Helmut Leopold Adam
Matr.-Nr. 9830200

Cooperative Diversity in Wireless Networks: Relay Selection and Medium Access

DISSERTATION

zur Erlangung des akademischen Grades
Doktor der technischen Wissenschaften

Alpen-Adria-Universität Klagenfurt
Fakultät für Technische Wissenschaften

Begutachter:

Univ.-Prof. Dr.-Ing. Christian Bettstetter
Institut für Vernetzte und Eingebettete Systeme
Alpen-Adria-Universität Klagenfurt

Univ.-Prof. Dr. Holger Karl
Institut für Informatik
Universität Paderborn

08/2011

Declaration of honor

I hereby confirm on my honor that I personally prepared the present academic work and carried out myself the activities directly involved with it. I also confirm that I have used no resources other than those declared. All formulations and concepts adopted literally or in their essential content from printed, unprinted or Internet sources have been cited according to the rules for academic work and identified by means of footnotes or other precise indications of source.

The support provided during the work, including significant assistance from my supervisor has been indicated in full.

The academic work has not been submitted to any other examination authority. The work is submitted in printed and electronic form. I confirm that the content of the digital version is completely identical to that of the printed version.

I am aware that a false declaration will have legal consequences.

(Signature) (Place, date)

Cooperative Diversity in Wireless Networks: Relay Selection and Medium Access

Wireless communication systems suffer from a phenomenon called small scale fading which causes rapid and unpredictable fluctuations in the received signal strengths. Traditional methods to mitigate small scale fading effects impose restrictions on the data exchange process and/or the used hardware which limit their applicability.

Recently, information theory has proven that cooperative diversity is an effective means to combat the effects of small scale fading. In such an approach common neighbors of a communication pair can act as relays for packets which would otherwise be lost due to bad channel conditions. These studies, however, have mainly focused on physical layer aspects such as link capacity, coding, and relay positioning. In such studies, source, destination, and relaying nodes are known a priori. Setting up cooperation in a network has found less attention.

In this thesis, we illustrate that obtaining theoretical gains of cooperative diversity is not straightforward and we address issues regarding networking and protocol aspects of cooperation.

We first elaborate on the relay selection process. We propose and evaluate relay selection methods which increase the efficiency of cooperative diversity in terms of energy, time, and success. We show how to incorporate channel and routing information into the selection process to reduce the energy consumption and time overhead of cooperation. We illustrate how the relay selection depends on the knowledge of relay candidate cardinality. Such knowledge is also of interest in numerous other fields like medium access, routing, and information dissemination to name a few. To this end, we propose and evaluate methods based on probabilistic trials which aim to estimate the number of neighbors with a desired accuracy and minimum time overhead. As a final step, we integrate our proposed mechanisms into the design of a novel medium access protocol which facilitates cooperative diversity by handling the cooperative packet flow, selecting a relay node, and making the necessary resource reservations. We evaluate the performance of the resulting system in terms of throughput and delay for different network parameters such as node density, channel coherence time, and data packet size.

Our findings indicate that by using the proposed simple yet efficient mechanisms that are not restricted by hardware, we can deploy cooperative diversity with substantial gains in the large-scale wireless networks of the future consisting of low-end devices.

Acknowledgments

First of all I would like to thank my advisor Prof. Dr.-Ing. Christian Bettstetter who gave me the opportunity to write this thesis in a professional, international and friendly environment. His guidance, support and patience made it possible for me to achieve publications at well known conferences and to finally write this thesis. I also want to thank Prof. Dr. Holger Karl for reading and commenting on my work.

Next, I thank all my colleagues at the Mobile Systems Group for their overall support, their advice and our fruitful and entertaining discussions. Their doors were always open for all my questions and concerns. In particular, I would like to mention the original members of the mobile systems group Udo Schilcher and Sérgio Crisóstomo, and our senior researchers Wilfried Elmenreich and Evşen Yanmaz.

Special thanks go to Sidi Mohammed Senouci who was the project leader in the cooperative diversity project with Orange Labs France. The outcome of this project forms the basis of this thesis. I appreciated our project meetings which brought up new research directions and ideas.

Writing a PhD thesis feels sometimes like a Sisyphus task. In that sense, I am grateful for the patience and the support of my family and my friends.

Last but definitely not least, I would like to express my deep gratitude to my girlfriend. When I was depressed I had her shoulder to lean on and she did not get tired of cheering me up, when I was occupied with research problems she gave me the time to figure out a solution without complaining, when I needed her professional opinion she was happy to provide it, and when I needed someone to proof read my thesis she had to suffer with my German-English writing style. My discussions with her and her hints heavily contributed to the quality of my thesis. Moreover, having her in my life makes me complete.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Mobile communication has undergone a tremendous revolution in recent years. The global number of mobile phone subscribers has increased from 750 million to 5.1 billion in the last decade. In developed countries, people have on average more than a single subscription [ITU11]. Beside the subscriber growth, also the achievable data rate of the devices has experienced enormous increases. For instance, Global System for Mobile Communications (GSM) offers a maximum data rate of 9.6 kbit/s, its successor Universal Mobile Telecommunication System (UMTS) reaches data rates up to 384 kbit/s, and Long Term Evolution (LTE) supports 326.4 Mbit/s.

We also see an emergence of a network of things, since more and more devices are capable of communicating with each other using the wireless medium. Having more devices which communicate with each other at higher data rates, put high demands on the used technology, especially since the wireless medium is a harsh environment. Mobile communications are affected mostly by a phenomenon called *Small Scale Fading*, which results in unpredictable and rapid fluctuations of the received signal levels. Since the achievable data rate mainly depends on the received signal strength, it is of utmost interest to communication engineers to effectively combat the effects caused by small scale fading.

Cooperative diversity is a promising means where wireless communication devices cooperate to mitigate those effects. While the information theory and physical layer aspects of cooperative diversity have been heavily investigated, networking aspects have been mostly unattended. This thesis focuses on the networking aspects of cooperative diversity.

1.1 Fading in Wireless Communication Channels

Radio signals are influenced by large-scale and small-scale fading phenomena [TV05]. Large-scale fading effects summarize influences on the radio signal due to motion over large areas. For instance, distance dependent path loss and shadowing are large-scale fading effects. The influence on the radio channel is typically frequency independent

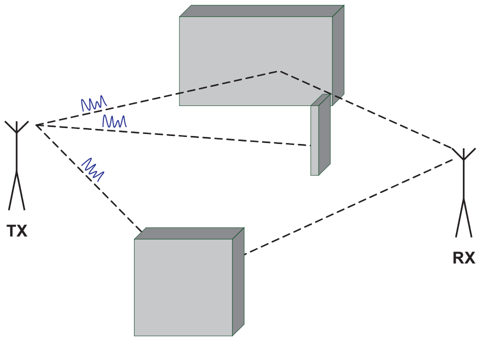


Figure 1.1: Multipath propagation

and changes only gradually over time. Large scale fading occurs on a time base of seconds up to minutes and is addressed by cell planning in cellular networks or by routing algorithms in ad-hoc networks.

Small-scale fading phenomena cause rapid fluctuations of the signal strength as a result of small changes in the communication scenario. For instance, the sender and/or the receiver move some fraction of the wavelength of the used carrier frequency, or changes in the communication environment occur. The effects of small-scale fading on the wireless channel are frequency dependent, highly dynamic and unpredictable. It is not possible to mitigate these effects by cell planning or routing approaches. Thus, small-scale fading represents the main limiting factor for wireless communication systems.

In the following, we elaborate on small-scale fading in more detail.

Small-Scale Fading

Electromagnetic waves that radiate from a transmitting antenna strike obstacles during their propagation toward the receiving antenna. Depending on the nature of those obstacles, the waves experience reflection, diffraction, or scattering (see Figure. 1.1), and finally, multiple waves which propagate via different paths (multipath propagation) impinge on the receiver. Those waves superimpose constructively or destructively depending on their phase shifts and time delay. Small changes in the communication setting, e.g., moving transmitter and/or receiver or changes in the environment, results in different multi-paths and thus in diverse received signal-to-noise ratios (SNRs). Indeed, deep fades, i.e., locations where the received signals are below the noise floor and places of error free receptions are only separated by some fraction of the wavelength of the carrier frequency [Skl97a]. Communicating nodes suffer from fading effects even when they do not move, which reveals the time variance of the channel caused by changes in the environment.

Small scale fading manifests itself in two ways [Skl97a]:

- *Time spreading of the signal:*
  Due to the varying propagation delay of the multiple paths, a single transmitted pulse is spread over a longer period than the pulse duration when it is received at the destination. We talk about *frequency selective* fading, if the time-spreading is longer than a symbol duration. This kind of fading causes interference between consecutive symbols (cf. inter symbol interference (ISI) [TV05]). We refer to *frequency non-selective* or *flat fading* if the time-spreading of the signal is smaller than a symbol duration.

  A means to assess the frequency selectiveness of a channel is the *coherence-bandwidth*. It corresponds to the frequency bandwidth which is affected similarly by the channel.

- *Time varying of the channel:*
  The wireless channel is time varying because of transmitter and receiver motions and/or changes in the communication environment which alter wave propagation paths. If the channel changes considerably during a single symbol duration we refer to *fast fading* conditions. In *slow fading* channels all components of a symbol gets affected similarly.

  A means to assess the time variance of a channel is the *channel coherence-time*. It is a measure of the expected duration in which the channel stays essentially constant.

We can differentiate small scale fading based on the existence of a line of sight between transmitter and receiver. We refer to *Rician fading* if a strong line of sight component among the waves impinging on the receiver exists. In such cases, we can model the received signal amplitude by a random variable following a Rician probability density function (pdf). We observe *Rayleigh fading* in the absence of a dominating wave component. A random variable having a Rayleigh pdf can model the received signal amplitude of this kind of fading.

We use Figure 1.2 to illustrate the effects of different fading realizations on the bit error rate (BER) of a Binary Phase Shift Keying (BPSK) modulated signal as a function of the averaged received SNR [Skl97a]. The BER of the Additive White Gaussian Noise (AWGN) channel decreases fast with increasing SNR. Flat and slow fading Rayleigh channels suffer from a loss in the received SNR due to potential destructive superimposing waves. We observe the worst BER performance over SNR for frequency selective and fast fading channels.

Small-Scale Fading Mitigation Techniques

Figure 1.2 indicates that the true limiting factor of wireless communication is represented by small-scale fading. For flat and slow-fading Rayleigh channels, we need some 30 dB more transmission power than for AWGN channels to achieve a BER of

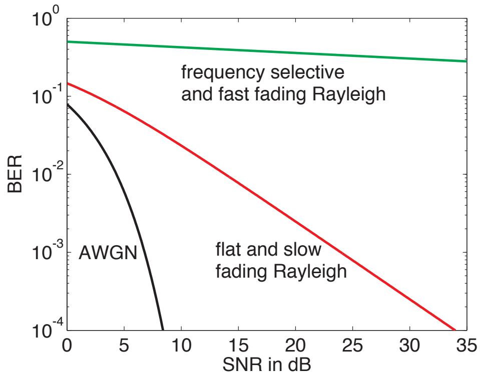


Figure 1.2: BER of BPSK modulated data in AWGN and Rayleigh channels

10^{-4}. The situation is even worse for frequency selective and fast fading channels. In such fading environments the communication suffers mostly from interference among consecutive symbols.

Especially for frequency selective and fast fading channels, it is not feasible to compensate the signal distortions by transmission power adjustments. It is essential to alleviate those signal distortions with appropriate techniques which we summarize here after [Skl97b]:

- **Equalization:**
  This method compensates the channel induced ISI by introducing a filter at the receiver that inverts the effects of frequency selective fading. The filter parameters need to be periodically adjusted due to the time-varying nature of the channel. Therefore, the source transmits predefined training sequences, i.e., bit pattern before the actual data transmission. The receiver node determines the channel transfer function based on the reception of the training data. Depending on the coherence-time, training sequences may need to be sent also during a packet transmission. However, when the receiver is in a deep fade, i.e., the received signal is below the detection threshold of the receiver, equalization fails.

- **Spread spectrum techniques:**
  These techniques spread signals over a larger bandwidth to increase the resistance of those signals against interference.
  - In *Direct Sequence Spread-Spectrum (DSSS)*, the transmitter substitutes information bits by chip codes. The receiver uses code correlation to obtain the original information bits. This decoding eliminates multi-path interference as long as the chip code duration is equal or greater than the time spread.
  - *Frequency Hoping Spread-Spectrum (FHSS)* mitigates channel induced ISI provided that the used frequency is changed before the arrival of the multi-path signals.

  - *Orthogonal Frequency-Division Multiplexing (OFDM)* addresses the problem of frequency-selective fading by broadening the symbol duration. OFDM divides the available signal bandwidth in multiple sub-bands and uses multiple carriers to transmit simultaneously in those sub-bands. The symbol rate of each sub-band should be smaller than the channel's coherence-bandwidth.

- **Error correction coding and interleaving:**
  Channel coding adds redundant information to transmitted packets. The receiver uses this information to detect and correct transmission errors. Additionally, the interleaving technique can protect transmissions against deep fades. Interleaving divides the coded data stream into chunks and changes the order of these chunks. The transmitter sends this scrambled data stream. The receiver puts the chunks back into their right order and decodes the data. The size of the interleaver should assure that a deep fade hardly ever affects two consecutive chunks in their right order. The maximum allowed delay in a communication system limits the size of the interleaver.

Most of the named techniques repair the signal distortions but do not recover the loss of SNR caused by superposition of multi-path signals. Thus the performance of the distortion-repaired frequency selective or fast fading channel is equivalent to the flat or slow fading channel (see Figure 1.2).

The combat of SNR loss is mainly achieved by exploiting diversity. The fundamental concept behind diversity is to send the same signal over uncorrelated channels to the receiver. Thus, during a deep fade in one channel, the fade will not be so severe in others. The receiver employs a diversity combiner to mix the received signals from the uncorrelated channels. Diversity can be classified by the method used to achieve the independence of the different channels [Skl97b]:

- Time diversity: a packet is transmitted several times at different time instances. When the time spacing between two transmissions is large enough, i.e., larger than the coherence-time of the channel, their fading conditions are uncorrelated from each other. For instance, Automatic Repeat Query (ARQ) schemes where the source retransmits the data packet on demand of the destination utilizes time diversity. Forward error correction coding in combination with an interleaver represents another example of time diversity.

- Frequency diversity: a packet is transmitted on different, sufficiently spaced carrier frequencies. When the difference between the carrier frequencies is larger than the coherence-bandwidth of the channel the transmissions experience uncorrelated fading situations. OFDM achieves both signal distortion mitigation and frequency diversity because of its multiple orthogonal carrier frequencies.

- Polarization diversity: a packet is transmitted via multiple antennas with different polarization. Due to the different polarization of the signals, waves behave differently when they hit obstacles.

- Spatial diversity: source and/or receiver use multiple antennas. When those antennas are spaced sufficiently wide apart from each other the signals sent and/or received experience different fading. The necessary spacing of antennas to achieve diversity, i.e., uncorrelated channels depends on the environment. Mobile devices are normally surrounded by many obstacles that scatter and reflect signals. Thus, their antenna spacing need to be just a half up to one wavelength of the used carrier frequency. On the other hand, base stations of cellular networks are normally mounted at high towers with only a few objects surrounding them. Their antenna spacing needs to be several wavelengths to obtain uncorrelated channels [TV05].

Wireless communication systems mostly apply multiple antennas at transmitter and/or receiver side to mitigate the SNR loss caused by fading. Frequency diversity schemes might not be applicable due to bandwidth regulation, and the effectiveness of time-diversity depends on the coherence-time of the channel and the required data throughput/delay. For instance, a system cannot use time-diversity if the maximum tolerable delay of a packet is smaller than the coherence time of the channel. Finally, it is possible and appealing to combine multiple-antenna techniques with other methods such as equalization, frequency diversity, and channel coding.

However, using multiple antennas at a node requires more complex radio architecture, increased energy costs, more expensive hardware, and a certain minimum device size. For an effective application in mobile ad-hoc networks (MANETs), all nodes need to be equipped with multiple antennas. This is not always practically feasible on small and cheap mobile devices.

1.2 Cooperative Diversity

Cooperative diversity [SEA98] is a promising technique that addresses the disadvantage of using multiple antennas. The main idea is that neighboring nodes cooperate by sharing their antennas to achieve spatial diversity. A single node does not require multiple antennas nor complex receiver hardware to benefit from diversity effects. The increasing node density ensures the existence of multiple neighbors that can virtually share their antennas (cf. virtual antenna arrays [DDA02]) among each other.

1.2.1 Basic Idea

Figure 1.3 illustrates the basic idea of cooperative diversity. In the given example, source node S tries to transmit a packet to destination node D. Due to the broadcast nature of the wireless medium, all nodes in transmission range of S can basically overhear this data exchange. This comes without any additional cost except the energy consumed for receiving the information. Depending on the actual channel properties, node D may not receive or may not correctly decode the packet from S. In such situations, a retransmission from S could — depending on the coherence

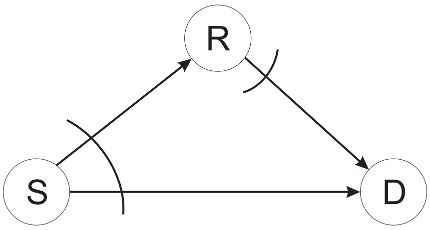


Figure 1.3: Simple example of cooperative diversity

time of the channel — fail again. Thus, it might be beneficial to exploit a common neighbor.

In the simplest form of cooperative diversity, a single node — in the depicted example denoted by R — overhears the transmission from S and relays it to D afterwards. Hence, this node is called *relay*. We observe that a communication attempt using cooperative diversity has at least two phases. In the first phase, the direct transmission from S to D takes place. During this phase, R also overhears this data transmission. We refer to this phase from now on as *direct transmission phase*. In the second phase, R forwards the packet to D. We denote this phase *cooperative transmission phase*. Since the packet from S reaches D via two independent paths, diversity is achieved. Furthermore, we observe that cooperative diversity exploits both spatial and time diversity.

1.2.2 Challenges of Cooperative Diversity

In this section, we present an overview of the challenges and research issues of cooperative diversity. The basic concept is intuitive: neighbors of a pair of communication nodes overhear their information exchange and eventually assist them (see Figure 1.3).

First of all, it is imperative to determine if and when the concept of cooperative diversity bears any gain compared to non-cooperative[1] schemes. More specifically, it has to be shown that cooperative diversity can achieve a lower outage probability[2] than a non-cooperative scheme in a fading environment. We have to keep in mind that cooperative diversity requires two data transmissions. For a fair comparison in terms of outage, cooperative diversity has to transmit with twice the data rate and must not consume more energy than the non-cooperative scheme, i.e., have the same spectral-efficiency. Therefore, a scheme using cooperative diversity needs to achieve a higher data rate between S and D than a non-cooperative scheme for a given error probability and equal total energy consumption.

---

[1] We use the term non-cooperative for schemes where each node has a single antenna and does not employ any small-scale fading mitigation technique in this work.

[2] The outage probability [Gol05] is an information theoretic term defined as $p_{\mathrm{out}} = \Pr\left[I\left(X;Y\right) < R\right]$, where $I\left(X;Y\right)$ is the mutual information which depends on the used protocol and fading coefficient and R is the target rate. An outage occurs when the mutual information $I\left(X;Y\right)$ is smaller than R, i.e., the destination can not correctly decode the packet from the source.

Once the basic concept has shown its potential, challenges regarding how to realize cooperative diversity need to be addressed. We distinguish between physical and network layer challenges.

To adequately represent the physical layer aspects, we consider the basic cooperative system of a source node S, a destination node D and one or more relaying nodes. Let us first assume a single relay node R. Intuitively, the performance of cooperative diversity heavily depends on the characteristics of R. Obviously, R needs to be in transmission range of S and D to be of any use. However, it is unclear where its optimum position with respect to S and D is.

The basic concept of cooperative diversity assumes simple repetition coding at the relay. It receives the data from S and forwards it to D. The combination of the packets from S and R at D represents a challenge. A solution would be to use Maximal Ratio Combining (MRC) as it is also employed in multiple-antenna systems, which requires certain features in the applied transceiver architecture. However, it is well known that repetition coding is not a worthy approach. Hence, it is of interest to investigate the integration of more powerful channel codes into the basic concept of cooperative diversity.

Another physical aspect deals with the actual number of relays assigned to a communication pair. In spatial-diversity schemes using multiple antennas per node, the outage probability improves with increasing number of antennas [Rap02]. It is natural to investigate whether a similar effect occurs in cooperative diversity by exploiting multiple relays. In addition, for cooperative diversity it is also necessary to explore methods to coordinate multiple relays and to investigate whether the overhead of employing multiple relays to support a single link delivers the desired gain.

Finally, it is of interest to quantify the advantages and disadvantages of cooperative diversity with respect to multiple-antennas systems. For instance, cooperative diversity might not be as efficient in terms of outage as spatial diversity schemes using multiple-antennas. On the other hand, in cooperative schemes nodes do not need to provide space for multiple-antennas and their transceiver-architecture is less complex. There may be other domains and application scenarios where cooperative diversity is superior which needs to be identified.

Next, let us shift our focus to networking aspects of cooperative diversity. First of all, it is not intuitive whether cooperation can be beneficial in a network scenario, even if it is beneficial to a single link. The increased number of transmissions due to cooperative diversity could increase the interference and hence reduce the spatial re-usability of the wireless medium. This might result in degradation of the overall performance of a network in terms of throughput and network life time.

Furthermore, in any network, regardless of whether it is cellular or ad-hoc, a key operation of cooperative diversity is to determine and assign relays to communication pairs. In this context, it is of interest to specify the criteria to efficiently select relays. It is also imperative to design the selection operation such that capable relays are found with minimum overhead and to integrate the necessary functionality for enabling cooperative diversity in the layered protocol stack. It is worth investigating potential synergy effects of cooperative diversity with existing layers in the protocol stack such as Medium Access Control (MAC) and routing.

Until now, we have focused on the challenges of cooperative diversity assuming the availability of potential relays. However, for the success of cooperative diversity nodes which have good channel conditions sacrifice some of their resources to help others. There is no conflict of interest as long as all nodes in the network aim to accomplish a common goal. However, in commercial networks each node has its own goal and might act selfishly. Hence, a challenge is to find incentives to enforce cooperation and to detect and punish selfishness.

A detailed overview of existing work that addresses some of these issues is provided in Chapter 2.

1.3 General Modeling Assumptions

Throughout this work, we assume low cost radio architectures: the transceiver does not support multiple antennas and does not utilize powerful channel codes. Moreover, the transceiver cannot simultaneously transmit and receive, i.e., it is constrained to half-duplex operations. The radio supports BPSK and Quadrature Phase Shift Keying (QPSK) modulation with a fixed symbol rate and a fixed energy per symbol value, i.e., it does not support power adjustment. Such low cost radios cannot or do not exploit any channel state information (CSI) at the transmitter side. The radios are, however, capable of determining the SNR-value of a received signal which is a common assumption in existing works ([OAF$^+$08, HZF04, CK08]). Alternatively, a node can estimate the BER and the corresponding SNR of a received packet by applying error estimating codes [CZZY10]. Furthermore, we assume that all nodes in a network use identical transceivers and the same transmission power. We see the usage of such radios in applications with high node densities with low power constraints and/or low data rates, such as Internet of Things (IoT) and Wireless Sensor Networks (WSNs) (see [ZGLB10, KW05]).

Let us introduce some variables and parameters which we use throughout this document:

- We define the SNR at the transmitter according to [Gol05] as

$$\gamma_{\text{tx}} = \frac{E_b}{N_0} \,, \tag{1.1}$$

  where E_b and N_0 are the energy per bit radiated by the transceiver and the spectral noise density, respectively.

- We determine the SNR of a signal as

$$\gamma = h^2 \, \frac{E_b}{E_I + N_0} \,, \tag{1.2}$$

where h and E_I are the fading coefficient and the inference generated by other signals, respectively. We determine the interference as $E_I = \sum_i h_i^2 E_b$ [Gol05].

- The fading coefficient h follows a Rayleigh distribution with $\mathrm{E}\left[h^2\right] = L$, where L accounts for the path loss [Gol05].
- We define the path loss as
$$L := \frac{1}{1+d^v} , \tag{1.3}$$
where d and v are the distance between transmitter and receiver and the path loss exponent, respectively. This model is a modification of the well known simple path loss model [Gol05] defined as $L = \left(\frac{d_0}{d}\right)^v$, where d_0 represents a reference distance and $d > d_0$. The $1 + d^v$ term in the denominator of (1.3) ensures that the received signal strength is strictly smaller than the transmitted one independent of distance d.
- A receiver can detect a signal if its SNR is above a certain detection threshold, i.e., $\gamma \geq \gamma_{\text{th}}$. If a signal is below that threshold, it increases the current noise floor as interference.
- Given a BPSK-modulated-signal we can determine the BER of the received signal [Kam04, Gol05] as
$$\text{BER}_{\text{BPSK}} = \frac{1}{2} \operatorname{erfc}\left(\sqrt{\gamma}\right) , \tag{1.4}$$
with erfc being the complementary error function defined as $\operatorname{erfc}(x) := \frac{2}{\pi} \int_x^\infty \exp\left(-t^2\right) \mathrm{d}t$.
- Due to the fixed energy per symbol assumption, a QPSK-modulated-signal experiences a higher BER than a BPSK-modulated-signal [Gol05].
$$\text{BER}_{\text{QPSK}} = \frac{1}{2} \operatorname{erfc}\left(\sqrt{0.5\,\gamma}\right) . \tag{1.5}$$
- In the absence of any channel coding, we determine the packet error rate (PER) of a packet consisting of b bits as
$$\text{PER} = 1 - (1 - \text{BER})^b . \tag{1.6}$$
- We define node density as
$$\rho := \frac{n}{d_{\max}^2 \pi} , \tag{1.7}$$
where n is the number of nodes which experience a BER ≤ 0.001 from a reference node in an AWGN channel and $d_{\max} = \left(\frac{\gamma_{\text{tx}}}{\left(\operatorname{erfc}^{-1}(2\cdot 0.001)\right)^2} - 1\right)^{\frac{1}{v}}$.

We use two different approaches to model Rayleigh fading in this work:

- *Rayleigh-Model-1*: This model assumes quasi-static flat fading where the fading coefficient h is constant during one communication cycle, i.e., during the entire period from relay selection, over direct source-destination transmission, until relay-destination transmission [TV05]. For each cycle, this model chooses randomly a coefficient h from a Rayleigh distribution with parameter $\sigma_R = \sqrt{L/2}$.
- *Rayleigh-Model-2*: This model generates fading coefficients which are correlated in time (cf. coherence-time) and allows us to investigate the impact of the coherence-time on the performance of cooperative diversity [PNS00]. This model updates the fading coefficient at the beginning of each packet transmission. The fading coefficient stays constant until the next packet transmission (any packet: control packet, data packet) starts. The time between those transmissions determine the correlation among the fading coefficients.

1.4 Outline and Contribution

In this thesis, we investigate networking aspects of cooperative diversity and we propose methodologies to achieve cooperative diversity in a wireless ad-hoc network. The organization of this thesis is as follows. The next chapter gives an overview of cooperative diversity. Chapters 3 and 4 focus on particular aspects of cooperative diversity, where we make specific research contributions. Chapter 5, finally, combines results to a coherent protocol on the MAC layer.

Chapter 2: Cooperative Diversity: An Overview
In this chapter, we present existing solutions to some of the challenges of cooperative diversity. First, we focus on physical layer challenges and summarize related literature. Second, we look at networking aspects, such as relay selection, packet flow, resource reservation, and why selfish nodes should cooperate. We also summarize related research contributions. Finally, we present existing and upcoming standards, which contain features of cooperative diversity and conclude with a discussion about used synonyms of cooperative diversity. A survey covering parts of this chapter has been presented in [EMA$^+$08].

Chapter 3: Relay Selection
In this chapter, we focus on the relay selection process which once completed, reduces the challenges of cooperative diversity to the well studied physical aspects. More specifically, we propose and evaluate relay selection methods/options to improve the efficiency of cooperative diversity.

To this end, we first analyze cooperative diversity regarding its energy-efficiency. Unlike most other research contributions in the field of cooperative diversity, we consider the energy consumption for transmitting *and* receiving during relay selection and data transmissions in our analysis. Our results indicate that using simple cooperative diversity for each transmission attempt is not efficient in terms of energy and time. Hence, it is better to employ it adaptively depending on the current channels between source, destination, and relay candidates. Based on these observations, we propose methodologies to exclude nodes, which cannot help, from the relay selection process and enable cooperation only on demand. Results regarding the energy-efficiency of cooperative diversity origin from joint research with Orange Labs France and have been published in part in [ABS08].

Besides improving the energy-efficiency, we also propose methods to enhance the time-efficiency of cooperative diversity in a multi-hop communication scenario. Original cooperative diversity schemes only consider data on a per link basis and not over multiple hops. In our work, we exploit routing information to improve the time-efficiency of cooperative diversity. More specifically, we propose different policies to select relays which are in transmission range of two consecutive hops of a route. Thus, if a packet transmission to the next hop node fails, the selected relay can replace this node and forward the packet to the two hop destination. Results regarding the time-efficiency of cooperative diversity origin from joint research with Orange Labs France and have been published in part in [ABS09].

Finally, we address the success-efficiency of cooperative diversity. Cooperative diversity depends on the existence of a relay and hence relies on a successful relay selection. Intuitively, the selection success increases with increasing selection time. However, a long selection time introduces a high overhead and therefore would degrade the time-efficiency of cooperative diversity severely. To this end, we focus on a slotted contention window approach to select a relay and evaluate two different candidate access strategies such that the probability of a successful relay selection is maximized. The parameters that maximize the selection success of these strategies depend on the actual number of relaying candidates. In that context, we show how uncertain knowledge of relaying candidate cardinality influences the selection success.

Chapter 4: Estimation of Neighbor Cardinality
In this chapter, we address the problem of estimating the number of relaying candidates of a communication pair. Having this information enables us to maximize the relay selection success as described in the previous chapter. The knowledge of the neighbor cardinality, however, is in general valuable information and influences the design and the performance of protocols developed for communication systems. For instance, the design of MAC and routing protocols, and the design of information dissemination protocols benefit from available neighbor cardinality information. To this end, we elaborate on how a node can estimate the cardinality of its neighbors that optionally exhibit certain attributes.

In general, such estimation methods should be fast and reliable. The identity of the neighbors, however, is likely not of interest. We propose different algorithms based on probabilistic trials with different levels of adaptability and feedback. These estimation methods do not need any coordination among polled nodes and are especially useful in densely connected networks. We show for each method how to minimize the number of trials in order to guarantee a desired estimation accuracy. Based on the constraints of the estimation methods, we discuss how to select the appropriate estimator for a given transceiver architecture. Finally, we evaluate the proposed schemes and compare their performance with a scheme which uses non-colliding packets to count nodes. The results of this chapter appear in part in [AYEB10, AYB11].

Chapter 5: Cooperative Medium Access
In this chapter, we focus on the integration of cooperative diversity in the wireless protocol stack. We start with a short discussion on the layers responsible for providing the necessary functionality for enabling cooperative diversity. Then, we discuss limitations of existing solutions and propose a novel cooperative MAC-protocol which addresses resource reservation, relay selection, and cooperative transmission. Our design is based on the results and insights gained from the previous chapters. We pay special attention to throughput and delay performance while keeping the protocol energy-efficient.

Evaluation results show that in good channel conditions and/or sparse networks — where communication partners hardly find any relays — our proposed cooperative MAC-protocol does not introduce any throughput degradation compared to a non-cooperative reference scheme. In dense networks and unreliable channel conditions, our cooperative MAC-protocol achieves a considerably higher network-wide reliability and throughput. The results of this chapter have been published in part in [AEBS09].

Chapter 2

Cooperative Diversity: An Overview

> In this chapter we provide an overview of existing work about cooperative diversity. To this end, we focus first on the physical layer aspects of cooperative diversity with fixed source, destination and relay nodes. In this context we address the characteristics of nodes in a cooperative scheme and find research contributions proving that cooperative diversity offers gains compared to non-cooperative schemes. We also summarize contributions about coding in cooperative diversity schemes, optimum position of a relay node in respect to source and destination, and using multiple relaying nodes.
>
> Second, we provide the related work regarding the networking aspects of cooperative diversity. More specifically, we summarize works on relay selection, MAC, and routing issues in cooperative diversity. We discuss also research contributions regarding the enforcement of cooperation among selfish nodes in a commercial network.
>
> Finally, we present existing or upcoming standards which incorporate ideas of cooperative diversity and conclude this chapter by discussing terms which are used as synonyms for cooperative diversity for clarification.

2.1 Building Blocks

In Figure 2.1, we provide an overview of the building blocks of cooperative diversity. The different blocks are assigned to the respective layers in the communication stack. The figure illustrates the organization of the following two sections where we elaborate on the different blocks in more detail and present existing work. We address the building blocks of the data link and network layer in the section regarding networking aspects of cooperative diversity.

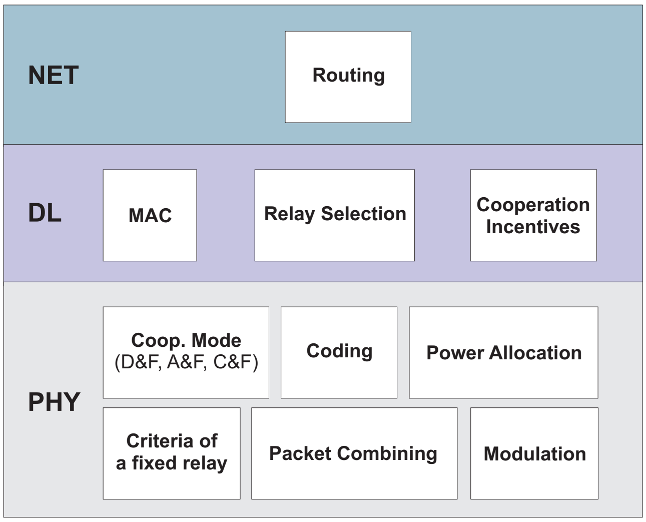


Figure 2.1: Building blocks of cooperative diversity

2.2 Physical Layer Aspects

In this section we elaborate on physical layer aspects of cooperative diversity. To this end, we consider scenarios where nodes have predefined roles (source, destination, relay) and where source and destination know their relaying nodes a priori.

