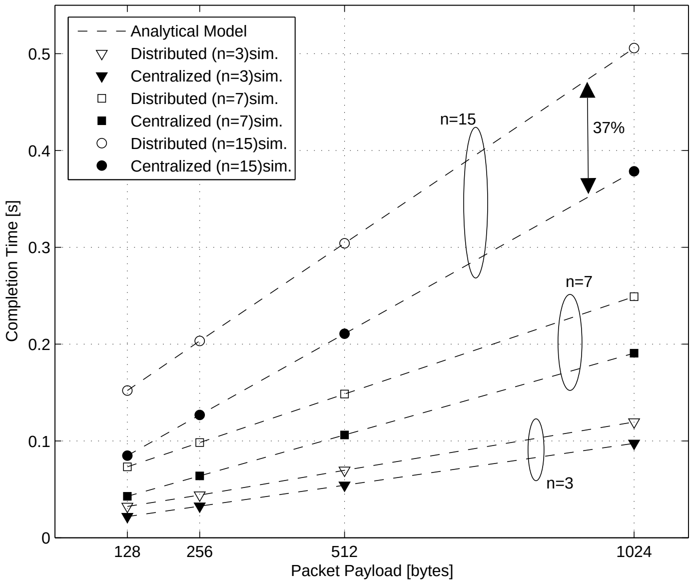

Figure 4.9: Data dissemination completion time in Topology A (Distributed vs. Centralized MAC strategy)

Figure 4.10 plots the analytical and the numerical results with regard to the energy efficiency performance of game theoretic strategies compared to the IEEE 802.11 Standard, considering five and fifteen sources ($n = 5$ and $n = 15$, respectively) in networks of Topology A. In this figure, we can see that our analytical model is validated, since the deviation from the simulation results is almost negligible. In addition, we observe that the proposed game theoretic policies are proven to be more energy efficient than the legacy DCF, with gains starting from 48% and reaching up to 260% for particular scenarios (i.e., centralized approach, $n = 5$, $P = 128$ bytes). It is also worth noticing that the distributed game theoretic strategy outperforms the IEEE 802.11 Standard in all cases, independently of the packet payload and the number of active source nodes in the network.

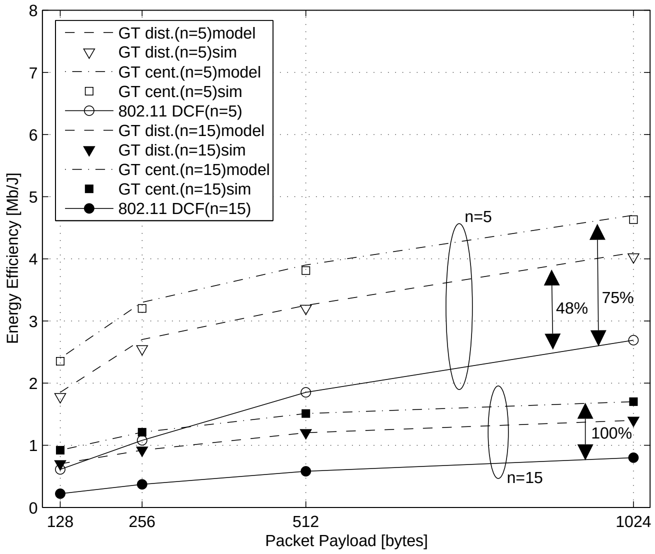

Figure 4.10: Energy efficiency of game theoretic MAC strategies vs. IEEE 802.11 DCF ($b = 1.0$, Topology A)

Topology B: Figure 4.11 plots the dissemination completion time considering seven source nodes ($n = 7$) in a network of Topology B. In this case, the completion time is significantly lower compared to the scenarios of Topology A, since all nodes in the network are in one-hop distance and, hence, the dissemination time does not depend on the number of sink nodes. Comparing our two approaches, it is evident that centralized approach achieves a better performance, especially for the transmission of small data packets. As the packet payload increases, the relative gain between the two strategies decreases, remaining in all cases over 30%.

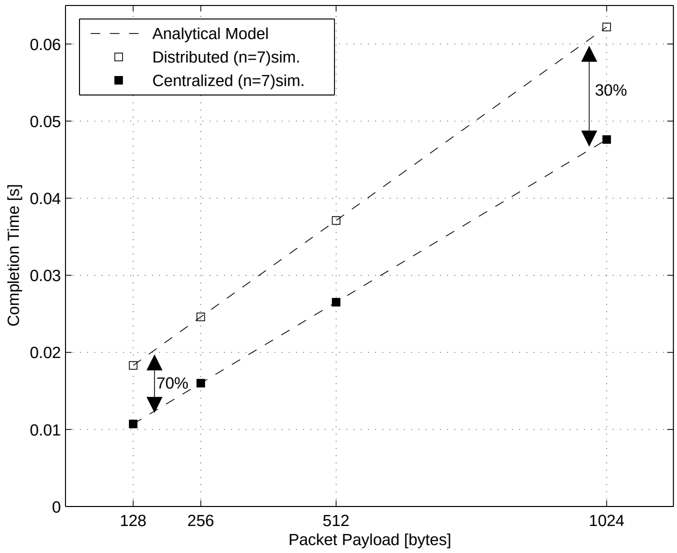

Figure 4.11: Data dissemination completion time in Topology B (Distributed vs. Centralized MAC strategy)

Figure 4.12 illustrates the simulation results with regard to the dissemination completion time of our proposed game theoretic access schemes versus the legacy IEEE 802.11 DCF in Topology B networks. In this particular experiment, the number of source nodes varies between 2 and 19, assuming $b = 0.8$ and $P = 1024$ bytes. In this figure, we observe the great time enhancement that the game theoretic approaches offer comparing to the IEEE 802.11 Standard. In particular, the distributed access strategy improves the completion time up to 80% ($n = 2$), while the improvement under the centralized approach exceeds 100%. With respect to the lowest DCF completion time $n = 7$, the achieve gains of 32% and 65%, for the distributed and the centralized approach, respectively. The second worthwhile observation concerns the dependence between the dissemination completion time and the number of source nodes in the network. More specifically, the flexibility of game theoretic access strategies allows for their smoothest adaption in networks with many sources. Therefore, the completion time under both distributed and centralized schemes is not significantly affected by the total number of source nodes. On the other hand, we can see that the CW dynamics in IEEE 802.11 are not able to bound the dissemination completion time, a fact that can be intuitively conceived by considering the backoff mechanism operation. More specifically, in case of few (e.g., $n = 2$) or many (e.g., $n = 19$) source nodes in the network, the completion time increases by either empty slots or collisions, respectively, generating a fluctuation of approximately 35%.

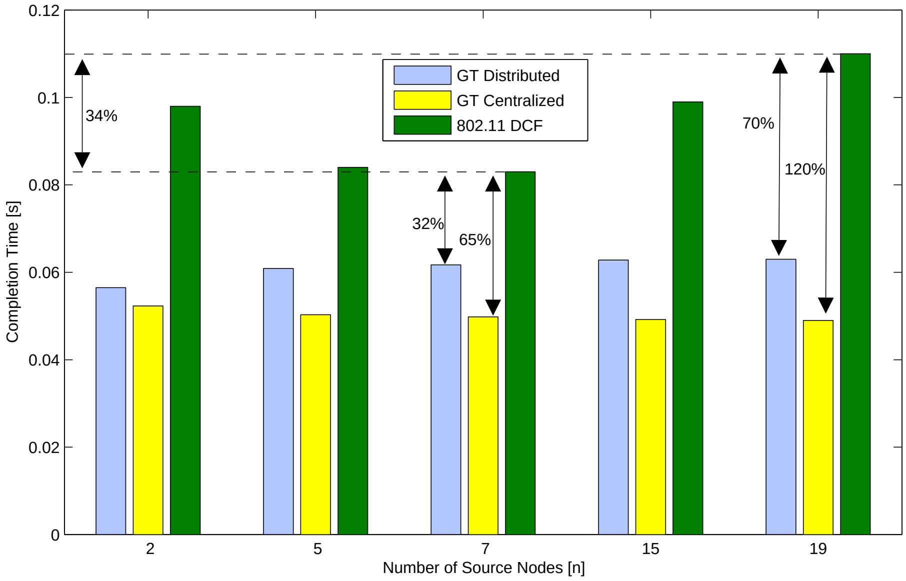

Figure 4.12: Data dissemination completion time vs. Number of source nodes ($b = 0.8$, $P = 1024$ bytes)

Figure 4.13 presents the energy performance of the proposed strategies in networks of Topology B, assuming three and nineteen sources ($n = 3$ and $n = 19$, respectively) in the network in order to study the scalability of our policies. With regard to the case where $n = 19$, we can see that the gain we achieve applying the distributed game theoretic access strategy remains steadily over 100% compared to the DCF, while the centralized policy increases this yield up to 300%. On the other hand, we observe a slightly different trend in the case of few source nodes in the network ($n = 3$). In this case, the gain of the distributed access strategy over the IEEE 802.11 Standard decreases as the packet payload grows, even though the initial gain for payload of 128 bytes reaches 100%. This fact can be explained by considering again the DCF implementation, which is designed to avoid collisions. This design is beneficial for packets of high payload but, on the contrary, creates idle slots in the network, thus affecting the energy performance for small packet payloads. Our proposed adaptive game theoretic strategies handle these points efficiently, hence dealing effectively with energy efficiency issues.

