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Cooperation for Next Generation Wireless Networks

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4.1 Introduction

Nowadays, users crave an "any-time-any-place" connectivity, using cutting edge devices, such as smartphones, tablets, 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. According to Cisco, by the end of 2017, there will be nearly 1.4 mobile devices per capita [1]. This vast proliferation of mobile devices, which is mainly attributed to the wide usage of social networks and multimedia sharing websites, has led to the introduction of fourth generation (4G) communications technologies, such as the Worldwide Interoperability for Microwave Access (WiMAX) and the Long Term Evolution Advanced (LTE-A), designed to provide higher data rates and increased network capacity.

Beyond 4G, in next generation networks, the increasing density of the mobile devices, along with the coexistence of diverse wireless technologies in typical urban areas, has motivated a new architecture paradigm: the Heterogeneous Networks (HetNets) [2]. The basic concept behind HetNets is the seamless integration and interoperation of different wireless access technologies in order to increase the system performance and the energy efficiency both at the operator's and the user's side. To that end, the development of low power micro base stations (BS) (femto, pico, WiFi) inside the coverage area of a macro BS (LTE, WiMAX) contributes in both directions: i) the traffic load balancing to different BSs implies better resource allocation and utilization, while ii) the use of low power short radio links leads to enhanced energy efficiency in the network.

Fundamentals of 5G Mobile Networks, First Edition. Edited by Jonathan Rodriguez.

HetNets can be considered as a tangible proof that different types of communication technologies (i.e., long, medium and short range) are not competitors, but they can work together to reduce the operator energy costs, providing at the same time enhanced Quality of Service (QoS) and Quality of Experience (QoE) to the end user. In addition, the introduction of this new paradigm once again raised the importance of medium/short range communications, motivating the research community to address novel ways to improve user satisfaction, taking into account the energy constraints posed by the European Union (EU) and several standardization organizations.

In this context, cooperative communications [3] have gained significant attention over the last decade. In particular, the close proximity of the mobile devices and the broadcast nature of the wireless medium prompt the end users to cooperate in order to further improve the experienced QoS, decreasing at the same time the required power for the transmissions. This cooperation can be achieved by transmitting the data to the final destination through the assistance of intermediate nodes (known as relays or helpers). Amplify-and-Forward (AF) [4] and Decode-and-Forward (DF) [5] are two of the most popular techniques in cooperative networking. In particular, AF is considered the simplest way of cooperation, where the relay node only amplifies the received signal from the source and forwards it to the final destination. On the other hand, the DF strategy allows the relays to decode the received information before forwarding it to the destination node. This extra capability that DF provides to the relays is particularly useful in cooperative Automatic Repeat reQuest (ARQ) schemes, where the reception failures at the destination are compensated through retransmissions by the neighboring relay stations that have correctly received the original information. Moreover, the increasing interest for exchanging information and bidirectional communication has triggered the design of new techniques, such as Network Coding (NC) [6], which are also facilitated by the DF strategy, as they require the decoding and re-encoding of the data in the relay nodes. For the aforementioned reasons, DF attracts a growing attention for both one- and two-way communication paradigms that use simple and NC-aided cooperative techniques, respectively.

The motivation behind our work is twofold. First, the performance analysis of the cooperative strategies (either AF or DF) is usually conducted from an information and communication theory point of view, following a pure Physical (PHY) layer perspective, neglecting the operation of the upper layers in the protocol stack. The second limitation concerns the role of the network topology in the system performance. In particular, although recent studies [7, 8, 9, 10, 11] have examined the impact of slow fading (shadowing) on the wireless communications, the increased node density implies higher correlation between the wireless links, restricting further the spatial diversity gains. This is particularly important in next generation networks, where several wireless systems will coexist and will even need to work in synergy requiring tight integration between them in order to preserve their optimal traits. Therefore, although cooperation has been widely investigated and applied somewhat to 4G systems, in 5G we need to consider an interdisciplinary design and drive the cooperation paradigm to a whole new level, where billions of devices will be connected to the internet, where the separations between protocol layers in the network are blurred and the close proximity of devices will have severe implications on the spatial diversity benefits, affecting the cooperation performance.

Therefore, in this chapter, we study the cooperation paradigm from a new perspective and investigate how the Medium Access Control (MAC) protocol can play a major role in harnessing the benefits of the underlying cooperative strategies through inter-layer design and, beyond that, work in synergy with the widely used NC approach. First, we study the impact of channel correlation on the performance of two-way cooperative MAC protocols. Secondly, motivated by the wide spread of DF, we provide a brief overview of a simple and a network-coded ARQ MAC protocol, both of them backwards compatible with our case study, the IEEE 802.11 Standard for medium-range communication. Our main contribution lies in a comprehensive cross-layer study of MAC-oriented cooperative strategies based on NC, taking into account the growing density of the terminals in next generation wireless networks.

The remainder of this chapter is organized in five sections. In Section 4.2, we introduce the concepts of simple and NC-aided cooperation, providing the state of the art in the cooperative ARQ MAC protocols. In Section 4.3, we explicitly describe the potential PHY layer effect on the actual performance of MAC protocols, focusing on the correct packet reception and the possible shadowing spatial correlation in the wireless links. In Section 4.4, we present an overview of a recently introduced NC-aided ARQ MAC protocol (NCCARQ), and we explicitly study the changes that the realistic channel assumptions bring to the protocol's operation. The PHY layer effect, and particularly the impact of correlated shadowing, is quantified in Section 4.5, where we provide the experimental results, obtained through extensive Monte Carlo simulations. Finally, Section 4.6 finalizes the chapter, summarizing the most important conclusions.

4.2 Cooperative Diversity and Relaying Strategies

4.2.1 Cooperation and Network Coding

Over the last decade, cooperative communications [3] have gained significant attention in the research community. The main idea of cooperative communications is the achievement of spatial diversity without having as a prerequisite the existence of multiple antennas in single terminals. More specifically, in cooperative systems, each mobile node becomes part of a large distributed array, sharing its single antenna (as well as its hardware, processing, and energy resources) to assist the communication between two nodes (source and destination), employing either AF or DF strategies. As a result, the final destination can receive multiple copies of the same message, which can be locally combined to improve the reliability of the transmission. Therefore, distributed cooperation profitably exploits the broadcast nature of the wireless medium, by potentially providing: (i) higher spatial diversity and throughput; (ii) lower energy consumption and reduced interference; and (iii) adaptability to network conditions.