We start with the characteristics of nodes in a cooperative diversity scheme. Then we present related work that prove that cooperative diversity has the means to effectively mitigate small-scale fading. We summarize work that elaborates on the coding schemes in context of cooperative diversity, find contributions regarding the optimum position of a relay node in respect to its source and destination node, and finally, discuss the benefit of using multiple relaying nodes for a source/destination pair.

2.2.1 Characteristics of Nodes

Let us first discuss the characteristics of nodes in cooperative diversity and their modified behavior with respect to non-cooperative schemes. To this end, we focus in the following on the characteristics of source, relay and destination:

- **Source**
  The source node needs to be aware that its transmission is forwarded by a relaying node. Since the relaying happens only after the transmission from the source, the destination may not acknowledge the packet transmission from the source until the reception from the relay.
- **Relay**
  Relays can basically operate in one of three modes which are called Amplify

and Forward (A&F), Decode and Forward (D&F), and Compress and Forward (C&F).

Relays working in A&F mode act as repeater. They do not demodulate and interpret received packets. Instead, they amplify and forward received signals. Since the relay regenerates the received signal without decoding, it also amplifies the received noise. A&F provides the destination with all the information the relay was able to observe leaving the decision to the destination. Nevertheless, if the SNR of the overheard signal is too low, no useful data can be forwarded and the time as well as the energy spent for the cooperative transmission is wasted. Thus, relays should only forward the overheard data when their received SNR is higher than a certain threshold [LTW04].

In D&F, relays decode the overheard information before forwarding it to the intended destination. Cooperation fails whenever the relaying node is not able to correctly decode the packet from the source. In this context, A&F performs better, since for the destination it is better to have additional information that is up to a certain level unreliable than having no additional information at all. The great advantage of D&F is that having decoded information enables the relay to further increase the reliability of the communication by applying special channel codes [HH06].

Naturally, the idea comes up to combine A&F and D&F in a hybrid protocol which uses D&F if the data from the source is received correctly at the relay and else uses A&F [SV06].

In schemes applying C&F [KGG05, BSTS10], relays only forward a compressed version of the signal they have received from the source. The original data cannot be reconstructed solely based on the compressed information (lossy compression). However, given that the destination holds information about the compressed data it can fully reconstruct the original information (cf. Wyner-Ziv source coding [WZ76]). The destination has to acquire the necessary information from the transmission of the source and/or transmissions of other relays.

- **Destination**
  Basically, the destination can try to decode the packet after the reception from the source or also wait until it has received the data from source and relay. In the former case, the destination could inform the source and the relay whether a cooperative transmission is necessary after the reception from the source (cf. incremental relaying [LTW04]). In case of a successful direct transmission, the time and energy needed for the cooperative transmission is spared.

  In case of cooperative transmission, the destination has to combine the received signals from source and relay. Obviously, this combination also depends on the operation mode of the relay. If no special coding is used at the relay, the destination could apply the same methods as used in traditional diversity techniques [Rap02] to combine the signals received via different paths on the physical layer:

- *Selection Combining*
  Selection Combining is the simplest combining method. The received packet with the highest actual received SNR is further processed; the packets received from other paths are discarded. The SNR of the combined packet is equal to the highest received SNR.
- *Maximal Ratio Combining*
  MRC exploits all signals received by the multiple antennas. The combining mechanism adjusts the phases of the signals, weights the phase-aligned signals by their SNR and adds them. The SNR of the combined signal is equal to the sum of all received signals.

Selection combining and MRC may require special costly hardware that facilitates the merging of packets on the physical layer. Although the gains of cooperation are highest when the data is directly processed in the physical layer, it can also be used with commercial-off-the-shelf transceivers. In the most straightforward way, the destination verifies the correctness of the received packets from source and relay by using some error detection code [LC04]. If one of those packets is free of error, the destination chooses it for further processing. If both packets contain errors, cooperation fails and the transmission attempt needs to be repeated. This only happens in the case of repetition coding, i.e., the relay sends the same data as the source and when there is a single checksum for the complete packet. If the source partitions the packet data into blocks which have their own checksum, the destination could combine the correct blocks of the transmissions from source and relay.

2.2.2 On the Benefits of Cooperative Diversity

In [SEA98, SEA03a, SEA03b], Sendonaris *et al.* introduce the basic idea of cooperative diversity in a cellular network. Each node is assigned to another node as an assistant in the communication with the base station. An assisting node overhears the transmissions being directed to and coming from its partner node. The additional expenses compared to non-cooperative transmission is the energy needed to forward the data from the assisting node to the destination. The gain due to cooperation is that less energy is needed to achieve a certain outage probability. The authors assume full duplex communication, i.e., nodes can simultaneously send and receive (cf. echo cancellation), and known CSI at the transmitter side. Based on their assumptions, Sendonaris *et al.* show that the gains of cooperation compensate the costs of it. Cooperative diversity can increase the throughput at fixed transmission power levels or reduce the energy consumption for constant throughput compared to non-cooperative transmissions.

Laneman *et al.* [LTW04] show the practical feasibility of cooperative diversity by dropping certain requirements imposed on it by the work of Sendonaris *et al.* [SEA98, SEA03a, SEA03b]. Nodes cannot send and receive simultaneously, i.e., they are limited to half-duplex communications, and transceivers do not know or do not exploit CSI. Only receiving nodes are able to obtain the CSI to the packet source. Based on these more practical assumptions, Laneman *et al.* introduce different cooperation strategies for A&F and D&F and derive their outage probability and diversity order[1]. The authors compare the performance of those strategies with non-cooperative transmissions. For a fair comparison, the cooperative protocols use twice the data rate of non-cooperative schemes. This is necessary to compensate for the two phase transmissions of cooperative diversity. The authors prove that cooperative diversity achieves a diversity order of two, i.e., the outage probability decays with $1/\gamma^2$ for high SNR, whereas the outage probability of non-cooperative transmission decays only with $1/\gamma$.

2.2.3 Coding at the Relay

The pioneer works of cooperative diversity which we summarized in the previous section, use repetition coding to forward packets from relay to destination. The idea to use more powerful coding schemes in combination with cooperative diversity has inspired numerous research proposals. We find one of the first real-world implementations inspired by cooperative diversity in [DFEV05]. Simple Packet Combining (SPaC), which is the name of the proposed protocol, is implemented and tested on low-cost WSN nodes. The authors use a routing protocol to establish routes between the nodes in the network. The links between two successive nodes of a route are usually good. Furthermore, it is possible that a node in a route overhears a transmission addressed to a precursor. Mostly, the overheard data is prone to errors and in traditional communication schemes not exploited at all. In SPaC, nodes buffer these overheard packets and use them on demand to correct contingently occurring packet errors in the communication with their direct predecessor in the route. The authors use two different packet types to increase the combining gain of packets. One packet contains only plain information and the other contains invertible parity information. The used packet type is alternated at each hop of the route. The documented gains in throughput of SPaC are not high which is probably due to the weak coding scheme (Hamming(8,4)) used. However, those gains come for no additional costs in terms of energy or time overhead.

The idea of using distributed coding to increase the performance of cooperative diversity is elaborated in [ZHF04, HN04, SE04, HN06, HH06, LSS05, LVWD06]. Figure 2.2 depicts the basic principle of those schemes. The source uses a specific code to protect the packet intended for the destination. The relay overhears the transmission from the source, decodes the packet, may use some kind of interleaver and encodes the data using a different code. When the destination receives both packets — from source and relay — it jointly decodes it. For instance, [HN06, ZHF04] propose to use punctured invertible convolutional codes.

---

[1] Diversity order expresses the dependency of the outage probability p_{out} on the SNR γ, as SNR goes to infinity and is defined as $\lim_{\gamma\to\infty} \frac{-\log(p_{\text{out}})}{\log(\gamma)}$ [Gol05]. Note that a higher diversity order does not necessarily imply a smaller outage probability for a given SNR-value.

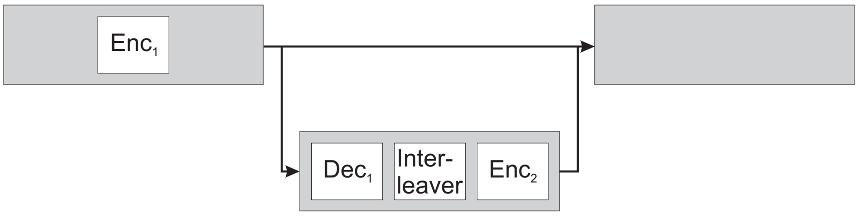


Figure 2.2: Distributed coding

Zimmermann *et al.* [ZHF04] compare the performance of different non-cooperative techniques to cooperative diversity using Hybrid-Automatic Repeat Query Type II (H-ARQ-II) [LC04]. Commonly in H-ARQ-II systems, a packet is first transmitted with an error detection code. When the decoding fails, the destination requests a retransmission. The source uses an error correction code for this retransmission. At every retransmission more redundant information is sent to the destination. The destination combines all of the received information until it can decode the packet. The authors of [ZHF04] also compare H-ARQ-II in non-cooperative and cooperative form. In the cooperative form, the relay takes over to answer the retransmission queries. For fair comparison, the authors take care that all schemes use the same overall amount of energy per information bit. Zimmermann *et al.* show via simulations that it depends on the position of the relaying node and the coherence time of the channel whether cooperative H-ARQ-II outperforms non-cooperative H-ARQ-II. In the slow fading regime, non-cooperative H-ARQ-II does not achieve any time diversity and an outage for the following transmission from the same node is more likely than in the case of cooperative H-ARQ-II.

The authors of [LSS05, HH06] exploit the structure depicted in Figure 2.2 to achieve Distributed Turbo Coding (D-TC). The basic idea is quite appealing since it combines the high SNR gains of Turbo Coding (TC) [LC04] with the gains offered by cooperative diversity. Furthermore, by using D-TC, cooperative diversity does not suffer from the inherent bandwidth inefficiencies caused by two consecutive transmissions. Instead of transmitting the complete turbo encoded data from the source, the transmission is split between source and relay. The source uses a convolutional code to protect its transmission. The relay node decodes the overheard packet from the source, uses an interleaver to scramble the data and applies another convolutional code. Thus, there is no difference for the destination in terms of received redundancy or decoding method to traditional turbo coding. The only additional delay compared to non-cooperative turbo coding is caused by the processing time, i.e., decoding, interleaving, and encoding of the data at the relay. However, when the destination is able to decode the packet with the information received from the source, the transmission from the relay can also be spared increasing the benefits compared to standard turbo codes.

The noisy source-relay channel is the vulnerability of D-TC. Only when the relay can decode the information from the source correctly it can forward it to the destination. Hence, researchers have assumed perfect source-relay channels in the original works of D-TC. This perfect channels are realized by ARQ schemes. Li *et al.* [LVWD06] addresses the imperfect source-relay channel and propose not to make hard decisions at the relay, i.e., to assign binary values to the overheard signals. Instead the relay should forward a packet consisting of soft information, i.e., the confidence of each coded bit is provided. Their analytical results indicate only slight effects on the system performance compared to D-TC with perfect source-relay channel assumption.

Cooperative diversity achieves diversity by transmitting the same data from two spatially separated nodes. However, the relay node needs to know the data it has to forward. Furthermore, today's wireless communication interfaces are constrained to half-duplex mode, i.e., nodes cannot receive and transmit simultaneously using the same frequency band. Hence, the two transmissions of cooperative diversity happen one by one: first, the source transmits its data and second, the relay forwards the overheard data. Thus, cooperative systems have a reduced spectral-efficiency compared to multi-antenna systems. Several researchers [CYQZ06, WVK07, MM09] address this issue of cooperative diversity by combining it with ideas from *network coding* [ACLY00]. Chen *et al.* [CYQZ06] assume a cellular network where two nodes U_1 and U_2 communicate with a common base station B (see Figure 2.3). A dedicated relaying node R assists the communication of both nodes. Relay R does not forward the transmissions from U_1 and U_2 one by one. It combines data from U_1 and U_2 using network coding, i.e., applying x-or function to bitwise merge the data. Then, node R forwards the combined packet to B. The base station needs to receive one of the packets from U_1 and U_2 correctly. It retrieves the information of the other user from the network coded transmission of R, i.e., using the x-or again. The authors show that cooperative diversity using network coding at the relay achieves the same diversity order as standard cooperative diversity, i.e., when R forwards the transmissions from U_1 and U_2 separately. However, the spectral-efficiency of the scheme that uses network coding improves since it requires in total only three transmissions instead of four. The spectral-inefficiency of cooperative diversity is also addressed in [RF06], where the source does not need to wait for the relay to forward its packet. Two relays assist each source node. While one of the relays is overhearing the transmission of the source, the other one is simultaneously transmitting the previous packet from the source to the destination. The relays alternate in overhearing and transmitting packets. This scheme relies on interference cancellation (cf. multiuser detection [Gol05]) at the relays and the destination.

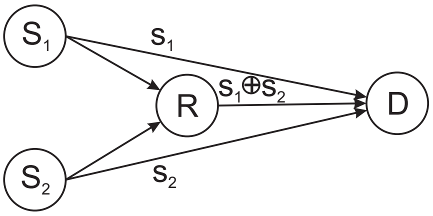


Figure 2.3: Cooperative diversity combined with network coding

2.2.4 Optimum Position of the Relay

The position of a fixed relaying node has obviously great impact on the performance of cooperative diversity.

Zimmermann *et al.* [ZHF04] compare the throughput of a non-cooperative scheme with a cooperative scheme using D&F and discover usage regions of relays.

Lim *et al.* [LSM06] compare the throughputs of schemes using a direct transmission between source and destination, using an intermediate routing node, and cooperative diversity. Assuming a pure AWGN channel the authors show that cooperative diversity with D&F outperforms direct transmission no matter where the relaying node is positioned on the line connecting source and destination. The best performance is achieved when the relay is closer to the destination. However, multi-hop routing outperforms cooperative diversity when the intermediate hop has equal distances to source and destination. Since the authors do not use any fading, these results indicate only the hopping gain of cooperative diversity and no diversity gain. In that context, cooperative diversity benefits from packet transmissions from the source which reach the destination directly without the relay forwarding it.

Souryal *et al.* [SV06] analyze the frame error rate (FER) of direct transmission, multi-hop routing, and cooperative diversity using different strategies as a function of the position of the relay. Their results indicate that cooperative diversity schemes outperform multi-hop routing regardless of the position of the the relay. For D&F with fixed relaying, the relay needs to be closer to the destination. Only when the relay can decode the packet from the source without error the transmission to the destination is successful. The optimum position for A&F and Hybrid-A&F/D&F is closer to the destination.

2.2.5 Multiple Relaying Nodes

Cooperative diversity schemes which exploit a single relay for each communication attempt can tremendously improve the reliability compared to non-cooperative schemes. Naturally, the question arises whether multiple relaying nodes for each communication attempt would improve the performance further. For a fair performance comparison the transmission energy and transmission time are equalized for different schemes. More specifically, for m relays using orthogonal channels, i.e., transmit at orthogonal times or frequencies, the rate of each single transmission of the m relays must be $m + 1$ times faster than the non-cooperative direct transmission. Furthermore, the power at the source and the m relays needs to be adjusted such that the overall consumed energy is the same as that of non-cooperative transmission.

Selection Decode-and-Forward as discussed in [VLK$^+$08] is a intuitive method to employ multiple relays. During the direct transmission phase, all neighbors of S try to receive and decode its packet. During the cooperative transmission phase, all nodes which have received the packet from S without error forward it to D using orthogonal channels. Node D, finally, combines the packets received from S and all m relays using MRC.

Distributed Beamforming [MBM07] allows all relays of a communication attempt to transmit their packets simultaneously. The relay nodes have to adjust the phase and the frequency of their transmitted signals such that they superimpose coherently at the receiving antenna. To this end, m relays have to know the instantaneous channel state information (ICSI) of the channels between them and the destination. This information is hard to obtain due to following reasons. Relays need to transmit training data to the destination. These transmissions need to be scheduled such that they do not collide. Finally, the destination has to feed the measured ICSI back to the corresponding relays. Due to the time-varying nature of the wireless channel, distributed beamforming only works when the overall time needed to setup and use it — time to transmit training data from the m relays plus the time to feedback ICSI to the relays plus the data transmission time — is shorter than the coherence time of the channel [MMMZ08].

Distributed Space Time Code (D-STC) is another means to compensate the negative influence of multiple relays on the spectral-efficiency [LW03, JH06]. It is based on space-time-codes [Ala98]. Relaying nodes encode the data using D-STC and transmit simultaneously. The destination needs to know the ICSI of the channel between relays and itself to decode the original data. The destination does not need to feed this information back to the relays. In that context Laneman *et al.* [LW03] answer the question about the achievable diversity gain of m relaying nodes using D&F and D-STC. Although all of the m nodes are in transmission range of source and destination only a subset of those nodes can decode the overheard packet from the source and forward it in a further step to the destination. The authors show that the diversity gain is determined by the number of cooperating nodes and not by the number of nodes that are able to decode the transmission from the source.

2.2.6 Power Allocation

Generally, researchers assume a total energy constraint which is equal for cooperative and non-cooperative schemes. Thus, the transmission energy of the source in a non-cooperative scheme needs to be shared among the source and the relays. Allocating the same energy amount to the source and all relays is a straight-forward solution which is preferable in case of unknown CSI [BSW07]. By knowing all actual CSI or at least their statistics, we can achieve higher cooperation gains by allocating the transmission energy depending on the CSI of the nodes [ZAL07a].

2.2.7 Modulation

Hierarchical modulation [Cov72] represent a promising research direction for cooperative diversity [HH07, EMA$^+$08]. This modulation technique uses simultaneously two modulation schemes in the same transmission. Thus, a single transmission consists of two data streams with different reliability. Applying hierarchical modulation to cooperative diversity means that the source uses the less robust but faster modulation scheme to transmit the data and the more robust one for signaling and controlling information. Thus, the relay is likely to decode the overall information where else the destination decodes only the signaling information. In the cooperative transmission phase, the relay complements the missing information at the destination.

2.3 Networking Aspects

The previous section summarized the physical layer aspects of cooperative diversity provided in the literature. It was shown that given a source, destination and one or more relaying nodes, cooperative diversity can increase throughput or can reduce the energy consumption compared to non-cooperative schemes using the same energy or having the same throughput. So far systems consisted of dedicated source and destination nodes, and a priori known set of relays. In this section, we move our attention to a more realistic setup of wireless ad-hoc networks. In such a setup, in addition to the physical layer challenges of the previous section, we also need to address networking layer aspects.

In the following, we present related work specifically aiming to address relay selection, packet flow, resource reservation, and routing challenges. We conclude the section with a discussion on why nodes should cooperate in an ad-hoc network.

2.3.1 Relay Selection

Success of cooperative diversity heavily relies on the selected relay. For instance, a relay which is barely in transmission range of source and/or destination unlikely supports the transmission between those nodes. In the following, we focus on the task of finding an appropriate relaying node for a given communication pair.

Intuitively, following questions arise in the context of relay selection for cooperative diversity:

- How many relays are necessary for each communication attempt?
- How frequent should relays be selected?
- Should relays be selected before or after the direct transmission?
- What are decision criteria for selecting a relay?
- Who selects a relay?
- How to select a relay?

Next, we will present how existing works address these questions.

Number of Relays

In [BKRL06, BA08, ZAL07b], the authors claim that selecting the best relay for a communication pair is more efficient than using all available ones. This claim assumes fair comparison, i.e., the time and the energy needed for the cooperative scheme must not exceed the time and the energy spent in the non-cooperative scheme. More specifically, it is more efficient to divide the time and energy resources between the source and the single best relay than to split the resources among the source and multiple relays. In that context, Bletsas *et al.* [BKRL06] show that a scheme which selects the best relay out of n potential candidates achieves the same diversity order as a scheme that uses all n nodes as relay. The reasoning is that if the best node fails all other would fail anyway.

Frequency of Relay Selection

The relays should be selected frequently enough to ensure that selected relays are able to support the corresponding communication attempt. Assuming that the channels between the nodes do not quickly change, i.e., the coherence-time of the channel is long compared to the transmission of a single packet, relays can be selected for long periods without performance degradation. Even a single relay selection at network start up time might be sufficient for static networks. Cooperative diversity requires more frequent relay selections in dynamic networks and networks where nodes experience time varying channel conditions. An indicator to reselect a relay is the single or multiple failure of a cooperative transmission attempt [LTN$^+$07]. In highly dynamic environments and/or networks with missing coherence-time and network topology information, it is advisable to select relays for each transmission attempt anew [BKRL06].

Relay Selection before or after Direct Transmission

In case of frequently occurring selections, i.e., a new selection for each communication attempt, the question is whether to select the relay before or after the direct transmission.

Pro-active relay selection methods select relays before direct transmission [BKRL06, LTN$^+$07, CYQZ06, ED06]. In such schemes, the corresponding communication pair is aware of the availability of a cooperating relay at the beginning of the direct transmission phase. Furthermore, the source may have knowledge about the cooperation gain provided by the selected relay and can exploit this knowledge by choosing an appropriate transmission rate [LTN$^+$07]. In context of MAC, proactively selected relays can reserve the wireless channel already during the direct transmission phase in their neighborhood. The reservation prevents nodes which are not aware of this communication to interfere with the reception of the relay [CYQZ06]. This is especially important in dense networks with high traffic loads, where it is likely that the interference generated by neighboring nodes hinder the relay to receive the transmission from source and hence to assist the communication to the destination. Pro-active relay selection inherently prioritize cooperative transmissions to direct transmissions.

Re-active relay selection, on the other hand, chooses relays after the direct transmission phase [LHV07, BA08, XZQ06]. It skips the relay selection if the direct transmission succeeds. The relay selection scheme chooses a node that has received the packet from the source and is in transmission range of the destination. The selection process focuses solely on the relay-destination channel. The selection occurs briefly before the cooperative transmission phase and hence bases its decision on measurements which reflects more likely the situation of the cooperative transmission. In re-active schemes, relaying candidates do not have channel reservations during the direct transmission phase. Thus, nodes outside the transmission range of source and destination can start their own data transmission and may block potential relays. Re-active relay selection inherently prioritizes non-cooperative transmissions. A significant drawback of re-active relay selection is the overall energy consumption. Multiple nodes have to overhear the data transmission from the source.

Relay Selection Criteria

The best relay, in terms of achievable throughput for a source-destination pair, is the node that minimizes the outage probability between those nodes. Due to the time-varying wireless channel, the best relay for a communication pair may change over time. The outage probability for a communication pair using cooperative diversity depends, beside source-destination channel, on the actual source-relay and relay-destination channels.

The selection criteria to minimize the outage probability is the received instantaneous SNR of the source-relay and relay-destination channels [BKRL06]. However, obtaining instantaneous SNRs for all potential relays to find the current best one can introduce non-negligible overhead [HK07]. For a given target data rate between source and destination, it is not necessary to find the best relay, but a relay which can most likely support successfully the communication attempt (cf. SNR-threshold based relay selection [HK07]).

When relays are selected for a longer period, e.g., for the overall lifetime of a network, a descent selection criteria is the average received SNR. The average SNR is equivalent to a distance based selection scheme as proposed in [ZV05]. However, a scheme using a single fixed relay achieves only a diversity order of two (see [LTW04, JJ09, SGL06]).

Relay selection can exploit also other criteria besides outage-determining factors. Chen *et al.* [CYQZ06] refine the relay selection with residual energy of the nodes to maximize the overall network life time, i.e., the time when the first node runs out of energy. Nodes are less likely to be selected as relay when their residual energy level is low.

Although cooperative diversity can increase the throughput of a single link, the impact of it on the overall network throughput is unknown. The relay creates additional interference and blocks nodes from accessing the channel. Hence, the spatial re-usability of cooperative diversity is smaller than the one for non-cooperative schemes. Marchenko *et al.* [MYAB09] address this circumstance by including degree information in the selection process. Relaying nodes that are capable of assisting the communication pair and that block the least amount of additional nodes are preferable.

Summarizing, in the existing works the relay selection use following criteria:

- instantaneous SNR
- average SNR (= distance between the nodes)
- energy consumption/residual energy level
- spatial re-usability of wireless channel
- overall transmission time

Who should select a Relay?

Relay Selection can be carried out in a centralized or distributed manner. An authority like a base station selects a relay in a centralized scheme. The authority needs to have all necessary information to select the best relay. Hence, nodes need to forward their local information, e.g., channel states, residual power, node degree, etc. to the central authority. Theoretically, a centralized controller can select for each communication pair the best relay such that the overall network performance is maximized. IEEE 802.16j is an example of a system using centralized relay selection.

However, the practical benefit of a centralized relay selection is questionable:

- It requires a central authority, i.e., a base station in a infrastructure-based network.
- All necessary information needs to be forwarded to this authority which results in a high overhead.
- The channels may change during the decision and response time making the selection suboptimal.

Especially for MANETs, decentralized relay selection is more feasible. In decentralized relay selection, the relay is selected by the source, the destination or by corresponding relaying candidates themselves.

When the source or the destination selects the relay, the candidates need to provide the decision maker with the required information. For instance, all nodes which have correctly received the packet from the source can send a notification to the destination [BA06]. The destination then evaluates all notification packets and chooses the node which offers the highest cooperation gain as relay. Clearly, such a scheme does not scale with the density of networks: with thousands of candidates, the relay selection itself would last forever. This is particularly true, since the notification packets need to be coordinated to prevent collisions.

A slotted contention window approach can address this scaling issue [LHV07, CYW07]. Relay candidates that expect to facilitate a certain minimum cooperation gain, chooses randomly a slot in a frame of known size and transmit a notification packet with a certain probability. The decision maker, i.e., the source or the destination, chooses from the non-colliding applications the best candidate. The frame size as well as the transmission probability of the relay candidates have to be chosen adequately to facilitate a selection success, i.e., having at least one non-colliding notification packet.

Bletsas *et al.* propose in [BKRL06] a distributed relay selection scheme which minimizes the number of packet exchanges. Relaying candidates apply distributed timers to find the best relay. The timer of each candidate starts from a value inversely proportional to the cooperation gain the candidate offers. A relaying candidate starts forwarding the packet to the destination when its timer expires. All other candidates backoff when they realize the transmission of the best relay.

Existing literature show the possible criteria for selecting relays. However, most contributions do not consider the time-overhead for exchanging this information or how the necessary packet exchange can be efficiently integrated in an existing packet flow.

2.3.2 Cooperative Diversity and Medium Access

An important task in wireless communication systems is the access control of the communication medium. It is essential that nodes follow certain principles in transmitting packets such that collisions are avoided if possible. Clearly, such mechanisms add certain overhead to every packet transmission. For instance, nodes have to take care that the channel is not in use before they start their own packet transmission (cf. Carrier Sensing Multiple Access (CSMA)).

All packet exchanges of cooperative diversity, e.g., for relay selection, have to adhere to the medium access rules. However, the setup and the execution of cooperative diversity have to be fast enough to react in time to the dynamics of the wireless channel. Furthermore, the relay selection process might need access to information held by the physical layer, e.g., residual battery, received SNR.

This motivates researchers to integrate the necessary functionality to facilitate cooperative diversity into MAC protocols. The challenge of designing a cooperative MAC protocol is that the overhead caused by setting up cooperative diversity — relay selection, and other controlling packets — should not consume the provided benefit of it.

Most of the proposed cooperative MAC protocols are based on Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) (see [LTN$^+$07, CYW07, MYPK07]). This is motivated by the following facts. CSMA/CA represents one of the most investigated MAC protocols as it is used in IEEE 802.11. Moreover, the hand-shaking signals used to reserve the channel for source S and destination D can be exploited in several ways in cooperative protocols, e.g., deciding on using cooperation based on the channel quality between S and D and determining the cooperation gain of certain nodes.

Cooperative Medium Access Control (CoopMAC) [LTN$^+$07] aims to increase the overall throughput in a network by applying dynamic routing in the MAC layer. Each node maintains a table which contains expected feasible data rates to all neighbors via direct link and the fastest indirect link (via another neighbor). Nodes update the table entries by overhearing the data traffic in their vicinity. When a node S wants to transmit a packet to a neighbor D, it first assesses its table to determine whether a direct or indirect transmission via a node R is more time efficient. If the direct transmission is faster, S uses standard CSMA/CA. Else, S uses this helping node to communicate with its destination.

In Cooperative Medium Access Control with Automatic Relay Selection (CMAC/ARS) [CYW07], S and D provide their neighbors with information about the quality of their current connection and the desired data rate. Based on this information, neighboring nodes decide whether the data exchange between S and D requires cooperation. In case of required cooperation, D selects a new relay for each cooperative transmission. CMAC/ARS uses a contention window of fixed size for the relay selection where each candidate transmits an application packet in a uniform randomly chosen slot.

Cooperative Diversity Medium Access Control (CD-MAC) [MYPK07] exploits cooperative diversity not only for the data transmission but also for the exchange of handshake signals. Initially, node S starts using standard CSMA/CA. Only if D does not react, S uses cooperation. In that case S sends the `RTS` (`Request-To-Send`) to a neighbor. Then, this neighbor and S use D-STC to simultaneously send the `RTS` to D. Node D recognizes the cooperative transmission and uses a neighbor to respond in a similar way. Each node selects the neighbor from which it has received packets with the highest SNR.

Cooperative Medium Access Control (C-MAC) [AAA05] represents a complex cooperative MAC protocol which uses two different access schemes. It uses CSMA/CA to manage the channel access of nodes and applies Code Devision Multiple Access (CDMA) such that multiple relaying nodes can transmit simultaneously their data to the destination.

Extending MAC protocols to facilitate cooperative diversity is not limited to CSMA/CA. Shea *et al.* [SWW04] propose a cross layer design which combines cooperative diversity, routing and a Slotted-ALOHA access scheme. Figure 2.4 represents a single slot of this ALOHA scheme. Each slot consists of several mini slots. The current source S_c transmits its data packet in the `DATA` slot. The final destination

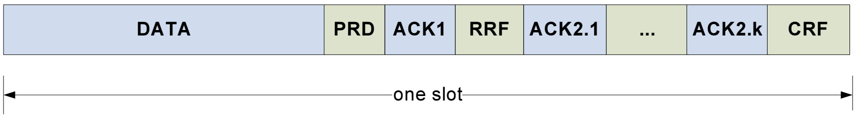


Figure 2.4: Slot partitioning of combined cooperative diversity, routing and Slotted-ALOHA scheme

uses the `PRD` (Packet Reached Destination) slot to inform all nodes of the route if it has received the data. The current destination D_c shows its success in receiving the data during the `ACK1` slot. If the transmission from S_c to D_c fails, S_c requests relays to forward the data in the `RRF` (Request for Relay Forwarding) mini-slot. Nodes that have successfully overheard the data transmission and can provide a route to the final destination that is shorter than or equal to the original route, select randomly one or more of the following k *ACK2.x* mini slots to indicate their willingness to cooperate. Finally, S_c chooses in the `CRF` slot a relay to forward the data.

Existing attempts of integrating cooperative diversity in MAC protocols are promising and indicate that theoretical gains can be observed also in real world networks. However, the solutions have certain drawbacks: they refrain from certain phases of cooperative diversity, e.g., relay selection; select relays based on probably outdated information; require too much overhead; or have restrictions which make solutions infeasible in real word applications.

2.3.3 Cooperative Diversity and Routing

In ad-hoc networks, the communication of nodes is not limited to their direct neighbors. Routing protocols allow nodes which cannot communicate directly to exchange data using other nodes as relaying node. The idea of routing and cooperative diversity share the concept of exploiting neighboring nodes to achieve certain goals. Thus, it is intuitive to analyze certain synergy effects between cooperative diversity and routing.

Simple Packet Combining [DFEV05] represents a cooperative protocol for WSN which exploits routing information. It explores weak links that routing protocols normally do not consider. In the simplest case, the route consists of three nodes: S, D_1, and D_2. In the Simple Packet Combining scheme D_2 tries to overhear all information on the wireless channel. Thus, it may collect some information from the packet transmission between S and D_1. It can exploit this information to repair eventually a corrupted transmission from D_1 to D_2. If D_2 has received the packet correctly during the transmission of S, it informs D_1 not to forward the packet.

Another synergy effect between cooperative diversity and routing is addressed in [AAA05]. Cooperative diversity requires common neighbors of the communication pairs to work. Hence, [AAA05] proposes a routing algorithm which aims to find routes through regions with a high node density such that cooperative diversity protocols can easily find suitable relaying candidates for transmission attempts.

Combining cooperative diversity and routing can also be beneficial in terms of energy savings [KMAZ07, IHL07]. Beres *et al.* [BA07] investigate different levels of interactions between cooperative diversity and routing protocols. The authors assume a static grid network with slow fading, such that the routing layer can adjust to channel changes. The main result of [BA07] is that a routing layer which is aware of cooperation and the link qualities of potential diversity nodes increases the overall end-to-end throughput.

2.3.4 Why should nodes cooperate?

Cooperation in overall is based on reciprocity: users sacrifice some of their resources for the benefit of others; in return, users expect that the other users behave accordingly if they need help. If everybody obeys this rule, fair cooperation is possible.

In case of cooperative diversity, the resources that nodes sacrifice to support other nodes are time, bandwidth, and energy. Cooperative diversity can increase the reliability of communications in a network only if nodes stick to the rules of cooperation.

In networks where all nodes belong to a single entity/owner, nodes inherently cooperate to increase the gains of this entity. For instance, this is the case for military networks and networks used in disaster relief situations.

For commercial networks using cooperative diversity, it is essential to include some mechanism that ensures cooperation. Otherwise, selfish nodes are tempted to misbehave: they exploit the benefits of cooperative diversity and only pretend to offer support to other nodes in return. In order to hide their selfish behavior to others, such nodes may participate occasionally in cooperations. Such misbehaving nodes degrade the diversity gain to the one of non-cooperative systems [DM08].

Incentives like reputation or payment can stimulate cooperation among nodes. For instance, in pricing based systems, nodes have expenses for transmitting data in the network, e.g., they have to pay for used bandwidth, or transmission power. A selfish node only cooperates if it benefits from it. Hence, it wants to get paid for its help. The reimbursement has to cover the expenses of a relay and provide additional profit. Based on the complexity of the system, pricing can be uniform or can depend on certain factors (e.g., transmission power, availability of relays) [SA06].

Game theory represents a tool to model the behavior of nodes and to analyze payments for cooperation. For instance, [WHL09] employs a buyer/seller game (cf. Stackelberg game) to adjust the transmission power of relays. The source acts as a buyer of transmission power. It aims to minimize its costs to achieve a certain performance. Relays represent sellers of transmission power. They intend to maximize their revenues. A relay can request more money for its transmission power if it has a good location and if it has only a few competitors.