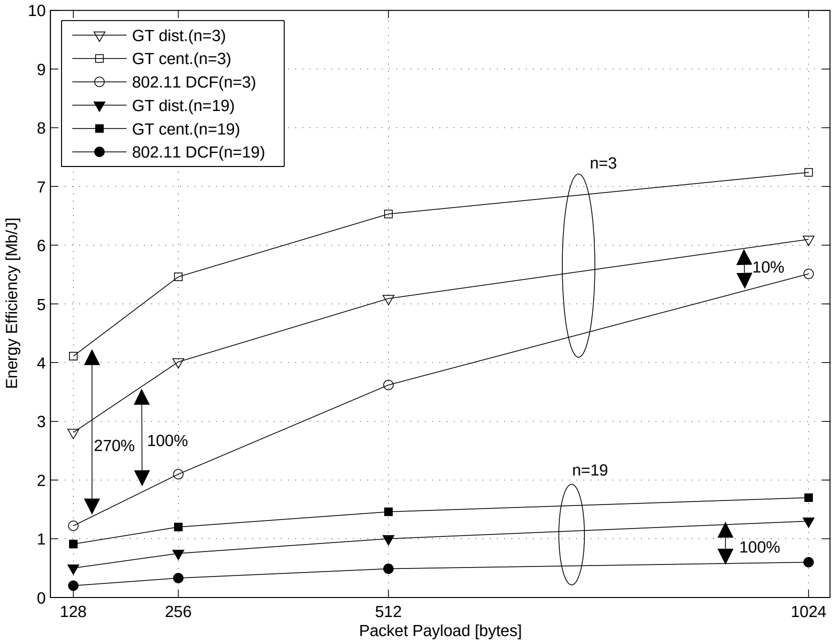

Figure 4.13: Energy efficiency of game theoretic access strategies vs. IEEE 802.11 DCF ($b = 1.0$, Topology B, $l = 1$)

4.9 Chapter Summary and Conclusions

This chapter introduced the second part of the thesis, dedicated to medium access strategies in data dissemination scenarios. In particular, we proposed two novel game theoretic MAC strategies to resolve the conflicts caused by the existence of multiple active source nodes in the network. The first approach is a distributed medium access strategy, where the nodes estimate their steady state transmission probabilities (NE) such that to maximize their lifetime, using energy-based utility functions. In the second, centralized approach, we consider the existence of a central controller that is occasionally used to resolve the conflicts, thus bounding the dissemination completion time. In addition, in all cases the exchanging of ACKs is eliminated by applying NC techniques. The most substantial conclusions can be summarized in the following:

- The application of game theoretic techniques on the design of MAC protocols generates important performance gains with regard to the time required for the dissemination of all packets in the network. We have demonstrated (by analysis and simulations) that both proposed schemes clearly outperform the IEEE 802.11 DCF, since the data dissemination completion time is considerably reduced. In particular, the dissemination process is expedited by applying game theoretic MAC policies independently of the scenario (i.e., number of nodes and topology).

- Compared to the legacy DCF of the dominant IEEE 802.11 Standard, our proposed protocols achieve significant enhancement in terms of energy consumption, since they were proven to be up to 3 times more energy efficient, without degrading the offered QoS (i.e data dissemination completion time). More specifically, DCF has been implemented to minimize the probability of collision in wireless networks. This design is beneficial in systems where big payload packets are transmitted but, on the other hand, causes idle slots in the network, hence harming the energy efficiency in case of small packet transmissions. Our proposed strategies tackle effectively all these energy efficiency issues.
- The adoption of RLNC techniques enables the wireless source nodes to transmit linear combinations of the native packets, thus eliminating the necessity of acknowledging the correct receptions. This is particularly fruitful in multicast scenarios, where the coordination of ACK transmissions constitutes a major issue.
- Our extensive analysis indicates game theory as a proper tool for MAC protocol design. Adopting the appropriate utility functions, we are able to implement adaptive medium access strategies that efficiently coordinate the transmissions in multi-source networks. It is also proven that game theory overcomes the inherent limitations of the IEEE 802.11 Standard operation due to the rigid dynamics of the DCF backoff mechanism.

The next chapter finalizes the main contributions of the thesis by introducing an ANC-aided game theoretic MAC protocol for data dissemination in wireless networks. We elaborate on the protocol design and analysis in order to demonstrate how novel techniques such as ANC and RLNC can be combined to improve the network performance in terms of QoS and energy efficiency.

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Chapter 5

Analog NC-aided Game Theoretic Energy Efficient Layout (ANGEL) for Data Dissemination

> *"Remember upon the conduct of each depends the fate of all."* **Alexander the Great**

Contents

5.1 Introduction

Recent developments in NC field focus on the physical part of the communication. In particular, ANC techniques [1] have been introduced to exploit packet collisions and achieve interference cancelation in wireless networks. In this context, ZigZag [2] was one of the fundamental works that caused significant impact in the research community. Gollacota and Katabi introduced ZigZag to combat the hidden terminal problem in wireless networks. Applying ZigZag, the decoding of the packets of two successive collisions becomes feasible, provided that the collisions offsets Δ_1 and Δ_2 are different (see Section 2.3.3). Therefore, the receiver can use the correctly received part of the data to decode the interfered bits of the collided packets.

ParendehGheibi *et al.* [3] studied the delay and throughput performance of ZigZag decoding for a single-hop wireless erasure network by representing the collisions algebraically. Using an algebraic framework, the authors were able to provide alternative collision recovery methods and generalizations in case the transmitted packets are coded versions of the original packets. Rahman *et al.* [4] proposed an iterative ZigZag decoding algorithm to mitigate the error propagation and further improve the system performance in the presence of collisions. In their work, the authors apply channel coding techniques which result in an iterative decoding process between the ZigZag decoder and the channel decoder.

Regarding the MAC layer, Khabbazian *et al.* [5] developed an ANC-based algorithm that implements an abstract MAC layer service, proving that ANC can significantly improve the performance of MAC layer services in terms of probabilistic time guarantees for packet delivery. Paek and Neely [6] applied ZigZag techniques to four different idealized multi-access system models in order to study the performance benefits of ANC in existing MAC protocols. Using analytical and simulation results, the authors demonstrated that ZigZag decoding can considerably improve the maximum throughput of random access systems.

Chorus [7] and KIC (Known Interference Cancelation) [8] are two protocols partly inspired by ZigZag. Chorus [7] uses a similar collision resolution mechanism as ZigZag, but it is able to resolve multiple packets from a single collision, given that the packets are identical. Moreover, Chorus exploits transmit diversity and spatial reuse, using cognitive sensing and broadcast scheduling. On the other hand, the key idea behind KIC [8] is that the interference caused by previously received packets can be canceled to decode the new packet involved in a collision.

In the previous chapter we introduced an RLNC-aided game theoretic MAC protocol for data dissemination by adopting energy-based utility functions that intrinsically imply power awareness. We proposed a channel access game to identify a state of balance (*equilibrium*) between saving energy and proceeding the dissemination in topologies where multiple source nodes have the highest impact on the network. However, the recent advances in NC domain have inspired us to adopt ANC techniques to exploit the potential benefits of collisions in data dissemination schemes.

In this chapter, we propose an **AN**C-aided **G**ame theoretic **E**nergy efficient **L**ayout (ANGEL) for data dissemination in wireless networks. On the top of our former game theoretic derivations, we apply ZigZag decoding techniques to turn data packets collisions into a benefit for the network performance. The contribution of this chapter can be summarized on the following:

1. We propose a novel MAC protocol that exploits to the maximum extend the collisions occurred in a wireless network where the main goal is the dissemination of data.
2. We exploit the benefits of both RLNC and ANC in order to enhance the network performance.
3. We study the game theoretic aspects of the proposed protocol.
4. We design a detailed analytical model to assess the performance of the proposed scheme.