Besides the obvious advantages, though, there are some limitations in the cooperation gains [12], since distributed cooperative systems require extra bandwidth resources (either time slots or radio frequencies) due to practical considerations, such as half-duplex constraints or interference avoidance issues. In addition, relay nodes in cooperative systems are forced to participate in the communication between other nodes, thus having an impact on their own packet delay. To overcome these limitations, which severely affect the network throughput, latency, and energy efficiency, NC has been introduced as an advanced encoding routing mechanism at the network layer, which allows intermediate nodes in the network not only to forward but also to process incoming data packets. The application of NC is facilitated by the advanced DF cooperative strategies, which enable the intermediate nodes to decode the data packets before encoding them again in the network layer, using bit-level techniques. This operation reduces the resource demands for the data transmission, implying straightforward gains in both energy efficiency and throughput performance.

4.2.2 Cooperative ARQ MAC Protocols

The overwhelming number of mobile devices (which are potential relay nodes) in legacy communications systems, which is expected to rise to unprecedented levels as we approach the 5G era, raises important challenges, such as the efficient channel access coordination for the design of effective cooperative systems. In a wireless context, this operation is very challenging, as the interference caused by different transmissions within the same communication range may lead to packet losses that deteriorate the network performance. Hence, the design of appropriate MAC protocols is fundamental in order to exploit the distributed cooperation by reducing the latency and the number of collisions in the network.

The existing cooperative MAC protocols can be classified as *proactive* or *reactive*, with regard to the time that the cooperation is triggered [13]. Regarding the former class, the mobile stations in multi-rate wireless networks assign the modulation scheme and the transmission rate according to the detected Signal-to-Noise-Ratio (SNR), using Adaptive Modulation and Coding (AMC) [14]. 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 proactive cooperation, 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.

With regard to the reactive cooperative protocols, ARQ is one of the main error control methods for data communications [15]. 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, 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), broadcast by the destination after a decoding failure.

Dianati *et al.* [16] has proposed one of the first cooperative ARQ MAC protocols, demonstrating the potential energy and throughput gains that can be achieved by exploiting node cooperation in mobile scenarios. The delay analysis of a single-source single-relay ARQ system has been presented in reference [17], where the authors identified the cases and the necessary prerequisites that have to be fulfilled in order for the cooperative ARQ schemes to outperform the traditional direct ARQ methods. In reference [18], the authors introduced the concept of frame combining and studied the conditions under which their proposal improves the classic ARQ. The performance of multicast cooperative ARQ (MCARQ) in wireless networks and its potential applications in practical systems, for example, Multi-user MIMO communications, are examined in reference [19]. The idea of cooperative ARQ has been also applied in infrastructure networks [20], where the nodes with the best channels are opportunistically selected as relays to forward the packets from the access point, improving significantly the achieved throughput. More recently, the work in reference [21] has introduced a theoretical framework to model cooperative ARQ protocols with relay selection. Within the proposed framework, the authors obtain the protocol performance in terms of throughput and energy efficiency, taking into account relay selection overhead and temporal correlation of fading channels. Regarding the application of NC in the MAC layer, the potential improvements that can be achieved in ARQ systems with one relay are investigated in reference [22], where it is proved that both the throughput and the packet delay can benefit by applying NC techniques.

The abovementioned works deal with relay selection or single-relay systems. However, in real systems, multiple users can be eligible as relays, and their efficient coordination becomes of paramount importance. To that end, the Persistent Relay Carrier Sensing Multiple Access (PRCSMA) [23] was the first MAC protocol designed to apply distributed cooperative ARQ techniques in wireless networks. In PRCSMA, all stations are invited to become active relays as long as they meet certain relay selection criteria. Multiple relays contend for channel access in the cooperative phase according to the Distributed Coordination Function (DCF) mechanism of the IEEE 802.11 Standard [24]. To overcome the limitations of PRCSMA and further enhance the system performance, He and Li [25] have proposed a multi-relay cooperative ARQ scheme, where the relays automatically schedule their retransmissions sequentially according to their instantaneous relay channel quality to the destination, thus solving the collision problem among multiple contending nodes. The involvement of multiple selfish nodes in the cooperation motivated the work in reference [26], where rewarding incentives were provided to the relays via game theory techniques in order to participate in the cooperation. Guaranteeing the compatibility with the IEEE 802.11, the work in reference [27] has introduced an NC-aided Cooperative ARQ (NCCARQ) MAC scheme that significantly improves the energy efficiency in the network by employing NC techniques, without compromising the achieved throughput and delay.

Summarizing the above, PRCSMA [23] and NCCARQ [27] constitute two pioneer works for simple and NC-based ARQ distributed MAC schemes, respectively, designed for WLANs according to the DCF rules. Despite the similarities in their concept and implementation, NCCARQ has been proved to significantly outperform PRCSMA in bidirectional communication scenarios, in terms of energy efficiency, throughput, and packet delay. This enhancement, which can reach 80% under certain conditions, is attributed mainly to the employment of NC, which potentially reduces the number of retransmissions, assisting the nodes to avoid the direct erroneous channel.

To further clarify, Figure 4.1 illustrates a packet exchange between nodes A and B in PRCSMA and NCCARQ. Regarding PRCSMA, the packet exchange takes place in two phases (Figure 4.1a). In the first phase, node A transmits packet a to node B and the relays overhear the transmission. Since the direct channel is assumed to be bad, the transmission fails and node B asks the neighboring nodes for cooperation. The relays that have successfully decoded packet a enter in a contention round in order to gain channel access and transmit the data to node B. Accordingly, in the second phase, the same procedure is repeated, but this time node B directly sends packet b to node A and the relays retransmit the packet after receiving the RFC message. Clearly, in cases of bidirectional communication, the overhead of control packets in PRCSMA deteriorates the network performance, while the end nodes continue to transmit through the direct channel, despite the high probability of packet errors. On the other hand, the operation of NCCARQ provides effective solutions to these issues, as the nodes avoid the direct link, reducing the control packet overhead in the network and the number of