In [DM09], the authors use a dynamic game approach to provide the foundation to develop a system where cooperative diversity benefits are confined to cooperating nodes. The system uses belief propagation among source nodes. In that context, [DT10] proposes methods for an ARQ based protocol to identify and ban misbehaving nodes.

2.4 Emerging Standards

The existing research contributions regarding cooperative diversity show its value for wireless communication systems. In the following we elaborate about an existing standard which already supports cooperative diversity. Furthermore, we take a look into the ongoing standardization efforts regarding International Mobile Telecommunications-Advanced (IMT-Advanced) (cf. fourth generation of cellular wireless standards).

2.4.1 WiMAX - IEEE 802.16j

The Worldwide Interoperability for Microwave Access (WiMAX) IEEE 802.16j standard [IEEE09] introduces dedicated relay stations which support their associated base stations and should reduce the cost of WiMAX infrastructure roll outs. Two different types of relay stations exist:

- *Transparent* relay stations do not transmit their own control frames and thus, do not extend the range of their base station but increase its capacity. This kind of relay stations have to use the same frequency channels as the base station.
- *Non-transparent* relay stations increase the coverage range of a base station by transmitting control frames. These relay stations are not limited to the frequency channels of the base station.

The channel scheduling, i.e., the transmission time of mobile stations can be done solely by the base station or in cooperation between non-transparent relay stations and base station. The standard facilitates the usage of multiple antennas at the communication sides. A further option of 802.16j is cooperative diversity, where the base station and one or multiple relay stations, or multiple relay stations transmit cooperatively to another relay station or mobile station. The base station controls the entire cooperation process. It decides when to use cooperation, which relay stations it invokes and which physical antenna elements those relay stations should use. The standard introduces three different modes for cooperation:

- *Cooperative Source Diversity:*
  all stations participating in the cooperation process transmit simultaneously the same signal using the same time-frequency resource.

- *Cooperative Transmit Diversity:*
  participating stations use D-STC to transmit the signals simultaneously using the same time frequency resource.
- *Cooperative Hybrid Diversity:*
  is a combination of both other modes using D-STC at participating nodes. Some of the stations transmit the same signal, i.e., use the same code for their transmission.

Transparent as well as non-transparent relay stations can be used in cooperative diversity. The standard does not regulate, when to use cooperation, which mode to use or how the cooperating relay stations are chosen [PH09]. This functionality resides in the base station and depends on the manufactures.

2.4.2 IMT-Advanced

International Mobile Telecommunications-Advanced is the name of the 4G wireless mobile broadband communications system.The International Telecommunication Union (ITU) plans to release the first IMT-Advanced air interface standard in 2011. Currently, there are two technologies under consideration for IMT-Advanced. Key features candidates for IMT-Advanced have to exhibit are [YHXM09]:

- 100 Mb/s in high speed environments (< 350 km/h)
- 1 Gb/s in pedestrian environments (< 10 km/h)
- Transmission bandwidth has to be variable from 20-100 MHz

WiMAX IEEE 802.16m

One of the candidates is WiMAX IEEE 802.16m. The relaying options of this ongoing standard are reduced compared to IEEE 802.16j[LWS$^+$10]. Relay stations are fixed, have to be non-transparent, and have to use the same frequency resources as the base station. The relay station is responsible for scheduling the access of the mobile stations assigned to it (decentralized scheduling). The standard supports at most two hop connections, i.e., it allows only one relay station between mobile and base station. Also other optional features specified in IEEE 802.16j are omitted in IEEE 802.16m, one of them being the support of cooperative diversity.

Long Term Evolution-Advanced (LTE-Advanced)

LTE-Advanced is the second candidate for IMT-Advanced standard. Basically, there are two kinds of relay stations in LTE-Advanced: Type 1 relays increase the coverage range of base stations by transmitting their own control frames (physical cell ID, synchronization, reference symbol, ...). From the perspective of a mobile station, the relay is equivalent to a base station. This type of relay can be further differentiated into Type 1a and Type 1b relay. The former operates in a different frequency band than its base station. Type 2 relays are intended to increase the capacity of a cell. They are transparent to mobile stations,i.e., do not broadcast their own cell control frames [LTEA10]. This type of relay is not part of the current version (version 10) of the not finalized standard [LWS+10]. Relay stations are essentially considered as multiple access base stations with a wireless backhaul link. Cooperative transmissions are open challenges for future releases.

2.5 Term Clarification

Cooperative diversity represents a huge research topic with hundreds of research contributions every year. Not surprisingly, authors use not always the same terms in their works. Over the years, the following synonyms for cooperative diversity have established in the research community:

- *User Cooperation Diversity* [SEA03a]
- *Cooperative Relaying* [MMMZ08]
- *Cooperative-MIMO (CO-MIMO)* [CGB04]
- *Virtual Antenna Array* [DDA02]

Another term which is worth to mention is *Cooperative - Automatic Repeat Request (C-ARQ)* [CFG07]. It represents a scheme where the destination of a communication attempt automatically requests a retransmission if the direct transmission from the corresponding source has failed (cf. ARQ). However, this retransmission is not served by the source but by a selected relay. Hence the C-ARQ represents a Cooperative diversity scheme, which emphasizes the fact that the cooperative transmission from the relay has to be requested by the destination (cf. incremental relaying [LTW04]).

The following list contains terms which can be confused with cooperative diversity:

- *Network MIMO* [KFV06] is an attempt to increase the throughput of cellular networks by reducing interference. Neighboring base stations coherently coordinate their transmissions and receptions.
- *Multi User - Multiple Input Multiple Output (MIMO) (MU-MIMO)* systems allow users which are equipped with multiple antennas to transmit simultaneously exploiting the multiplexing gain of MIMO [GKJ+07] .
- *Distributed Antenna System (DAS)* is a term which origins from multiple antennas being distributed in a building to combat fading phenomena. The antennas are connected to a single base station [SJR87].

- *Multi User Diversity* [TV05] aims to schedule transmissions among nodes such that only the node which has currently the best channel condition to its destination transmits. To this end, the scheduler needs to know the current CSI of all nodes. Using cooperative diversity to reliably deliver the CSI to the scheduler is proposed in [VK10].

Hereafter, we use exclusively cooperative relaying as a synonym for cooperative diversity.

Chapter 3

Relay Selection

The concepts of cooperative relaying promise gains in robustness and energy-efficiency in wireless networks. As mentioned in Chapter 2, these gains are proven by information theory based analysis which focuses on physical layer aspects with known source, destination, and relays. Whether cooperative relaying can show similar performance gains in an unknown network scenario remains mainly unattended.

In this chapter, we focus on the relay selection aspects to improve the energy, time, and success efficiency of cooperative relaying.

First, we concentrate on the energy-efficiency of cooperative relaying. We consider the energy consumption for transmitting and receiving of all nodes in the network for the relay selection and data packet transmissions. We propose new methods of *adaptive* relay selection to increase the energy-efficiency of cooperative relaying by allowing only common neighbors with link qualities that can support the S-D pair to be relay candidates and employing relay selection on-demand, where cooperation is highly likely required.

Second, we elaborate on the time-efficiency of cooperative relaying in a multi-hop communication scheme and propose a new system architecture which exploits routing information in the relay selection process. Moreover, we investigate different selection policies regarding their end-to-end throughput.

Finally, we focus on the success of the relay selection phase. This is crucial since cooperative relaying only works if a relay is available. We focus on relay selection based on a slotted contention window and investigate two different access strategies of candidates. For those strategies we determine the optimum access probabilities that maximize their selection success.

3.1 Introduction and Motivation

Cooperative relaying is proposed as a means to increase the achievable throughput of wireless communication channels (see [SEA98, LTW04]). Some researchers also claim that cooperative relaying can decrease the energy consumption of wireless communication networks, i.e., nodes which exploit cooperative relaying can decrease their transmission power to achieve the same throughput as non-cooperative schemes [LTW04]. These claims, however, are based on research contributions which mostly limit their considerations on the physical layer aspects of cooperative relaying with *known* source, destination, and relays. The performance of cooperative relaying in an unknown network scenario where each node is a potential source, destination and relay is not thoroughly investigated yet.

Moreover, we observe that hardly any claims regard for any energy consumptions caused by receiving data. This is in fact unfair, since cooperative relaying requires more receiving intervals than non-cooperative schemes. Only two nodes participate in a non-cooperative transmission scheme: a source that transmits data and a destination that receives the data transmission. In a cooperative scheme, at least three nodes participate in the communication attempt: a source transmits its data to relay and destination; afterwards, the relay forwards the data to the destination. Thus, if a relay is known a priori cooperative relaying needs at least twice the number of transmissions and three times the number of reception cycles as non-cooperative schemes. Most research contributions focus their energy considerations on transmission cycles only. For instance, Laneman *et al.* [LTW04] propose to introduce feedback from the destination (cf. incremental relaying) to skip transmission from the relay when the destination has received the packet from the source correctly. However, at that time the relay has already spent energy in overhearing the transmission from the source. When both the energy and time spent for selecting a relay are considered, the efficiency of cooperative relaying degrades substantially.

Let us briefly elaborate on the achievable throughput of cooperative relaying. We note that even though the cooperative link might support theoretically a higher data rate than the direct link between source and destination, the used radio architecture might not support multiple different data transmission rates. Hence, in the case of a simple radio which only supports one transmission rate, cooperative relaying requires at least twice the time to deliver a packet than a non-cooperative scheme in perfect channel conditions. Moreover, for using cooperative relaying, a source/destination pair has to select a relay out of the set of its common neighbors first. However, if the direct transmission succeeds in a cooperative relaying scheme using pro-active relay selection, the time spent for the relay selection is wasted. MAC issues introduce further time and resource usage. For instance, source, destination, and selected relay may reserve the channel for the direct and cooperative transmissions and prevent other nodes in their vicinity to communicate for the whole reservation period regardless of the success of the direct transmission.

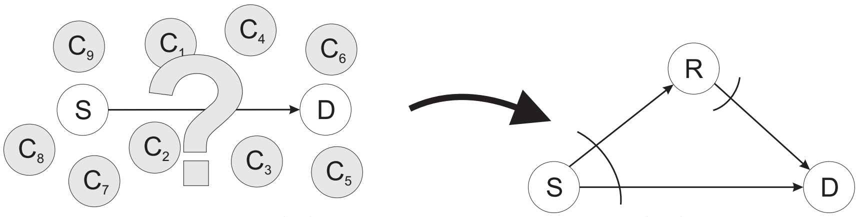


Figure 3.1: Relay selection (R) from several candidates (C_i) to assist S and D.

In this chapter, we elaborate on the efficiency of cooperative relaying in ad-hoc networks. More specifically, we focus on the relay selection process where a communication pair selects relays out of the set of their common neighbors. The relay selection, once successfully completed, mainly reduces the challenges of cooperative relaying to the well studied physical layer aspects (see Figure 3.1). Hence, relay selection has to address major issues of the networking aspects of cooperative relaying and thus, has great impact on its overall performance and efficiency.

The contributions of this chapter are as follows:

- Analysis of the total energy consumption of cooperative relaying in an ad-hoc network.
- Introduction of new methods of adaptive relay selection to increase the energy-efficiency of cooperative relaying:
  - incorporation of relaying capability assessment into relay selection, and
  - initiation of relay selection on demand.
- Proposal of multi-hop-aware cooperative relaying which exploits routing information in the relay selection process to increase the throughput in a multi-hop network:
  - introduction of a system architecture for multi-hop-aware cooperative relaying, and
  - analysis of different relay selection policies for multi-hop-aware cooperative relaying.
- Investigation of two basic access strategies of candidates for relay selection based on a slotted contention:
  - analysis of the impact of imperfect knowledge of candidate cardinality on the selection success, and
  - introduction of an algorithm to choose the parameters of the contention window to achieve a desired relay selection result.

The remainder of this chapter is structured as follows. In Section 3.2, we first analyze a pro-active relay selection mechanism, then we propose and evaluate two new relay selection mechanisms to improve the energy-efficiency of cooperative relaying. In Section 3.3, we propose and evaluate multi-hop-aware cooperative relaying and provide a system architecture and various selection policies to improve the time-efficiency of cooperative relaying. Finally, in Section 3.4, we focus on the success of the relay selection phase, analyze different access strategies for a slotted contention window, and elaborate on the impact of imperfect candidate cardinality information on the selection success.

Results have been achieved in cooperation with coauthors of [ABS08, ABS09].

3.2 Energy-Efficiency

This section aims to increase the energy-efficiency of cooperative relaying. We first analyze the packet complexity and energy consumption of a cooperative relaying protocol using distributed timers to select the best relay [BKRL06]. We refer to this protocol as basic relay selection (RSbasic) hereafter. We have chosen this protocol as our benchmark because it minimizes the packet exchange during relay selection. In our considerations, we do not regard for any MAC issues and focus solely on the selection process. Based on our findings, we introduce two simple modifications to RSbasic which increase the overall energy-efficiency as compared to the basic protocol: (i) common neighbors of $\{S, D\}$ determine if they are suitable relay candidates based on their channel qualities, (ii) D decides whether to enable cooperation based on the direct link quality.

3.2.1 Basic Relay Selection

RSbasic employs pro-active relay selection, i.e., the destination D selects the relay prior to the data transmissions from S to D. Figure 3.2 illustrates the different phases of RSbasic [BKRL06]:

I Node S transmits a `ready-to-send` (`RTS`) packet. Neighbors of S use this packet to measure the SNR γ_{SC_i} between S and themselves.

II The destination D reacts with a `clear-to-send` (`CTS`) packet transmission. Neighbors of D exploit this packet to obtain the SNR γ_{C_iD} from them to D. Here, we assume that if D transmits with the same power as C_i then $\gamma_{C_iD} = \gamma_{DC_i}$, i.e., the channel between D and node C_i has identical behavior as the channel between C_i and D (cf. reciprocity theorem [Rap02]).

III After the transmission of `RTS` and `CTS`, only nodes which have received both packets are potential relaying candidates. Each candidate C_i, combines its measured γ_{SC_i} and γ_{C_iD} to get an indicator of its suitability to act as a relay. Let $\chi_i = f\left(\gamma_{SC_i}, \gamma_{C_iD}\right)$ be the relaying suitability of candidate C_i. Determining the function $f\left(\cdot\right)$ that yields the "best" relay is not straightforward. The authors of [BKRL06] propose to use a simple max-min policy. The suitability of a candidate is determined by the worst link. This is intuitively clear, since when one of the links is bad, relaying fails no matter how good the other one is. Thus, all candidates determine their suitability $\chi_i = \min\left(\gamma_{SC_i}, \gamma_{C_iD}\right)$. The question is how to find the best relay, given that every candidate only knows its own χ_i. Each C_i sets a timer to a value inversely proportional to its χ_i-value, i.e., $t_i = \frac{\Lambda}{\chi_i}$. The parameter Λ is a constant. Clearly, the timer of the best relay expires first. As soon as the timer expires, the corresponding node sends an `apply-for-relay` (`AFR`) packet. Every candidate overhearing the `AFR` transmission of the best node, stops its own timer and quits the cooperation process.

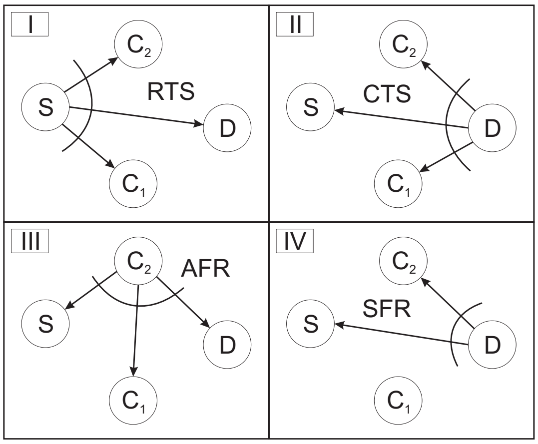


Figure 3.2: Packet exchange in RSbasic

IV The destination answers the reception of an `AFR` packet with a `select-for-relay` (`SFR`) packet containing the identity of the selected relay R. This packet accounts for hidden nodes among the relaying candidates, i.e., nodes which are not in transmission range of the best relay.

The relay selection ends with the reception of the `SFR` packet. Note that D needs to use a time-out timer that expires after a specified time if no `AFR` packet is received. This timer avoids deadlocks in case of missing relays. If no relay exists, D informs S to start the data transmission without using cooperation.

Node S starts its data transmission after the relay selection, i.e., after reception of the `SFR`. Node D and relay R listen to this transmission. If the destination is able to decode the packet correctly it answers with an `acknowledgment` (`ACK`). Otherwise, D stays silent indicating that it needs cooperation.

In the case the direct transmission has failed and if R has successfully received the data from S, R forwards the data to D (triggered by a time-out event if no `ACK` transmission is observed). If R has failed to overhear the transmission from S, it quits cooperation.

In case D has not received the data from S and no relay was selected or R has not decoded the packet from S successfully, S starts a retransmission attempt, including a new relay selection.

This scheme assumes that the coherence-time of the channel is longer than the entire time needed to select a relay R, transmit the data from S, and finally, forward the overheard packet from R to D. RSbasic achieves a diversity gain that is equal to the number of relay candidates, i.e., the number of nodes that have received both packets `RTS` and `CTS`. Furthermore, it outperforms more complicated schemes using multiple relay nodes [BKRL06]. Note that RSbasic considers only packet transmissions for enabling cooperative relaying and does not consider any resource reservation overhead. Thus, the intention of `RTS` and `CTS` is not to reserve the channel but to select a relay.

Packet Complexity

First, let us look at the packet complexity of RSbasic in terms of the number of transmissions (TX) and receptions (RX). All n_S neighbors of S receive the `RTS` transmission and all n_D neighbors of D receive the `CTS` reply. Only common neighbors of S and D, i.e., nodes that have received both packets are relaying candidates. Let n denote the number of common neighbors with $n \leq \min\{n_S, n_D\}$. We count only those receptions that are necessary for the protocol, i.e., nodes that stop participating in the selection process, e.g., nodes that have only received an `RTS` or `CTS` packet, do not receive any following packets. Table 3.1 summarizes the reception and transmission cycles of RSbasic. The column named "waiting" accounts for the period during which all nodes wait for the best relay to start its `AFR` transmission. This time span depends on the parameter Λ, which influences the collision probability of `AFR` packets, i.e., the probability that a relay selection fails. Clearly, this probability decreases with increasing Λ. However, the relay selection delay increases with Λ. The author of [Ble05] determines a collision probability of 0.6 % for $\frac{t_{\mathrm{RxTx}}}{\Lambda} = \frac{1}{200}$, where t_{RxTx} represents the turnarround time, i.e., the switching time between receive and transmit mode of the used radio. We choose $\Lambda = 5$ ms (corresponds to $t_{\mathrm{RxTx}} = 25\,\mu$s) for the following considerations.

For simplicity, we assume that all n relaying candidates are in transmission range of each other. Hence, all $n+2$ nodes receive the `AFR` transmission of the best relay. All relaying candidats hearing the transmission from the best candidate, quit the selection process. Hence, only S and the best relay receive the `SFR` transmission from D which serves two purposes. First, it confirms the identity of the best relay, and second informs S to start the data transmission. The `SFR` packet is only necessary in case of relay nodes being hidden from each other, or when two nodes start transmitting nearly at the same time.

Table 3.1: Packet complexity of RSbasic

mode	RTS	CTS	waiting	AFR	SFR
TX	1	1	–	1	1
RX	n_S	n_D	$n+2$	$n+1$	2

Table 3.1 indicates that RSbasic requires more reception than transmission cycles. The number of transmission cycles are constant, the number of overall reception cycles depends on the degree, i.e., the number of neighbors of S and D.

System Model Assumptions

For the following investigations we assume a network topology as given in Figure 3.3. The distance between S, D and n relaying candidates is d. The intention of this setting is to cancel out hopping gains and to show the pure benefits of cooperative relaying compared to non-cooperative transmissions.

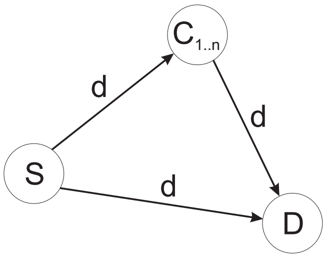


Figure 3.3: Simulation scenario: equal distances

We assume that signaling packets are error free and node D uses selection combining, i.e., it chooses the correct packet if available but does not combine corrupted packets, in the cooperation scheme.

Our focus is on the energy consumption of cooperative relaying. It is common to bound the overall transmission energy of the cooperative scheme by the one of the non-cooperative scheme in order to achieve a fair comparison between cooperative and non-cooperative scheme: the transmission energy used in the non-cooperative scheme by S is split between S and R in the cooperative scheme [LTW04]. However, the energy per transmitted bit and the energy consumed by transceiver circuit to radiate this energy are not directly proportional to each other. In other words, reducing the transmission energy by 50 % does not necessarily reduce the energy consumption of the radio by 50 %. For instance, reducing the transmission power by 60% (from 50 mW to 20 mW) results only in a 6 % reduction of the energy consumed by the IEEE 802.11 interface analysed in reference [EAK$^+$02]. Furthermore, reducing the transmission energy of a radio does not influence the power consumption in receive, idle and sleep modes. This motivates us, to keep the transmissions energy of nodes in both schemes the same. Clearly, the result regarding the outage rate are biased in favor of cooperation in that case. However, we focus on the energy used to deliver a packet, and account for all necessary transmission and reception cycles.

The average energy consumption to successfully deliver a data packet is

$$\bar{E} = \bar{b}_{\mathrm{TX}} \cdot E_{\mathrm{TX}} + \bar{b}_{\mathrm{RX}} \cdot E_{\mathrm{RX}} + \bar{t}_{\mathrm{waiting}} \cdot P_{\mathrm{idle}} \,. \tag{3.1}$$

The terms $\bar{b}_{\mathrm{TX}}$ and $\bar{b}_{\mathrm{RX}}$ represent the average number of transmitted and received bits per correctly delivered packet, respectively. Both values account also for possible overhead caused by cooperative relaying, i.e., relay selection, packet overhearing and cooperative transmission. The term $\bar{t}_{\mathrm{waiting}}$ corresponds to the average contention time per packet of all nodes. We do not regard the energy consumed in sleep mode since it is insignificant compared to the consumption of the other modes. The terms E_{TX} and E_{RX} represent the required energy per bit the radio consumes in transmit and receive mode, respectively. The variable P_{idle} represents the power consumption of the node being in idle mode. We obtain the energy and power values from Table 3.2 using $P_{\mathrm{mode}} = U \cdot I_{\mathrm{mode}}$. The mode is either TX, RX, or idle. The corresponding energy per bit for TX and RX modes for a data rate r in bit/s is determined by $E_{\mathrm{mode}} = P_{\mathrm{mode}}/r$.

Table 3.2: Current consumption of different modes of an IEEE 802.11 interface operating at 4.74 V [FN01]

mode	TX	RX	idle	sleep
I [mA]	284	190	156	10

In the following, for a given SNR-value we simulate packet transmissions between source S and destination D in Matlab. The number of common neighbors of S and D is set to $n = 6$. The size of a data packet is 1 000 bytes and the size of signaling packets (`RTS`, `CTS`, `AFR`, `SFR`, `ACK`) are 3 bytes. The SNR detection threshold $\gamma_{\text{th}} = 1.5$. Only signals which have a received SNR $> \gamma_{\text{th}}$ are detected at nodes. This value also defines the time out of the relay selection process: $t_{\text{time-out}} = {}^{\Lambda}\!/\gamma_{\text{th}}$. The used data rate is $r = 250\,000$ bits/s. We use Rayleigh-Model-1 (see Section 1.3) to model the wireless channel between the nodes. Each data point in our simulations corresponds to an averaged value obtained from at least 50 000 data transmissions from S. We indicate the 90%-confidence interval of the averaged values in our figures. For figures representing the relative gains of the cooperative schemes to the non-cooperative one, we illustrate the corresponding true values including confidence intervals in the Appendix (see Figure A.1).

Figure 3.4a indicates the ratio of required cooperations; i.e., the ratio of number of failed direct transmissions to overall number of transmissions from S, for RSbasic as a function of the average received SNR γ_d. The average received SNR is the same for all nodes in our system model (cf. equal distance assumption). It indicates the probability that D requests a cooperative transmission from the selected relay. In the low SNR regime ($\gamma_d \leq 6$ dB), the transmission from S hardly succeeds and cooperation is highly demanded. Around an average SNR of 10 dB, cooperation is required in 50 % of all transmissions. In the high SNR regime ($\gamma_d > 20$ dB), the direct transmission from S nearly always succeeds; a cooperative transmission, therefore, is hardly ever necessary.

Figure 3.4b depicts the ratio of successful cooperation attempts to overall cooperative transmission requests from D. Cooperation is successful if D receives the data correctly although the direct transmission has failed. In the low SNR regime, relays can hardly ever support the direct transmission between S and D. At 12 dB, cooperative relaying succeeds 90 % of the time it is requested from D.

From Figures 3.4a and 3.4b we draw the following conclusions:

- At low SNR-values, D has nearly no chance of receiving data from S. Cooperative relaying cannot overcome the bad average received SNR.
- With increasing average received SNR, cooperative relaying can support the communication S-D. For instance, at $\gamma_d = 10$ dB, cooperative relaying succeeds in over 75 % of the cases it is required (=50 %).
- At high SNR-values, cooperative relaying hardly ever fails. However, the likelihood that cooperation is requested by D vanishes.

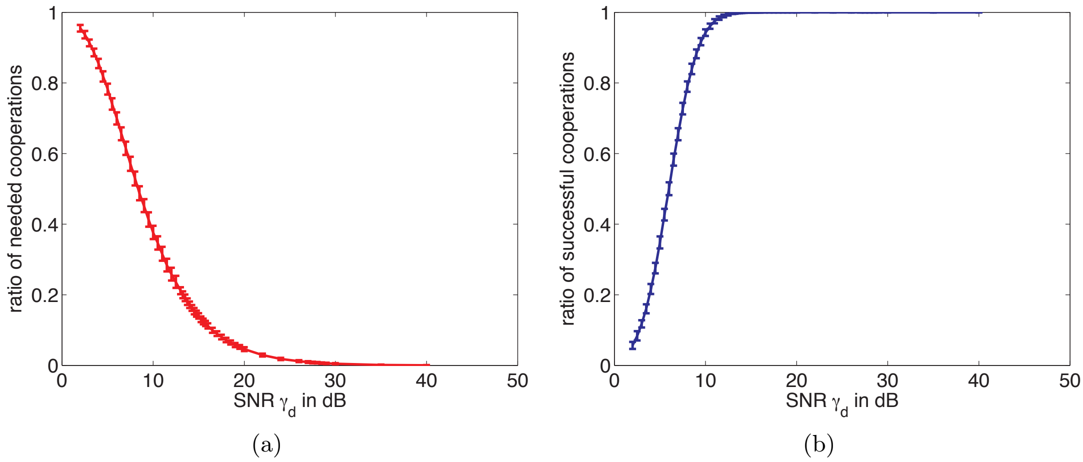


Figure 3.4: RSbasic: ratio of (a) demand and (b) success of cooperative relaying as a function of average received SNR γ_d.

RSbasic selects a relay for each communication attempt between S and D. Whenever cooperative relaying fails or the cooperative transmission is not required by D, the time and the energy spent for selecting the relay and the energy consumed by the relay to overhear the data transmission from S is lost without benefit. Table 3.2 states that the energy needed for receiving data is in magnitude equal to the amount of energy needed for transmitting data. That is why designers of cooperative protocols should not neglect the impact of reception cycles in the overall energy consumption of protocols. For instance, it is common practice for communication-protocols in WSN to maximize the time in which transceivers are in sleep mode [KM07]. This is our motivation to introduce methods to make relay selection adaptive to the channel conditions.

3.2.2 Relay Selection with Early Retreat

The previous experiment has shown that cooperative relaying cannot overcome a lack of transmission power. Due to the equal distance setting of the investigated topology, it is barely possible that a relay successfully overhears the transmission from the source in the low SNR regime. Even if one would succeed, its channel to D suffers from the same low average SNR. These observations lead to following conclusion: Nodes should not try to help at all costs.

The idea of relay selection with early retreat (RSer) is that neighboring nodes receiving `RTS` and `CTS` should assess their own relaying capability. Based on this assessment, they should decide whether to participate in the relay selection. RSer does not require any additional packets compared to RSbasic. The only required modification is that not all nodes that have received `RTS` and `CTS` are candidates. Instead, on reception of `RTS` and `CTS`, nodes determine their expected PER based on the measured SNR-values. If the expected PER for any link is above some threshold

Ω ($0 \leq \Omega \leq 1$) the corresponding node retreats from the relay selection process and hence does not need to receive any further information regarding the cooperative relaying process of S-D, i.e., further signaling packets of the selection process and probably overhearing the transmission of S. In this context we differentiate between `RTS`-early retreat and `CTS`-early retreat depending on which signaling packet triggers the retreat. For instance, nodes which retreat because of a `CTS`-packet have a link to S with PER $< \Omega$.

Let us determine the early retreat probability of a node which is a function of the fading coefficient h. Remember that we choose h randomly for each communication cycle, consisting of relay selection, direct transmission and cooperative transmission, from a Rayleigh distribution with $\mathrm{E}\left[h^2\right] = L$, where L represents the path loss. The BER of a BPSK modulated signal is [Kam04]

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\gamma}\right) , \tag{3.2}$$

where $\gamma = \frac{h^2\,E_b}{N_0}$. The parameters E_b and N_0 are the energy per transmitted bit and the noise spectral density, respectively. The PER of an uncoded data packet containing b bits is

$$\mathrm{PER} = 1 - (1 - \mathrm{BER})^b . \tag{3.3}$$

For quasi-static fading following a Rayleigh distribution the probability of the PER being above a given threshold Ω is

$$\begin{aligned}
\Pr\left[\mathrm{PER} > \Omega\right] &= \Pr\left[1 - (1 - \mathrm{BER})^b > \Omega\right] \\
&= \Pr\left[h^2 < -\frac{N_0 \cdot \left(\mathrm{erfc}^{-1}\left(2 \cdot \left(1 - (1-\Omega)^{\frac{1}{b}}\right)\right)\right)^2}{E_b}\right] \\
&= 1 - \exp\left(-\frac{N_0 \cdot \left(\mathrm{erfc}^{-1}\left(2 \cdot \left(1 - (1-\Omega)^{\frac{1}{b}}\right)\right)\right)^2}{L\,E_b}\right) .
\end{aligned} \tag{3.4}$$

The probability that a node retreats at the reception of an `RTS` packet given Ω is $p_{\mathrm{RTS}}(\Omega) = \Pr\left[\mathrm{PER} > \Omega\right]$. We determine the `CTS`-early retreat probability for a given Ω-value by

$$\begin{aligned}
p_{\mathrm{CTS}}(\Omega) &= \left(1 - \Pr\left[\mathrm{PER} > \Omega\right]\right) \cdot \Pr\left[\mathrm{PER} > \Omega\right] \\
&= \Pr\left[\mathrm{PER} > \Omega\right] - \left(\Pr\left[\mathrm{PER} > \Omega\right]\right)^2 .
\end{aligned} \tag{3.5}$$

The overall early retreat probability is determined by

$$\begin{aligned}
p_{\mathrm{er}}(\Omega) &= p_{\mathrm{RTS}}(\Omega) + p_{\mathrm{CTS}}(\Omega) \\
&= 2\Pr\left[\mathrm{PER} > \Omega\right] - \left(\Pr\left[\mathrm{PER} > \Omega\right]\right)^2 .
\end{aligned} \tag{3.6}$$

The probability that out of n relaying candidates at least one does not retreat from the selection process and hence the probability of having a relay is

$$p_{\mathrm{relay}} = 1 - \left(p_{er}\left(\Omega\right)\right)^{n} \ . \tag{3.7}$$

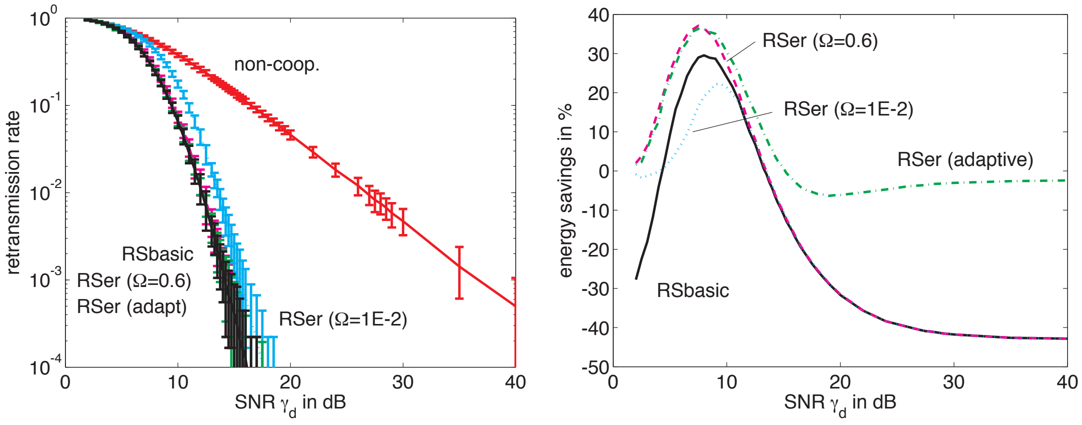
The Ω-value changes also the maximum time the destination has to wait for an `AFR` packet. The time out value for RSer with given Ω-value is:

$$t_{\mathrm{time-out}} = \frac{\Lambda}{\left(\mathrm{erfc}^{-1}\left(2 \cdot \left(1 - (1-\Omega)^{\frac{1}{b}}\right)\right)\right)^{2}} \ . \tag{3.8}$$

We use the packet retransmission rate of S to infer about the outage rate in the absence of coding. The retransmission rate of the non-cooperative scheme corresponds to the PER of the direct link. The retransmission rate of the cooperative scheme is

$$p_{\mathrm{ret}} = \mathrm{PER}_{\mathrm{direct}} \cdot \left(\mathrm{PER}_{\mathrm{relay}} \cdot p_{\mathrm{relay}} + 1 - p_{\mathrm{relay}}\right) \ , \tag{3.9}$$

where $\mathrm{PER}_{\mathrm{direct}}$ and $\mathrm{PER}_{\mathrm{relay}}$ are the PERs of the direct and relay link, respectively.



(a) (b)

Figure 3.5: RSer: (a) retransmission rate of S and (b) energy savings as a function of average received SNR γ_d.