The rest of the chapter is organized as follows. Section 5.2 presents our system model along with the game formulation. Section 5.3 introduces ANGEL and provides a detailed example of the protocol operation. The analytical model of our scheme is included in Section 5.4. The simulation scenario and the performance evaluation of our protocol are provided in Section 5.5. Finally, Section 5.6 concludes the chapter.

5.2 System Model and Game Formulation

We consider a wireless network topology, as it is depicted in Figure 5.1, consisting of a BS that holds the total amount of information and a set of nodes that are interested in the available data set. Since not all the stations are inside the coverage area of the BS, the dissemination takes place in two phases: i) the BS broadcasts the data packets to the nodes inside its transmission range (source nodes), and ii) the source nodes that have already obtained the data forward the information to the nodes outside the range of the BS (so called sink or destination nodes). We focus on the second phase of the dissemination, where we assume that there are two nodes that have received the whole information and a set $\mathcal{L}$ of l sink nodes ($\mathcal{L} = \{1....l\}$) that desire the disseminated data. The respective transmission ranges of the two sources are partially overlapped with a subset of nodes located within the intersection of the coverage areas. In addition, both source nodes affect the same number of sink nodes, thus having the highest impact on the network.

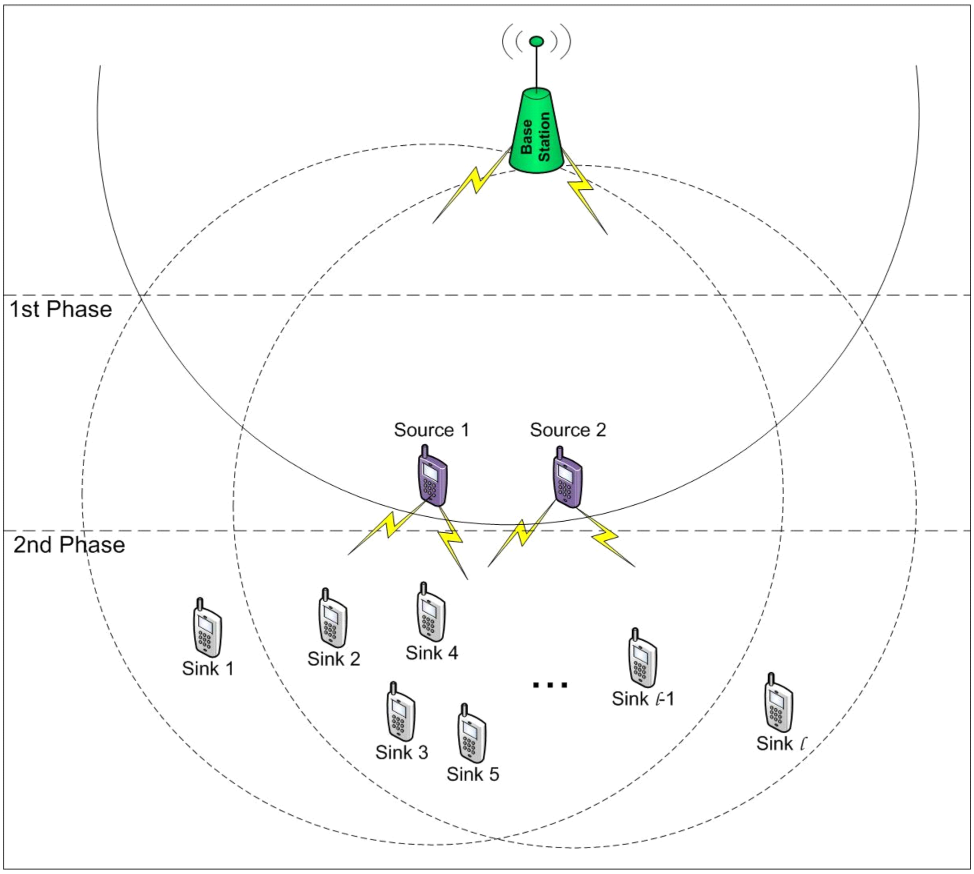

Figure 5.1: System model

We further assume a slotted system where the node with the greatest impact in the network transmit in every slot, since this technique has been proven to accelerate the dissemination process [9]. Apparently, the existence of two source nodes with the maximum impact generates conflicting situations that are resolved using game theoretic techniques which enhance the system performance, as we have already demonstrated in Chapter 4.

Regarding data transmissions, RLNC [10] techniques are used to facilitate the dissemination and eliminate the need of exchanging ACK control packets. In addition, the nodes are able to perform ZigZag decoding techniques on the received packets, thus exploiting the collisions incurred in the network. However, it is worth noting that RLNC techniques impose an extra overheard due to the introduction of the NC header which is necessary for the packet decoding, while the adoption of ANC techniques presupposes the acceptance of the assumptions in [2].

Taking into account the system model, the game can be represented by the tuple $\Gamma = (\mathcal{N} = \{1, 2\}, \mathcal{A} = \{Transmit(T), Wait(W)\}, U_i = \frac{\mathcal{E}_{TOTAL_i}}{\mathbf{E}[\mathcal{E}_i])})$, where $\mathcal{N}$ is the set of players, $\mathcal{A}$ is the action set, U_i corresponds to the utility function of player i, $\mathcal{E}_{TOTAL_i}$ represents the total energy available in each node and $\mathbf{E}[\mathcal{E}_i]$ is the expected energy consumption in each slot.

The straightforward representation of the game in its strategic form is presented in Figure 5.2, where three different cases derive:

1. **Both nodes transmit:** The nodes waste energy for the transmissions ($\mathcal{E}_T$), while the collision of the packets adds an extra cost ($\mathcal{E}_{COST}$), since the dissemination does not proceed.
2. **One node transmits - One node waits:** The transmitting node wastes energy for the transmission ($\mathcal{E}_T$), while the backoff node has a zero-consumption since the data dissemination proceeds normally.
3. **Both nodes wait:** The nodes do not spend energy on transmissions but they have a cost $\mathcal{E}_W$, since they consume energy while the dissemination does not proceed.

In this point, we have to clarify that the null consumption of the waiting node in the second aforementioned case is used to facilitate our game formulation. Using a zero-consumption representation we are able to differentiate from the third case where both nodes wait. More specifically, although the actual consumption in these two cases is the same, the payoff of the nodes is different due to the dissemination progress.

		Node 2	
		T	W
Node 1	T	$\mathcal{E}_T + \mathcal{E}_{COST}, \mathcal{E}_T + \mathcal{E}_{COST}$	$\mathcal{E}_T, 0$
	W	$0, \mathcal{E}_T$	$\mathcal{E}_W, \mathcal{E}_W$

Figure 5.2: Game model

In our attempt to estimate efficient NE, we move to the mixed strategies domain, where each node selects a transmit probability, s_i, independently of the other. Therefore, the expected energy consumption for the two nodes is given by:

$$\mathbf{E}[\mathcal{E}_1] = s_1 \cdot \bar{s}_2 \cdot \mathcal{E}_T + s_1 \cdot s_2 \cdot (\mathcal{E}_T + \mathcal{E}_{COST}) + \bar{s}_1 \cdot \bar{s}_2 \cdot \mathcal{E}_W \tag{5.1}$$

$$\mathbf{E}[\mathcal{E}_2] = s_2 \cdot \bar{s}_1 \cdot \mathcal{E}_T + s_2 \cdot s_1 \cdot (\mathcal{E}_T + \mathcal{E}_{COST}) + \bar{s}_2 \cdot \bar{s}_1 \cdot \mathcal{E}_W \tag{5.2}$$

In the above equations, the first term represents the average energy consumed during successful transmissions, the second term is the average energy spent during collisions, while the third term denotes the average energy wasted on idle slots. The symmetry of the two functions motivates us to search for symmetric strategies.

In order to deduce a strategy for player 1 that provides the same payoff independently of the player 2's strategy[1], we have to estimate the roots of the partial derivative of the expected cost of player 1 with respect to s_2:

$$\frac{\partial \mathbf{E}[\mathcal{E}_1]}{\partial s_2} = 0 \tag{5.3}$$

For simplicity reasons and without loss of generality, let us assume that $\mathcal{E}_W = a \cdot \mathcal{E}_T$ and $\mathcal{E}_{COST} = b \cdot \mathcal{E}_T$. Consequently:

$$\mathcal{E}_T \cdot (a \cdot (s_1 - 1) + b \cdot s_1) = 0 \Longrightarrow s_1 = \frac{a}{a+b} \tag{5.4}$$

As use case, we consider the IEEE 802.11 Standard, where the power level of the idle state is the 70% of the transmission state [15], and hence we set $a = 0.7$, while we assume

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[1] The indifference principle defines that the mixed strategy NE of a game can be simply computed by making each player indifferent among his strategy choices. [14]

that $b = 1$. Figure 5.3 shows a plot of client 1's utility for various strategies of s_2, using the following numerical values: $\mathcal{E}_{TOTAL_i} = 100\ J$, $\mathcal{E}_T = 9.5 \cdot 10^{-4}\ J$, $\mathcal{E}_{COST} = 9.5 \cdot 10^{-4}\ J$ and $\mathcal{E}_W = 6.7 \cdot 10^{-4}\ J$.