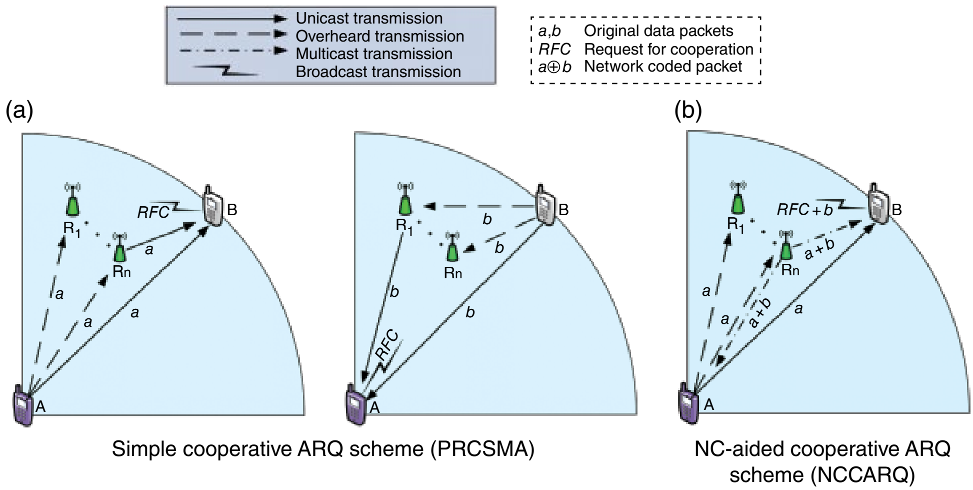

Figure 4.1 Packet exchange in PRCSMA and NCCARQ.

excessive retransmissions. More specifically, as shown in Figure 4.1b, upon the erroneous reception of packet *a*, node *B* broadcasts the RFC packet along with the data packet *b* to the relays. The relays, having received both packets, are able to perform NC and multicast the coded packets to the end nodes.

Despite their novel insights on the cooperative MAC protocol design, all the aforementioned works assume either ideal channel conditions or oversimplified channel models, although the PHY layer significantly affects the actual protocol performance [28] and, in many cases, restricts the benefits that the cooperation and the NC could ideally provide. In particular, it is very important to predict the type of fading that may occur, in order to mitigate its effects or to estimate the probability of having a link in outage. To that end, two basic fading types are identified in the literature: *fast and slow fading*, which introduce small and large scale variations, respectively, to the received signal strength. In the remainder of this chapter, we study the PHY layer impact on the MAC protocol analysis and operation, focusing on the impact of slow fading and the possible spatial correlation among the cooperative links on the performance of NCCARQ.

4.3 PHY Layer Impact on MAC Protocol Analysis

There are two key aspects regarding the proper assessment of MAC protocols under realistic PHY layer and fading channels. The first issue consists in distinguishing between correctly received and corrupted (or erroneous) packets. In particular, a packet is characterized as 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 both the initialization of a cooperation phase and the set of relays that have an active role during the retransmission phase. In this context, special attention should be paid to the shadowing slow variations, in order to choose the most appropriate QoS metric for protocol analysis.

The second key issue lies in the realistic analysis of 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 through similar wireless channels. 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 two aforementioned key issues are extensively analyzed in the following sections, 4.3.1 and 4.3.2, respectively.

4.3.1 Impact of Fast Fading and Shadowing on Packet Reception for QoS Guarantee

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 by the application layer. To that 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, and packet length) and channel models. More specifically, the minimum requirement on the received power for the target QoS 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 eventually determine the performance of MAC protocols. Due to the non-deterministic nature of wireless propagation, protocol analysis and design can be made only statistically, that is, by using proper QoS requirements that account for the statistical distribution of the wireless channel.

To make the discussion more concrete, in our work, the Packet Error Rate (PER) is employed as a metric for QoS provisioning, since we assume that the PER should be lower than a given threshold for a reliable data transmission and packet reception. However, the statistical characterization of the PER strongly depends on the environment in which the study is conducted. In environments where only fast fading is considered, the employment of average metrics, such as the Average PER (APER), is strongly recommended for identifying the correct transmissions, as the rapid fluctuations of the signal over small distances (i.e., on the order of a wavelength) makes it an ergodic process. On the other hand, the criterion of correct packet reception is substantially modified in the presence of slow fading, which, unlike fast fading, is a non-ergodic process for the duration of a communication that is composed of the transmission of several packets. Specifically, although shadowing might change during the communication, its fluctuations are not fast enough to experience all the states of the distribution. Figure 4.2 provides an illustrative example of the received signal strength during a particular communication for the combined effects of fast fading and shadowing. It is clearly illustrated 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 APER exceeds a predetermined value that depends on the QoS requested by the application layer.

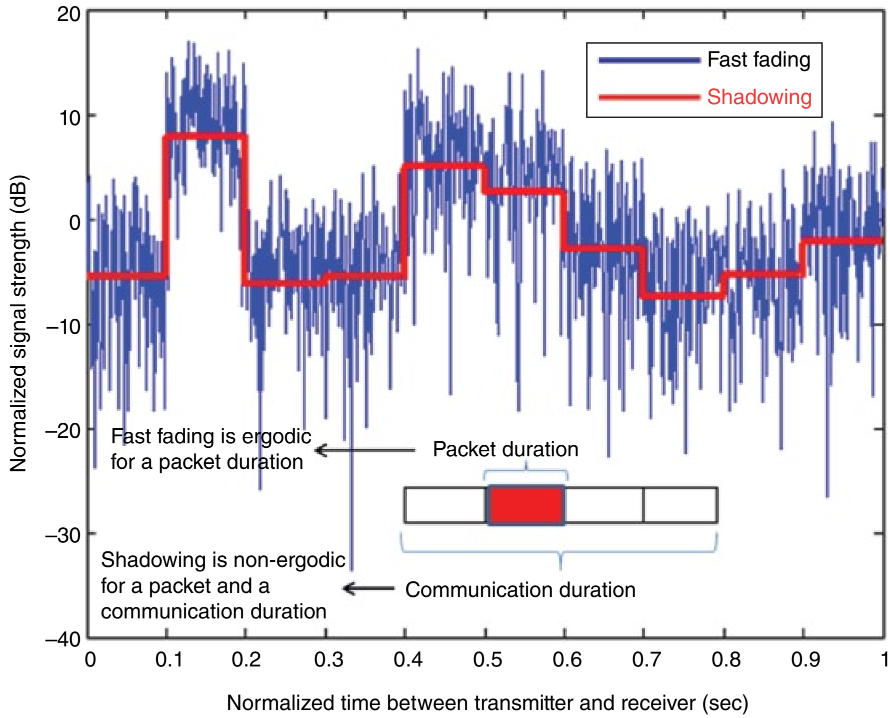

Figure 4.2 Ergodicity of fast-fading vs non-ergodicity of shadowing during a packet and a communication duration.

4.3.2 Impact of Shadowing Spatial Correlation

The lack of spatial diversity is one of the main disadvantages of traditional networking. In conventional networks, packets retransmitted from the same node in subsequent time slots may experience similar, time-correlated bad channel conditions, something that leads to many successive failures. Cooperative communication has been introduced to overcome this limitation, providing the potential for a given packet to reach its destination via different wireless paths, thus increasing the probability of correct reception.