Figure 3.5a illustrates the retransmission rate of S over the average received SNR γ_d for non-cooperative, RSbasic, and RSer with different Ω-values, respectively. The curve labeled “RSer (adapt)” represents an early retreat mechanism which depends on the SNR of the direct channel. Nodes retreat if the channel from S to D via themselves has a PER that exceeds the one of the direct channel. Node D can include the SNR or the PER of the direct channel in its `CTS` transmission.

Regarding retransmission rate, we observe that the cooperative schemes perform always better or at least as good as the non-cooperative scheme. The retransmission rate of RSer is always greater than or equal to the retransmission rate of RSbasic and depends on Ω. The retransmission rate increases with decreasing Ω. For $\Omega = 1$, RSer behaves like RSbasic; i.e., all common neighbors of S and D compete for becoming the relay. For $\Omega = 0$, it is impossible to find a relay for S and D. In that case, RSer performs regarding retransmissions like the non-cooperative scheme. If we choose Ω too small, we exclude nodes from the relay selection process which could assist the communication. We do not see any performance degradation in RSer with $\Omega = 0.6$ and RSer (adapt) compared to RSbasic in the considered SNR range.

Figure 3.5b depicts the influence of parameter Ω on the energy savings of RSer compared to the non-cooperative scheme as a function of the average received SNR γ_d. A positive value indicates that the cooperative scheme is more energy efficient in delivering a packet from S to D, whereas a negative value shows that it is in terms of energy better to apply a non-cooperative scheme. First, we notice that RSbasic provides energy savings for $5\,\text{dB} \leq \gamma_d \leq 13.2\,\text{dB}$ and consumes for the remaining γ_d-values more energy than the non-cooperative scheme. The energy savings offered by RSer depend on the selected Ω-value. For $\gamma_d < 10\,\text{dB}$, we observe the highest savings for $\Omega = 0.6$. The savings of RSer with fixed Ω-values converge to the savings of RSbasic for increasing γ_d-values. This is not the case of RSer using an adaptive Ω-threshold. Here, the performance of the cooperative link, i.e., the link offered by the relay, needs to be better than the direct link between S and D. Hence, in high SNR regions most of the relay candidates retreat.

Let us summarize our analysis results of RSer: An intuitive result is that cooperative schemes outperform the non-cooperative scheme in terms of required retransmissions. This is clear because of our transmission-energy policy (all nodes use in all schemes the same transmission power). The smaller number of retransmissions results in energy savings of RSbasic compared to the non-cooperative scheme only in a certain range of SNR. Due to the assessment method of the nodes' relaying capabilities in RSer, only those nodes which can support the S-D communication remain in the selection process. In our test-scenario, RSer is able to achieve energy-gains up to an SNR-value of 15 dB. The offered gain depends on the used Ω-value. If we choose Ω too small, also relays which could assist the direct communication retreat; if we choose Ω too big, relays which cannot contribute to the communication success stay in the selection process and consume energy. Our findings indicate that there is no optimum Ω-value for all SNR domains. Considering the overall SNR-range, the results suggest to use an adaptive early retreat threshold which depends on the S-D link quality. To increase the performance in the low SNR regime, we impose an additional criterion on the adaptive threshold which demands a certain minimum quality regardless of the direct link. Hereafter, RSer refers to a scheme where nodes retreat if any of its link to S and D has a PER > 0.6 and if it cannot provide a better overall connection between S and D than the direct one.

3.2.3 Relay Selection on Demand

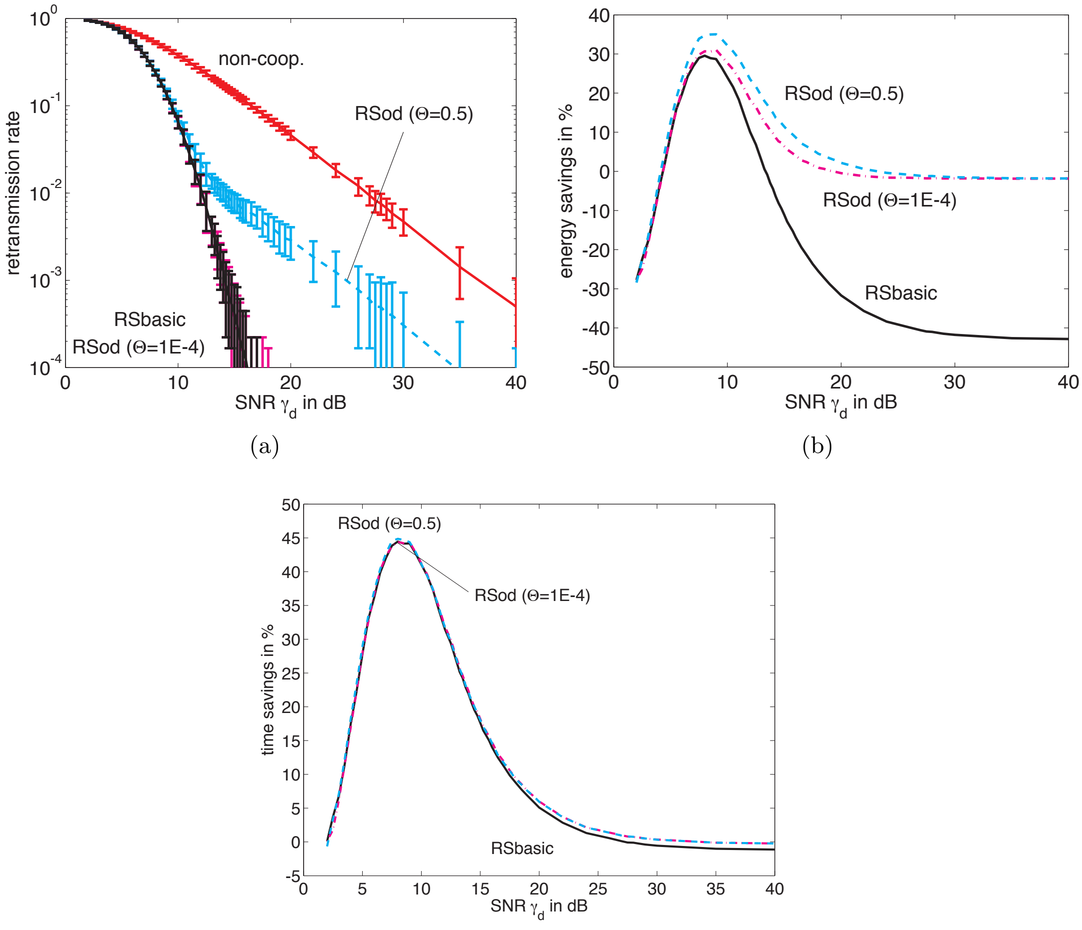
As our results in Section 3.2.1 indicate, if the link between S and D is in a state that facilitates the communication between these nodes, the nodes should not invest resources, i.e., energy and time to setup cooperation. In this section, we propose relay selection on demand (RSod), which aims to avoid relay selection when the S-D channel is in a good state. Relays are only selected, if required with sufficient likelihood. Upon reception of the `RTS` packet, D exploits the measured SNR to infer about the expected PER of the direct channel. If the S-D link provides a lower PER than a certain threshold Θ, D skips the relay selection scheme by replying with an `SFR` packet. This `SFR` packet informs all nodes that cooperation is not required and S can start transmitting its data right away. We envision, since the relay selection is only performed when needed that this scheme will save energy and time and hence will improve throughput compared to RSbasic. In case the expected PER of the direct link is above the given threshold Θ, the basic relay selection is carried out. The parameter Θ should be chosen in such a way that the desired system performance can cope with the expected packet loss. Given Θ we can derive the probability of demanding cooperation similarly to (3.4):

$$\Pr\left[\mathrm{PER} > \Theta\right] = 1 - \exp\left(-\frac{N_0 \cdot \left(\mathrm{erfc}^{-1}\left(2 \cdot \left(1 - (1-\Theta)^{\frac{1}{b}}\right)\right)\right)^2}{L\, E_b}\right) . \tag{3.10}$$

Figure 3.6a depicts a comparison of the retransmission rates of the non-cooperative scheme, RSbasic and RSod using different Θ-values. Clearly, RSod does not perform better than RSbasic in terms of required retransmissions. The parameter Θ defines that retransmission rate up to which RSod behaves like RSbasic. For $\Theta = 0$, RSod becomes RSbasic; for $\Theta = 1$ RSod never demands cooperation. In that case, RSod behaves like the non-cooperative scheme.

Figure 3.6b indicates that the energy consumption of RSod and RSbasic is comparable in the low SNR-regime. With increasing SNR, cooperation is less often demanded by RSod which results in a better energy-efficiency. However, in the high SNR-region cooperative relaying requires more energy than the non-cooperative scheme. Our results indicate the highest energy savings for $\Theta = 0.5$. The smaller PER of $\Theta = 10^{-4}$ requires more relay selection cycles and the selected relay to overhear the data transmission. The increased number of retransmissions caused by the higher PER of $\Theta = 0.5$ requires less energy than the additional overhead of preparing cooperation of RSod using $\Theta = 10^{-4}$.

Finally, Figure 3.6c depicts the savings in time for a successful packet transmission compared to the non-cooperative scheme. A positive value indicates that the cooperative scheme requires less time to deliver a packet from S to D. For high SNR-values cooperation requires more time than the non-cooperative scheme to transmit a packet. RSbasic selects for each transmission, regardless of the link quality between S and D, a relay. Although RSod skips the relay selection when cooperation



(a) (b)

(c)

Figure 3.6: RSod: (a) retransmission rate of S, (b) energy savings, and (c) packet transmission time savings as a function of average received SNR γ_d.

is unlikely, it still needs to exchange `RTS` and `SFR` packets which negatively influences the transmission time of packets in the high SNR-regime. We observe time gainings of RSbasic and RSod up to an SNR-value of 27 dB and 34 dB, respectively. Again, $\Theta = 0.5$ achieves higher savings than $\Theta = 10^{-4}$.

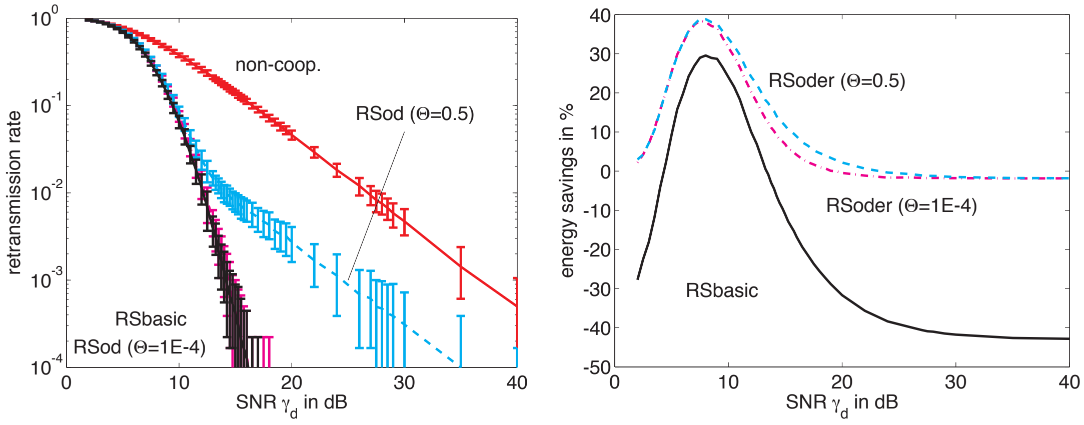
Summing up, RSod skips relay selection in cases where the S-D channel performs in terms of retransmission rate better than a certain predefined Θ-value. Our results indicate that RSod saves time and energy compared to RSbasic.

The reliability of RSod increases with decreasing Θ-values; however so does the energy and time consumption per transmitted packet. A system which has to rely on a certain outage rate and does not use retransmissions for corrupted packets should use a corresponding low Θ-value. Systems using retransmissions for corrupted packets may choose $\Theta = 0.5$. Assuming that the wireless channel stays constant, a PER $= 0.5$ implies that S requires on average two transmissions to deliver a packet to D. A cooperative scheme would need the same number of data transmissions and additional signaling packets to prepare the cooperation.

3.2.4 Relay Selection on Demand with Early Retreat

RSer and RSod provide means to increase the energy-efficiency of RSbasic. While RSer addresses common neighbors of S and D to assess their cooperative relaying capability before competing to become a relay, RSod introduces a mechanism at D to decide about the necessity of cooperation at all. An intuitive approach is relay selection on demand with early retreat (RSoder) which is the combination of both methods and aims to use cooperation only when necessary and prevents nodes which are barely able to support the direct communication from competing to become a relay.

Figure 3.7a illustrates the retransmission rate of RSoder for $\Theta = \{0.5, 10^{-4}\}$. RSbasic and RSoder with $\Theta = 10^{-4}$ perform regarding this value similarly. RSoder with $\Theta = 0.5$ performs regarding the number of required retransmissions better than the non-cooperative scheme; their retransmission rate curves have beyond 13 dB a similar slope.



(a) (b)

Figure 3.7: RSoder: (a) retransmission rate of S and (b) energy savings as a function of average received SNR γ_d.

In Figure 3.7b we can see the energy savings of RSoder compared to the non-cooperative scheme. RSoder consumes less than RSbasic in the entire SNR-range. The savings depend on the chosen Θ-value.

In an ad-hoc network, a source-destination pair has to select a relay in order to use cooperation. Selecting a relay and having that relay overhearing a data transmissions consumes time and energy. Thus, it is import to decide when to enable cooperation (RSod) and which nodes should candidate to become relay (RSer). By using RSoder, we improve both the time as well as the energy-efficiency of cooperative relaying.

3.3 Time-Efficiency

While the previous section has addressed the energy-efficiency of cooperative relaying, this section focuses on the time-efficiency of cooperative schemes. Although RSoder also addresses the time-efficiency via relay selection by carefully choosing when to cooperate, cooperative relaying when employed still requires double the transmission time of a successful direct transmission using the same data rate. In this section, we aim to improve the efficiency of cooperative relaying by exploiting routing information in the cooperation process.

Using information from different layers of the communication stack (cf. cross layer design) violates the established layering approach of the protocol stack and can lead to solutions which are hard to maintain and have unexpected behavior [KK05]. Despite these, we envision that a careful information exchange between routing layer and cooperative relaying can improve the achievable performance.

In the following, we use knowledge from routing to have a more time-efficient cooperative relaying mechanism. To this end, we propose multi-hop-aware cooperative relaying (MHA-Coop-Relaying). The idea of utilizing routing information in the cooperation process is also proposed independently in [LVK$^+$08]. While we focus on the overall system architecture and selection policies, [LVK$^+$08] elaborates on the necessary modifications in the MAC-layer where relaying candidates are computed in advance.

3.3.1 Multi-Hop-Aware Cooperative Relaying: Basic Idea

Let us use Figure 3.8 to motivate the basic idea of MHA-Coop-Relaying where we exploit routing information in the cooperation process. The figure shows an example of a multi-hop network. Node S intends to send a packet to D_2. First, S employs a routing algorithm to find a route to the destination. The resulting route uses D_1 as an intermediate hop. The end-to-end packet delivery consists of two direct transmissions (S-D_1-D_2). Classic cooperative relaying treats both of these transmissions independently. For each hop it finds a relaying node that supports the current link. Hereafter, we refer to such a scheme as hop-by-hop cooperative relaying (HbH-Coop-Relaying). Relaying candidates for the S-D_1 and D_1-D_2 transmissions are $\{C_1, C_3\}$, and $\{C_2, C_3\}$, respectively. Node C_3 is in terms of its connectivity between S and D_2 like D_1, and in fact, could replace D_1 as an intermediate hop of the route. The candidates $\{C_1, C_2\}$ are not equivalent to D_1 since they are only in transmission range of $\{S, D_1\}$ and $\{D_1, D_2\}$, respectively. Hereafter, the term *single-hop-relay* refers to nodes like C_1 and C_2 which can exclusively support a single hop of a route. A *multi-hop-relay*, e.g., node C_3, can act as an intermediate routing node.

The overall task in the example of Figure 3.8 is to deliver packets from S to D_2. The intermediate node D_1 is only a means to connect S and D_2. In such a scenario, HbH-Coop-Relaying suffers from its limited perspective since it selects another relay for each hop.

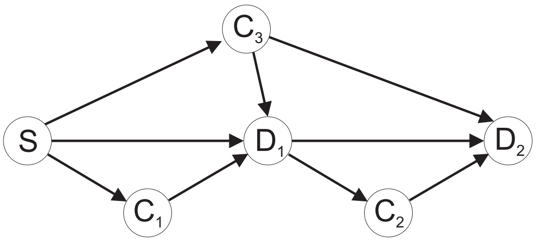


Figure 3.8: Multi-hop network with potential cooperative relaying nodes

In this section, we propose to exploit routing information in the cooperative selection process. For instance, if C_3 is the selected relay for the S-D_1 transmission and if D_2 is aware that the transmission of C_3 to D_1 is also of interest for itself, D_2 can overhear the relay transmission to D_1. It might receive the whole packet correctly which makes a transmission from D_1 redundant. And, if D_2 receives only parts of the packet, it can store them and use them as incremental information for the transmission D_1 to D_2 (cf. [DFEV05]).

3.3.2 Multi-Hop-Aware Cooperative Relaying: Protocol Architecture

This section introduces the basic protocol architecture of MHA-Coop-Relaying and elaborates on the different phases of the cooperation process. We do not yet address any MAC issues. The proposed protocol uses the same probing packets as the RSbasic protocol of the previous section to measure the SNR of links. As for all pro-active schemes the cooperation process consists of relay selection phase, direct transmission phase and cooperative transmission phase.

Relay Selection Phase

The relay selection of HbH-Coop-Relaying considers the link qualities from the candidate to S and D_1. In the RSbasic scheme, the relay candidates gather this information when S and D_1 exchange the probing packets `RTS` and `CTS`.

The relay selection of MHA-Coop-Relaying has to regard additionally the link quality between relay candidate and D_2. Therefore, also D_2 needs to send a probing packet `CTS2`. To achieve this, D_2 needs to be aware of the packet exchange between S and D_1 and that this transmission is of interest to it. The selection scheme needs to have access to the routing information of packets, e.g., the address of D_2. For instance, the `RTS` packet can piggyback the address of D_2, and D_1 includes this information in its own `CTS` transmission. In case D_2 is not blocked by another transmission in its vicinity, it replies with a `CTS2` packet.

Based on the exchanged probing packets, we can differentiate two sets of relaying candidates:

- Set $\mathcal{H}$: nodes that have only links to S and D_1 but are not in transmission range of D_2, i.e., have received `RTS` and `CTS` but not a `CTS2` packet.
- Set $\mathcal{M}$: nodes that have links to S, D_1 and D_2, i.e., have received `RTS`, `CTS` and `CTS2` packets.

Obviously, $\mathcal{H}$ and/or $\mathcal{M}$ can be empty, indicating that there are no potential relays in that region. The set $\mathcal{T}$ is the union set of $\mathcal{H}$ and $\mathcal{M}$, i.e., the set of all potential relays. RSbasic [BKRL06] operates on $\mathcal{T}$ to find the best single-hop relay by using the following selection criterion:

$$R = \underset{C_i \in \mathcal{T}}{\operatorname{argmax}} \left(\min \left(\gamma_{SC_i}, \gamma_{D_1C_i} \right) \right), \tag{3.11}$$

where R is the selected relay and γ_{SC_i} and $\gamma_{D_1C_i}$ are the received SNRs of the links between nodes S and C_i and nodes D_1 and C_i, respectively. This selection criterion considers only the worst link of a relay candidate and selects that node which has the “best worst” link.

For MHA-Coop-Relaying, we investigate five different relay selection policies:

- *MHA-HbH*-policy:
  This policy does not regard the link quality of relay candidates to D_2. It uses the same selection policy as RSbasic. MHA-Coop-Relaying is not enforced. If a selected relay is in transmission range of D_2 multi-hop cooperation is used.
- *Delivery*-policy: Each relay candidate C_i determines the expected BER based on the received SNR of the probing packets. Candidates calculate an end-to-end delivery value defined as:

  $$\begin{aligned} \forall C_i \in \mathcal{T} : G(C_i) \quad = \quad & (1 - \mathrm{BER}_{SC_i}) \cdot (1 - \mathrm{BER}_{D_1C_i}) \cdot (1 - \omega_{D_2}) + \\ & (1 - \mathrm{BER}_{SC_i}) \cdot (1 - \mathrm{BER}_{D_2C_i}) \cdot \omega_{D_2} \ . \end{aligned} \tag{3.12}$$

  The terms BER_{xy} refer to the expected BER of the link between node x and node y. The parameter ω_{D_2} decides on the importance of delivering packets to D_2. If $\omega_{D_2} = 0$, the selection policy does not regard link qualities from candidates to D_2. If $\omega_{D_2} = 1$, the policy does not consider the link qualities of the candidates to D_1. We use $\omega_{D_2} = 2/3$ in this section. Our motivation is that the relay should provide help in the packet delivery to D_2. If the relayed packet reaches D_1 at least another transmission is required to reach D_2. If the relay delivers the packet to D_2 no further transmission is necessary. Hence, the success in reaching D_2 is twice as important as reaching D_1. For all nodes C_i in $\mathcal{H}$ the policy sets $\mathrm{BER}_{D_2C_i} = 1$. The best relay according to the delivery-policy is the relay which has the highest end-to-end delivery value of all potential candidates:

  $$R = \underset{C_i \in \mathcal{T}}{\operatorname{argmax}} \ G\left(C_i\right) \ . \tag{3.13}$$

- The following policies do not regard any candidates of set $\mathcal{H}$ as long set $\mathcal{M} \neq \emptyset$. If $\mathcal{M} = \emptyset$, the selection policy of RSbasic is used. For $\mathcal{M} \neq \emptyset$, we select the relay R as
$$R = \underset{C_j \in \mathcal{M}}{\operatorname{argmax}} B\left(C_j\right) \tag{3.14}$$
  The comparison function $B(C_j)$ depends on the used policy:
  - *Min*-policy:
    The min-policy chooses the smallest SNR over the links from S, D_1 and D_2 to the relay candidate:
$$\forall C_j \in \mathcal{M} : B(C_j) = \min\left(\gamma_{SC_j}, \gamma_{D_1C_j}, \gamma_{D_2C_j}\right) \tag{3.15}$$
  - *Max*-policy:
    The max-policy selects the best SNR over the links from S, D_1 and D_2 to the relay candidate:
$$\forall C_j \in \mathcal{M} : B(C_j) = \min\left(\gamma_{SC_j}, \max\left(\gamma_{D_1C_j}, \gamma_{D_2C_j}\right)\right) \tag{3.16}$$
  - *Harmonic*-policy:
    The harmonic-policy combines SNR of the links from relay candidate to D_1 and D_2 using the harmonic mean. Afterwards, it compares that value with the SNR over the link from S to the relay candidate, and chooses the smaller one:
$$\forall C_j \in \mathcal{M} : B(C_j) = \min\left(\gamma_{SC_j}, \frac{2 \cdot \gamma_{D_1C_j}\,\gamma_{D_2C_j}}{\gamma_{D_1C_j} + \gamma_{D_2C_j}}\right) \tag{3.17}$$

Direct Transmission Phase

The direct transmission phase starts after the relay selection phase. It mainly consists of the data transmission from S. If a single-hop relay is selected, D_1 informs S and the relay about its success in receiving the data packet. If D_1 has received the data packet correctly, it sends an `ACK` and the cooperative transmission phase of S-D_1 is skipped. If D_1 stays silent, the relay assumes a reception error and proceeds with the cooperative transmission phase.

However, in case of a multi-hop relay, D_1 does not give any feedback about its reception success. The cooperative transmission phase is *always* conducted.

Cooperative Transmission Phase

Based on the reception success of D_1 and R in the direct transmission phase one can differentiate 4 cases:

- Neither D_1 nor R have received the data transmission from S: In that case, cooperation fails and S starts a retransmission which includes a new relay selection.

- D_1 has not received the packet and R has received it: R forwards the packet to D_1 and in case of a multi-hop relay also to D_2.
- D_1 has received the packet and R has not received the packet: If D_1 has selected a multi-hop relay (a relay can convey this information in its `AFR` packet), D_1 forwards the packet to D_2 which utilizes the resource reservation of the cooperative phase.
- D_1 and R have received the packet: D_1 and R transmit the data packet simultaneously to D_2 using D-STC (see [LW03, SB05, MYPK07]).

If D_1 has selected a multi-hop relay, it waits after the data transmission from R and/or itself for an `ACK` packet from D_2. If D_1 receives this `ACK`, it forwards it to S. Note that it is not important whether D_1 itself has received the packet. D_1 marks this packet as received and forwarded. If D_1 does not sense an `ACK`, it informs S about its own success in receiving the data packet.

3.3.3 Cooperation Process at each Node

This section uses Standard Description Language (SDL) flowcharts to explain the processes performed at the communication partners.

Relay R

Figure 3.9 depicts the flowchart of the process in R after reception of the direct transmission. If R fails to receive the direct transmission from S, it quits the cooperation process. If R has overheard the direct transmission successfully, it checks whether it was in transmission range of D_2 during the relay selection. If it is a multi-hop relay it encodes the received data packet from S using a D-STC (for two nodes) and forwards the data. A single-hop relay waits for a positive `ACK` from D_1. If R does not receive an `ACK` within some time, it assumes that D_1 requires cooperation and transmits the received data.

One Hop Destination D_1

Figure 3.10 presents the process at D_1 after the direct transmission phase. If D_1 is not able to decode the packet via direct link it waits for the relay to forward the data. If the relay does not respond within a certain period of time, node D_1 transmits a `negative-acknowledge` (`NACK`) to S. If D_1 receives a packet from R, D_1 combines it with the data received from S using MRC.

If D_1 decodes the packet during direct transmission phase and a multi-hop relay is chosen, D_1 transmits the packet instantly to D_2. This is done concurrently with the transmission from R using D-STCs.

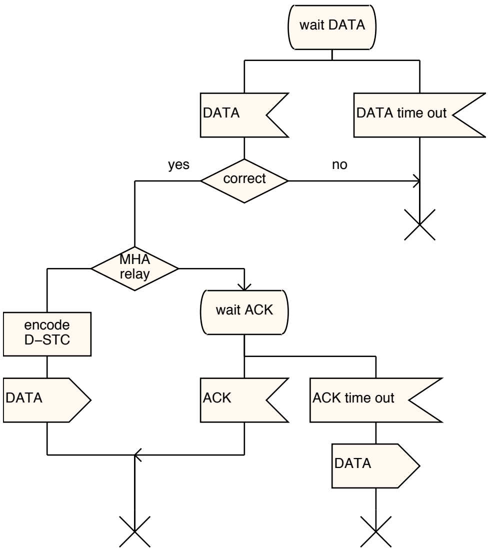


Figure 3.9: Cooperative transmission phase: R

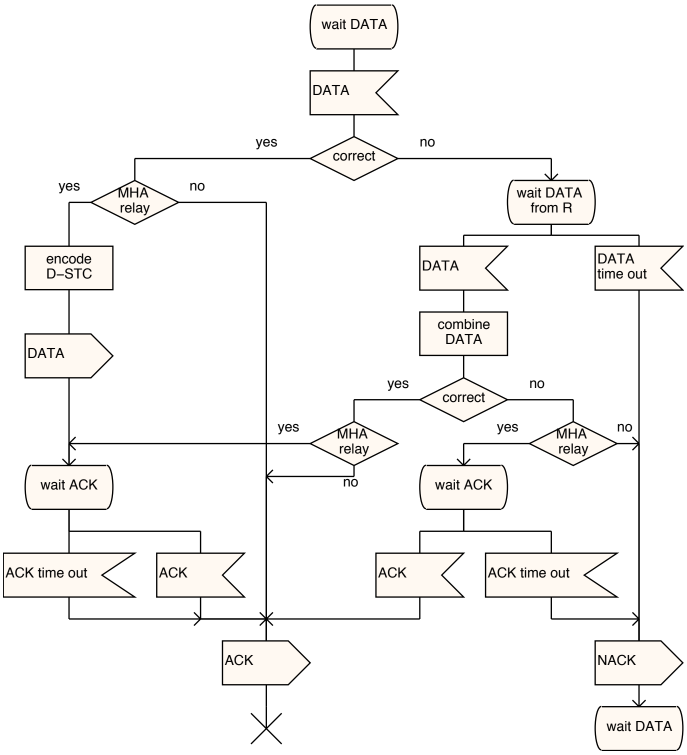


Figure 3.10: Cooperative transmission phase: D_1

Furthermore, in the case of a selected multi-hop relay, D_1 waits after the cooperative transmission for an `ACK` from D_2. If it receives an `ACK` it informs S about the success of the transmission. In such a case, D_1 does not need to forward the packet to D_2.

If R is a single-hop relay or D_2 does not send an `ACK` within some time interval, D_1 informs S about its own success of receiving the data packet. In a further step, D_1 transmits the packet to D_2.

Two Hop Destination D_2

Figure 3.11 reflects the action flow at D_2. For D_2 it is important to collect as much information as possible for decoding the packet of S. It may overhear parts of the direct transmissions from S to D_1 (cf. to [DFEV05]). However, it is more likely that D_2 can receive more information in the cooperative transmission phase. D_2 requires the CSI of the channels from S and R to itself to have the means for decoding D-STCs. D_2 stores this information during the relay selection phase. In the cooperative transmission phase, D_2 compares the CSIs from the relay selection phase with the one of the current reception. If the current CSI differs significantly from the ones stored during the relay selection, D_2 assumes a simultaneous transmission from S and R. In that case it uses the known CSIs to decode the received D-STC signal. Otherwise, only one of the nodes is forwarding the packet to D_2. If D_2 receives the data correctly it sends an `ACK`.

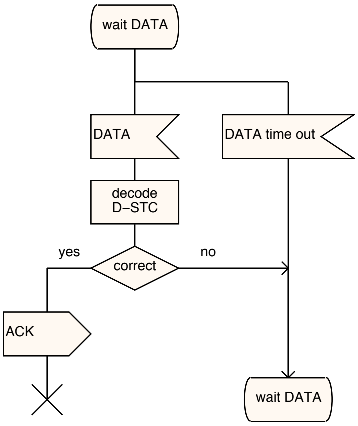


Figure 3.11: Cooperative transmission phase: D_2

3.3.4 Evaluation of multi-hop-aware cooperative relaying

Assumptions and Simulation Settings

We assume that the relay selection protocol has access to routing information. It knows at least the addresses of the next two hops. All considered schemes use the same transmission power and data rate. In the evaluation, we focus on data transmissions and do not regard any overhead caused by the exchange of signaling packets.

In our test scenario, we distribute nodes S, D_1 and D_2 on a line, with distance d between S-D_1 and D_1-D_2 (see Figure 3.12). The value d_{th} represents the signal detection threshold range in an AWGN channel model. Node S transmits its packets via D_1 to the final destination D_2. Potential relaying candidates are uniformly distributed around those nodes with a certain node density ρ. We employ Rayleigh-Model-1 with a cycle equal to the duration of two data transmissions to model the communication channel. Each data point represents the averaged value of 500 relay candidate distributions simulating 500 data packet transmissions from S. Nodes D_1 and D_2 use MRC to combine received signals from source and relay.

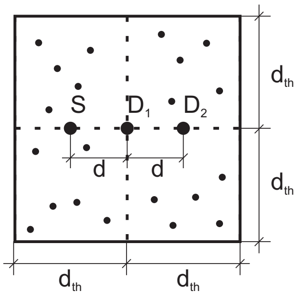


Figure 3.12: Simulation scenario: MHA-Coop-Relaying

In addition to the retransmission rate of node S, we use the *average number of data transmissions to deliver a packet from S to D_2* as a performance criterion. Note that the minimum number of transmissions to deliver a packet from S to D_2 via D_1 is 2 (error free case).

Simulation Results

In a first step, we set the hop-distance d such that the average received SNR at d $\gamma_d = \{10, 20\}$ dB and vary the density of the potential relay candidates.

Figures 3.13a-3.13b show the retransmission rate of node S as function of the node density for the different schemes for $\gamma_d = 10\,\text{dB}$ and $\gamma_d = 20\,\text{dB}$, respectively. For $\gamma_d = 10\,\text{dB}$, the non-cooperative scheme experiences a retransmission rate around 0.1, independent of the node density. For the cooperative schemes, the retransmission rates decrease with increasing node density and are always smaller than that of the non-cooperative scheme. It is more likely to find a proper relay in a dense network than in a sparse one. HbH-Coop-Relaying and MHA-Coop-Relaying with MHA-HbH-policy have similar retransmission behaviors and the steepest declines with increasing node density. The retransmission rate of MHA-Coop-Relaying depends heavily on the used selection policy. The min-policy has the highest retransmission rate of the cooperative schemes. For $\gamma_d = 20\,\text{dB}$, the retransmission rate of node S drops for all schemes. More interestingly, we observe that HbH-Coop-Relaying

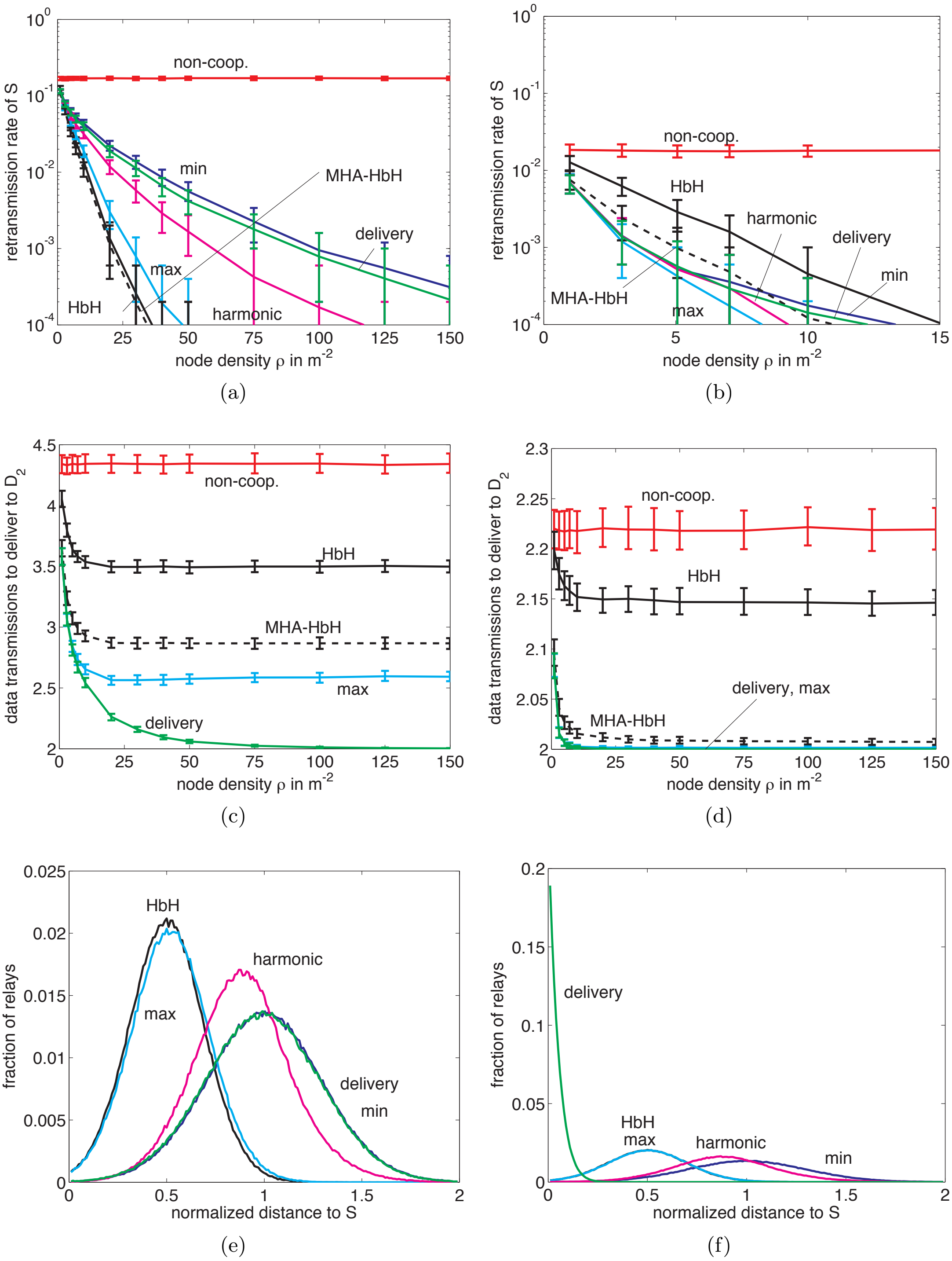


Figure 3.13: MHA-Coop-Relaying: (a-b) retransmission rate of S, (c-d) average number of required data transmissions as a function of node density ρ, and (e-f) fraction of selected relays depending on the distance from S for $\gamma_d = 10\,\text{dB}$ (a, c, e) and $\gamma_d = 20\,\text{dB}$ (b, d, f).

has the highest retransmission rate of all considered cooperative schemes for low node densities. For small hop-distances, it is likely that the selected relay is in transmission range of D_2 independent of the applied selection policy and thus reduces the retransmission rate of node S.