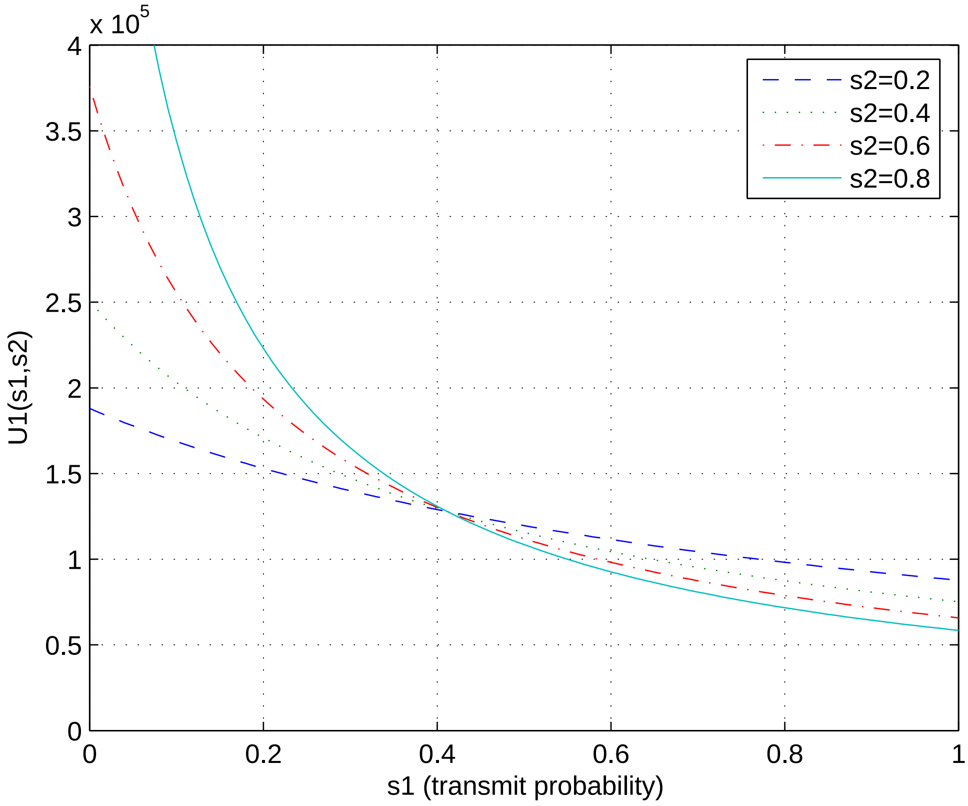

Figure 5.3: Player 1's Utility vs. s_1

The observation of Figure 5.3 leads to some interesting conclusions:

- The maximum utility of node 1 increases with s_2.
- For large values of s_2, the optimal strategy for node 1 is to wait.
- If node 1 transmits with $s_1 \simeq 0.412$, its utility is independent of node's 2 strategy, s_2. Since the game is symmetric, the same holds for player 2, as well. This value of s_1 verifies our analysis (equation (5.4)) for $a = 0.7$ and $b = 1$.

Hence, considering the symmetry of the game, we conclude that the strategy $\mathbf{s}^* = (s_1 \simeq 0.412, s_2 \simeq 0.412)$ constitutes the NE of our game, since any other strategy would violate the indifference principle.

5.3 Protocol Description

ANGEL is introduced to coordinate the transmissions among a set of wireless nodes that broadcast the same content to a group of sink nodes with ANC capabilities. Therefore, it can be perfectly applied to our model and, particularly, in the second phase of the dissemination.

First, in the beginning of each slot, the two source nodes select their transmission probabilities (s_i) by estimating the NE of a *non-cooperative game with complete information* using energy-based utility functions, as we have analytically shown in Section 5.2. Accordingly, depending on the probabilities that the nodes choose, we have the following contingencies:

1. **Idle slot**, if both nodes decide to remain idle.
2. **Successful transmission**, if exactly one node decides to transmit.
3. **Collision**, if both nodes decide to transmit.

Upon a collision, the destination nodes initiate the ZigZag decoding procedure by transmitting a NACK message to the source nodes, after sensing the channel idle for $SIFS$ period of time. The simultaneous transmission of NACK packets can be effectively handled by our protocol, since it has been recently proven that overlapping NACKs can be correctly recognized at the receiver side, provided that the packets are identical [11]. Hence, the source nodes are informed that the packets have collided and retransmit the same coded packets in the next slot with transmission probability equal to one ($s_i = 1$), thus resulting in a second, "useful" collision. Therefore, the sink nodes are able to extract both packets by applying ZigZag techniques to the two collision sets.

In this point, it has to be clarified that data transmissions in ANGEL take place after a random $DIFS$ time, uniformly distributed between $SIFS$ and $DIFS$. In this way, it is ensured that the offset of the collisions (Δ) will be sufficient for the decoding of the packets, without violating the rule that control packets have higher priority compared to data packets. Moreover, ANGEL is backwards compatible with several CSMA-based standards (e.g., IEEE 802.11, IEEE 802.15.4 etc.) with the modification that the $DIFS$ period in ANGEL is not used for actual sensing of the channel, since collisions are beneficial for our protocol.

For the sake of clarity, an example of frame sequence in ANGEL is depicted in Figure 5.4. In particular, the protocol operates as follows:

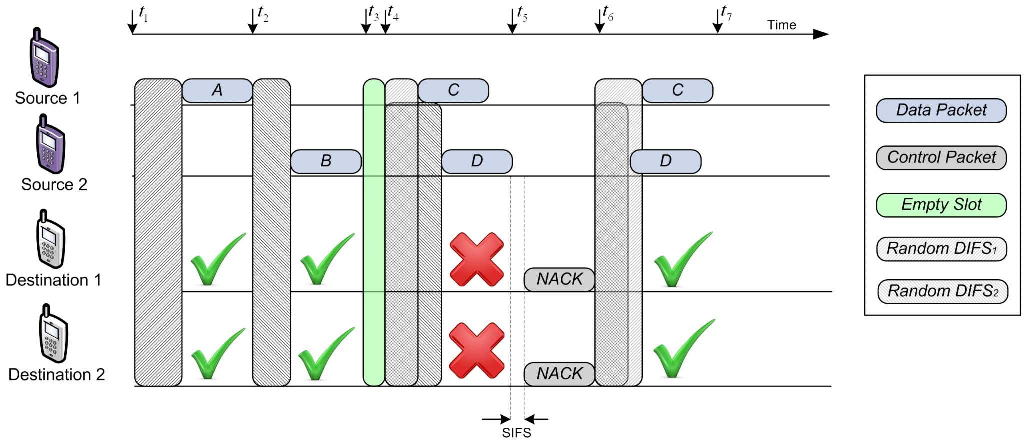

Figure 5.4: Example of frame sequence in ANGEL

1. At instant t_1, source 1 decides to transmit the network-coded packet A after a random $DIFS_1$ time. Source 2 decides to stay idle and, therefore, the destination nodes are able to extract packet A.
2. At instant t_2, source 1 remains idle, while source 2 transmits the network-coded packet B after a random $DIFS_2$ time. Since there is only one transmission, the destination nodes are able to extract packet B.
3. At instant t_3, both sources 1 and 2 decide to remain silent, thus resulting in an idle slot in the system.
4. At instant t_4, both sources 1 and 2 decide to transmit the coded packets C and D after different random $DIFS$ times, $DIFS_1$ and $DIFS_2$, respectively.
5. At instant t_5, the destination nodes are not able to extract the received packets and, hence, they transmit a NACK packet after sensing the channel for $SIFS$ period of time.
6. At instant t_6, the source nodes extract the received overlapped NACKs [11] and retransmit the same packets C and D after $DIFS_1$ and $DIFS_2$, respectively.
7. At instant t_7, the destination nodes are able to extract both packets C and D by applying ZigZag decoding techniques to resolve the two consecutive collisions with different Δ intervals.