To further clarify, let us consider a cooperative network where two nodes exchange data, assisted by a set of intermediate NC-capable nodes. In such topologies, each transmission path is determined by a relay node, which overhears the transmitted packets, thus being able to apply NC and further forward them to the final destination. In ideal cases, 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, geographically close relays experience correlated shadowing conditions, which usually lead to severe performance degradation.

Hence, in the context of cooperative networks, shadowing spatial correlation is the most important aspect to be considered for a complete performance assessment, as 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 requirement, which affects the overhead associated with the cooperation and the total energy consumption in the network.

4.4 Case Study: NCCARQ

The goal of this section is to highlight the impact of realistic PHY layer on the performance of NC-aided MAC protocols. To that end, we consider as a representative case study the NCCARQ MAC protocol, which coordinates the channel access among a set of NC-capable relay nodes in a bidirectional wireless communication. In the following sections, we briefly review the protocol's operation and we explicitly study the changes due to the realistic PHY layer consideration.

4.4.1 NCCARQ Overview

NCCARQ MAC protocol has been designed to exploit the benefits of both ARQ and NC in two-way cooperative wireless networks, being backwards compatible with the DCF of the IEEE 802.11 Standard. The function of the protocol is based on two main factors: (i) the broadcast nature of wireless communications, which enables the cooperation between the mobile nodes, and (ii) the capability of the intermediate relay nodes to perform NC before any transmission. Figure 4.3 presents an example of the frame sequence in NCCARQ, where two end nodes (*A* and *B*) want to exchange their data packets (*a* and *b*, respectively) with the assistance of three NC-capable relay nodes (R_1, R_2, R_3). The cooperation phase is triggered via the transmission of an RFC control packet after an erroneous packet reception at the destination node. In addition, unlike conventional cooperative ARQ protocols, NCCARQ allows piggyback data transmissions along with the RFC, thus leveraging the NC application. After this notification for cooperation, the relays apply NC to the two data packets and set up their

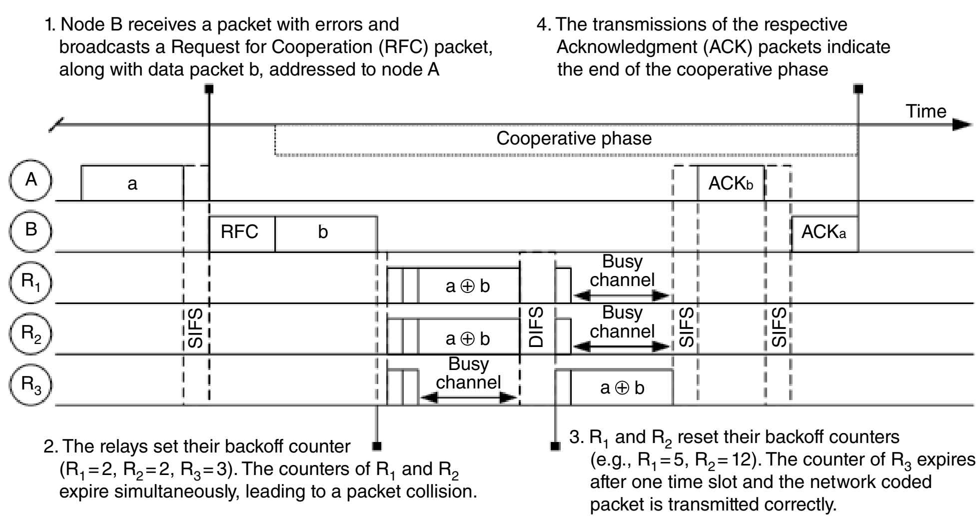

Figure 4.3 NCCARQ operation under ideal channel conditions.

backoff counters according to the DCF rules in order to gain channel access so as to transmit the NC packet ($a \oplus b$) to the end nodes.

The participation of multiple nodes in the contention phase results in idle slots and collisions in the network, before eventually a relay node manages to successfully transmit the coded packet. Subsequently, the correct reception of the coded packet enables the two destinations to sequentially broadcast acknowledgment (ACK) packets, terminating the cooperation phase. However, apart from the collisions and the idle periods, the protocol performance may be also degraded due to fading (either fast or slow) introduced by taking into account non-ideal channel conditions. In the next section, we provide some insights for the modifications that the realistic PHY layer potentially brings to the protocol operation.

4.4.2 PHY Layer Impact

The PHY layer consideration significantly modifies the protocol operation, as it is depicted in Figure 4.4. In particular, the correct packet transmissions define the active relay set, introducing the concept of a node being in outage. Hence, in the extreme case where no relay node has received both packets from *A* and *B*, the relay set is in outage and the cooperation phase ends after a predefined time ($T_{Timeout}$), which is not considered in systems that operate under ideal channel conditions. On the other hand, the reduction of the active relay set due to non-successful packet receptions could be beneficial in networks with many relays, since a smaller number of active relays would lead to a lower packet collision probability in the network. Hence, the aforementioned issues stress the necessity for designing accurate cross-layer models that consider the protocol operation in realistic conditions.

In terms of clarity, let us examine step by step the operational example depicted in Figure 4.4. Initially, node *A* transmits the packet *a* to node *B* and the relays overhear the transmission, but only relays R_1 and R_2 receive a correct copy of the packet. Since node *B* fails to receive the packet, it broadcasts an RFC along with its packet *b* to the relays and, in this case, only R_3 is able to correctly demodulate packet *b*. Apparently, no node has received both packets and, as a result, the relay set is declared to be in outage. After the predefined timeout, node *A* transmits again its packet and, this time, R_1 and R_3 receive the packet correctly. Similar to the previous round, node *B* broadcasts the packet *b* piggybacked on the RFC and all the relays are able to extract this information. However, the active relay set includes only R_1 and R_3, since these are the only nodes with both original packets in their buffers. In this particular example, R_1 sets its backoff counter to 2, while R_3 selects the value of 3. As a result, after two slots, R_1 transmits the network coded packet to the end nodes, which acknowledge the correct reception of the packet, terminating the cooperation phase.

Therefore, as we have mentioned above and as derived by the example, the adoption of a realistic PHY layer can be either beneficial or detrimental for the actual MAC protocol performance. In particular, when all the relays are in outage, there is extra overhead due to the timeout, and a whole communication period could result in no data exchange (e.g, the first communication round in Figure 4.4). On the other hand, in topologies with many relays, the realistic PHY layer assumption could decrease the active relay set, implying a lower collision probability between the contenting stations (e.g, the second communication round in Figure 4.4). To cope with these issues, in the following section we evaluate the actual performance of NCCARQ under realistic correlated shadowing conditions.