Let us now focus on the number of data transmissions required to deliver a packet from S to D_2 as a function of the node density (see Figures 3.13c-3.13d for $\gamma_d = 10\,\text{dB}$ and $\gamma_d = 20\,\text{dB}$, respectively). For $\gamma_d = 10$ dB, the non-cooperative scheme requires some 4.3 transmissions which is the highest value of all schemes. HbH-Coop-Relaying requires the second most transmissions. However, its performance depends on the node density: the number of transmissions decreases with increasing density and finally saturates at 3.5 transmissions for $\rho \geq 30$. The schemes using the MHA-HbH and max policies require fewer data transmissions on average. However, both schemes saturate above 2.5 transmissions. The performance of the remaining schemes are quite similar to each other. For representation purposes, we only illustrate the performance of the scheme using the delivery-policy. Its number of data transmissions has the steepest decline with increasing node density. For high densities, the number of transmissions converges to 2 (the minimum number). A smaller hop-distance considerably reduces the number of data transmissions required to deliver packets between S and D_2 (see Figure 3.13d). We observe that the differences between the MHA-Coop-Relaying policies become less significant for decreasing hop-distances.

Figures 3.13e-3.13f depict the fraction of selected relays as function of their distance to S on the x-axis for $\gamma_d = 10\,\text{dB}$ and $\gamma_d = 20\,\text{dB}$, respectively. The distances are normalized by the hop-distance d (e.g., D_1 and D_2 have a normalized distance of 1 and 2 from S, respectively). We obtain these figures by distributing potential relaying candidates on the line connecting S and D_2 with a normalized distance of 0.01 between the candidates and noting the frequency of each relay being selected during 500 000 transmissions cycles. All selection policies but the delivery-policy select their relays in regions which are independent of γ_d. In the case of HbH-Coop-Relaying the selected relays tend to be in a region with equal distances to S and D_1. This is also the distribution of relays selected by the MHA-HbH-policy of MHA-Coop-Relaying. The preferred location of relays selected by the max-policy is close to 0.5 which is considerably far away from D_2.

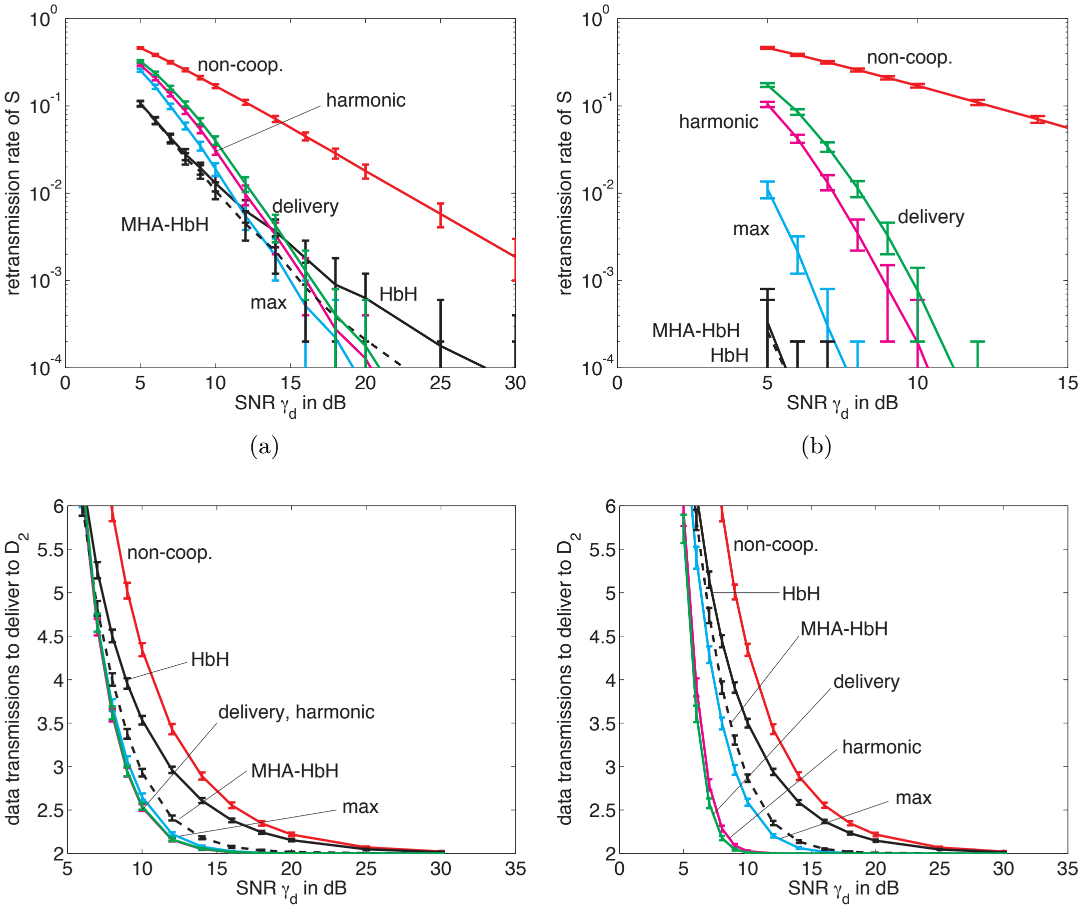
Relays selected by the min-policy are likely to be in the vicinity of D_1. In that region, the SNR from relays to S and D_2 are on average equal. Cooperative transmissions using this policy hardly ever benefit from hop gains which explains the higher retransmission rate compared to the other cooperative schemes.

The harmonic-policy combines link qualities from relay candidates to D_1 and D_2 using the harmonic mean. Relays selected by this policy are in the region between the ones from the max and the min-policy.

The preferred location of relays selected by the delivery-policy depends on the hop-distance. While we observe a similar location characteristic of selected relays from min and delivery policies for $\gamma_d = 10\,\text{dB}$ we notice that the preferred relay location shifts towards S for small hop-distances. The reason is that the delivery-policy considers end-to-end BERs of the links S-R-D_1 and S-R-D_2 in the relay selection. For

small hop-distances, it is likely that a selected relay has low BERs to both D_1 and D_2. From (3.12), we can observe that this augments the importance of the link from S to R.
The relays selected by the min, harmonic and delivery policies have a higher likelihood to temporarily replace D_1 in the route to D_2.

In a second scenario, we fix the node density $\rho = \{10, 100\}\,\mathrm{m}^{-2}$ and vary the distance d of a hop. We present this distance in average received SNR γ_d. In the following, we omit the results of the min-policy scheme: it has always a higher retransmission rate and a higher number of data transmission than the delivery-policy.



(a) (b)

(c) (d)

Figure 3.14: MHA-Coop-Relaying: (a-b) retransmission rate of S and (c-d) average number of required data transmissions as a function of the average received SNR γ_d for $\rho = 10\,\mathrm{m}^{-2}$ (a, c) and $\rho = 100\,\mathrm{m}^{-2}$ (b, d).

Figures 3.14a-3.14b depict the retransmission rate of node S of the schemes as a function of the average received SNR at D_1 for $\rho = 10\,\mathrm{m}^{-2}$ and $\rho = 100\,\mathrm{m}^{-2}$, respectively. The retransmission rate of all schemes decreases with increasing SNR, i.e., smaller hop-distances. While the node density has no influence on the behavior of the non-cooperative scheme, it is intuitive that higher node densities are more beneficial for the cooperative schemes. For $\rho = 10\,\mathrm{m}^{-2}$, the number of potential relay candidates is small and the best candidate is not always able to provide any support. As a result, the retransmission rate of HbH-Coop-Relaying declines with the same slope as the one of the non-cooperative scheme. For $\gamma_d \geq 15\,\mathrm{dB}$, the retransmission rate of the MHA-Coop-Relaying schemes is smaller than the one of HbH-Coop-Relaying. In that domain, a selected relay is able to serve D_1 and D_2: even if the cooperative transmission cannot help D_1, it may help deliver the packet to D_2 avoiding a retransmission. This also explains why the scheme using MHA-HbH policy performs better than HbH-Coop-Relaying although they tend to use the same relays. The retransmission rate of the other MHA-Coop-Relaying policies show similar trends: the max-policy has the lowest one of them, we observe the highest one for the delivery-policy. For $\rho = 100\,\mathrm{m}^{-2}$, the steepness of the retransmission rate as function of the hop-distance increases significantly due to the higher diversity gain. HbH-Coop-Relaying and MHA-Coop-Relaying using MHA-HbH policy experience the smallest retransmission rate with the highest decline with increasing SNR.

Finally, we consider the total number of data transmissions required to deliver a packet from S to D_2 (see Figures 3.14c-3.14d). Clearly, the required number of transmissions decrease with decreasing hop-distances for all schemes and node densities. For large hop-distances, i.e., small average received SNR we hardly ever find a relay which can deliver the packet to D_2. This changes with increasing SNR. For low node densities, the performance differences of the MHA-Coop-Relaying policies are small due to the low number of available candidates. It is interesting to see that the difference between non-cooperative scheme and HbH-Coop-Relaying vanishes fast for increasing SNR-values. The gain in reliability does not transfer itself in fewer transmissions. For $\rho = 10\,\mathrm{m}^{-2}$ and low SNR values ($< 7\,\mathrm{dB}$), HbH-Coop-Relaying requires less transmissions than most of the policies of MHA-Coop-Relaying. Only the scheme using the MHA-HbH-policy achieves fewer transmissions in this region. All MHA-Coop-Relaying schemes reach the minimum number of transmissions before 20 dB.

For $\rho = 100\,\mathrm{m}^{-2}$, delivery and harmonic policies reach the minimum number of required data transmissions around 10 dB. For the same node density, max and MHA-HbH policies require additional 5 dB to deliver data within two data transmissions between S and D_2.

We can draw the following conclusions from our analysis:

- The performance of MHA-Coop-Relaying depends on the node density in the network and on the hop-distance. For high node densities and/or small hop-distances we can find a relay node which can likely replace a node in the route and saves data transmissions thereby.
- We also saw that using the same relay selection as in HbH-Coop-Relaying for MHA-Coop-Relaying reduces the retransmission rate and the number of transmissions to deliver packets from a source to its final destination.

- For high node densities and medium hop-distances, a relay selection policy which enforces multi-hop-relays achieves better performances in terms of overall data transmissions. However, such policies require an increased signaling overhead than the MHA-HbH policy.
- While the delivery-policy achieves the lowest number of data transmissions to deliver packets in dense networks, we propose to use the MHA-HbH policy in sparse networks. Results indicate that MHA-HbH does not cause any retransmission rate degradations compared to HbH-Coop-Relaying but can result in considerably less data transmissions. Furthermore, it does not require any probing packets to determine the channels from candidates to D_2 which could reduce the signaling overhead.

3.4 Success-Efficiency

In this chapter, we proposed and analyzed several methodologies to increase the efficiency of cooperative relaying. So far, we did not discuss the timing aspects or success of the relay selection. In particular, we followed the timer based approach of RSbasic to select the best relay [BKRL06]. The timer approach minimizes the number of packet exchanges during the relay selection. It, however, does not necessarily minimize the duration of the selection process. Furthermore, RSbasic offers no mechanisms to recover from collisions of `AFR` packets, assumes symmetrical links (the transmission quality from A to B is identical to the one from B to A), and does not facilitate the selection of more than one relay.

Relay selection based on slotted contention windows can overcome these shortcomings. In such a scheme, relaying candidates — nodes that are able to support D — transmit `AFR`-packets during a contention frame of s slots. The relay selector, e.g., node D, stores all `AFR` packets it receives during this contention period. If more than one node transmits an `AFR` packet in a slot, their transmissions collide and D cannot receive any of them. After the contention period, D chooses among the correctly received `AFR` packets the most suitable relay. For a successful relay selection it is important that D receives at least one `AFR` packet. However, D would prefer to receive as many distinct `AFR` packets as possible which would increase the probability of selecting a good relay, or would allow D to select multiple relays.

In general, such a slotted contention window approach might not select the current best relay as achieved by RSbasic. However, this is not a drawback as long as relaying candidates are only those nodes that can ensure a successful transmission (cf. SNR-threshold based relay selection [HK07]).

Hereafter, we elaborate on two different contention strategies for relay selection based on slotted contention windows. We derive the success probability; i.e., the probability that there is at least one non-colliding `AFR`-packet, and the expected number of distinct `AFR` receptions of the two approaches. Afterwards, we discuss the impact of imperfect relay candidate cardinality information on the selection result and introduce a method to determine the contention parameters for obtaining a desired selection result.

3.4.1 Strategy 1

Contention strategy 1 works as follows: each potential relay selects one of the s slots of the contention window and transmits in this slot with a certain probability p_{s1}. Hereafter, n denotes the number of relay candidates.

The probability that out of n candidates k select the same slot in a contention frame of size s is:

$$P_k = \binom{n}{k} \cdot \left(\frac{1}{s}\right)^k \cdot \left(1 - \frac{1}{s}\right)^{n-k} \quad . \tag{3.18}$$

The probability that only one of those k nodes transmits in the selected slot is

$$P_{1,k} = k\, p_{s1}\, (1 - p_{s1})^{k-1} \quad . \tag{3.19}$$

The probability that there is exactly one `AFR` transmission in a given slot is

$$\begin{aligned} P_{1_{s1}} &= \sum_{k=1}^{n} P_k \cdot P_{1,k} \\ &= (s - p_{s1})^{n-1}\, \frac{n\, p_{s1}}{s^n} \quad . \end{aligned} \tag{3.20}$$

The success probability of the contention frame, i.e., the probability that there is at least a single non-colliding transmission from a relay candidate is

$$P_{s_{s1}} = 1 - (1 - P_{1_{s1}})^s \quad . \tag{3.21}$$

Furthermore, we can determine the expected number of distinct `AFR` receptions m at D as:

$$\mathrm{E}_{s1}\,[m] = s\, P_{1_{s1}} \quad . \tag{3.22}$$

The access probability p_{s1} that maximizes $P_{s_{s1}}$ is

$$p_{s1,\max} = \begin{cases} \frac{s}{n} & \text{for } s \leq n \\ 1 & \text{for } s > n \quad . \end{cases} \tag{3.23}$$

3.4.2 Strategy 2

Potential relaying nodes following strategy 2 transmit an `AFR` packet in *each* of the s slots with probability p_{s2}. The probability of a single `AFR` transmission during any slot of the contention frame is

$$P_{1_{s2}} = n\, p_{s2}\, (1 - p_{s2})^{n-1} \quad . \tag{3.24}$$

The selection success probability of strategy 2 is

$$P_{s_{s2}} = 1 - (1 - P_{1_{s2}})^s \ . \tag{3.25}$$

The calculation of the expected number of distinct `AFR` receptions m is a little bit trickier than in the case of strategy 1, since here multiple non-colliding `AFR` packets can origin from the same relay candidate:

$$\mathrm{E}_{s2}[m] = \sum_{k=1}^{s} \Pr[k \ \texttt{AFR}] \cdot \sum_{j=1}^{k} j \cdot \Pr[j \text{ distinct } \texttt{AFR} | k \ \texttt{AFR}] \ . \tag{3.26}$$

The probability of D receiving k `AFR` packets (including duplicates) is

$$\Pr[k \ \texttt{AFR}] = \binom{s}{k} P_{1_{s2}}^{k} \left(1 - P_{1_{s2}}\right)^{s-k} \ . \tag{3.27}$$

The probability of having j distinct applications given k applications in total is:

$$\Pr[j \text{ distinct } \texttt{AFR} | k \ \texttt{AFR}] = \frac{f(n,k,j)}{n^k} \ , \tag{3.28}$$

with

$$f(n,k,j) := \binom{n}{j} \cdot \left(j^k - \sum_{l=1}^{j-1} f(j,k,l) \right) \ . \tag{3.29}$$

Equation (3.29) determines the number of j distinct applications given n candidates and k total applications. It calculates the total number of variations with repetitions of j elements choose k and subtracts those cases which have less than j distinct applications in a recursive manner.

Finally, the access probability p_{s2} that maximizes the selection success is

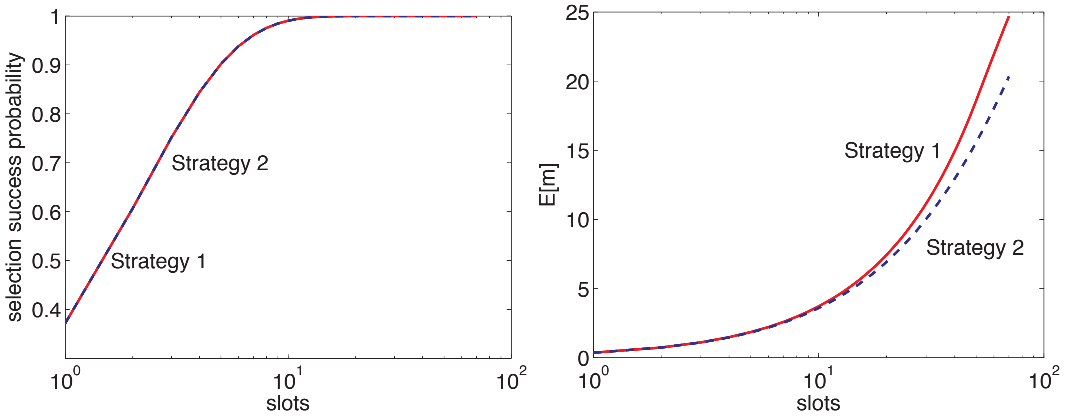
$$p_{s2,\max} = \frac{1}{n} \ . \tag{3.30}$$

3.4.3 Comparing Strategy 1 and Strategy 2

Figure 3.15a illustrates the selection success probabilities of strategy 1 and strategy 2 as a function of the contention window size s for $n = 50$. The relay candidates use the optimum access probability for the corresponding contention strategy. The selection success probability of both strategies are identical; it rises with increasing s. The success probability is higher than 90 % for $s \geq 5$.

Figure 3.15b shows $\mathrm{E}[m]$ of both contention strategies for $n = 50$ and variable s. For small contention windows ($s \leq 10$), the difference between the strategies is marginal. With rising s, strategy 1 results in considerably more distinct `AFR` receptions than strategy 2.

So far, we assumed that the number of relay candidates is known and used in determining the access probabilities of both strategies (i.e., $\frac{s}{n}$ and $\frac{1}{n}$). However,



(a) (b)

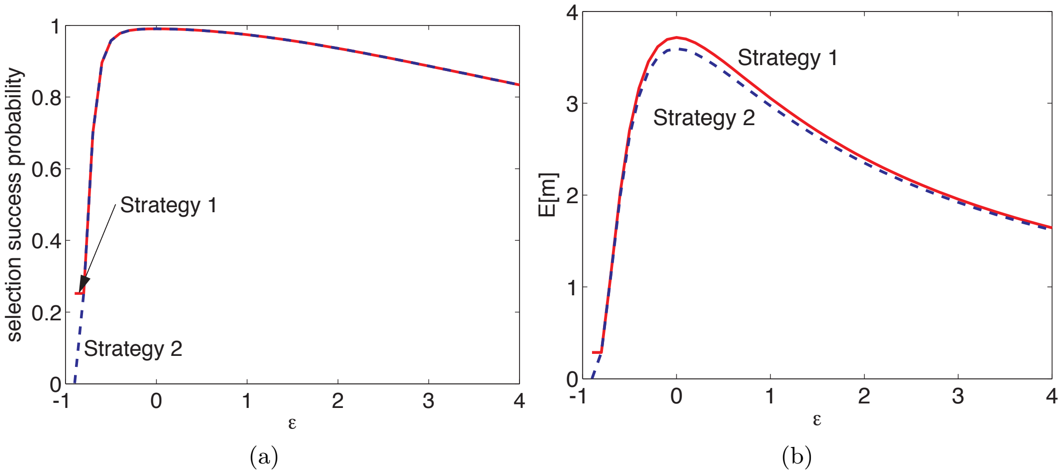
Figure 3.15: Contention strategy comparison: (a) selection success probability and (b) expected number of distinct `AFR` receptions as a function of s for $n = 50$.

in reality the number of relay candidates is most likely unknown. At best, there exists an estimation $\hat{n}$ for this number which obeys a certain accuracy. Using an inaccurate relay candidate cardinality in the calculation of the access probability for the contention based selection scheme can lead to suboptimal results. In this context, it is important to know, which strategy is more robust against inaccurate node estimations. In the following analysis, the access probability determination uses an estimation $\hat{n}$ of n with a known relative error $\epsilon = (\hat{n} - n)/n$. Methods to estimate n will be discussed in Chapter 4.

Figure 3.16a illustrates the success probability of the contention strategies as a function of ϵ for $n = 50$ and $s = 10$. Both strategies behave similarly. Their success probabilities peaks for $\epsilon = 0$ and their success probabilities are more vulnerable to neighbor cardinality underestimations than to overestimations. In the given example, one can observe a difference between both strategies for $\epsilon \leq -0.8$. In this domain, the access probability of strategy 1 is $p_{s1} = 1$ (since $\hat{n} \leq s$) and does not change any more with further decreasing ϵ. The selection success probability of strategy 2 keeps decreasing because of its increasing access probability (we observe more collisions of `AFR` packets).

Figure 3.16b indicates the number of distinct `AFR`s of both strategies as a function of the estimation error ϵ. The difference between both strategies peaks at $\epsilon = 0$ ($\hat{n} = n$) and reduces with increasing $|\epsilon|$.

The analysis shows that both strategies behave similar against estimation errors of n regarding selection success and robustness. Both strategies result in the same number of expected transmissions from relay candidates and hence produce the same amount of interference and consumes the same amount of energy consumption. However, it is beneficial to apply strategy 1 since it results in more distinct applications than strategy 2. Therefore, we focus exclusively on strategy 1 in the remainder of this section.



(a) (b)

Figure 3.16: Contention strategy comparison: (a) selection success probability and (b) expected number of distinct `AFR` receptions as a function of the relative error of $\hat{n}$ for $n = 50$ and $s = 10$.

3.4.4 Determining the Contention Window Size

In the context of slotted contention window based relay selection, determining the number of slots s is essential. With increasing s both the relay selection success probability and the expected number of distinct `AFR` reception increases. A bigger contention window can also compensate for imperfect access probabilities. However, parameter s defines the time overhead of the selection process. Informally speaking, one wants s to be as small as possible.

To this end, a design question can look as follows. The number of relay candidates is estimated prior to each relay selection attempt with a certain maximum error limit $|\epsilon|$ (see Chapter 4). Based on this estimation, relaying candidates determine their access probability for the contention period. How many slots are needed such that the selection success probability is at least P_s and that D receives on average m distinct `AFR` packets?

To answer this question, we simplify (3.21) by substituting $p_{s1} = s/\left(n\ (1+\epsilon)\right)$ and using the approximation $\left(1 - 1/\left(n\ (1+\epsilon)\right)\right)^{n-1} \approx \exp\left(-1/\left(1+\epsilon\right)\right)$ for large n [Bar01]. These operations yield:

$$P_1 \approx \frac{1}{1+\epsilon} \exp\left(-\frac{1}{1+\epsilon}\right) . \tag{3.31}$$

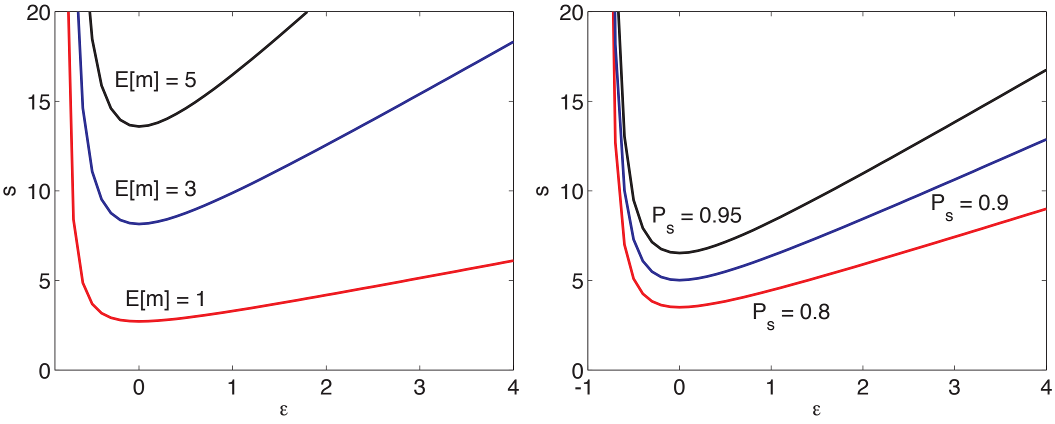
Equation (3.31) is independent of the current number of relay candidates. Using (3.31) in (3.21) and rearranging for s yields the required number of slots to achieve a selection success probability P_s as:

$$s \geq \frac{\log\left(1 - P_s\right)}{\log\left(1 - \frac{1}{1+\epsilon} \exp\left(-\frac{1}{1+\epsilon}\right)\right)} . \tag{3.32}$$

We obtain the number of required slots such that D receives on average m distinct `AFR` packets by substituting (3.31) in (3.22) and rearranging for s:

$$s \geq E\left[m\right] \cdot (1+\epsilon) \cdot \exp\left(\frac{1}{1+\epsilon}\right) . \tag{3.33}$$

Figure 3.17a and Figure 3.17b depict the required number of slots s to receive on average m distinct `AFR` packets and to have a selection success probability of P_s as a function of ϵ, respectively. These results indicate again that we have to consider only negative ϵ values in determining s (i.e., underestimation).



(a) (b)

Figure 3.17: Contention strategy comparison: number of slots required for (a) receiving $E\left[m\right] = \{1, 3, 5\}$ distinct applications and (b) achieving a selection success probability of $P_s = \{0.8, 0.9, 0.95\}$ as a function of the relative error of $\hat{n}$ for $n = 50$.

For instance, for $|\epsilon| \leq 0.5$ one needs a contention window of size $s \approx 6$ to achieve a selection success probability of 0.9 and to receive on average $m = 1.9$ distinct `AFR` packets. For the same accuracy, one needs $s = 11$ to receive on average $m = 3$ distinct `AFR` packets and to achieve a selection success probability $P_s = 0.97$.

3.5 Summary

In this chapter, we elaborated on relay selection aspects of cooperative diversity.

First, we focused on the energy-efficiency of cooperative relaying via improving the relay selection process. To this end, we considered the energy consumption of a radio in transmit, receive, and idle modes. We introduced two methods to increase the energy-efficiency of a basic cooperative pro-active relay selection protocol. First method, RSer reduces the energy consumption by allowing nodes to assess their cooperative contribution before participating in the relay selection process. The results suggest that only those nodes which offer a better link between source and destination than the direct one should try to become a relay. RSod, on the other hand, avoids the relay selection phase, when the direct link between source and destination is above a system dependent threshold. Skipping the relay selection phase in such situations reduces the energy consumption and also increases the throughput.

Looking at the time-efficiency of cooperative relaying, we exploited synergy effects between cooperative relaying and packet routing in wireless ad-hoc networks. In MHA-Coop-Relaying, relays are selected by taking route information into account, such that they are in transmission range of three consecutive nodes of a routed packet. We analyzed five different selection policies and showed that all of them outperform hop-by-hop cooperative relaying. The delivery-policy promises the highest throughput of all schemes in dense networks. However, using a relay selection as in RSbasic in a multi-hop-aware protocol results also in a significant reduction of data transmissions.

Finally, we investigated two basic strategies for slotted contention window based relay selection. In the first one, each relay candidate chooses one slot in the contention window and transmits an `AFR`-packet in this slot with a certain probability. Relay candidates following strategy 2, transmit an `AFR`-packet in each slot of the contention window with a certain probability. Our question was: which of these strategies is better? To this end, we determined the optimal transmission probabilities for both strategies and the required number of slots to achieve a certain selection success. Our results indicate that both schemes behave regarding relay selection success similarly. However, strategy 1 results in more distinct `AFR` receptions and hence offers the relay selector with more choices. In a second step, we showed the influence of uncertain candidate estimation on the selection result and the parameters of the selection scheme. Finally, we showed how to choose the parameters of the contention window to achieve a desired relay selection result.

Based on our observations, we consider RSoder and contention strategy 1 in our relay selection procedure.

Chapter 4

Estimation of Neighbor Cardinality

In the previous chapter, we observed the dependency of the relay selection success on the candidate cardinality, i.e., the number of common neighbors of source and destination which experience channel states above a certain threshold to them. Many other applications and communication protocols build on the knowledge of the neighbor cardinality of a node that optionally exhibit certain attributes. One option to reliably obtain this information is to exchange explicit packets. The time and energy overhead, however, of such an approach is substantially high in densely-connected networks.

In this chapter, we propose probabilistic methods enabling a network node to quickly estimate the number of its neighboring nodes. The presented estimators do not require any coordination among polled nodes but are based on a simple random medium access scheme with busy tones, where the number of empty slots is exploited to infer about the neighbor cardinality. We propose and compare three estimators with different levels of adaptability and feedback from the query node. We derive and discuss system design aspects in detail. A performance comparison is made in terms of estimation accuracy and delay. Finally, we give suggestions as to which estimator is most suited for a given application.

4.1 Introduction and Motivation

The topology of a network or more specifically the *number of neighbors of a node* (also known as *neighbor cardinality* or *degree*) carries valuable information and heavily influences the design and the performance of communication systems. For instance, the neighbor cardinality determines the connectivity [Bet04] and capacity [GK00] of ad hoc networks. This information has also been substantially utilized in designing medium access and routing protocols (see [HHL06, MWH01]). In WSNs, the neighbor cardinality finds itself in the design of energy-efficient probabilistic broadcasting, information dissemination, epidemic propagation mechanisms, activation scheduling methods, and optimizing transmission ranges of sensors (see [SCS03, WC02, Yan08, ZK03]). In addition, it is used to control and maintain the topology of wireless networks [San05]. The usage of neighbor cardinality information is not limited to wireless networks. For example, the well-known Barabási-Albert's preferential attachment based topology generation algorithm uses the degree of nodes to generate scale-free networks [BB03].

While the impact of the degree of a node is profound and has been widely addressed and utilized in network design, sometimes not only the actual number of neighbors, but the number of neighbors that exhibit a certain property is also of great importance. For instance, a node might need to know how many of its neighbors have energy above a certain threshold [CJBM02], or how many neighbors will benefit from it being awake, or what its redundant degree is [GWL03]. In medium access schemes using Slotted-ALOHA, nodes can adjust their access probability to maximize the throughput, if they know the number of nodes that have data to transmit [KST04]. Finally, in cooperative wireless networks, a node might need to know its common neighbors with another node to determine its potential relaying neighbors (see [LTW04, AEBS09]).

Although the neighbor cardinality is an important aspect, the mere estimation of the neighbor cardinality is not a well addressed research topic in communication systems. Mostly, the cardinality is gathered when addressing other problems where the *identity* of the nodes is of interest. Commonly, a coarse estimation is performed by overhearing data transmissions, where all neighbors transmit periodically some dedicated `hello`-packets [CE04]. However, such an approach is not well suited for some more specialized problems mentioned above.

The problem of neighbor cardinality estimation also plays a very important role in the context of Radio Frequency Identification (RFID) systems (tag-counting [LWCY10, KN06, KNL07]). However, since the technical limitations faced in such systems significantly differ from those of the aforementioned wireless communication systems, the methodologies proposed for RFID schemes are not directly applicable.

In this chapter, we focus on neighbor cardinality estimation, where the identity of nodes is *not* of interest. We introduce and evaluate several estimation methods based on probabilistic trials with different levels of adaptability and feedback. Hereafter, the term „neighbor estimator" is used synonymously for „neighbor cardinality estimator".

The contributions can be summarized as follows:

- Introduction of neighbor estimators based on probabilistic trials in a slotted random access scheme. The proposed estimators do not require any coordination among polled nodes and are especially useful in densely connected networks (networks with high node degrees).
- Showing how to minimize the number of required trials to achieve a desired estimation accuracy.