In the following section, we provide a detailed analytical framework for the expected dissemination completion time and the energy efficiency of the proposed scheme.

5.4 Performance Analysis

5.4.1 Completion Time

The minimum number of slots (R_{ideal}) in collision-free schemes, i.e., ideal scheduling among contenting nodes, is easy to be calculated, since it depends on a set of known parameters, such as: i) the total number of the information data packets (M), ii) the number of sink nodes (l), and iii) the impact of the source nodes on the network (J). It has already been proven in [9] that the ideal number of slots for the data dissemination can be expressed as:

$$R_{ideal} = M \cdot \left\lceil \frac{l}{J} \right\rceil \tag{5.5}$$

On the other hand, in realistic MAC schemes, this ideal number is affected by the actual contention between the nodes, which results in collided and idle slots. Nevertheless, in ANGEL, the incurred collisions do not have a significant negative impact in the system performance, but instead they can be exploited as a benefit for the network. Hence, the average number of slots needed for the completion of the data dissemination is given by:

$$\mathbf{E}[R] = \frac{R_{ideal}}{p_s + p_c}, \tag{5.6}$$

while the average total completion time can be represented as:

$$\mathbf{E}[T_{total}] = \mathbf{E}[R] \cdot ((p_s + p_{pos}) \cdot (\overline{DIFS} + T_{tr}) + p_i \cdot \sigma + p_{neg} \cdot (\overline{DIFS} + T_c + SIFS + T_{NACK})) \tag{5.7}$$

In the above expressions, the terms p_{pos} and p_{neg} represent the probability of having a collision that can be resolved using ZigZag decoding and the probability of having an initial collision that can not be resolved, respectively. Moreover, the probabilities of having a successful transmission, a collision and an idle slot, are given by p_s, p_c and p_i, respectively. The terms T_{tr}, T_{NACK}, σ, T_c and $SIFS$ represent the duration of a network-coded data packet transmission, a NACK packet transmission, an empty slot, a collision and a $SIFS$ period of time, while the $\overline{DIFS}$ is used to denote the average random time, uniformly distributed between $SIFS$ and $DIFS$, that the sources wait before starting the transmission.

Since the success of the transmission in one random slot depends on the status of the preceding slot, conditional probabilities are exploited to model our protocol. In particular, the overall probabilities p_s, p_c and p_i can be calculated as:

$$p_s = \sum_{\forall x \in \{succ, col, idle\}} p(x_i, succ_j), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.8}$$

$$p_c = \sum_{\forall x \in \{succ, col, idle\}} p(x_i, col_j), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.9}$$

$$p_i = \sum_{\forall x \in \{succ, col, idle\}} p(x_i, idle_j), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.10}$$

where i and j are two consecutive slots, while $succ_i$, col_i and $idle_i$ represent the fact that the random slot i is successful, collided or idle, respectively. In ANGEL, one slot is considered successful if exactly one node gains the access to the channel to transmit, collided if both nodes transmit simultaneously, and idle if both nodes remain idle. Therefore, we can write:

$$p(succ_i) = \sum_{k \neq l} s_k \cdot \bar{s}_l, \forall i \in \mathbb{N}, (k, l) \in \{1, 2\} \tag{5.11}$$

$$p(col_i) = s_1 \cdot s_2, \forall i \in \mathbb{N} \tag{5.12}$$

$$p(idle_i) = \bar{s}_1 \cdot \bar{s}_2, \forall i \in \mathbb{N} \tag{5.13}$$

where $s_i \in (0, 1)$ is the probability of a node i to transmit, as it has been estimated using game theoretic techniques, and $\bar{s}_i$ denotes the complementary probability of s_i, i.e., $\bar{s}_i = 1 - s_i$.

The statistical independency of the events along with the joint probabilities allow us to use the definition of conditional probabilities in order to simplify the formulas (5.8)-(5.10). Hence, we have:

$$p_s = \sum_{\forall x \in \{succ, col, idle\}} p(succ_j | x_i) \cdot p(x_i), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.14}$$

$$p_c = \sum_{\forall x \in \{succ, col, idle\}} p(col_j | x_i) \cdot p(x_i), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.15}$$

$$p_i = \sum_{\forall x \in \{succ, col, idle\}} p(idle_j | x_i) \cdot p(x_i), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.16}$$

Table 5.1: Conditional probabilities

slot i	slot j		
	success	collision	idle
success	$p(succ_j)$	$p(col_j)$	$p(idle_j)$
collision	0	1	0
idle	$p(succ_j)$	$p(col_j)$	$p(idle_j)$

where the conditional probabilities can be found in Table 5.1.

In addition, in order to probabilistically estimate the average number of collisions that can be resolved in our protocol, we need to expand the equation (5.15), as follows:

$$p_c = p(col_j) \cdot p(succ_i) + p(col_j) \cdot p(idle_i) + 1 \cdot p(col_i), i \in \mathbb{N}, j \in \mathbb{N}^* \tag{5.17}$$

where the first two terms represent the portion of the collisions that can not be resolved (i.e., p_{neg} in equation (5.7)) and the third term represents the percentage of collisions that can be resolved using ZigZag techniques (i.e., p_{pos} in equation (5.7)).

5.4.2 Energy Efficiency

Let us recall that the energy efficiency (η) of the system is a useful indicator that provides information about the useful data that are delivered in the network as a function of the total energy consumption, represented as [12]:

$$\eta = \frac{D_{useful}}{\mathcal{E}_{total}}, \tag{5.18}$$

where D_{useful} is the total amount of useful data delivered and $\mathcal{E}_{total}$ denotes the total consumed energy.

In the context of ANGEL, the numerator has a deterministic value which can be calculated as:

$$D_{useful} = M \cdot payload \cdot l \tag{5.19}$$

where M is the number of packets, $payload$ is the useful packet payload without taking into account the overhead due to the headers, and l is the number of destination nodes.

On the other hand, the expected value of the energy consumption can be probabilistically estimated by exploiting our analysis in Section 5.4.1. Similar to previous comparable cases, we consider three different modes for the radio interface, i.e., transmission, reception and idle, with power levels P_T, P_R and P_I, respectively. Having analyzed ANGEL's performance, we are able to derive a closed-form formula that describes the average energy consumption in the network:

$$\mathbf{E}[\mathcal{E}_{total}] = \mathbf{E}[\mathcal{E}_{succ}] + \mathbf{E}[\mathcal{E}_{idle}] + \mathbf{E}[\mathcal{E}_{zigzag}] \tag{5.20}$$

where $\mathcal{E}_{succ}$, $\mathcal{E}_{idle}$ and $\mathcal{E}_{zigzag}$ represent the energy consumed during the successful transmissions, the idle periods and the ZigZag procedure, respectively. Let us recall that the network consists of two source nodes, a set $\mathcal{L}$ of l sink nodes and a subset $\mathcal{W} \subseteq \mathcal{L}$ of w nodes that are placed in the coverage areas intersection of the two sources and experience the collisions. Therefore, considering the network topology, we have:

$$\mathbf{E}[\mathcal{E}_{succ}] = p_s \cdot ((l+2) \cdot P_I \cdot \overline{DIFS} + (P_T + J \cdot P_R + (l-J) \cdot P_I) \cdot T_{tr}) \tag{5.21}$$

$$\mathbf{E}[\mathcal{E}_{idle}] = p_i \cdot (l+2) \cdot P_I \cdot \sigma \tag{5.22}$$

$$\begin{split}\mathbf{E}[\mathcal{E}_{zigzag}] = p_{neg} \cdot ((l+2) \cdot P_I \cdot (\overline{DIFS} + SIFS) + (2 \cdot P_T + l \cdot P_R) \cdot T_c + \\ + (w \cdot P_T + 2 \cdot P_R + (l-w) \cdot P_I) \cdot T_{NACK}) + p_{pos} \cdot ((l+2) \cdot P_I \cdot \overline{DIFS} + (2 \cdot P_T + l \cdot P_R) \cdot T_c)\end{split} \tag{5.23}$$

where all parameters have been already defined. The above equations (5.21)-(5.23) are based on the following principles:

- All stations remain idle during the $SIFS$, $DIFS$ and σ times.
- All stations **inside** the coverage area of a transmitting node are in **reception** mode.
- All stations **outside** the coverage area of a transmitting node are in **idle** mode.

Therefore, we are able to estimate the average energy consumption, since all the variables are known and the respective probabilities have already been calculated in Section 5.4.1.

5.5 Performance Evaluation

We have implemented a time-driven C++ code that simulates the operation of ANGEL. Monte Carlo simulations have been carried out to validate our analysis and further evaluate the performance of our proposed protocol. In this section, we present the simulation setup along with the experimental results.