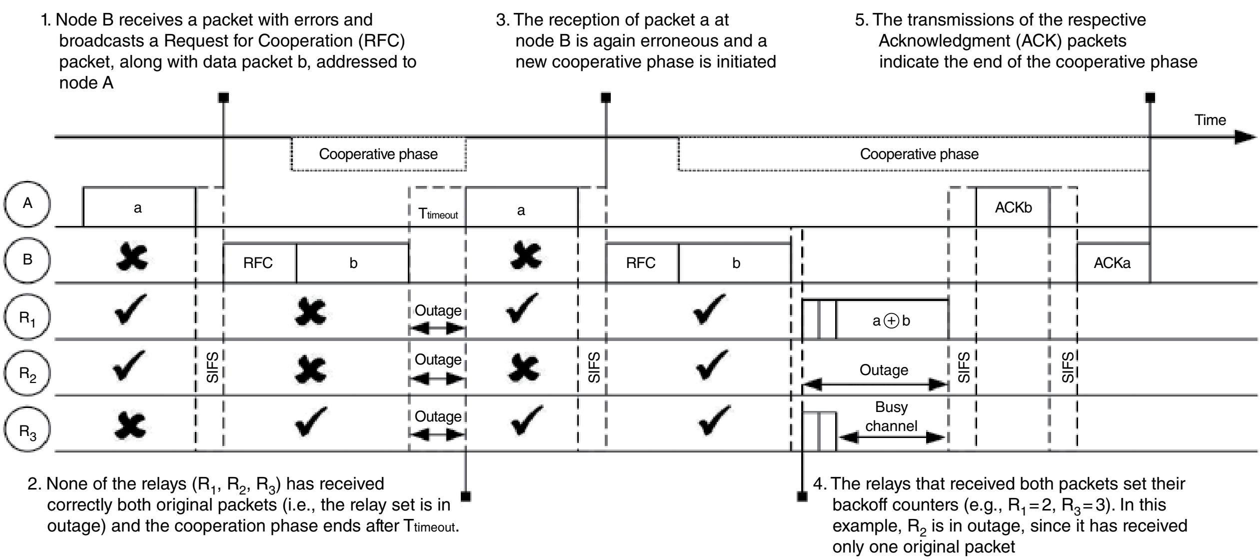

Figure 4.4 NCCARQ operation under realistic channel conditions.

4.5 Performance Evaluation

In order to assess the performance of NC-aided MAC protocols under realistic PHY layer conditions, we have developed an event-driven C++ simulator that implements the NCCARQ rules along with the channel model presented in Figure 4.2. In this section, we present the simulation setup and the results of our experiments.

4.5.1 Simulation Scenario

The considered network, depicted in Figure 4.5, consists of two nodes (N_1 and N_2) that participate in a bidirectional wireless communication, and n relay nodes (R) that contribute to the data exchange. In the same figure, the shadowing correlation between the different links is highlighted, and the close proximity of the relays implies that: (i) any pair of $\left(N_1 \rightarrow R_i, N_1 \rightarrow R_j\right)$ links is equally correlated[1] with correlation factor ρ_1; (ii) any pair of $\left(N_2 \rightarrow R_i, N_2 \rightarrow R_j\right)$

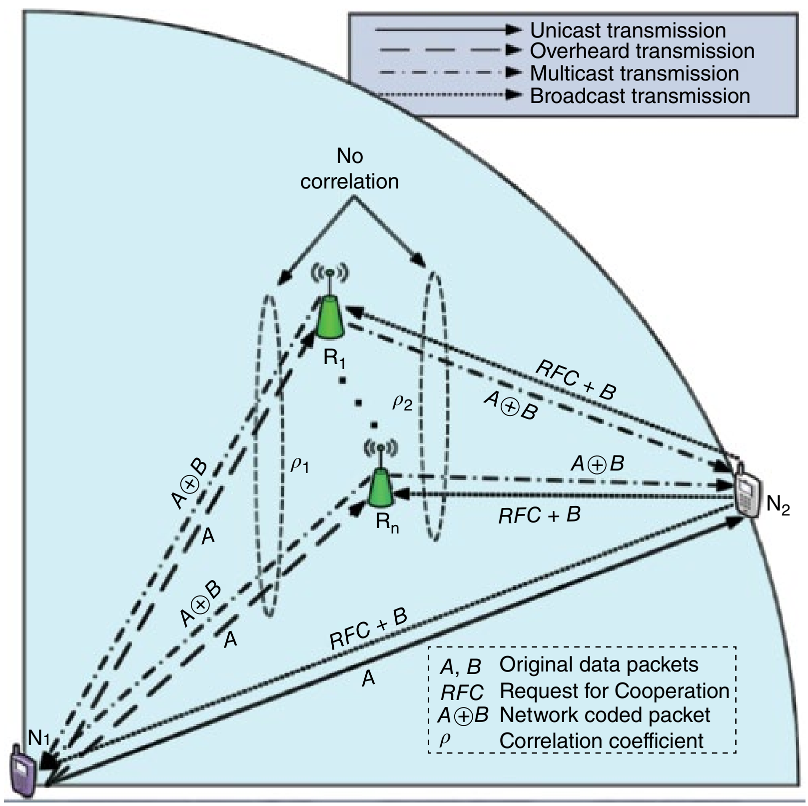

Figure 4.5 Simulation scenario.

[1] Please note that different correlation models (e.g., exponential) could be also considered. [29]

links is also equally correlated with correlation factor ρ_2; and (iii) pairs of $N_1 \rightarrow R_i$ and $N_2 \rightarrow R_i$ links are independent, which is a reasonable assumption according to measurements in reference [30]. Furthermore, we adopt a symmetric network topology with $\rho_1 = \rho_2 = \rho$.