- Investigation of different levels of adaptivity by introducing methods to change estimator parameters during the estimation process.
- Providing information on how to select the appropriate estimator for a given transceiver architecture.
- Elaboration on the efficiency of the proposed estimators compared to a scheme using non-colliding packets to count reachable nodes.

The chapter is structured as follows. Section 4.2 discusses the options of using probabilistic trials to estimate the number of nodes in the neighborhood, introduces the basic estimation method common to all proposed estimators, and establishes quality assurance means. Section 4.3 introduces the Non-Adaptive Neighbor Estimator (NAE) which requires a single data transmission from the query node for the overall estimation process. Section 4.4 introduces the Single-Feedback Neighbor Estimator (SFE) and the Multi-Feedback Neighbor Estimator (MFE), respectively, where the level of feedback is increased, i.e., the query node uses data transmission to change the parameters of the probabilistic trials such that the estimation delay is reduced. Section 4.5 infers about the duration of busy tone slots used in the probabilistic trials of our estimators and the explicit data transmission duration in different transceiver technologies. Section 4.6 compares the different proposed methods based on practical aspects. Section 4.7 summarizes related literature.

The results presented in this chapter have been achieved in cooperation with coauthors of [AYEB10, AYB11].

4.2 Basic Neighbor Estimator Block

A node is interested in the cardinality of its neighbors. It is interested either in the number of all neighbors or those fulfilling certain attributes, such as minimum battery level or connectivity to other nodes[1]. The node initiates the estimation process by broadcasting a `neighbor-query`-packet. This packet contains the attributes neighbors should fulfill, the number of time slots s, and a slot access probability p to be used in the estimation process. Each node that has received the `neighbor-query`-packet and satisfies the required attributes transmits in each of the s slots of the following contention window with probability p a busy tone (Bernoulli process). A busy tone only indicates activity on the communication medium and does not convey any additional information (cf. [KBW04]). It does not cause any overhead required by data transmissions, such as bit synchronization or coding. The query node observes the communication medium during those s slots and exploits the channel occupancy to infer about the cardinality of participating neighbors.

---

[1] While the neighbor estimator will be used to determine the number of relay candidates in Chapter 5, in this chapter we do not specify the desired attributes for generality.

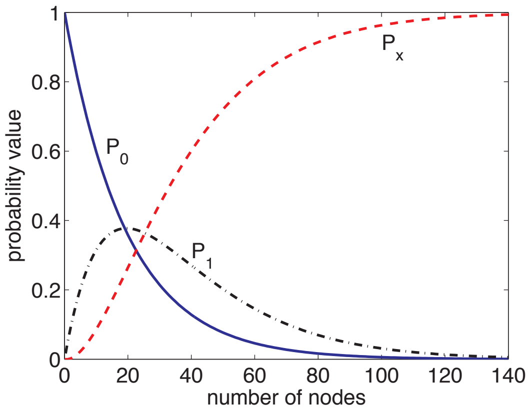


Figure 4.1: Slot probabilities for $p = 0.05$ versus n

4.2.1 Design Options

In principle, the query node can observe one of the following events per given slot during the contention frame:

- empty slot (no node transmits in this slot),
- singleton slot (one node transmits in this slot), and
- colliding slot (multiple nodes transmit in this slot).

If n is the actual number of nodes, the probability of these events are as follows:

$$\begin{aligned} \text{Empty Slot: } P_0 &= (1-p)^n \,, && (4.1)\\ \text{Singleton Slot: } P_1 &= n\,p\,(1-p)^{n-1} \,, && (4.2)\\ \text{Colliding Slot: } P_x &= 1 - P_1 - P_0 \,. && (4.3) \end{aligned}$$

The query node can estimate these three probabilities by counting the number of empty, singleton, and colliding slots during a sufficiently large number of slots. Based on such a probability, it can estimate n using the inverse functions of the above expressions.

The following questions arise: Which of these events are well-suited to estimate the number of nodes? Should the node count all three events? Is one event more beneficial in practice? Figure 4.1 provides hints to answer some of those questions. It illustrates the different slot event probabilities for a given p as function of n. The probability P_1 first rises with increasing n, has its maximum at $n = 1/p$, and starts decreasing for higher n-values. For a given n, there are in general two different values of P_1, meaning that the function is not injective. Thus, counting only the number of singleton slots is impractical for estimating n.

In contrast, the probabilities P_0 and P_x are monotonic with respect to n and can thus be inverted to get an unambiguous value of n. Hence, in theory, both slot types provide means to estimate n. In practice, however, in order to detect collisions, the transmission of special codewords might be necessary. This would in turn require a longer transmission time than simple busy tones. Furthermore, capturing effects [ZR94] could cause a misinterpretation of colliding slots as singleton slots. These facts motivate us to focus on *empty slots* for neighbor cardinality estimation hereafter.

4.2.2 Neighbor Estimation Counting Empty Slots

Given the empty slot probability P_0 and the access probability p, one can calculate the neighbor cardinality n by rearranging (4.1) as

$$n = \frac{\ln P_0}{\ln(1-p)} \ . \tag{4.4}$$

For estimating n, it is thus sufficient to estimate P_0 and apply it in (4.4). To do so, the query node counts the number of empty slots e in a frame with s slots. The relative frequency is

$$\hat{P}_0 = \frac{e}{s} \ . \tag{4.5}$$

According to the relative frequency definition of probability, $\lim_{s\to\infty} \hat{P}_0 = P_0$, $\hat{P}_0$ is a good estimate for P_0, if s is sufficiently large.

After an contention period of s slots, the query node can obtain one of the following two cases:

1. *Useful statistics* ($0 < e < s$):
   If some of the observed slots s are empty and some are non-empty, the estimator will return
   $$\hat{n} = \frac{\ln\left(\frac{e}{s}\right)}{\ln(1-p)} \tag{4.6}$$
   as a successful estimate for neighbor cardinality n.
2. *No useful statistics* ($e = 0$ *or* $e = s$):
   If all observed slots are either empty or non-empty the query node cannot estimate n since (4.4) results in 0 or goes to ∞, respectively. The query node can only infer about upper and lower bounds for n in such cases. For $e = 0$, the query node can determine a lower bound by
   $$n > \frac{\ln\left(\frac{1}{s}\right)}{\ln(1-p)} \ ; \tag{4.7}$$
   for $e = s$ an upper bound for n is
   $$n < \frac{\ln\left(\frac{s-1}{s}\right)}{\ln(1-p)} \ . \tag{4.8}$$

> These are the highest and smallest values of n that can be estimated with the given access probability p and contention frame size s, respectively. The query node needs to increase s and/or adjust p to obtain useful statistics. Eliminating $e = s$ as valid result, the query node cannot estimate $n = 0$. One way to detect this case is to use one dedicated test slot with access probability $p = 1$.

The quality of the estimation depends on the parameters p and s. For poorly-selected p and s, the estimator can only provide bounds for n. The parameter p affects the estimation duration: if p is chosen bad, s needs to be large to collect useful statistics. Thus, it is essential to choose both parameters in such a way that a) the estimator returns a valid result and b) the estimation duration is as small as possible.

4.2.3 Accuracy of Neighbor Estimation

The estimator has to provide a certain confidence in its results defined by

$$\mathrm{P}\left[\epsilon \leq \theta\right] \geq \alpha\,, \tag{4.9}$$

where $\epsilon = \left|\frac{\hat{n}-n}{n}\right|$ is the relative error, and α, θ are parameters of the estimator defining its quality. In words, the relative error of the estimator has to be smaller than θ with confidence α.

An estimator based on probabilistic trials, where n nodes transmit with probability p in each of s slots, will in general produce different values of $\hat{n}$ for the same n. For any accuracy assessments, it is necessary to determine the distribution of $\hat{n}$ for given p and s values. Following the steps of [Rao73] (Example 6a.2.1), one can show that $\hat{n}$ follows a normal distribution with mean $\mathrm{E}[\hat{n}] = n$ and variance

$$\mathrm{Var}[\hat{n}] = \frac{1}{s} \cdot \frac{1-(1-p)^n}{(1-p)^n \cdot \big(\ln{(1-p)}\big)^2} \tag{4.10}$$

if the following two prerequisites are fulfilled:

- The number of empty slots e has to follow a normal distribution:
  Since the probability that a given slot is empty is a Bernoulli variable with parameter P_0, the total number of empty slots e during s slots is binomially distributed with parameters (P_0, s). For large s values and P_0 values which are neither close to 0 nor to 1, the binomial distribution can be approximated by a normal distribution with mean $\mu = s\,P_0$ and variance $\sigma^2 = s\,P_0\,(1-P_0)$. As a rule of thumb, this approximation is accurate if the products $s\,P_0$ and $s\,(1-P_0)$ are larger than 5 [LT96].
- Function (4.6) has to be differentiable:
  This condition is fulfilled, since (4.6) is a monotonically decreasing function of the number of empty slots e.

Based on the distribution of $\hat{n}$ we can determine:

$$\begin{aligned}
\mathrm{P}\left[\epsilon \leq \theta\right] &= \mathrm{P}\big[(1-\theta)n \leq \hat{n} \leq (1+\theta)n\big] \\
&= \Phi\left(\frac{(1+\theta)\ n - n}{\sqrt{\mathrm{Var}\left[\hat{n}\right]}}\right) - \Phi\left(\frac{(1-\theta)\ n - n}{\sqrt{\mathrm{Var}\left[\hat{n}\right]}}\right) \\
&= \Phi\left(\frac{\theta\, n}{\sqrt{\mathrm{Var}\left[\hat{n}\right]}}\right) - \Phi\left(-\frac{\theta\, n}{\sqrt{\mathrm{Var}\left[\hat{n}\right]}}\right) \\
&= 2 \cdot \Phi\left(\frac{\theta\, n}{\sqrt{\mathrm{Var}\left[\hat{n}\right]}}\right) - 1 \ . \qquad (4.11)
\end{aligned}$$

The function $\Phi\left(\cdot\right)$ is the cumulative distribution function (cdf) of the standard normal distribution with the property that $\Phi\left(-x\right) = 1 - \Phi\left(x\right)$. Applying (4.11) in (4.9) and rearranging for θ yields

$$\Psi := \frac{1}{n} \cdot \Phi^{-1}\left(\frac{1+\alpha}{2}\right) \cdot \sqrt{\mathrm{Var}\left[\hat{n}\right]} \leq \theta \ . \qquad (4.12)$$

If the inequality $\Psi \leq \theta$ is fulfilled, the accuracy (4.9) is met. Ψ represents an ,,upper bound" for the relative estimation error ϵ guaranteeing $\mathrm{P}\left[\epsilon \leq \Psi\right] = \alpha$. For given n and fixed access probability p and estimation confidence α, Ψ is indirect proportional to s. The estimator meets the accuracy condition (4.9) if the number of slots s is sufficient high such that $\Psi \leq \theta$.

4.3 Non-Adaptive Neighbor Estimator

We now use the basic estimator block to propose a practically feasible estimator. From the previous section we know that the estimation quality and duration depend on the parameters p and s. The hereafter NAE called estimator, is non-adaptive since the query node does not exploit the observed empty slot statistics to update the estimation parameters p and s during the contention period. The `neighbor-query-packet`, which initializes and starts the estimation process, has to contain all needed information. Hence, a query node must first determine suitable values for the parameters p and s.

4.3.1 Determining a Suitable Slot Access Probability

Following (4.7) and (4.8), for given p and s, the NAE will produce meaningful results only in a range of operation $[n_{\min}, n_{\max}]$, where the likelihood of the events *no empty slots* and *all empty slots* is low.

Furthermore, there is a tradeoff between the estimation quality and the estimation delay, i.e., the required number of slots.

The goal is to determine a suitable value for the access probability p that

- works in a given estimation range $[n_{\min}, n_{\max}]$,
- achieves the required estimation quality (see (4.9)),
- minimizes the number of required slots s.

Since Ψ is a convex function in n (see Appendix), the maximum relative estimation error for a range of operation ($n_{\min} \leq n \leq n_{\max}$) occurs at either $n_{\min}$ or $n_{\max}$. Thus, if the estimator achieves the desired accuracy for $n_{\min}$ and $n_{\max}$ it achieves it for all values in the range of operation. Thus, we can limit all further considerations regarding finding suitable p and s-values to the borders of the range.

For any p we can determine the required number of slots s by

$$s = \max\left(\frac{\left(\Phi^{-1}\left(\frac{1+\alpha}{2}\right)\right)^2 \cdot \left(1-(1-p)^{n_{\min}}\right)}{n_{\min}^2 \cdot \theta^2 \cdot (1-p)^{n_{\min}} \cdot \ln(1-p)^2}, \frac{\left(\Phi^{-1}\left(\frac{1+\alpha}{2}\right)\right)^2 \cdot \left(1-(1-p)^{n_{\max}}\right)}{n_{\max}^2 \cdot \theta^2 \cdot (1-p)^{n_{\max}} \cdot \ln(1-p)^2}, \frac{5}{(1-p)^{n_{\max}}}, \frac{5}{1-(1-p)^{n_{\min}}} \right). \tag{4.13}$$

The first two terms of (4.13) represent the number of slots required to achieve the desired estimation accuracy for $n_{\min}$ and $n_{\max}$, respectively. It is obtained by substituting (4.10) into (4.12) and solving for s when $n = \{n_{\min}, n_{\max}\}$ respectively. The last two terms of (4.13) ensure the validity of approximating the distribution of e with a normal distribution which has been used to derive (4.10).

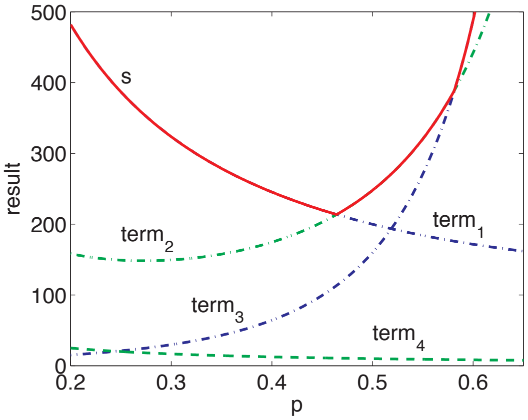


Figure 4.2: Value s and the terms of (4.13) for $n_{\min} = 2$, $n_{\max} = 5$, $\theta = 20\%$ and $\alpha = 95\%$.

Figure 4.2 illustrates the terms of (4.13) as functions of p. The red solid line represents the maximum of all of those terms and hence the number of required slots s. The labels in the figure correspond to the order of the terms in (4.13). It is intuitive that the first two terms as well as the last two terms of (4.13) intersect once, independently of the estimator's parameters. These intersections represent the minimum of the maximum of these terms. However, there can be also intersections between other terms as shown in Figure 4.2. The minimum of s is co-located with one of those intersections.

The query node has to find all $p \in (0\,,\,1)$ where terms of (4.13) intersect, determine with (4.13) the corresponding number of slots s and finally choose the p-value with the smallest corresponding s-value as access probability.

The complexity of the functions defining the intersections prevent closed form solutions for the corresponding p-values. It is not difficult, however, to find these intersections with numerical methods, e.g., bisection method. To reduce the calculation burden of query nodes, they can store lookup-tables with precomputed values of p and s for certain operation ranges.

Table 4.1 gives some examples for the number of slots s required to estimate n assuming a certain estimation range $[n_{\min},\, n_{\max}]$. The value $\eta := n_{\max}/n_{\min}$. An error threshold θ is requested with a confidence of $\alpha = 95\,\%$.

Table 4.1: Slots required to estimate the neighbor cardinality

$n_{\min}$	$n_{\max}$	η	θ	s
1	10	10	10%	1 210
1	10	10	20%	303
1	100	100	10%	6 095
1	1 000	1 000	10%	42 636
1	1 000	1 000	20%	12 344
1	1 000	1 000	50%	2484
1	10 000	10 000	10%	344 977
10	100	10	10%	1 210
100	1 000	10	10%	1 210
1 000	10 000	10	10%	1 210
100	200	2	10%	637

The number of required slots depends on the estimation range $[n_{\min}, n_{\max}]$ assumed by the estimator and the desired estimation accuracy. Clearly, the smaller the estimation range is — the more a priori information the query node has about the neighbor cardinality — the faster is the estimation. It is also straightforward that the estimation is faster for more relaxed estimation accuracy requirements. Finally, we observe that s just depends on η for a given accuracy. For instance, an estimation for the interval $[1, 10]$ requires the same number of slots as an estimation for the interval $[100, 1\,000]$. Figure 4.3 generalizes these insights by depicting s as a function of η for different θ-values.

Summarizing, a time-efficient non-adaptive estimation algorithm has to regard the η-value of the operation range. If a large range of operation is needed, i.e., big

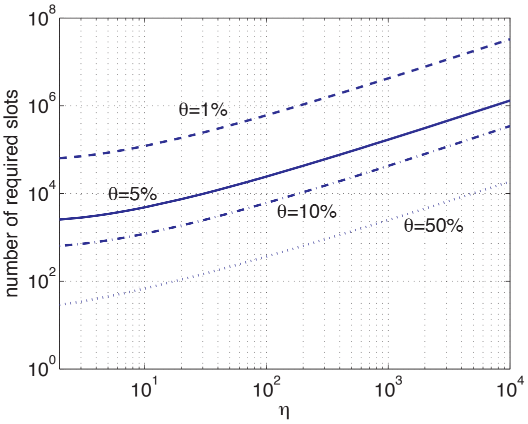


Figure 4.3: Number of slots s required to estimate n as function of $\eta = n_{\max}/n_{\min}$ for various θ-values at $\alpha = 95\%$.

η-values, it is inefficient to choose a single p-value to cover the whole interval of $[n_{\min}, n_{\max}]$. It is more time efficient to partition the operation range into subranges of smaller size ($\eta_{\text{sub}} < \eta$) and to use for each subrange a different p-value. For instance, using $\eta_{\text{sub}} = 10$ on the operation range $[1, 10\,000]$, the query node can reduce the number of slots necessary to obtain a result of accuracy $\theta = 10\%$ from 344 977 down to 4 840.

4.3.2 Determining Suitable Subranges of Operation

Let us now elaborate on how to find the subranges of operation which minimize the overall number of slots for a non-adaptive estimation with parameters η, θ and α. We assume that all subranges have the same η_{sub}-value and thus require the same number of slots. Given η, η_{sub}, θ, and α, the overall number of slots required to perform the estimation can be expressed as

$$s = k \cdot s_{\text{sub}}\left(\eta_{\text{sub}}, \theta, \alpha\right) \ , \tag{4.14}$$

where $k = \left\lceil \frac{\ln(\eta)}{\ln(\eta_{\text{sub}})} \right\rceil$ is the number of partitions needed to cover the complete range of operation η and s_{sub} represents the number of slots required to estimate with accuracy parameters θ and α in a subrange of size η_{sub}.

Due to the complexity of the relation between p and s, we do not have a closed-form expression for s_{sub}. Using the curve fitting tool ZunZun [Phi10] to find a function that approximates s_{sub} yields

$$\tilde{s}_{\text{sub}}\left(\eta_{\text{sub}}, \theta, \alpha\right) = \mathrm{a_z} \cdot \left(\mathrm{d_z} \, \frac{\theta}{\Phi^{-1}\left(\frac{1+\alpha}{2}\right)} + \mathrm{e_z} \right)^{\mathrm{b_z}} \cdot \left(\mathrm{f_z} \; \eta_{\text{sub}} + \mathrm{g_z}\right)^{\mathrm{c_z}} \ , \tag{4.15}$$

whose coefficients are listed in Table 4.2. As we will show later, the number of slots

Table 4.2: Constants used in (4.15)

name	value	name	value
a_z	2.405	b_z	-1.877
c_z	0.872	d_z	14.331
e_z	-0.010	f_z	40.217
g_z	228.674		

used to process a subrange is usually below 2 000. In these cases, (4.15) approximates s_{sub} very good (see columns 5 and 6 in Table 4.3). Furthermore, also for large values, $\tilde{s}_{\text{sub}}$ shows the same trends as s_{sub}.

A fast and simple method to find the optimum number of subranges is to determine the s-values for $k = 1, 2, ...$. As k is an integer one gets $\eta_{\text{sub}} = \eta^{1/k}$. If s decreases from $k = 1$ to $k = 2$, partitioning the range of operation reduces the estimation delay, i.e., the number of required slots. The value of s will reach its minimum for some k before its starts increasing again. The k-value which obtains the smallest s-value represent the optimum number of partitions. This number k is usually small which keeps the computational effort small.

Once we have found the number of partitions k and the size of each partition η_{sub}, the query node applies the methods presented in the previous section to determine s_{sub}, i.e., the real number of slots required to process a subrange. Note that approximation errors caused by $\tilde{s}_{\text{sub}}$ do not influence the accuracy of the estimator but only have impact on the estimation duration.

Example: The query node has to conduct an estimation for an operation range $n \in [1\ 2\,000]$ and accuracy parameters $\theta = 10\,\%$ and $\alpha = 95\,\%$. According to the proposed method, the query node partitions the operation range in $k = 4$ subranges of size $\eta_{\text{sub}} \approx 6.69$. Each subrange requires $s_{\text{sub}} = 978$ slots. The corresponding access probabilities are $p_i = \{0.4017, 0.0739, 0.0114, 0.0017\}$. The query node includes s_{sub} and the access probabilities in the `neighbor-query`-packet. The neighbors use each p_i for s_{sub} slots. For each partition, the query node counts the number of empty slots and estimates based on these observations n (see next section on how to combine the results of the different partitions).

Table 4.3 summarizes some cases of applying the partitioning concept to the estimation process. The last three columns show the following: the approximated number of slots $k\,\tilde{s}_{\text{sub}}$, the actual number of slots $k\,s_{\text{sub}}$, and the number of slots s_{np} required if no subrange partitioning was applied. Comparing the last two columns we observe a tremendous reduction in the number of required slots to guarantee a certain estimation accuracy. For instance, for $\eta = 10\,000$ and $\theta = 10\%$ the number of slots and thus the estimation time is reduced by 98.62%.

4.3.3 Combining Estimations from Subranges

Using multiple subranges to estimate the number of neighbors can result in multiple valid estimations, depending on the current range of potential neighbors as well as

Table 4.3: Number of slots needed to estimate n within an operation range of size η if k subranges are used ($\alpha = 95\%$)

η	θ	k	η_{sub}	$k\tilde{s}_{\text{sub}}$	s	s_{np}
10	10%	1	10	1 229	1 210	1 210
100	10%	2	10	2 458	2 420	6 095
1 000	10%	3	10	3 687	3 630	42 636
10 000	10%	5	6.31	4 865	4 755	344 977
10	50%	1	10	59	68	68
100	50%	2	10	118	136	366
1 000	50%	3	10	177	204	2 484
10 000	50%	4	10	236	272	18 688

on the estimation parameters. Therefore, the question arises how to find the final result: Should the query node choose the result with minimum variance? Or should it choose the estimation which falls into the corresponding subrange? Can it combine all estimations from the subranges, and if so how?

The query node could combine all estimation results from the different subranges using their variance (cf. confidence-weighted averaging [Elm07]). However, the query node does not know in general the variance of each estimation.

An approach to use all information observed by the query node during the contention period it to apply a maximum likelihood estimation (MLE). It takes into account the access probabilities p_i for each subrange i and the observed number of empty slots e_i. The final estimation result is the number z that maximizes the likelihood L_z to obtain the measured e_i for the given p_i with $i = 1...k$. In a mathematical form, this is

$$\begin{aligned} \hat{n} &= \underset{z}{\operatorname{argmax}} \, (L_z) \text{ with} \\ L_z &= \prod_{i=1}^{k} \binom{s}{e_i} \, {q_i}^{z \cdot e_i} \, (1 - {q_i}^{z})^{s-e_i} \quad , \end{aligned} \tag{4.16}$$

where $q_i := 1 - p_i$ is used to simplify the equation. Taking the logarithm of (4.16), subsequently taking the derivative with respect to z, equating the result with 0, and some rearrangements yield

$$\sum_{i=1}^{k} e_i \cdot \ln q_i = \sum_{i=1}^{k} \frac{s - e_i}{1 - q_i^z} \cdot q_i^z \cdot \ln q_i \, . \tag{4.17}$$

Solving (4.17) numerically, the query node obtains a final estimate for n.

4.3.4 Early Stop by Feedback from Query Node

Instead of performing the estimation in all subranges, the query node may stop the process as soon it has obtained a valid estimation from processing one of the subranges, i.e., the estimated neighbor cardinality $\hat{n}$ is within the processed subrange.

To enable an early stop mechanism, the query node has to provide some feedback to polled nodes after the procession of a subrange. The polled nodes only need to know whether they need to continue processing the next subrange. Thus, it is sufficient to provide feedback of binary nature, i.e., reserving a single slot for the querying node at the end of each subrange contention frame which signals to stop the process if the query node transmits. We call this optional modification of the NAE *binary feedback*.

We propose and compare two variants of binary feedback:

- *Variant 1:* The estimation process starts with the lowest subrange and proceeds toward higher subranges. This variant requires one feedback slot after each of the first $k-1$ contention frames to indicate an early stop.
- *Variant 2:* The estimation process starts in the subrange covering the center of the entire operation range. In addition to early stop slots, this variant requires one additional feedback slot after the first subrange contention frame. During this slot, the query node indicates whether to proceed toward higher or lower subranges, if the estimation process has not come to a stop before.

4.3.5 Performance

Let us now perform a case study to evaluate the feedback options of the NAE scheme. To this end, we set the operation range to $[10\,,\,2\,000]$, the error threshold $\theta = 5\,\%$ with confidence $\alpha = 95\,\%$. We vary the number of neighbors n from 1 to 3 000. For each of these n-values, we repeat the estimation process 10 000 times and average the results over these repititions. In the figures, we indicate the 90 %-confidence interval of the averaged values.

Figure 4.4a depicts the average number of slots required to perform an estimation for the given parameters using the NAE. The NAE without feedback option has to process always all subranges. This yields a constant estimation time which is independent of n.

Using binary feedback can reduce the estimation time. The binary feedback variant 1 reduces the estimation time for small values of n. The required slot number increases with rising n. For large n-values this variant requires as many slots as the NAE without binary feedback. The NAE using binary feedback variant 2, starts its estimation process in the subrange covering the middle of the operation range. Hence, it requires the least amount of slots for values of n being in this subrange. The number of slots increase for smaller and larger n-values. However, this variant is always faster than the NAE without feedback. At most $\lceil \frac{k+1}{2} \rceil$ subranges are processed.

Figure 4.4b illustrates the achieved error bound Ψ of the estimation as a function of the real n. The best performance is achieved by the scheme without feedback. This is expected, as it collects statistics for all subranges and uses this information

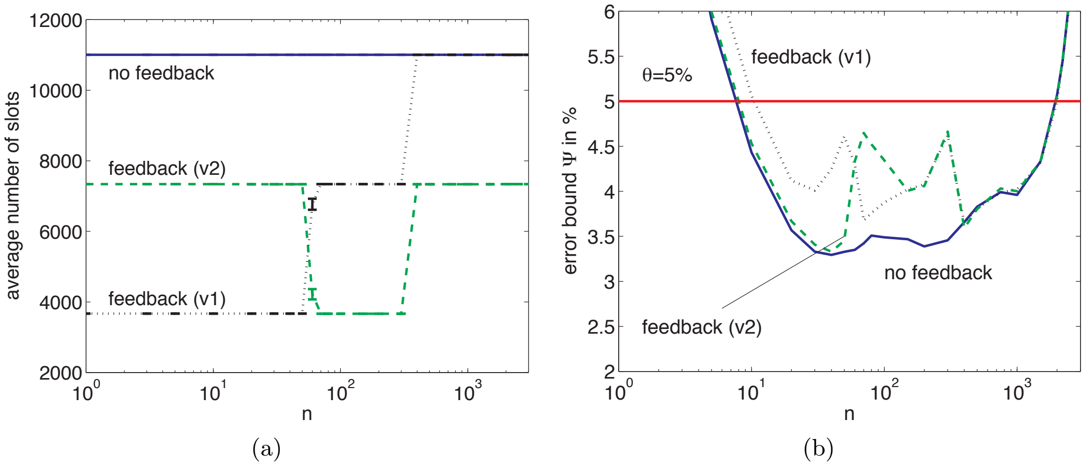


Figure 4.4: Non-Adaptive Neighbor Estimator: (a) average number of required contention slots and (b) achieved error bound Ψ over n, when maximum error $\theta = 5\%$ with confidence $\alpha = 95\%$ using different feedback options.

for its estimation. The feedback schemes use only a subset of all subranges for their observations and experience higher error bounds. Nevertheless, all schemes perform within the requested accuracy parameters for n being in the operation range. The estimation error increases tremendously when n is outside the defined operation range.

In summary, the NAE does not require any data transmission during the estimation phase, i.e., after the transmission of the `neighbor-query`-packet. The introduction of an early stop mechanism reduces the average estimation delay; although it decreases the estimation accuracy, the required accuracy can be adhered. The evaluation suggests to use NAE with binary feedback (Variant 2). If not mentioned otherwise, the term NAE refers to this variant hereafter. Algorithm 1 and Figure 4.5 summarize the resulting NAE scheme.

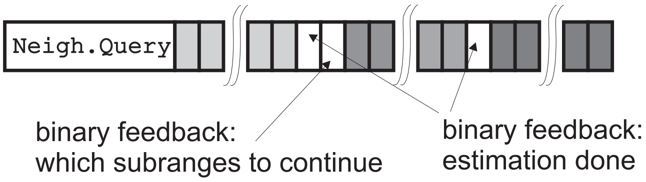


Figure 4.5: Slot structure of the Non-Adaptive Neighbor Estimator

Algorithm 1 Non-Adaptive Neighbor Estimator (NAE)

```
Input parameters: $n_{\min}$, $n_{\max}$, $\theta$, $\alpha$.
1. Query node determines $k$, $\eta_{\text{sub}}$, $s_{\text{sub}}$ (see Sec. 4.3.2).
2. Query node computes $p_i$ for $i = 1...k$ (see Sec. 4.3.1).
3. Query node sends neighbor-query containing parameters $p_i$ for $i = 1...k$ and $s_{\text{sub}}$.
4. Nodes set initial $i = \lceil \frac{k}{2} \rceil$ and $inc = 0$.
5. Each polled node sends a busy tone with probability $p_i$ during each of $s_{\text{sub}}$ slots.
6. Query node determines $\hat{n}$ using (4.17).
7. If $(i = 1 \,\&\, inc = -1)$ or $(i = k \,\&\, inc = 1)$ estimation stops.
8. Early Stop Indicator:
    • Query node stays silent if $\hat{n}$ is within processed subranges. Estimation ends.
    • Otherwise Query node transmits busy tone.
9. Direction Indicator (only when $inc = 0$): query node gives feedback whether to proceed with the subrange smaller or greater than the $\lceil \frac{k}{2} \rceil^{\text{th}}$:
    • Query node sends busy tone: nodes set $inc = 1$.
    • Query node stays silent: nodes set $inc = -1$.
10. Nodes set $i = i + inc$ and proceed at step 5).
```

4.4 Adaptive Neighbor Estimators

In the previous section, we introduced a neighbor estimator that guarantees a specific level of accuracy as long as the real number of nodes is within the operation range assumed by the query node. The estimation time significantly depends on this range for given accuracy. In this section, we propose extensions and modifications to the neighbor estimation process in which the query node updates the access probability and/or the number of slots to the polled nodes during the contention phase. In this way, the neighbor estimation process becomes adaptive based on the observed empty slots. Such updates require feedback packets, which add overhead to the estimation process.

4.4.1 Single-Feedback Neighbor Estimator

The Single-Feedback Neighbor Estimator (SFE) uses a data transmission to update the access probability of the polled nodes. The overall estimation process is divided into two phases: In the first phase, the estimator performs a *coarse estimation* using a low accuracy in a large operation range. The result of the coarse estimation, $\hat{n}_c$, is used to find a tighter operation range for the second phase which is called *fine estimation*. We treat both estimation phases as NAEs as described in the previous section. The coarse estimation covers the entire operation range assumed by the query node and requires an error threshold $\theta_c \in (0,1)$. The range of the fine estimation is determined by the result of the coarse estimation; it is set to $[n_{\min}, n_{\max}] = [\hat{n}_c\,(1-\theta_c)\,, \hat{n}_c\,(1+\theta_c)]$.

The task is to find the θ_c that minimizes the overall number of slots required for the entire estimation. For both estimation phases, a range partitioning may be performed to minimize the total number of slots. Denoting the number of subranges in the coarse and fine estimation phases by k_c and k_f, respectively, the optimization problem to solve is:

$$\min \left[k_c\, s_{\text{sub}}\left(\eta_c, \theta_c, \alpha\right) + k_f\, s_{\text{sub}}\left(\eta_f, \theta, \alpha\right) \right] \tag{4.18}$$

with range parameters

$$\eta_c = \begin{cases} \eta^{1/k_c}, & k_c > 0 \\ 0, & k_c = 0 \end{cases} \quad \text{and} \quad \eta_f = \begin{cases} \left(\frac{1+\theta_c}{1-\theta_c}\right)^{1/k_f}, & k_c > 0 \\ \eta^{1/k_f}, & k_c = 0 \end{cases} \tag{4.19}$$

and the following constraints:

$$\theta \le \theta_c \le 1\ ,\ k_c \ge 0\ ,\ k_f \ge 1\ ,\ k_c, k_f \in \mathbb{N}_0\ .$$

Note that in some domains a coarse estimation just increases the overall number of slots, and a fine estimation alone leads to a smaller number of overall required slots, in which case $k_c = 0$.

To solve this optimization problem, we vary θ_c in the interval $(\theta, 1)$ with a certain step size. We use a step size of 0.001 here. For each θ_c-value, we find the subrange that minimizes the number of slots for the coarse estimation and fine estimation. Finally, we select the θ_c-value that minimizes the sum of the required slots for both phases.