5.5.1 Simulation Scenario

The network under simulation consists of five nodes in total, where two of them have already received the total amount of information broadcasted by the BS ($n = 2$), while the rest three are sink nodes affected (i.e., placed inside the transmission range) of both sources ($l = 3$), as it is depicted in Figure 5.5. Therefore, during the dissemination, the two sources have the same impact on the network.

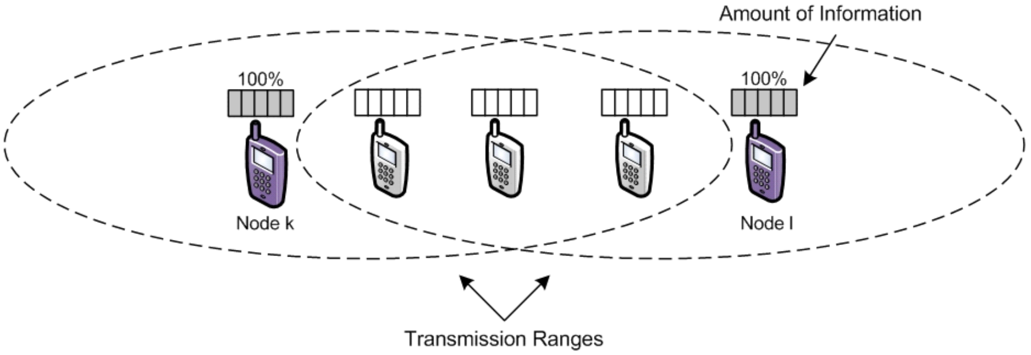

Figure 5.5: Simulation scenario

In addition, as we have already mentioned, the nodes are capable of performing RLNC techniques to their buffered packets before forwarding them. Similar to the experiments of Chapter 4, the item to be disseminated is an RGB image file of dimensions 256×256 - translated into 256 packets of 256 pixels - where the length of each packet depends on the image resolution. In this set of simulations we consider packet lengths of $PHY + MAC + NC_H + P$ bytes, where PHY and MAC are the physical and the MAC header, respectively, with $PHY = 192$ bits and $MAC = 224$ bits. NC_H is the NC header, while P is the packet payload which varies between 64 and 1024 bytes with regard to the image resolution. The coding of the packets is performed over a finite GF2^8, since it has been proven to be sufficient for linear independence among the packets (see Chapter 4) [13]. The specific field implies that the number of the encoding packets represents the number of the bytes in the encoding vector. Accordingly, we have created 16 generations of 16 packets each, which results in NC_H of 17 bytes in total (16 bytes for the encoding vector, 4 bits for the generation size and 4 bits for the generation identifier).

Furthermore, in our attempt to focus our study on the access part of the proposed technique, we have adopted the concept of error-free data transmissions. The time slot has been selected equal to 20 μsec according to the IEEE 802.11g PHY layer [16], while we consider two different transmission rates with regard to the SNR values: i) 54 Mb/s for *high SNR* conditions and ii) 24 Mb/s for *low SNR* conditions. Similar to the previous chapters, we have chosen the power levels for our scenarios according to the measurements carried out by Ebert *et al.* [15]: $P_T = 1900mW$, $P_R = P_I = 1340mW$.

In order to evaluate ANGEL and highlight the promising benefits of ANC in wireless communication, we compare our proposed protocol with two alternative RLNC-aided protocols for data dissemination: i) the distributed access approach (Chapter 4), where game theory is used to resolve the potential conflicting interests between the nodes, and ii) the IEEE 802.11 DCF, where the conflicts are resolved employing CW and backoff mechanisms. The simulation parameters are summarized in TABLE 5.2.

Table 5.2: System parameters

Parameter	**Value**	**Parameter**	**Value**
Packet Payload	64-1024 bytes	σ	20 μsec
DIFS	50 μsec	*SIFS*	10 μsec
$\overline{DIFS}$	30 μsec	*Generation Size*	16
MAC Header	28 bytes	*PHY Header*	24 bytes
NC Header	17 bytes	*NACK*	14 bytes
CW_{min}	32	P_T	1900 mW
Tx.Rate (High SNR)	54 Mb/s	P_I	1340 mW
Tx.Rate (Low SNR)	24 Mb/s	P_R	1340 mW

5.5.2 Performance Results

Figure 5.6 depicts the performance results (both analytical and experimental) of the proposed ANGEL in terms of completion time for low SNR conditions. In the same figure, the performance of the two RLNC-based solutions - game theoretic (GT) and IEEE 802.11 DCF - is also depicted for evaluation purposes. First, it can be clearly observed that ANC techniques have a positive effect in the completion time of the dissemination. In particular, in the low SNR region, ANGEL achieves a significant gain up to 270% over the standard DCF, while the enhancement compared to simple game theoretic strategies without ANC capabilities remains steadily over 50% independently of the packet payload.

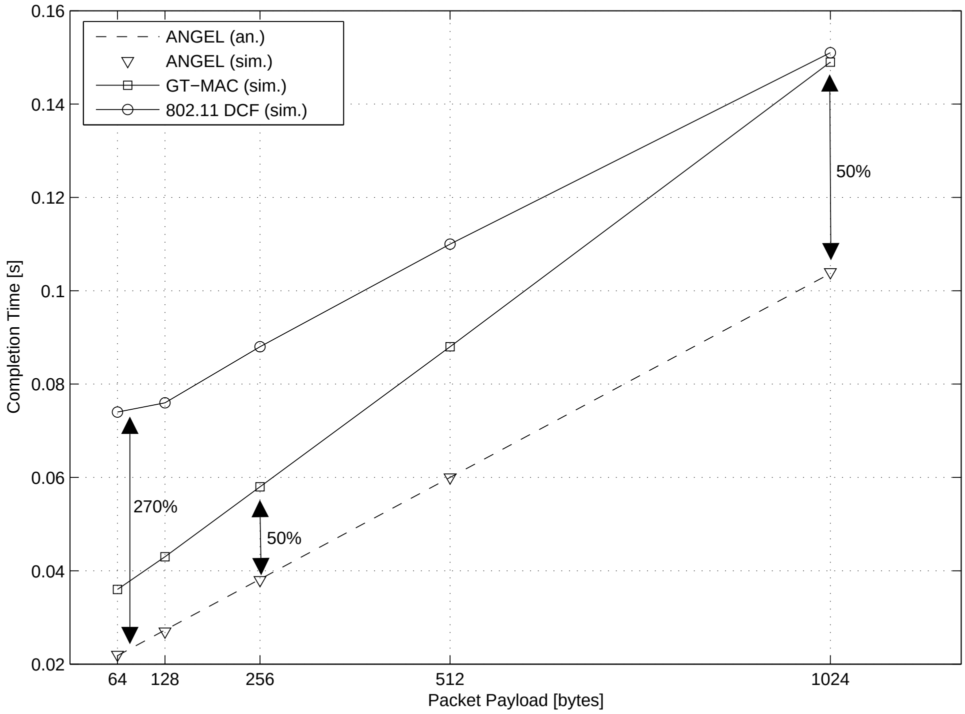

Figure 5.6: Data dissemination completion time (Low SNR)

Another important observation that derives from Figure 5.6 is that the performance of the simple RLNC-based protocols (i.e., GT approach and DCF) converges for large packet payloads. This fact can be explained by considering the impact of collisions in the network. Specifically, the relatively low data rate (24 Mb/s) in scenarios where the packet payload is 1024 bytes implies high transmission time for each packet. Hence, the RLNC-aided GT MAC strategy cannot provide advantages over the DCF, which has been essentially designed to avoid packet collisions. Nevertheless, even in this case, the ANC techniques applied in ANGEL contribute significantly to the reduction of dissemination completion time, as we achieve an enhancement of 50% by turning the collisions into a benefit for the system.

Figure 5.7 demonstrates the dissemination completion time in ANGEL for high SNR channel conditions. In this particular case, the time reduction compared to the IEEE 802.11 DCF is quite significant, starting from 100% for high packet payload, reaching up to 290% for packets of 64 bytes. With respect to the GT approach, the gain ranges between 35% and 65%, while it is clear that GT techniques outperform the CSMA-based operation of DCF. This behavior can also be explained by taking into account the effect of the collisions in the system. In particular, as the transmission data rate increases, the packet transmission time decreases, reducing the influence of the collisions. As a result, the GT strategy achieves clearly higher performance than DCF, which is affected by the idle slots in the network due to the backoff operation. Adopting ZigZag decoding techniques, ANGEL is able to decode two packets of two consecutive collisions, thus totally eliminating the interference in the network.