The MAC layer parameters have been selected in line with the IEEE 802.11g Standard specifications [24]. In particular, the initial Contention Window (CW) for all nodes is 32, the MAC header overhead is 34 bytes, while the time for the application of NC to the data packets is considered negligible, as the coding takes place only between two packets. We also consider time slots, SIFS, DIFS and timeout intervals of 20, 10, 50, and 80 μs, respectively. In addition, based on the work of Ebert *et al.* [31] on the power consumption of the wireless interface, we have chosen the following power levels for our scenarios: $P_{Tx} = 1900$ mW and $P_{Rx} = P_{idle} = 1340$ mW. Regarding the PHY layer parameters, we have set the reliability threshold $\gamma^* = 16.14\,\text{dB}$, which corresponds to a target $APER = 10^{-1}$. Furthermore, we assume a relatively weak direct $N_1 \rightarrow N_2$ link ($\bar{\gamma}_{N_1 \rightarrow N_2} = 8\,\text{dB}$) with respect to the SNR threshold γ^*, in order to trigger the cooperation and focus our study on the impact of correlated shadowing. To that end, we also consider two different cases for the $N_1 \rightarrow R_i$ and $N_2 \rightarrow R_i$ links: (i) a scenario where the average SNR in the cooperative links is lower than γ^* (i.e., $\bar{\gamma}_{N_1 \rightarrow R_i} = \bar{\gamma}_{N_2 \rightarrow R_i} = 10\,\text{dB}$), and (ii) a scenario where the average SNR in the cooperative links is higher than γ^* (i.e., $\bar{\gamma}_{N_1 \rightarrow R_i} = \bar{\gamma}_{N_2 \rightarrow R_i} = 20$ dB). The simulation parameters are summarized in Table 4.1.

4.5.2 Simulation Results

Figure 4.6 depicts the average number of active relays[2] for different values of shadowing standard deviation σ, assuming strong links between the end nodes N_1, N_2) and the relays (R_i), that is, $\bar{\gamma}_{N_1 \rightarrow R_i} = \bar{\gamma}_{N_2 \rightarrow R_i} = 20$ dB. In this plot, we consider different total number of relays and various indicated values for the correlated factor (ρ), deriving two important conclusions. First, the experiments show that the average number of active relays is independent of the

Table 4.1 Simulation parameters.

Parameter	Value	Parameter	Value
Packet Payload	1500 bytes	CW_{min}	32
T_{slot}	20 μs	$T_{Timeout}$	80 μs
SIFS	10 μs	*DIFS*	50 μs
MAC Header	34 bytes	*PHY Header*	96 μs
Data Tx. Rate	54 Mb/s	*Control Tx. Rate*	6 Mb/s
γ^*	16.14 dB	σ	[0, 10] dB
$\bar{\gamma}_{N_1 \rightarrow R_i} = \bar{\gamma}_{N_2 \rightarrow R_i}$	{10, 20} dB	$\bar{\gamma}_{N_1 \rightarrow N_2}$	8 dB
P_{Tx}	1900 mW	P_{Rx}	1340 mW
P_{idle}	1340 mW	ρ	[0,1)

[2] In our experiments, we assume that the channel conditions remain unchanged for one communication round, which includes the direct and the cooperation phase, and the average number of active relays results from several iterations.

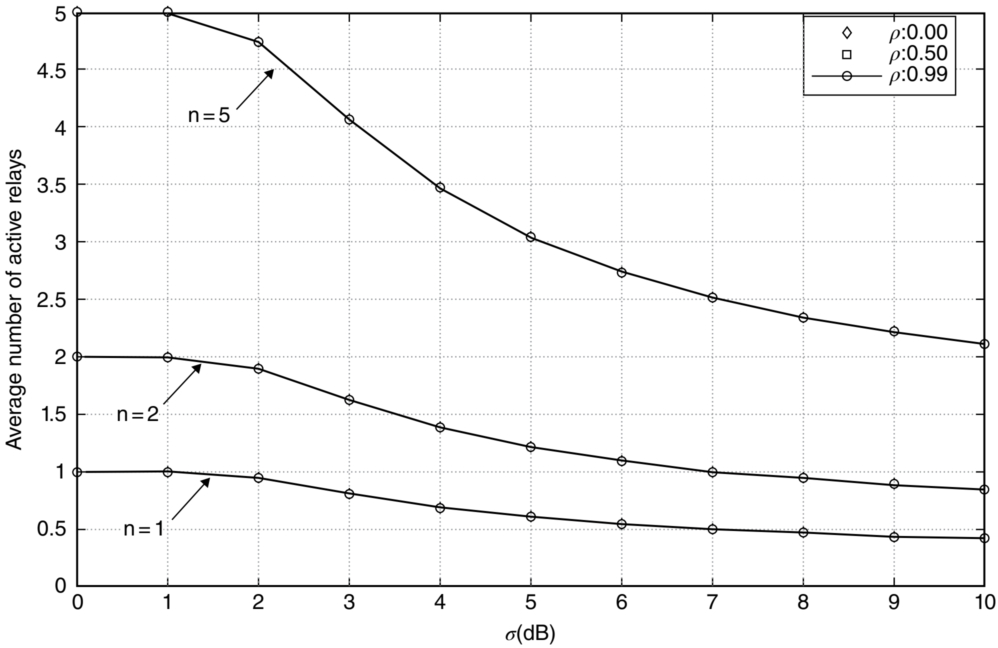

Figure 4.6 Average number of active relays vs shadowing standard deviation (σ).

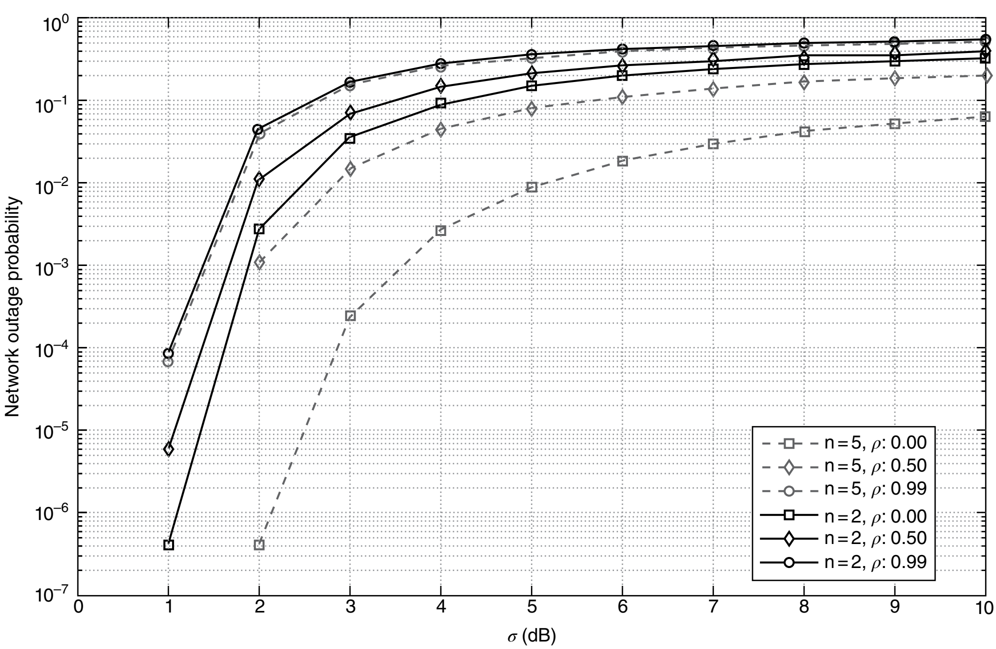

Figure 4.7 Network outage probability vs shadowing standard deviation (σ).

shadowing correlation among the wireless links. The second important remark concerns the negative effect of σ in the number of active relays. In this particular scenario, where the mean SNR value is above the threshold γ^*, the shadowing variation has a detrimental role in the communication. As a result, higher values of σ reduce the expected size of active relay set, thus restricting the diversity benefits from cooperation.