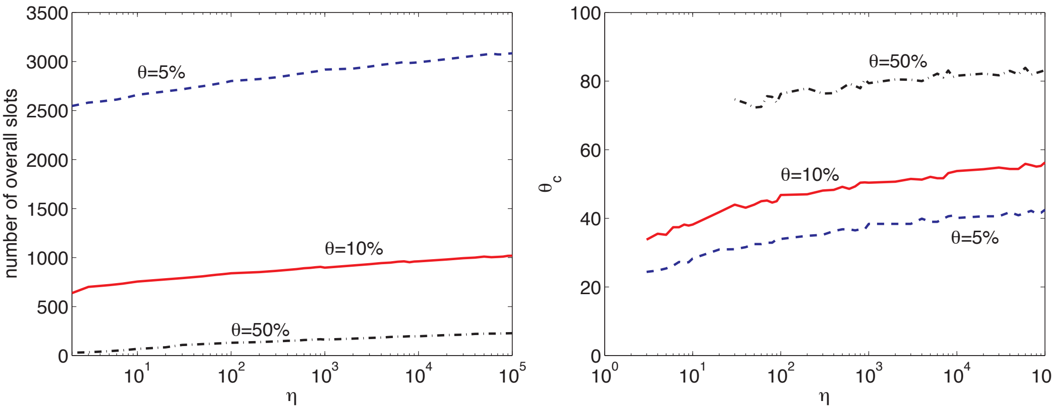
Algorithm 2 summarizes the SFE scheme.

Performance

Figure 4.6a depicts the number of slots required to achieve an accuracy θ as a function of η. The number of required slots only increases with the logarithm of η. For

Algorithm 2 Single-Feedback Neighbor Estimator (SFE)

```
Input parameters: $n_{\min}$, $n_{\max}$, $\theta$, $\alpha$.
  1. Query node determines $k_c$ and $\theta_c$ using (4.18).
  2. If $k_c = 0$ no coarse estimation is necessary:
       • Query node executes NAE with parameters: $n_{\min}$, $n_{\max}$, $\theta$, $\alpha$.
  3. else
       (a) Query node executes NAE with parameters: $n_{\min}$, $n_{\max}$, $\theta_c$, $\alpha$.
       (b) Query node executes NAE with parameters: $\max[1, \hat{n}_c \cdot (1-\theta_c)]$, $\hat{n}_c \cdot (1+\theta_c)$, $\theta$, $\alpha$.
```



(a) (b)

Figure 4.6: Single-Feedback Neighbor Estimator: (a) average number of required contention slots and (b) accuracy of coarse estimation θ_c over η, when maximum error $\theta = \{5\%, 10\%, 50\%\}$ with confidence $\alpha = 95\%$.

example, to achieve an estimation with an accuracy of $\theta = 10\%$, 637 slots are needed for $\eta = 2$ and 961 slots for $\eta = 10\,000$. Comparing these results with those of Table 4.3 shows that the estimation delay can be decreased tremendously by using feedback from the query node.

Figure 4.6b shows the accuracy of the coarse estimation θ_c as a function of η and the accuracy of the fine estimation θ. To improve the overall estimation (to decrease θ), also the accuracy of the coarse estimation must become better (decreasing θ_c). For given θ, the required θ_c increases with increasing η. For a given θ, a coarse estimation is only needed above a certain η-value. For instance, while a coarse estimation is required for $\theta = \{5\,\%, 10\,\%\}$ and $\eta > 2$, for $\theta = 50\,\%$ using a coarse estimation is beneficial for $\eta > 29$.

4.4.2 Multi-Feedback Neighbor Estimator

A single feedback round in which the query node updates the access probability decreases the estimation delay. What happens if the query node provides more feedback? To answer this question, we introduce an estimator which uses multiple feedback rounds in this section. Since every feedback also adds time to the overall estimation duration, we aim nevertheless to keep the number of feedback rounds small. From the lessons learned so far, the query node has to aim at quickly finding an appropriate access probability that enables it to collect statistics, i.e., yields empty as well as occupied slots during an observation period. This is especially important, since we also drop the constraint of the query node knowing something about the operational range in this section, i.e., $[n_{\min}, n_{\max}]$.

Functionality

The estimator proposed in the following is called Multi-Feedback Neighbor Estimator (MFE). As shown in Figure 4.7, which depicts the slot structure of this estimator, the estimation process is split into two phases: The task of the *initial phase* is to quickly come up with an access probability that leads to empty and non-empty slots. The *main phase* consists of several rounds. At the beginning of each round the query node estimates the number of nodes based on the slot occupation statistics of all previous rounds and verifies whether the required accuracy is met. If the accuracy is met, the query node stops the estimation process. If the accuracy is not met yet, it informs the polled nodes about a new access probability and a new number of contention slots for the following observation round.

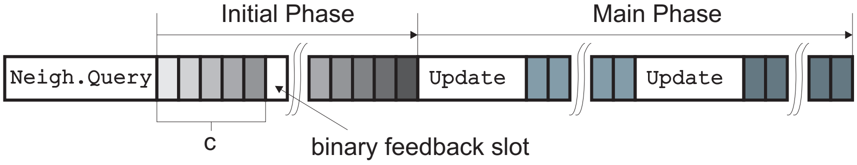


Figure 4.7: Slot structure of the Multi-Feedback Neighbor Estimator

In the **initial phase**, polled nodes update their access probability from slot to slot such that the query node can quickly determine a suitable access probability for the first round of the main estimation phase. Recall that a suitable access probability results in empty as well as non-empty slots. The polled nodes decrease their access probability in an exponential way such that a huge operation range is covered fast. Nodes determine the access probability p_i for the i^{th} slot by

$$p_i = \left(\frac{1}{2}\right)^i . \tag{4.20}$$

Every c slots, where c is the binary feedback interval of the MFE, polled nodes listen for feedback from the query node for the duration of one slot. If the query node has not spotted any empty slots, it stays silent in the binary feedback slot and thus signals the polled nodes to continue in the initial phase. The query node ends the initial phase as soon as it detects at least one empty slot.

The **main phase** consists of several rounds where each round starts with a transmission from the query node in which it informs the polled nodes whether the estimation process continues or ends. If the process continues, the query node provides an updated access probability and frame size. At the beginning of each round the query node performs the followings steps:

- creates a new estimation of neighbors based on all gathered statistics so far,
- determines the accuracy of the estimation,
  - if the desired accuracy is met: ends the estimation,
  - if not: determines a new access probability based on the current estimation,
- determines the number of slots to be used in the current round, and
- broadcasts the access probability and the number of slots for the current round to the polled nodes.

The MFE uses MLE to combine the slot occupation statistics of all previous observation periods including the initial phase. Equation (4.17) requires modifications to address the fact that the number of slots s_i is varied between rounds. At the beginning of the j^{th} round of the main phase the query node wants to find the value z that fulfills

$$\sum_{i=1}^{o+j-1} e_i \ln q_i = \sum_{i=1}^{o+j-1} \frac{s_i - e_i}{1 - q_i^z} \cdot q_i^z \cdot \ln q_i \ . \tag{4.21}$$

The variable o accounts for the number of slots used in the initial phase of the MFE. The z-value that solves (4.21) is the estimation $\hat{n}_j$ of the j^{th} round of the main phase. In the first round of the main phase, the estimation is based on the observations made during the initial phase where $s_i = 1$ for $i = 1 \ldots o$.

Next, the query node checks whether this estimation meets the required accuracy. Based on the access probabilities p_i and frame sizes s_i it computes the variances $\mathrm{Var}_i\left[\hat{n}\right]$ by substituting $\hat{n}_j$, p_i and s_i into n, p and s in (4.10). Taking into account the initial phase and all processed rounds of the main phase, it then computes the overall variance of the j^{th} estimation by (see Appendix):

$$\mathrm{Var}\left[\hat{n}_j\right] = \frac{1}{\sum_{i=1}^{o+j-1} \frac{1}{\mathrm{Var}_i[\hat{n}]}} \ . \tag{4.22}$$

Given this variance, the error bound of the j^{th} round is $\Psi_j = \sqrt{\mathrm{Var}\left[\hat{n}_j\right]} \cdot \Phi\left(\frac{1+\alpha}{2}\right) \cdot \hat{n}^{-1}$. The MFE stops the estimation process when $\Psi_j \leq \theta$ is achieved.

If $\Psi_j > \theta$ after a given round, the query node computes a new access probability based on the current neighbor estimation. The query node chooses the access probability that minimizes $\mathrm{Var}\left[\hat{n}\right]$ for $n = \hat{n}$. This access probability is found by taking the derivative of (4.10) with respect to p, setting the result to zero, and solving it for p. This yields

$$p = 1 - \exp\left(-\frac{1.594}{n}\right) . \tag{4.23}$$

The query node uses $\hat{n}_j$ instead of n in (4.23) to calculate the access probability p_j of the j^{th} round.

Let us now focus on the calculation of the number of slots s_i for the i^{th} round for $i > o$, i.e., the $j = (i - o)^{\text{th}}$ round in the main phase of the MFE. The motivation behind updating the number of slots for each round is to keep the number of feedback rounds small. At the beginning of an estimation attempt, the estimated value fluctuates considerably. Frequent access probability updates in this case reduce the overall required slots substantially. On the other hand, after some rounds one could observe that the estimated value gets more stable and that its deviation decreases. In this case, frequent updates of the access probability might not be necessary and, depending on the feedback duration, just prolong the overall estimation delay. That is why the query node adjusts the number of slots for each round based on the current variance of the estimation and the time required to transmit an updated access probability to the polled nodes. Therefore, we introduce a new parameter β. It represents the number of contention slots which would fit into the duration required for the query node to transmit the updated access probability of the polled nodes.

At the beginning of the i^{th} round we assume that $\hat{n}_i \cdot (1 - \Psi_i) \leq n \leq \hat{n}_i \cdot (1 + \Psi_i)$ with probability α. Given p_i we can determine the number of contention slots necessary to finish the estimation phase for $n = \{\hat{n}_i \cdot (1 - \Psi), \hat{n}_i, \hat{n}_i \cdot (1 + \Psi)\}$ after the current round. Therefore, we derive the maximum variance of the i^{th} round such that the estimation process finishes after it:

$$\mathrm{Var}_i\left[\hat{n}\right] = \frac{\mathrm{Var}\left[\hat{n}_i\right] \cdot \mathrm{Var}\left[\hat{n}\right]}{\mathrm{Var}\left[\hat{n}_i\right] - \mathrm{Var}\left[\hat{n}\right]} , \tag{4.24}$$

with $\mathrm{Var}\left[\hat{n}\right] = \left(\frac{\hat{n} \cdot \theta}{\Phi^{-1}\left(\frac{1+\alpha}{2}\right)}\right)^2$. By using the result of (4.24) in (4.10) the query node can determine the required number of slots to finish the estimation process after this round. For $n = \hat{n}$ we get s_{b_i} which represents the smallest number of necessary slots. Let $\hat{n}_{w_i} \in \{\hat{n}_i \cdot (1 - \Psi_i), \hat{n}_i \cdot (1 + \Psi_i)\}$ be the number that requires more slots to finish the estimation process after the current round and let s_{w_i} denote this number. Clearly, if $s_{w_i} \leq s_{b_i} + \beta + 1$ the query node does not need to update the access probability, since it can finish the estimation process with the current access probability faster than using an additional round where the query node gives feedback. For $s_{w_i} > s_{b_i} + \beta + 1$ it is more efficient not to finish the estimation process with the current access probability p_i. But how should the query node choose s_i? If it sets $s_i = s_{b_i}$ it may waste time since p_i is not suitable to improve the statistics regarding n and thus cannot reduce the deviation of $\hat{n}_{i+1}$ considerably. If the query node chooses s_i too small, it may not get further references to base the subsequent decisions on.

Without claiming that it is the best solution, we propose the following method to determine the number of slots of the i^{th} round:

$$s_i = \begin{cases} 1, & i \leq o \\ s_{w_i}, & i > o \,\&\, s_{w_i} \leq s_{b_i} + \beta + 1 \\ \max\left(s_{q_i}, \beta\right) & i > o \,\&\, s_{w_i} > s_{b_i} + \beta + 1 \end{cases} \tag{4.25}$$

with

$$s_{q_i} = \left\lceil \frac{\left(1 - q_i^{\hat{n}_i}\right) \cdot (1+\beta) \cdot \hat{n}_{w_i}^2}{q_i^{\hat{n}_i} \cdot \left(\hat{n}_{w_i}^2 - \hat{n}_i^2\right) + q_i^{\hat{n}_i - \hat{n}_{w_i}} \cdot \hat{n}_i^2 - \hat{n}_{w_i}^2} \right\rceil, \tag{4.26}$$

where $q_i = 1 - p_i$. Equation (4.26) determines the number of slots such that by using p_i the error bound Ψ of the estimation for $n = \hat{n}_i$ is the same as for $n = \hat{n}_{w_i}$ when the latter can use $\beta + 1$ more slots than the former. Especially in the first rounds of the main phase it can happen that (4.26) results in small values, e.g., 1. However, the query node cannot gain significant insight by using a single slot in a round. The query node has to consider the time costs of feedback transmissions, too. Thus, the query node uses a lower limit for the number of contention slots per round (see (4.25)) which is equal to the ratio of feedback data transmission to contention slot duration.

Algorithm 3 summarizes the MFE scheme.

Performance

For the performance evaluation of the MFE we choose a feedback interval of $c = 5$ for the initial phase.

Figure 4.8a shows the error bound Ψ of the MFE. Since the MFE tries to minimize the used number of observation slots it tries to get as close to the requested error bound as possible. This is in particular true for small β-values where the MFE frequently updates the access probability. For instance, for $\theta = 10\%$, the MFE using $\beta = 10$ performs around the bound. For $\beta = 400$, it is too expensive to update the access probability too often. Thus, the MFE spends more observation slots to assure the demanded accuracy also for worst case scenarios, i.e., where the real value is far off the value used to determine the access probability.

Figures 4.8b and 4.8c depict the average number of slots and feedback rounds needed to perform the estimation for different θ and β-values, respectively. Both the average number of slots and feedbacks are almost independent of n for given (θ, β)-pairs. Since the MFE gives on average less feedback for $\beta = 400$ than for $\beta = 10$ we need in overall more contention slots for $\beta = 400$ to end the estimation process.

Algorithm 3 Multi-Feedback Neighbor Estimator (MFE)

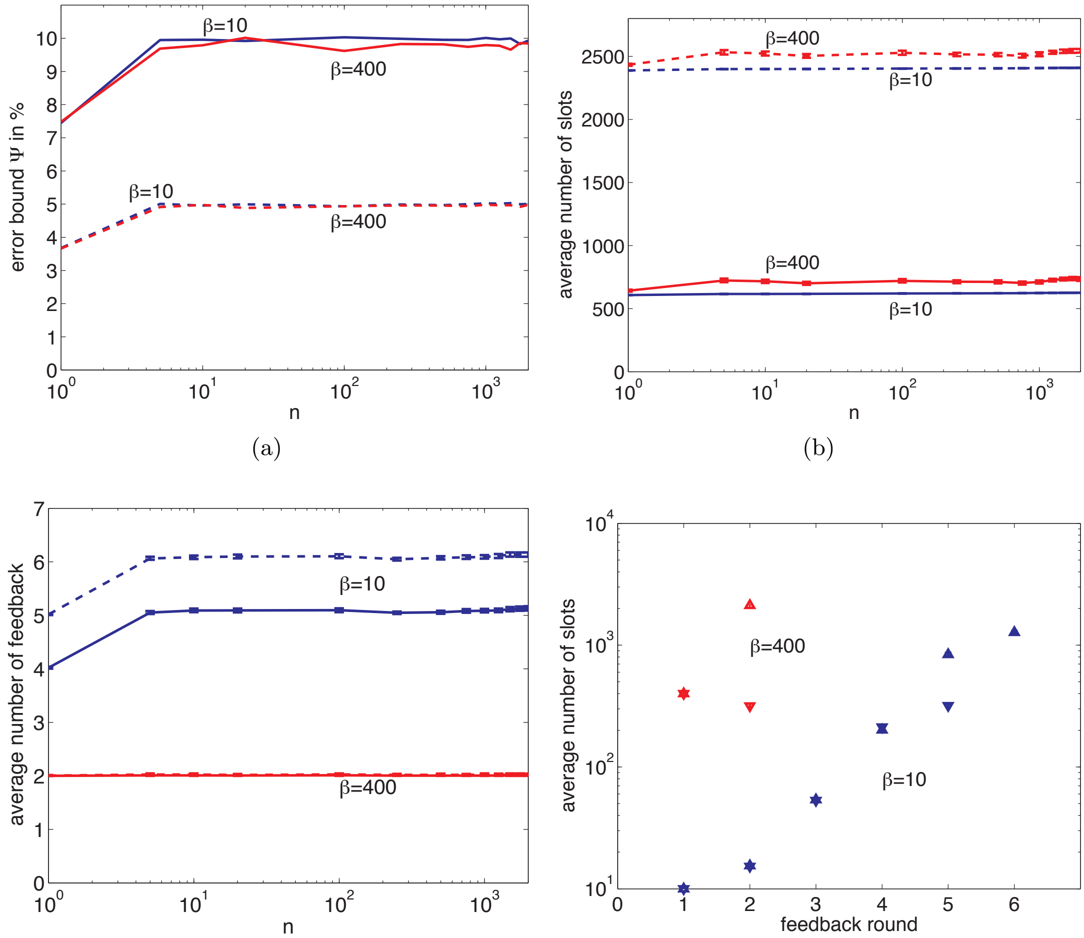
```
Input parameters: $c$, $\beta$, $\theta$, $\alpha$
  1. Query node sends neighbor-query containing parameters $c$.
  2. Initial phase:
     (a) Every polled node transmits in slot $i$ with probability $p_i$ given by (4.20).
     (b) After $c$ slots, polled nodes listen for 1 slot:
         • If $\sum_i e_i = 0$ : query node stays silent; all nodes continue in the initial phase.
         • If $\sum_i e_i \neq 0$ : all nodes proceed with main phase.
  3. Main phase:
     (a) Query node determines $\hat{n}_j$ using (4.21) and assesses accuracy using (4.22):
         • Accuracy is met:
           – If $1^{\text{st}}$ round of main phase: query node informs nodes that the estimation is completed.
           – else: query node stops estimation by staying silent.
         • Accuracy is not met: Query node determines $p_i$ and $s_i$ for next round using (4.23),(4.25) and broadcasts these values.
     (b) Each polled node transmits with probability $p_i$ in each of the $s_i$ slots.
     (c) Proceed at 3).
```

We also observe that in the majority of the cases a certain number of feedback rounds is used. For instance, for $\beta = 10$ and $\theta = 5\%$ in most cases the MFE uses 6 rounds. In fact the average values presented in Figure 4.8c are only slightly higher than the values observed in the most likely case.

Finally, Figure 4.8d illustrates the average number of slots used in the j^{th} round of the main phase of MFE corresponding to these majority cases for $n = 1\,500$. For small β-values, i.e., time-inexpensive feedbacks, the MFE uses more rounds in the main phase of the estimation process. In the first few rounds, the number of contention slots per round increases only gradually. With increasing accuracy of the estimation results the number of contention slots increases exponentially. For $\beta = 400$, we observe considerably fewer estimation rounds.

4.5 Technology Aspects

Let us elaborate on the duration of busy tone slots and feedback data transmissions. We consider two different technologies: radios compliant to the wireless LAN standard IEEE 802.11g and the Infineon TDA5250 low power transceiver.



(a) (b)

(c) (d)

Figure 4.8: Multi-Feedback Neighbor Estimator: (a) achieved error bound Ψ, (b) average number of required contention slots, and (c) average number of feedback transmissions over n; (d) average number of required contention slots used in the rounds of the main phase for $n = 1\,500$, when maximum error $\theta = 5\%$ (dashed lines or Δ-markers) and $\theta = 10\%$ (solid lines or ∇-markers) with confidence $\alpha = 95\%$ for $\beta = \{10, 400\}$.

In one busy tone slot the query node needs to detect the presence of another node which started busy tone transmission at the beginning of the same slot. During one slot, a node needs to switch on its transmitting unit, start transmitting the busy tone, keep transmitting until the query node is able to detect the channel activity, and, finally, switch off its transmitting unit. The time frame for the active busy tone transmission, i.e., the time from starting busy tone transmission until switching off the transmitting unit, is defined by the signal propagation time and the clear channel assessment time of the query node's receiver.

For data transmission, i.e., a transmission which contains more than a single bit information, a node needs to transmit at least the overhead introduced by the physical layer of the radio besides the user data (i.e., which are bit streams containing synchronization, demodulation, and parity information).

Next, we present examples of possible durations for busy time slots and feedback transmissions. For the data transmission, we assume that the query node only updates the access probability p and the number of slots s by using a single precision float number (4 bytes) and an unsigned short number (2 bytes), respectively.

In IEEE 802.11g [IEEE03], the slot duration used in the backoff process of the collision resolution protocol is 9 μs. It is determined such that an IEEE 802.11g interface knows at the beginning of a slot whether another node has started its transmission at the beginning of the previous slot. The transmission of the feedback information would last at least 139 μs assuming usage of a short preamble and the transmission of feedback information directly in the physical layer without invoking the MAC. Given both durations we determine the number of busy tone slots that can be transmitted instead of one data transmission for IEEE 802.11g to be $\beta_{802.11\text{g}} \approx 15.4$. Due to inexpensive feedback, it is beneficial to use the MFE in IEEE 802.11g systems.

As a second example, we mention a low power transceiver used in wireless sensor networks. The TDA5250 transceiver [Inf02] has a maximum turnaround time of 2.86 ms between receive and transmit mode and a maximum data transmission rate of 64 kbps using either Amplitude Shift Keying (ASK) or Frequency Shift Keying (FSK). Switching the radio between receive and transmit mode is too time consuming during a busy tone slot. However, we obtain a similar effect of a busy tone transmission by using the ASK mode, which works in on/off manner. When a node wants to send a busy tone it puts a 1 on the input of the transceiver otherwise a 0. In this way, the busy tone slot duration is limited to the duration of a single bit transmission of the radio being 16 μs. What is the minimum feedback duration of this low power transceiver? First, note that the transceiver works on a bit level. Thus, a protocol designer needs to define a proper physical layer packet format. For wireless transmissions one would need at least a preamble (1-2 bytes), one start frame delimiter (1 byte), and some checksum information (1-2 bytes). Summing up, the data to be transmitted including the feedback information is at least 9 bytes, requiring a total transmission time of 1.125 ms. Additional to this time span, we have to account for two times the turnaround time resulting in an overall minimum feedback duration of 6.854 ms. Thus, for this receiver, we get $\beta_{\text{TDA5250}} \approx 427$. The MFE is not suitable for devices using the TDA5250 transceiver because of the time-consuming feedback rounds. It is also infeasible to use binary feedback options for transceivers with such a long turnaround time. Depending on the demanded estimation accuracy, it is better to use NAE or SFE.

4.6 Comparison of the Estimators

In this section, we compare the performance of the presented estimation methods NAE, SFE, and MFE. The NAE and SFE both exploit the early stop mechanism (Variant 2) and work at an operation range of $[1, 2\,000]$. The MFE uses the parameters $c = 5$ and $\beta = 15.4$.

Figure 4.9a compares the error bounds Ψ achieved by the three estimators for given θ-values and varying n. The achieved Ψ-values are below the required threshold θ for all estimators when n is within the operation range; the MFE always achieves the required accuracy independent of n. In the given operation range, the NAE yields the lowest Ψ-value, the accuracy decreases with increasing feedback, and the error bound achieved by the MFE is actually very close to the required threshold θ. This is due to the fact that the MFE aims to reduce the estimation duration by getting as close to the required threshold as possible when we adaptively update the access probability. However, we observe that the NAE is strictly limited to the given operation range. At the borders, the desired accuracy is just met; outside the operation range the estimation error increases significantly. Although the SFE also requires an operation range, it is able to estimate values of n slightly outside this interval within the accuracy demands. This is due to the sequential execution of two NAEs and the fact that the operation range of the second NAE is determined by the first one.

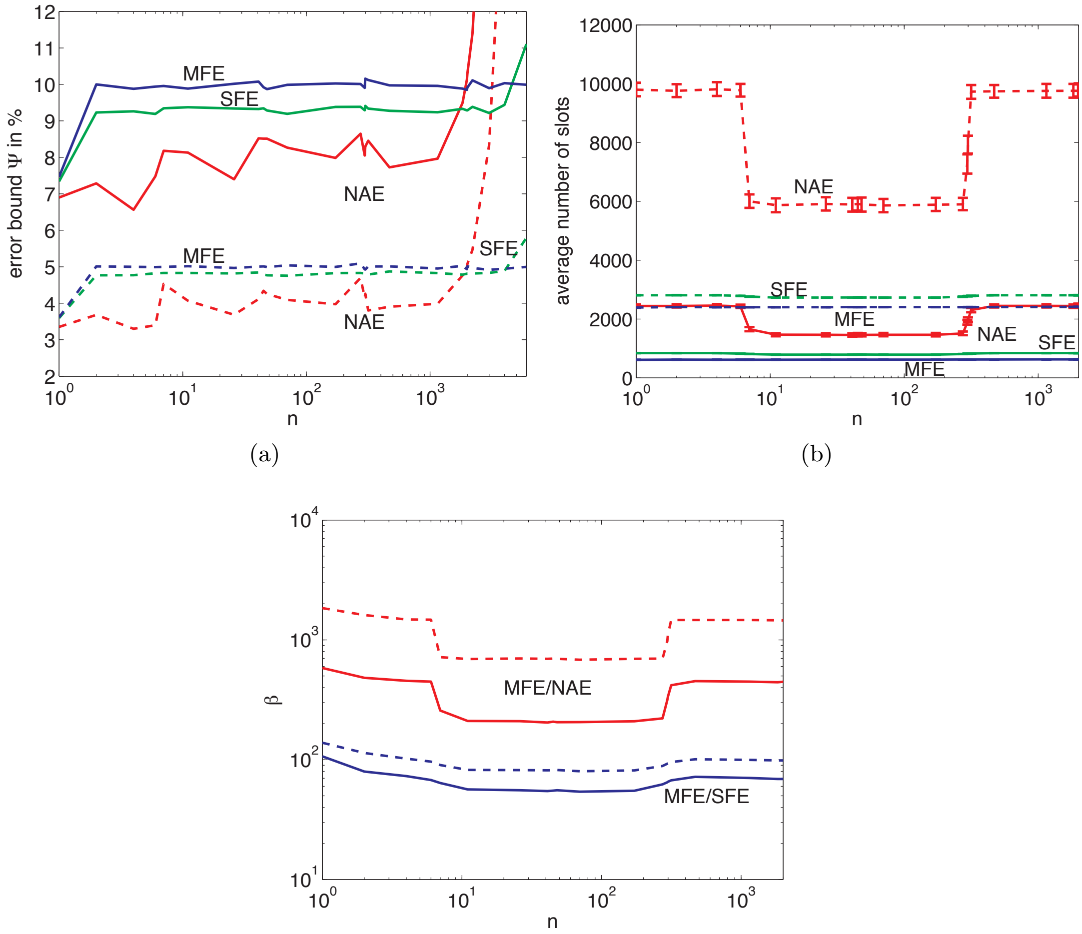
Figure 4.9b shows the average number of contention slots needed to finish the estimation process. As expected, the more feedback is used, the less contention slots are necessary. Independent of n, the MFE always requires less contention slots than the other methods.

However, the overall estimation delay depends, besides the number of contention slots, also on the number of feedback transmissions and their durations. Thus, Figure 4.9c analyzes for how many slots a feedback transmission can last such that NAE and SFE perform as good as MFE in terms of estimation speed. E.g., for $\theta = 5\%$ and $n = 500$ the duration of a feedback transmission needs to equal the time needed for processing 2 000 slots such that NAE is as fast as MFE.

Figure 4.10 shows the estimation delay, i.e., the time span after `neighbor-query` transmission until the estimation stops, in multiples of slots as function of θ. As performance reference, we provide a lower bound labeled "ideal (known n)", which was derived by assuming that n is known and asking the question as to how many slots are needed to verify this assumption. We use (4.23) to calculate p which is used in (4.10) to determine the required slots; a contention-based estimation method needs at least this number of slots.

The following qualitative results can be stated from Figure 4.10:

- If only very small estimation errors are tolerated, say $\theta < 5\,\%$, the estimation delays of SFE and MFE are similar and close to the minimum number of required contention slots.



(a) (b)

(c)

Figure 4.9: NAE, SFE, MFE comparison: (a) achieved error bound Ψ, (b) average number of required contention slots, and (c) ratio of slots per feedback such that NAE and SFE are faster than MFE over n, when maximum error $\theta = 5\%$ (dashed-line) and $\theta = 10\%$ (solid-line) with confidence $\alpha = 95\%$.

- For medium accuracy, say $40\,\% < \theta < 65\,\%$, the estimation delay of SFE exceeds the one of NAE. The SFE tries to minimize the number of contention slots regardless of the feedback duration.
- The estimation delay of NAE and SFE converge for large θ-values. This is due to the fact that for low accuracy we do not need any coarse estimation phase and thus the SFE turns into an NAE.

Finally, Figure 4.11 shows the overall estimation delay of the proposed methods as a function of n. The depicted values account for slot duration ($= 9\,\mu$s) and data transmissions ($= 139\,\mu$s) to update parameters p and s. We also address the question

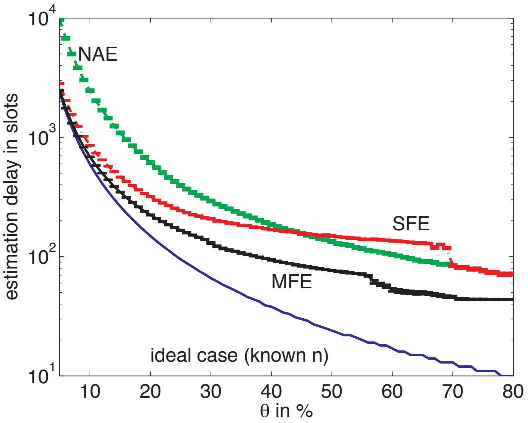


Figure 4.10: Estimation delay as a function of θ for: ideal case, NAE, SFE, and MFE at $\alpha = 95\%$.

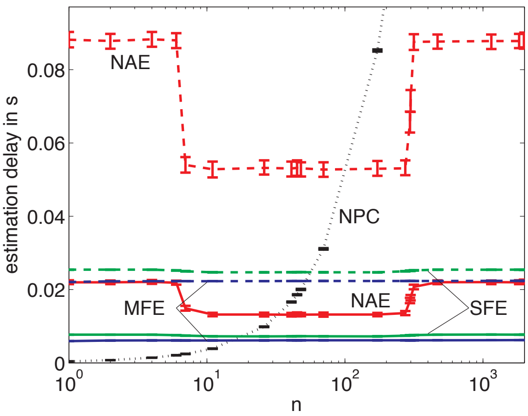


Figure 4.11: Estimation delay as a function of n for NPC, NAE, SFE, and MFE with a maximum error of $\theta = 5\,\%$ (dashed lines) and $\theta = 10\,\%$ (solid lines) with confidence $\alpha = 95\,\%$.

how long the estimation would last when we use a scheme where nodes reply to a `neighbor-query` with `hello`-packets which are counted by the query node to infer about its neighbor cardinality. We denote such a scheme by Non-Colliding Packet Counting (NPC). The query node needs to `acknowledge` (`ACK`) received `hello`-packets. Nodes which have received an `ACK` for their `hello`-packet stop transmitting. NPC uses CSMA to control the channel access of the nodes. An unanswered `hello`-packet is assumed to have collided. Polled nodes use exponential backoff to resolve collisions. The size of the initial and the maximum backoff windows are 31 and 1023, respectively. `hello` and `ACK`-packets last 139 μs each. An advantage of NPC over estimators is its error freeness ($\theta = 0$). As we neglect any interframe spacings, such as `SIFS` and `DIFS`, and assume that `ACK`s do not collide with `hello`-packets, the illustrated result of NPC represents a lower bound of the estimation delay.

Figure 4.11 reveals that NPC outperforms the proposed schemes for small values of n. For an error threshold of $\theta = 10\,\%$ it is faster to exchange data packets up to a neighbor cardinality of $n = 17$. Above this value, the number of collisions rises tremendously and SFE and MFE are faster. For $\theta = 5\,\%$ the break even point for MFE and NPC is around 50 nodes.

4.7 Related Work

Neighbor estimation is expected to become important as the density of wireless devices grows. At this point, estimating the number of neighbors with certain quality regardless of their identity is not a well-addressed topic in the wireless networks domain. However, several researchers investigate tag cardinality estimation methods in RFID systems. It should be noted that the main interest in these works is to count the number of all tags in a very large network with single or multiple readers. Therefore, the challenges that need to be addressed differ from that of estimating the neighborhood cardinality in communication networks. We nevertheless summarize some methodologies and highlight the differences. Note that in these schemes, different than the proposed methods, each tag chooses a slot randomly and transmits at this slot with a given probability instead of transmitting in all slots with a given probability. Moreover, none of these schemes takes the impact of feedback durations into account. Finally, bit streams defined by RFID standards are transmitted at each slot instead of busy tones. The idea of using busy tones to exchange single bit information is reported in [KBW04] for ad-hoc wireless networks. Busy tones are used to reduce signaling overhead for transmitting single bit information, e.g., yes-no answers.

Kodialam and Nandgopal [KN06] introduce tag cardinality estimations in RFID systems, where an estimation round consists of several frames with multiple contention slots. The access probability is updated at the end of each frame, using both the number of empty and collided slots in one frame. The estimation process ends, if the estimator *believes* that the result fulfills the accuracy demands. Due to the iterative nature of the estimator, the actual estimation time cannot be known a priori. Apart from the fact that detecting collisions is nontrivial, the authors report in [KNL07] that their estimator is biased. That publication addresses some of the shortcomings of [KN06]. It introduces an enhanced zero-based estimator (EZB), which relies only on the number of empty slots during the contention frames and determines the number of trials in advance. The EZB algorithm splits large operation ranges in smaller ranges to reduce the estimation duration. For each subrange, the algorithm performs an estimation and combines the results of the subranges. While NAE *without* feedback is similar to this approach, since the contention method is different, the way the subranges are determined and the results from each subrange is combined is also different.

The authors of [SLY09] extend [KNL07] to unreliable radio channels. It is shown that in the presence of fading, one needs to increase the number of trials to obtain the required accuracy. In our work, we are interested in the number of neighbors with a certain quality. To this end, the instantaneous logical topology is of more interest than the actual physical topology. Therefore, impact of fading does not need to be considered.

The algorithm in [HST$^+$10] uses the number of slots before the first non-empty slot to estimate the tag cardinality. The access scheme allows the reader to give feedback after each contention slot. The estimator needs considerably more contention slots for small tag sizes than the one from [KNL07]. An enhanced version is also proposed to overcome the shortcomings of the basic method. While the methodology provides results for estimation delay in absolute time for standard RFID systems, the paper still lacks the impact of feedback duration on the delay.