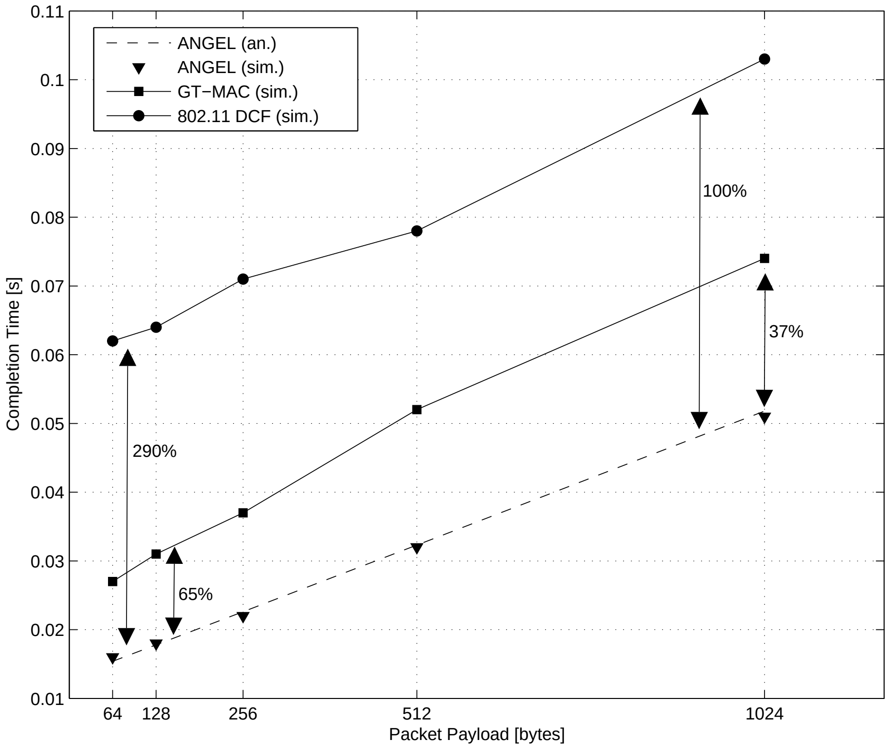

Figure 5.7: Data dissemination completion time (High SNR)

Figure 5.8 presents the achieved energy efficiency in the low SNR region, for the three schemes discussed in this chapter. The simulation results for ANGEL are almost perfectly matched to the theoretical derivations, thus validating our analysis. Similar to the delay performance, the application of ANC techniques provide the network with higher energy efficiency. In this figure, it is clearly observed that ANGEL is more energy efficient than both reference schemes, regardless of the packet length. In particular, ANGEL provides a great enhancement up to 100% over the GT-MAC scheme, while the energy efficiency compared to the standard DCF is more than doubled for small data packets.

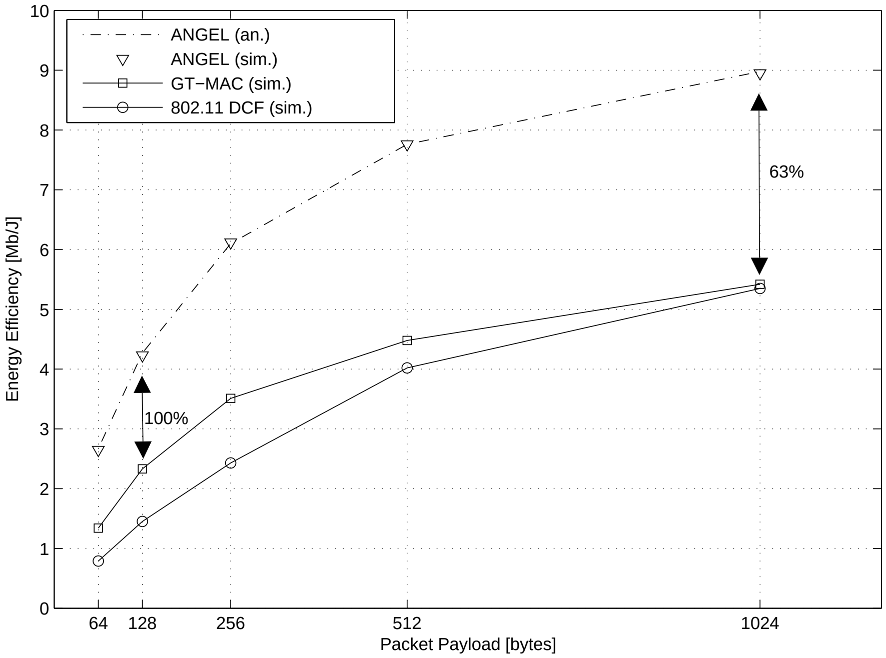

Figure 5.8: Energy efficiency (Low SNR)

Figure 5.9 plots the results with regard to the achieved energy efficiency in high SNR conditions. Considering the high data speed scenario of 54 Mb/s, ANGEL increases the network energy efficiency up to 100% compared to the GT MAC approach for packets of 64 bytes. As the packet payload increases, the rate of profit reduces, but still remains considerable and always higher than 60%. Regarding the DCF, benefits exhibited by the ANC in the energy efficiency aspect of the network are even higher, since the improvement ranges from 120% to 300% for packets of high and low payload, respectively.

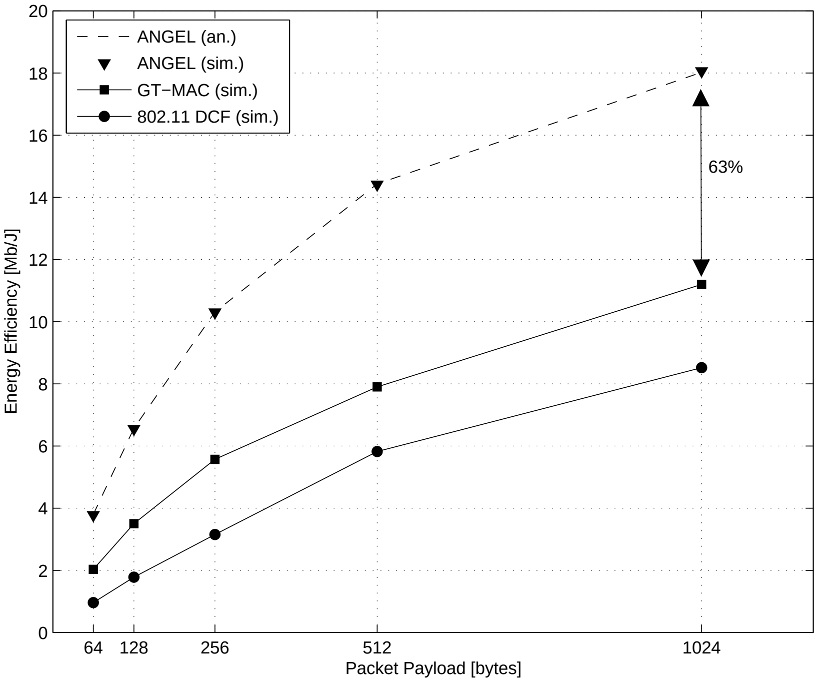

Figure 5.9: Energy efficiency (High SNR)

5.6 Chapter Summary and Conclusions

In this chapter, an **AN**C-aided **G**ame theoretic **E**nergy efficient **L**ayout (ANGEL) for data dissemination in wireless networks was presented. ANGEL is a novel protocol that exploits state-of-the-art NC techniques in a game theoretic framework to boost the network performance. In particular, RLNC is used to eliminate the need of transmitting ACK packets, while ZigZag decoding method is applied to turn the collisions into a benefit for the system. The key conclusions of this chapter are summarized in the following:

- The exploitation of ANC provides significant performance gains with regard to the completion time of the data dissemination. More specifically, ANGEL provides a reduction up to 75% to the dissemination completion time compared to other simple RLNC-aided schemes without ANC capabilities.

- Regarding energy efficiency, the enhancement reaches 100% under certain preconditions. The application of ZigZag decoding is particularly beneficial in scenarios of low transmission data rates and high packet payloads, where the duration of collision increases dramatically. In such scenarios, even though the performance of conventional random access RLNC-aided protocols converges, ANGEL overcomes these limitations by turning the packet collisions into a benefit for the network.

With this chapter we have completed our main scientific contributions. The last chapter of the thesis contains the main conclusions, drawing the road map for the future work.

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Chapter 6

Thesis Conclusions and Future Work

"The future depends on what you do today." **Mahatma Gandhi**

Contents

This chapter completes the dissertation by summarizing our main contributions, while also providing some potential research lines for future investigation. In particular, Section 6.1 contains the most significant concluding remarks of each chapter, while Section 6.2 outlines the open research issues related to our contributions.