Figure 4.7 illustrates the simulation results for the network outage probability (i.e., the probability that none of the relays receives both original packets) for different factors of correlation (ρ) and number of relays (n). The impact of shadowing correlation on the system is clearly demonstrated in the figure, since high values of ρ cause almost identical outage probability for the network independently of n, annulling the advantages of distributed cooperation. On the other hand, independent wireless links ($\rho = 0$) exploit the diversity offered by the relays, considerably reducing the outage probability as the total number of relays in the system increases (e.g., $n = 5$). In addition, similar to the previous case, where the expected active relay set was studied, the shadowing deviation deteriorates the system performance, increasing the probability of having no active relay in the system. However, even for high values of σ, the factor ρ determines and sets the boundaries for the gains that can be achieved in cooperation scenarios.

In Figure 4.8 and Figure 4.9, we study the impact of shadowing standard deviation (σ) on the network throughput for different numbers of relay nodes (n). In particular, Figure 4.8 corresponds to the case where the mean value of the average SNR between the end nodes and the relays is below the SNR reliability decoding threshold and, consequently, the average throughput increases with the σ, since it is not possible to achieve a successful communication without the random fluctuations introduced by shadowing. On the other hand, in Figure 4.9, we are

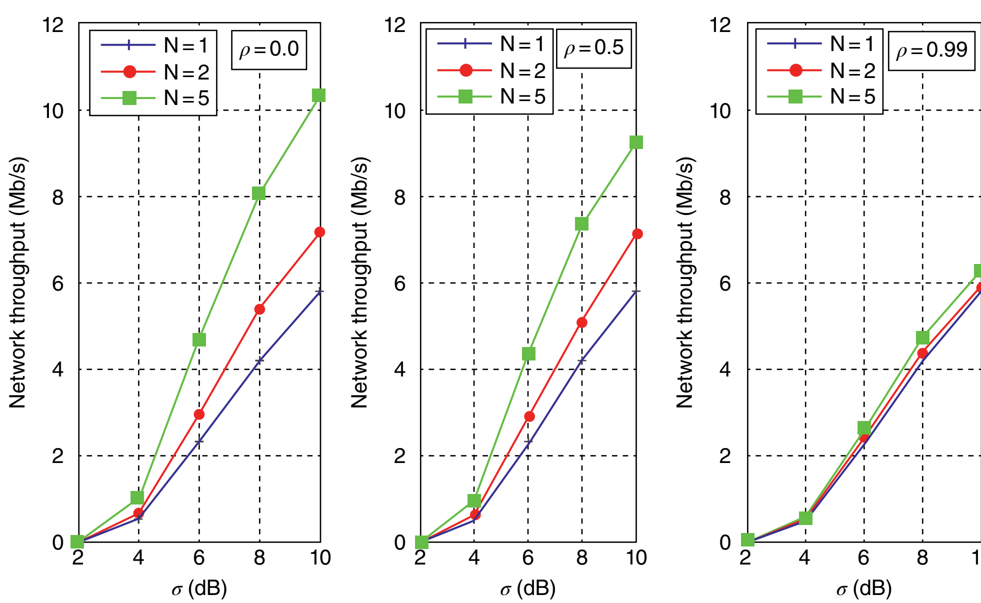

Figure 4.8 Average network throughput vs shadowing standard deviation (σ) for relatively weak cooperative links.

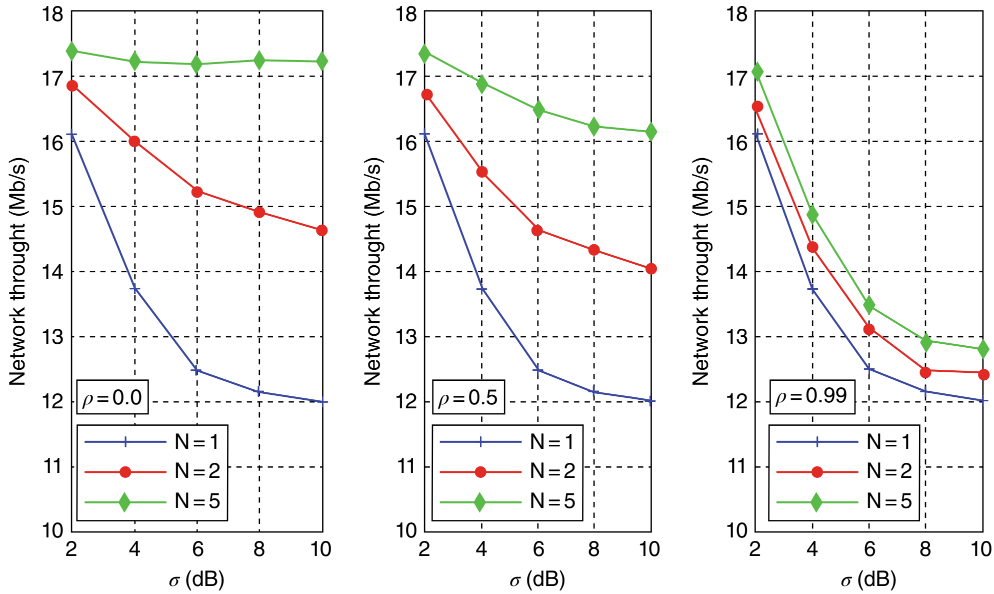

Figure 4.9 Average network throughput vs shadowing standard deviation (σ) for relatively strong cooperative links.

interested in the network throughput performance in a scenario where the mean SNR value is above the reliability threshold. In this specific case, the wireless communication would be always successful without the shadowing random fluctuations and, hence, shadowing is harmful for the system, as it introduces many events where the received SNR is below the threshold γ^*.

In both case studies, we highlight two important remarks regarding the network throughput: (i) distributed cooperation is beneficial, as the throughput increases with the number of available relays (n), and (ii) shadowing correlation is detrimental to the potential gain introduced by cooperation. Specifically, distributed cooperation tends to be useless for high correlated factors ($\rho \to 1$), since all the relays experience very similar shadowing attenuations, and the throughput reduces to that of a single-relay network. This result is important for network design, where the deployment cost (Capital Expenditure – CapEx) of many relays cannot 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 of the shadowing parameters σ and ρ), we are able to choose the best (minimum) number of relays that achieves the desired performance, as well as the most appropriate placement of the relays for network topologies with fixed relay stations. However, the CapEx minimization does not imply optimum Operational Expenditure (OpEx) for the network. To that end, the energy efficiency in the network should be also studied, since energy consumption has been a matter of paramount importance for the operators in order to reduce their costs and provide "green" services to the mobile users.

Figure 4.10 and Figure 4.11 present the network energy efficiency for $\bar{\gamma}_{N_1 \to R_i} = \bar{\gamma}_{N_2 \to R_i} = 10$ dB and $\bar{\gamma}_{N_1 \to R_i} = \bar{\gamma}_{N_2 \to R_i} = 20$ dB, respectively, revealing intriguing facets of the problem. In Figure 4.10, we observe that the energy efficiency in multi-relay networks decreases as the

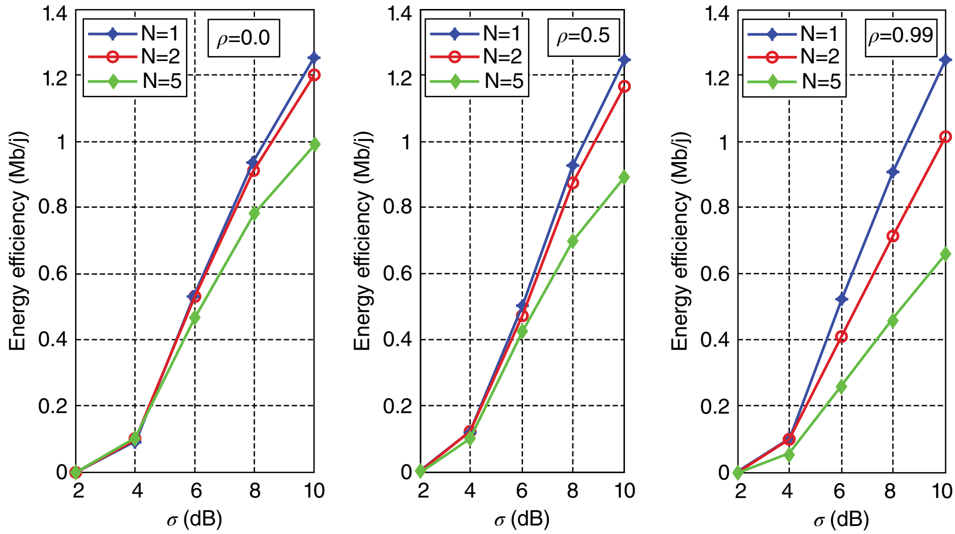

Figure 4.10 Average energy efficiency vs shadowing standard deviation (σ) for relatively weak cooperative links.

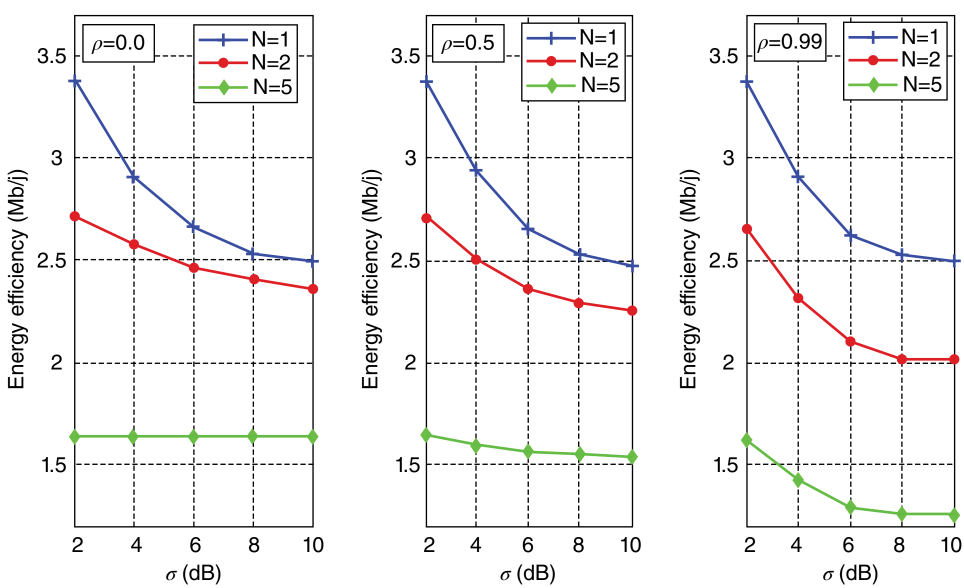

Figure 4.11 Average energy efficiency vs shadowing standard deviation (σ) for relatively strong cooperative links.

correlation between the links increases. This result can be intuitively explained by the fact that the number of relays does not affect the system performance in highly correlated links and, hence, the deployment of many relays in the network affects the OpEx of the system without providing better QoS. The plots in Figure 4.11 are even more impressive, since they disclose a notable trade-off between the system throughput and energy efficiency. In particular, although distributed cooperation provides significant gains in the throughput for high SNR scenarios (Figure 4.9), it has a negative impact on the energy efficiency, reducing it by up to 100% under specific conditions. This fact can be explained by taking into account the high throughput (12 Mb/s) achieved in single-relay networks under good channel conditions. Cooperation may increase this performance up to 18 Mb/s, but the aggregated energy consumption of many relays in the network results in a significant reduction of the total energy efficiency. These interrelated results can be exploited by network designers to decide the optimum network topology and the most efficient relay placement in cooperative networks, taking into account their provided services along with the expected expenditures.

4.6 Conclusion

In this chapter, we have discussed cooperation scenarios in next generation networks and we have thoroughly investigated the impact of realistic PHY layer and channel conditions on the performance of two-way ARQ cooperative MAC protocols. As a case study, we investigated the performance of NCCARQ, a MAC protocol for wireless networks that exploits NC and distributed cooperation in bidirectional communication scenarios. The performance assessment of the protocol has revealed notable trade-offs between the achieved throughput and energy efficiency in the network. Our results clearly showcase the importance of considering realistic channel models for a sound design and analysis of cooperative MAC protocols, motivating the operators to take into account non-ergodic spatially correlated shadowing for an optimum network deployment and relay placement in next generation networks.

Acknowledgements

This work has been funded by the Research Projects GREENET (PITN-GA-2010-264759) and CROSSFIRE (MITN-317126).

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