6.1 Concluding Remarks

This dissertation has dealt with MAC issues in modern cooperative ad hoc wireless networks. Taking into account the recent "green" trends in ICT industry, we have particularly focused on the design, implementation and performance evaluation of NC-aided MAC protocols that enhance the energy efficiency of the system, without compromising the offered QoS. In our attempt to model the interactive behavior of the autonomous wireless nodes in infrastructureless scenarios, game theory has been proven a valuable and appropriate tool, providing effective solutions. The major contributions of the thesis have been divided into two main parts: i) the first part is confined in Chapter 3, and ii) the second part includes Chapters 4 and 5. The detailed contributions of each chapter are summarized in the following:

Chapter 3 In this chapter, we introduced NCCARQ, an NC-aided cooperative ARQ MAC protocol for wireless networks. The proposed scheme coordinates the channel access among multiple relay nodes with NC capabilities that support a bidirectional wireless communication between two nodes.

Combining the benefits of cooperation and NC, we were able to implement a MAC protocol that provides diversity gains, while compensating the channel impairments. In NCCARQ, the wireless nodes are enabled to transmit data packets piggybacked on control packets, in order to assist the helper nodes in exploiting the NC advantages.

The essential differences of CSMA-based Standards (e.g., IEEE 802.11, IEEE 802.15.4) further motivated us to propose two NCCARQ variants for short and medium range wireless communication, i.e., NCCARQ-WSN and NCCARQ-WLAN, respectively. To model the operation of both approaches, detailed probabilistic models have been designed, demonstrating the significant potential gains we can achieve over conventional cooperative ARQ protocols.

Employing accurate simulation tools , we were able to verify our analytical models and evaluate further the NCCARQ performance. In particular, it was shown that NCCARQ achieves a tremendous enhancement up to 90% in terms of system throughput, energy efficiency and packet delay, compared to traditional cooperative ARQ protocols without NC adaptations. The main reason for this improvement is the considerable reduction of backoff phases as well as the circumvention of the weak direct link between the source and the destination.

The performance assessment of NCCARQ under realistic channel conditions was another major contribution of this chapter. Motivated by the PHY layer impact on the MAC protocols performance, we studied various NCCARQ aspects considering correlated shadowed wireless links, concluding that the distributed cooperation benefits tend to be negligible as the correlation among different links increases. Hence, our results clearly demonstrate the importance of taking into account realistic PHY layer models for a novel design of cooperative NC-aided MAC protocols.

Chapter 4 In this chapter, we dealt with the conflicting situations caused among the source nodes in data dissemination scenarios due to the selfish nature of the wireless devices. In such scenarios, the nodes that already hold the information to be disseminated want to preserve their individual energy status, while, at the same time, the dissemination completion constitutes the global goal in the network.

To this end, we introduced two NC-aided multiplayer game theoretic MAC approaches for data dissemination schemes in wireless networks: i) a distributed approach where the players (source nodes) estimate the NE channel access probabilities, such that to maximize their particular payoff, i.e., battery lifetime, and ii) a centralized strategy where the players act in the same way to estimate the transmission probabilities, assisted further by a central controller that occasionally intervenes to expedite the dissemination procedure.

We have proven that game theory can overcome the IEEE 802.11 DCF limitations - due to the inflexible contention window dynamics - by providing precise and adaptive medium access probabilities depending on the particular network size and topology. In addition, by adopting RLNC techniques we were able to eliminate the necessity of exchanging ACKs, thus further reducing the completion time in multicast scenarios, where the control packets transmissions cause serious impediments.

For both access schemes (distributed and centralized), detailed analytical models have been developed and validated by extensive Monte Carlo simulations. Our game theoretic approaches have been proven to be up to 300% more energy efficient than the IEEE 802.11 standard, while, at the same time, the dissemination completion time was significantly reduced. The outcome results also indicate the need of designing modern MAC solutions for wireless networks, as the impact of collisions is continuously decreasing.

Chapter 5 This chapter introduced ANGEL, an **AN**C-aided **G**ame theoretic **E**nergy efficient **L**ayout for data dissemination in wireless networks. Motivated by the recent advances in NC field, we proposed a novel game theoretic protocol that effectively exploits both RLNC and ANC techniques in order to facilitate the data dissemination in the network.

Employing ZigZag decoding, ANGEL improves up to 100% the energy efficiency in the network, reducing up to 75% the dissemination completion time compared to other RLNC-assisted approaches. In addition, an analytical model was designed to estimate the theoretical performance bounds of ANGEL in topologies where two sources have the maximum impact on the network. The analytical results confirmed the respective simulation outcomes, proving that collisions can be turned into a considerable gain for the system performance.

6.2 Future Work

The main contributions presented in this dissertation are precursors of several new research lines for future investigation. The main open topics with regard to the first part of the thesis on NCCARQ MAC protocol can be summarized in the following:

- The successful application of game theory for MAC conflicts resolution in the second part of the thesis provides some strong incentives to adopt game theoretic strategies that coordinate the relay transmissions in NC-aided cooperative ARQ schemes. By selecting the most appropriate utility functions, we might be able to optimize the network performance with respect to different metrics such as energy efficiency or fairness.
- The key findings derived by the consideration of PHY layer aspects in the design of the NCCARQ further motivate us to study the protocol performance under other realistic channel models and advanced PHY layer implementations. In particular, state-of-the-art PHY schemes (e.g., MIMO, turbo coding, etc.) provide different packet reception criteria which affect both the triggering of cooperation, as well as the relay set formation.
- Complete analytical models need to be designed in order to validate the experimental conclusions of taking into account shadowing correlation in the NCCARQ performance. Although this process is complicated due to the non-ergodic nature of shadowing fading, these models would be a fundamental guide for studying and optimizing various theoretical aspects of the protocol behavior under real network conditions.
- The actual implementation of NCCARQ in real devices would be an important step ahead. So far, we have evaluated the protocol performance using detailed analytical probabilistic models (mainly based on Markov theory) and by means of extensive simulation experiments. However, the employment of the protocol rules in real testbeds would reveal unidentified weaknesses, while it would allow for a better and more complete performance assessment.

Regarding the second part of the dissertation, which proposes NC-aided game theoretic MAC strategies for efficient data dissemination in wireless networks, several open research lines are also identified:

- In the proposed game formulation, we have adopted energy-based utility functions that provide fair resource allocation among the wireless sources. However, different payoff functions (based, for instance, on the individual battery status level), could potentially provide higher energy efficiency and performance gains in topologies where fairness is of minor importance. Moreover, the adaptation of the proposed MAC approaches could be studied in realistic networks, without taking into account the impact of each source node in the network.

- The adjustment of our game theoretic strategies in large scale networks would be of great interest. Although one straightforward solution is proposed in the dissertation (i.e., the sink nodes in one phase constitute the source nodes of the next phase), there might be more sophisticated solutions that could reduce the dissemination completion time by considering cross layer information, mainly obtained by the network layer.

- In this dissertation, the focus has been set on the access part of the communication. However, as it was showcased in the first part of the thesis, the PHY layer impact poses significant challenges and, thus, cannot be neglected. The incorporation of channel characteristics into the game formulation, as well as the performance assessment of the proposed medium access strategies under realistic fast and slow fading conditions would be great steps towards the design of a complete MAC protocol.

- The cooperative nature of the data dissemination problem motivates the application of cooperative game theory. Even though our non-cooperative game theoretic approaches have been proven beneficial for the system, cooperative game theory could study the same problem from a different point of view, providing interesting solutions for coalitions formation and user cooperation.

- The tradeoffs between exclusively centralized solutions and the proposed centralized access strategy deserve to be investigated in the future. Through this study, various protocol parameters could be optimized, as for example the number of unsuccessful slot (referred as k_f in our analysis) before the central controller intervention.

- Regarding ANGEL, the immediate next step is the extension of the protocol for network with multiple sources. The recent advances in the NC domain allow us to adapt the proposed scheme to multi-source networks, since the resolution of collisions with more than two packets involved is at the moment an active research topic. Although the extension does not seem to be straightforward, it would constitute a great scientific contribution, providing further network performance enhancements.

- Finally, similar to the NCCARQ case, the implementation of game theoretic MAC techniques in real hardware would overcome the inherent limitations of theoretical analysis and system-level simulations. After detailed analytical and simulation studies, we are convinced that the protocols implementation in real testbeds would further highlight the need for designing novel, adaptive MAC schemes for modern wireless networks, where the impact of collisions tends to become increasingly negligible.