The focus of [LWCY10] is on energy-efficiency of active RFID tags. It tries to minimize the number of transmissions during the estimation process and not the estimation delay. An estimation process consists of an initial and an iterative phase. In the initial phase, the estimator aims to find an appropriate access probability for the iterative phase such that on average only one tag transmits. In the iterative phase, the estimator updates the access probability based on previous rounds. The new estimate is derived by using MLE where all previous rounds are considered. While the results show improvement on estimation delay compared to other work and performs some type of MLE, different than MFE the feedback delay is not considered in that paper either.

Finally, there are also publications that aim to count tags with different constraints and objectives. For instance, [QNL10] considers efficient counting of the whole tag population with multiple readers; [XST$^+$10] counts tags in a mobile scenario; and [SLM10] tries to detect the nodes that leave and enter the system.

4.8 Summary

In this chapter, we proposed different methods to track the number of neighbors of a node that optionally exhibit certain properties. All proposed methods share a common design block that utilizes probabilistic trials to infer about the number of nodes. Busy tones are used in the probabilistic trials that allow for very short communication slots and thus fast executions of the estimation algorithms.

The proposed methods differ from each other in the level of feedback, i.e., the number of data transmissions used by the query node during the estimation process. The NAE does not require any data transmission besides the one starting the estimation phase. The SFE uses a coarse estimation phase in which it makes an estimation with reduced accuracy. The query node uses this result to find a better access probability for the following fine estimation. Finally, the MFE uses multiple feedback rounds to minimize the number of probabilistic trials.

We accounted for the overhead caused by using feedback in the design and the analysis of the estimation methods. Based on two different technologies we inferred about the ratio of a feedback transmission duration to the time needed for a contention slot and showed that the timing constraints of the used transceiver determines which estimator is faster. Finally, using timing specifications of IEEE 802.11g, we compared the estimation delay of the proposed methods with a counting scheme that uses explicit packet exchanges.

Based on the desired accuracy, network density, and technology one needs to decide which of the proposed estimators is more suitable.

Chapter 5

Cooperative Medium Access

In Chapter 3, we focused on the relay selection aspects of cooperative relaying. We introduced methods to increase the energy and time-efficiency of cooperative relaying. In our considerations, however, we did not regard for resource reservation. Moreover, we assumed that signaling packets were error free.

In this chapter, we discuss the integration of cooperative relaying into a protocol stack. More specifically, we introduce a cooperative MAC protocol which takes care of resource reservation, relay selection and the cooperative packet flow.

To this end, we discuss the feasibility of the existing work (presented in Section 2.3.2) for specifically low end radio transceivers. Based on this discussion and our results from the previous chapters we propose a cooperative MAC protocol for low budget off-the-shelf hardware. Finally, we rigorously evaluate this protocol and discuss its performance.

5.1 Introduction and Motivation

Information theory based analysis of cooperative relaying [LTW04] promises high potential gains in throughput and/or energy-efficiency compared to non-cooperative communication schemes. Theoretical analysis, however, focuses mainly on simple scenarios where source and destination know their relaying node a priori. In Chapter 3, we addressed scenarios where relays are not a priori known but need to be selected. We elaborated on relay selection aspects and their impact on the overall performance of cooperative relaying in terms of energy, delay, and throughput. Results indicate that cooperative relaying with relay selection can achieve gains compared to non-cooperative schemes as long as nodes enable cooperation *only if* needed. Enabling cooperation continuously, regardless of the direct communication quality between source and destination, leads to increased overhead and energy consumption which reduces the benefits of cooperative relaying. We have, however, not yet studied the impact of resource reservation or the possibility that signaling packets are lost due to transmission errors or collisions, i.e., communication could not be initiated.

Both factors influence the performance of cooperative relaying. In the context of resource reservation, it is intuitive that cooperative relaying requires adjustments in the MAC protocol compared to non-cooperative schemes. Let us consider a MAC protocol with collision avoidance as used in IEEE 802.11. CSMA/CA [KRD06] reserves the channel in the vicinity of source and destination by using `request-to-send` (`RTS`) and `clear-to-send` (`CTS`) packets. In a cooperative scenario, such a MAC needs to regard relay selection and cooperative transmission. Hence, source and destination have to reserve the channel in their vicinity for relay selection phase, direct and cooperative transmissions. Besides source and destination, also the relay may require a channel reservation in its vicinity. Intuitively, resource reservation for cooperative relaying imposes an additional overhead to the communication scheme and needs to be handled carefully. As we saw in Chapter 3, whether or not cooperation is required depends on the channel condition but remains in general a probabilistic event. If cooperation is enabled but not needed, a channel reservation of source, destination, and relay hinders other nodes from using the channel and negatively affects the overall network throughput.

Another important question is how imperfect signaling packets affect the performance of cooperative relaying. For instance, all considered selection schemes so far assume that the destination is aware of the data transmission from the source and that it supports the cooperation process: it transmits signaling packets during the selection process. However, in a deep fade the destination would not know about a transmission attempt from the source. Clearly, this affects the performance of cooperative relaying.

Finally, we need to discuss which layer of the protocol stack controls the cooperation process, i.e., decides when to enable cooperation, selects the relay, and requests the cooperative transmission if necessary. This layer has to interact closely with the physical and MAC layers. Figure 5.1 depicts the interaction between nodes in a cooperative protocol stack where the necessary functionality of cooperative relaying is integrated within the physical and the MAC layer. Cooperative relaying enhances the reliability of the physical link between source and destination by introducing a cooperative link. This cooperative link consists of the physical links source-relay and

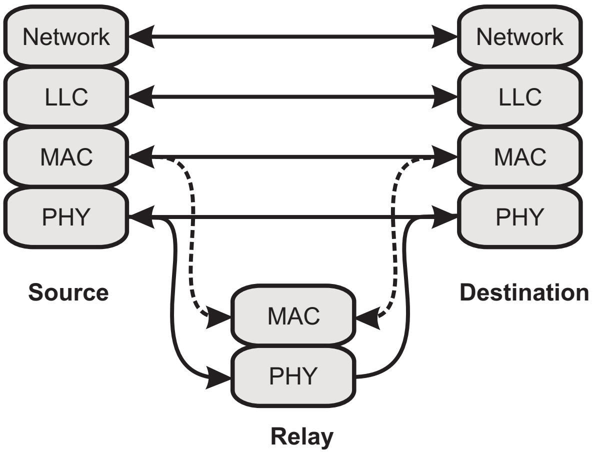


Figure 5.1: Layering aspects of cooperative relaying

relay-destination. The physical layer of the destination may combine the received signals from source and relay, e.g., using MRC. The MAC protocol decides — based on channel measurements between source and destination — on enabling cooperation, selects relays and reserves the channel for the duration of the cooperative transmission for source, destination, and relay. Therefore, only the lowest two layers of the protocol stack are influenced by cooperative relaying. Moreover, including the necessary functionality in those layers enables fast reaction of cooperative relaying to channel fluctuations.
Hereafter, the term cooperative MAC protocol refers to MAC protocols which facilitate the necessary functionality for performing cooperative relaying.

Existing attempts of integrating cooperative diversity in MAC protocols have certain drawbacks. Some proposals select relays based on likely outdated information from the past and cannot react on either fast changing channels or node movements (see [LTN$^+$07, MYPK07]). Others assume special transceiver architectures which support D-STC or CDMA for simultaneous packet transmissions (see [MYPK07, AAA05]), and/or offer adaptive data rates (see [LTN$^+$07, CYW07]). In certain application domains, however, such transceiver architectures are infeasible due to their costs, energy consumption and/or size constraints. This motivates us to introduce a new cooperative MAC protocol called CoRe-MAC (Cooperative Relaying Medium Access Control).

The contribution of this chapter can be summarized as follows:

- Introduction of a novel cooperative MAC protocol which does not impose any restrictions on used hardware.
- Ensuring that the protocol is backward compatible to CSMA/CA.
- Providing a throughput oriented design built on re-active relay selection, which
  - does not introduce additional overhead if the direct channel condition is good, or the network is sparse such that no relays are available, and
  - performs significantly better if the direct channel quality is bad.
- Providing methods to form and use a prioritized candidate set to increase the energy and time-efficiency of cooperative relaying.
- Showing how to efficiently integrate neighbor cardinality estimation in the relay selection process.
- Evaluation of the protocol under realistic assumptions.

The remainder of this chapter is structured as follows. In Section 5.2, we describe CoRe-MAC in detail. To this end, we first give a brief introduction to CSMA/CA. Then, we explain the different phases of the cooperative communication process and discuss the behavior of the nodes in these phases. In Section 5.3, we rigorously evaluate and discuss the performance of CoRe-MAC with respect to CSMA/CA in terms of channel coherence time, network topology, data packet size, and spatial re-usability.

Results have been achieved in cooperation with coauthors of [AEBS09]. Some of the presented ideas have been filed as patents [AEB09a, AEB09b].

5.2 Protocol Description

MAC changes considerably in the presence of cooperative relaying. The channel reservation needs to be extended in space and time for relaying. The relay selection scheme has also a great impact on the achievable performance of cooperative MAC protocols. In schemes using pro-active relay selection, relays are selected before the direct transmission. To ensure the reception of the `DATA`, relays need to reserve the channel in their surroundings. Thus, whenever the direct transmission succeeds, those reservations unnecessarily block other communications and degrade the overall throughput. Use of a re-active relay selection can avoid such over reservation situations at the expense of more complex signaling and increased energy costs.

Cooperative relaying is a means to overcome fading effects in wireless communications. It should not, however, negatively influence the throughput during good channel conditions which we expect majority of the time. Moreover, we ensure that CoRe-MAC operates in heterogeneous networks with some nodes supporting only standard CSMA/CA (compatibility to CSMA/CA).

CoRe-MAC follows a re-active relay selection approach. Therefore, it has no additional signaling overhead compared to CSMA/CA during good channel conditions. Another advantage is that it prioritizes direct transmissions to cooperative ones. Relay candidates do not reserve the channel during direct transmission. Only if the candidates have received the `DATA`-packet and D requires support, they become active and might block other communications.

The major drawback of a re-active relay selection scheme is that it requires all relay candidates to overhear the `DATA` transmission from S. Depending on the used energy saving options, this can tremendously increase the energy consumption compared to cooperative relaying using a pro-active selection scheme.

We address this issue in the design of CoRe-MAC by using *cooperation on demand* and *relay selection with early retreat*. Using cooperation on demand, D decides to enable cooperation depending on the channel state between S and D (cf. RSod). In case D enables cooperation, relay selection with early retreat (cf. RSer) ensures that only those nodes which are likely to support the communication between S and D remain as candidates. Furthermore, CoRe-MAC supports prioritized candidates, i.e., nodes that have participated in a relay selection process for $\{S, D\}$ before and are known by D. CoRe-MAC limits the nodes which need to overhear the `DATA` transmission to this set of candidates.

Table 5.1 summarizes all signaling packets in CoRe-MAC. Those marked with * are newly introduced packets compared to CSMA/CA. We have chosen the length

Table 5.1: List of used signaling packets

Abr.	Name	bytes
`RTS`	`request-to-send`	20
`CTS`	`clear-to-send`	14
`ACK`	`acknowledge`	14
`CCTS`*	`cooperative-clear-to-send`	16
`CACK`*	`cooperative-acknowledge`	14
`ECR`*	`extend-channel-reservation`	14
`AFR`*	`apply-for-relay`	14
`SFR`*	`select-for-relay`	20
`BUSY`*	`busy-tone`	-

of the packets in compliance with IEEE 802.11.

Figure 5.2 illustrates the different phases of CoRe-MAC. In direct transmission phase, D decides on enabling cooperation and S transmits the `DATA`-packet. If cooperation was enabled and the direct `DATA` transmission has failed, node D selects a relay in the relay selection phase. The relay selection phase consists of 3 steps. The feedback step gathers information about available candidates, the estimation step aims to determine the number of available candidates, and the candidate contention step determines the current relay and a set of prioritized candidates for future cooperations. Finally, the selected relay R forwards the `DATA`-packet to D during the cooperative transmission phase.

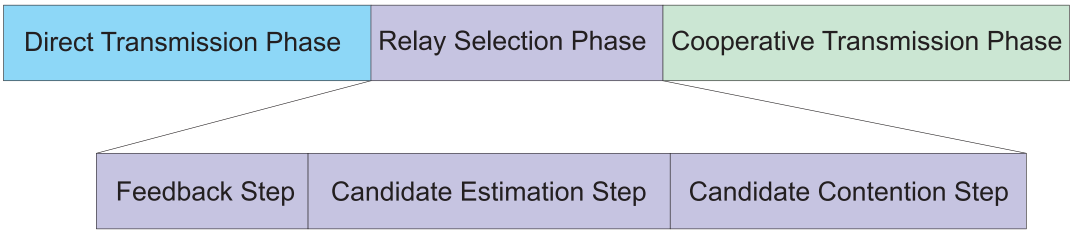


Figure 5.2: Phases of CoRe-MAC

In the following, we briefly summarize CSMA/CA as we use it as a basis in our protocol design. Then, we elaborate on the different phases of CoRe-MAC.

5.2.1 Overview of Standard CSMA/CA

Figure 5.3 illustrates the packet exchange of CSMA/CA. Light gray boxes represent physical channel assessment periods, and dark gray bars illustrate active channel reservations of nodes.

When S has a `DATA`-packet to transmit it has first to wait until the communication channel is free. CSMA/CA uses two mechanisms to determine the occupation state of the channel. While the physical channel assessment exploits the received

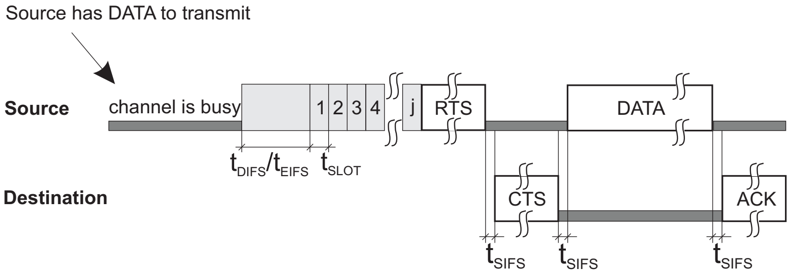


Figure 5.3: Packet exchange and timings in CSMA/CA

signal strength, the virtual channel assessment uses channel reservation information of nodes. Each packet in CSMA/CA can piggyback those channel reservation information. When a node receives a packet which is not addressed to it, it updates its virtual channel reservation, i.e., the time it assumes that the channel is busy, based on the content of the packet.

If S detects a clear channel, it depends on the previous reception success of S how it proceeds. After a corrupt packet reception, nodes have to defer from accessing the channel for at least t_{EIFS}. This duration is equal to the sum of t_{SIFS} and the transmission time of an `acknowledge` (`ACK`) packet. The t_{SIFS} duration defines the time between a transmission and its response which belong to the same communication attempt. A new communication attempt needs to be at least t_{DIFS} apart from a previous one.

If the channel is unused during this initial observation period (see big light gray box in Figure 5.3), S chooses randomly a value j out of the interval $\left[0, 2^{CW} - 1\right]$, with $CW = \min\left(CW_{\text{base}} + CW_{\text{counter}}, CW_{\text{max}}\right)$. Node S increases its CW_{counter} each time it fails to receive a response of D, i.e., it assumes a collision of packets. Node S resets its CW_{counter} to zero in case it receives a response or drops a `DATA` packet. The variables CW_{base} and CW_{max} represent parameters of the backoff algorithm (see [IEEE07, IEEE03]).

Node S keeps observing the channel for the duration of $j \cdot t_{\text{slot}}$ (see small light gray boxes in Figure 5.3). If some other node starts a transmission within communication range of S during this time, S suspends the observation period until the channel is free for at least t_{DIFS} again. If the observation time expires, S transmits its `RTS`-packet.

The `RTS` reserves the channel for the time the destination needs to reply with a `CTS`-packet. Besides reserving the channel, the `RTS` informs the intended destination D about the pending `DATA`-packet and its transmission duration.

Node D responses with a `CTS` if it is not blocked by other reservations or transmissions in its vicinity. The `CTS` response has to start within t_{SIFS} after the `RTS` transmission. This holds for all spacings of packets belonging to the same transmission attempt. The `CTS` reserves the channel in the neighborhood of the destination for the duration of the `DATA`-packet transmission from S. If S does not receive this `CTS` it assumes a collision and increases its CW_{counter} and its small retry counter *src*.

If the small retry counter reaches a maximum value $src_{\max}$, S drops the `DATA`-packet. Else, S tries to start the transmission again.

If S receives the `CTS` it starts the `DATA` transmission. Besides delivering the data to D, the `DATA`-packet also reserves the channel to allow S to receive an `ACK` from D in response.

After reception of the `DATA`-packet, D informs S about its decoding success using an `ACK`-packet. If the data transmission is not successful, i.e., S does not receive a positive `ACK`, it increases its CW_{counter} and its large retry counter lrc. The source retransmits the `DATA`-packet until the large retry counter reaches a maximum value $lrc_{\max}$. If this happens, the source drops the data packet and informs the next higher layer about the delivery failure.

5.2.2 Direct Transmission Phase

Figure 5.4 and Figure 5.5 illustrate the packet exchanges and node behaviors in CoRe-MAC during the direct transmission phase.

The direct transmission phase consists of the channel reservation of $\{S, D\}$, the direct packet transmission and, if successful, of the `ACK` transmission from D. Moreover, D decides on enabling cooperation and a set of potential relaying candidates is formed.

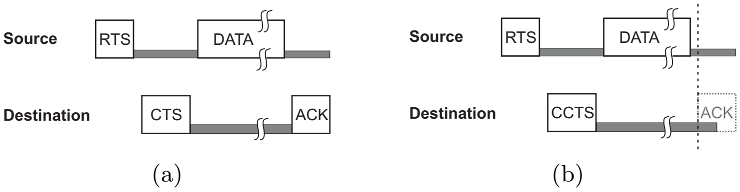


Figure 5.4: Packet exchange/channel reservation during direct transmission phase: (a) cooperation disabled and (b) cooperation enabled.

CoRe-MAC behaves similar to standard CSMA/CA during the direct transmission phase. The difference is that D exploits the received SNR of the `RTS`-packet to estimate the expected PER of the direct `DATA` transmission (see 5.5b). CoRe-MAC uses a threshold Θ to decide whether the direct channel is in a bad or good state, i.e., whether cooperation should be enabled or not. (cf. relay selection on demand).

If the channel is in a good state, D replies with a `CTS`-packet and hence disables cooperation for the following `DATA` transmission. In this case, the whole communication process is equivalent to CSMA/CA. Depending on energy saving options, neighboring nodes of S and D may switch off their radio during the `DATA` transmission to save energy.

If the estimated PER reveals a bad channel condition, however, D replies with a `cooperative-clear-to-send` (`CCTS`) packet. This packet informs S and potential relay candidates that D requests to enable cooperation. Furthermore, the `CCTS`-packet

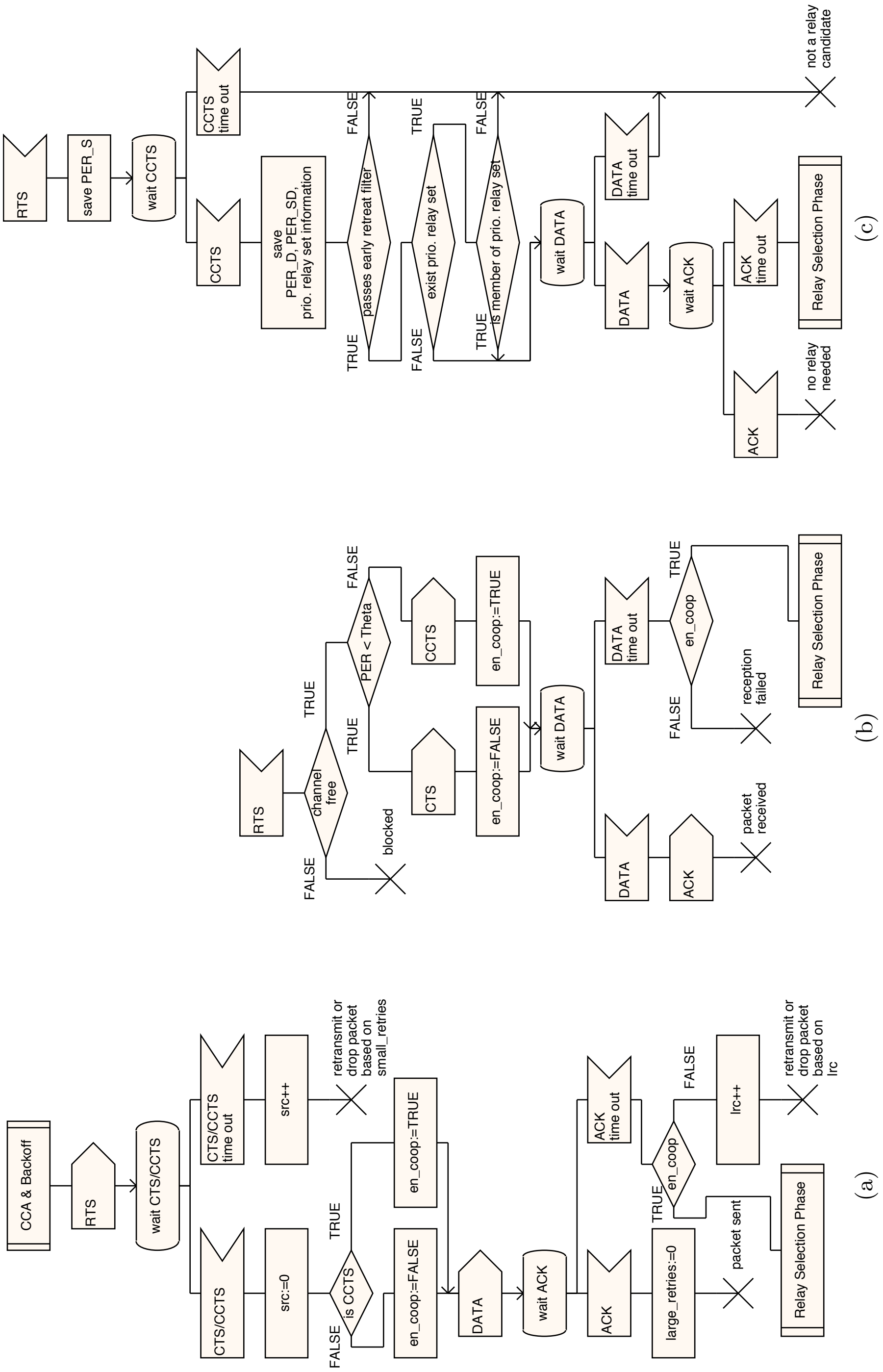


Figure 5.5: Behavior of nodes during direct transmission phase: (a) source S, (b) destination D, and (c) neighbors of S and D.

contains additional information for the cooperation process: 1 byte information about expected PER for the direct channel and 1 byte to identify a prioritized relay set. Clearly, 1 byte is too less to name each member of this set. However, it is enough to inform neighbors about the number of nodes in this set and a short sequence number identifying the set. Candidates verify based on locally stored information whether they are members of this prioritized relay set based on the combination of the sequence number and the addresses of S and D. If D enables cooperation and the direct transmission is successful these 2 bytes represent the total overhead of CoRe-MAC compared to CSMA/CA. Intuitively, this overhead is in general not significant compared to the overall `DATA`-packet transmission time.

Let us briefly elaborate on the threshold Θ. CoRe-MAC aims to keep the PER between any source and destination pair below Θ but does not try to make transmissions as reliable as possible at the expense of additional overhead. Generally, a smaller value of Θ enables cooperation more often than a larger one. While in proactive relay selection schemes a small value of Θ can negatively affect the throughput between S and D, in a re-active one it affects exclusively the energy consumption in the network — neighbors are more often requested to overhear the transmission of S.

CoRe-MAC addresses the energy-efficiency issues of re-active relay selection schemes with following methods. First, cooperation on demand reduces the time neighbors have to overhear the direct `DATA` transmissions. Second, CoRe-MAC applies relay selection with early retreat (cf. RSer). The initial candidate set comprises all nodes which have received the `RTS` and `CCTS`-packets. Those nodes exploit the PER information provided in the `CCTS`-packet and determine expected PERs to S and D based on the received SNR-values of `RTS` and `CCTS` (see Figure 5.5c) . Let PER_{SD}, PER_{SC_i} and PER_{DC_i} be the expected PERs for the `DATA` transmission for the links S-D, S-C_i and D-C_i, respectively, with C_i denoting the i^{th} candidate. Candidate C_i retreats from the cooperation process, if

1. $\mathrm{PER}_{SC_i} \geq 0.6$,
2. $\mathrm{PER}_{DC_i} \geq 0.6$,
3. $\mathrm{PER}_{SD} \leq 1 - ((1 - \mathrm{PER}_{SC_i}) \cdot (1 - \mathrm{PER}_{DC_i}))$.

Rules 1 and 2 ensure that candidate C_i has at least a forty percent chance of receiving the `DATA`-packet from S and can deliver it to D (cf. RSod). The third rule ensures that the cooperative link via C_i is better than the direct one. These rules aim to prevent nodes to participate in the cooperation process which are hardly able to support the communication between S and D and would only unnecessarily increase the overall energy consumption in the network. Finally, CoRe-MAC provides the option to limit the number of overhearing nodes to the cardinality of a prioritized candidate set (see relay selection phase). The members of this set identify themselves by the information provided in the `CCTS`-packet. Members of that set, however, also retreat if their channel conditions to S and D are not sufficient based on the retreating rules.

An `ACK` transmission from D ends the direct transmission phase and the complete transmission attempt if the packet transfer from S to D was successful. The transmission attempt ends also if D has not enabled cooperation but did not receive the `DATA` from S. If D has enabled cooperation and has not received the `DATA`-packet from S, D defers its `ACK` transmission, which triggers a time-out event at S and the relaying candidates. Candidates which have failed in receiving the `DATA`-packet from S quit the cooperation process.

Summing up, CoRe-MAC requires following adaptations compared to CSMA/CA during the direct transmission phase:

- The `RTS`-packet needs to reserve the channel for a longer period to account for a `CCTS` response of D.
- The `CCTS`-packet needs to be introduced. This packet is two bytes larger than the standard `CTS`-packet and it reserves the channel for a longer period. This extended reservation is shorter than an `ACK` transmission and has no effect on the throughput if direct transmission succeeds.

5.2.3 Relay Selection Phase

CoRe-MAC conducts the relay selection phase only if the direct transmission has failed and D has enabled cooperation. The relay selection phase starts if D does not transmit an `ACK` after the direct transmission. In such a case, S and potential relaying candidates do not detect any channel activity within t_{SIFS} after the `DATA` transmission. The relay selection phase itself consists of 3 steps.

Feedback Step

Relay selection is a time intensive task and should only be performed if necessary. For instance, if there are no candidates it does not make sense to start a selection process. On the other hand, a previously selected relay could, depending on the coherence time of the channel and the node mobility, be *re-used*. To this end, CoRe-MAC uses the feedback step to gather information about the availability of prioritized candidates or new candidates at D. In this context, availability means that the corresponding candidate has received the `DATA`-packet from S without error.

(a) (b)

Figure 5.6: Packet sequence during feedback step: (a) with and (b) without prioritized candidate set.

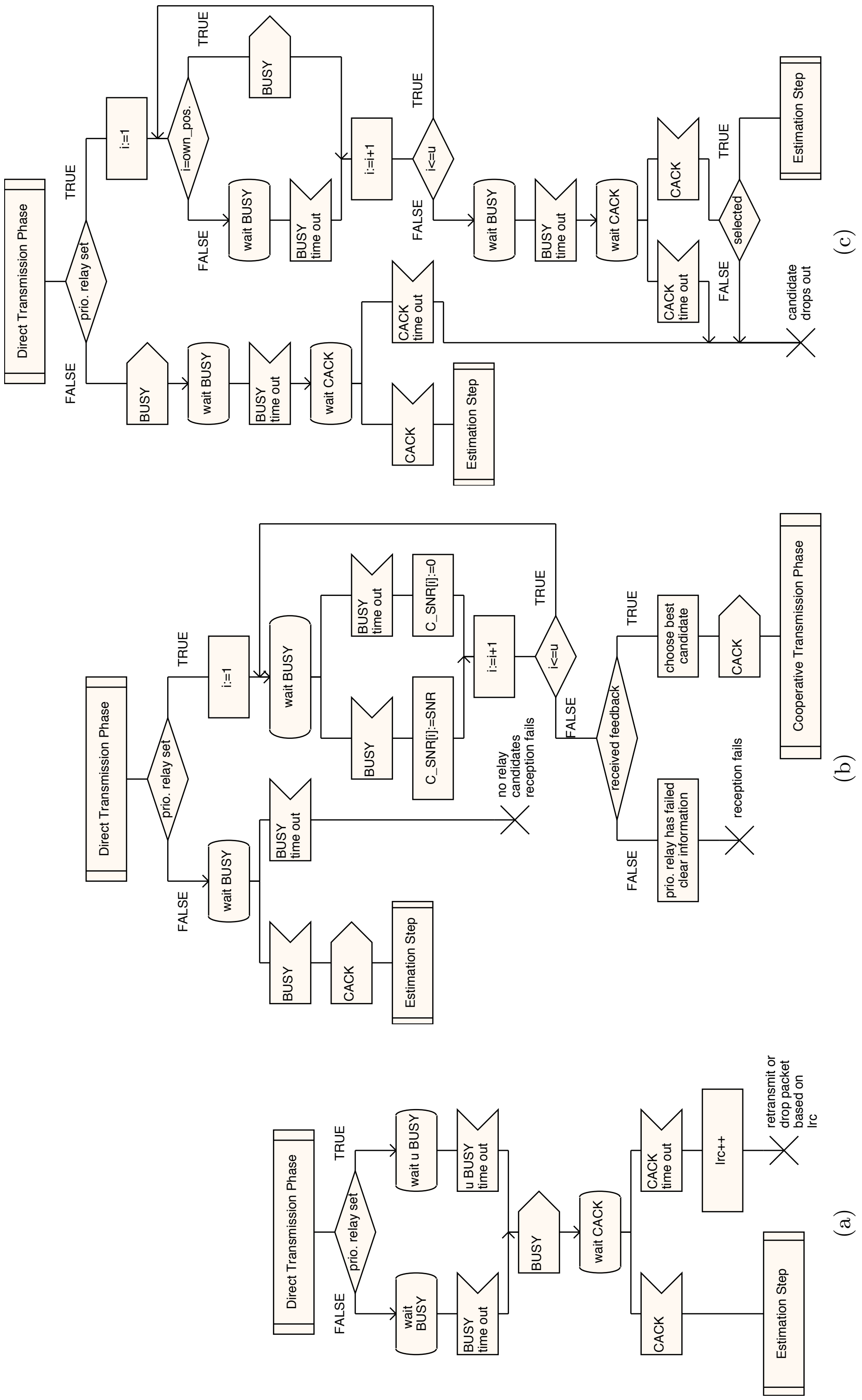


Figure 5.7: Behavior of nodes during feedback step: (a) source S, (b) destination D, and (c) relay candidates.

Figure 5.6 and Figure 5.7 illustrates the packet sequence and the node behavior during the feedback step.

The feedback step starts right after the direct transmission phase. Relay candidates use `busy-tone` (`BUSY`) transmissions (illustrated by gray-frames in Figure 5.6) to indicate their `DATA` reception success. The duration of a `BUSY` is t_{SLOT}. It is enough time only to detect activity on the channel. Nodes which receive a `BUSY` and do not participate in the cooperative communication attempt, assume an erroneous packet transmission and refrain for t_{EIFS} from accessing the channel.

In the feedback step, we distinguish two cases based on the content of the `CCTS`-packet (see Figure 5.6 and Figure 5.7):

- The `CCTS`-packet contains information about a prioritized relay set with cardinality u: The first u `BUSY`s of the feedback step are reserved for nodes in the set to report their availability. The feedback sequence is equal to the ordering of the candidates at selection time (see Figure 5.6a).
- The `CCTS`-packet contains no information regarding a prioritized relay set: all candidates transmit in the first slot of the feedback step a `BUSY` to indicate their availability (see Figure 5.6b).

Finally, all former candidates and S transmit a `BUSY` to block any communication in their surrounding for another t_{EIFS} period.

If there are no relaying candidates available, i.e., if D has not observed any `BUSY` transmissions during the candidate feedback slots, D stays silent which informs S about the failed transmission attempt. This implies that, if D has utilized a prioritized candidate set, no member of this set was able to help D— they were not allowed by their neighbors, had bad channel conditions, or had moved out of transmission range of S and/or D. Independent of the reason, D does not rely again on this prioritized candidate set and will select a new relay and a new prioritized candidate set in the next cooperation attempt with S.

If D has learned about the availability of relay candidates, it ends the feedback step by sending a `cooperative-acknowledge` (`CACK`) (see Figure 5.7b).

If no prioritized candidate set exists, D uses the `CACK` to inform S and the available candidates to proceed with the relay selection step. The `CACK`-packet reserves the channel until the end of the contention step.

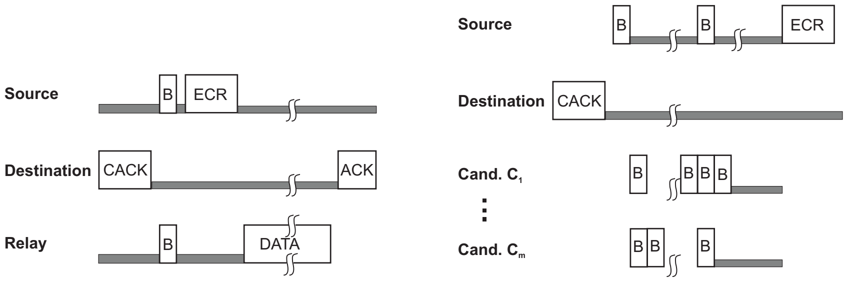
If a prioritized candidate set exists, D chooses the best member as current relay and includes its decision in the `CACK` transmission. Node D determines the best member based on the received signal strength of the observed `BUSY`s during the feedback step. We call this kind of relay selection *fast relay selection* since its overhead in time is much smaller than a selection out of all available candidates. The `CACK`-packet reserves the channel for the overall remaining cooperation process.

Estimation Step

The success of a contention-based relay selection depends on the contention window size, the number of candidates, and their access probability. For a fixed contention window size, the access probability which maximizes the success probability of the relay selection depends on the number of competing candidates. Clearly this number varies over time due to small scale fading effects and node mobility.

The purpose of the estimation step is to quickly estimate the number of available relaying candidates for $\{S, D\}$ such that the relay selection succeeds with high probability. The estimation step is important for dense networks where the number of candidates is considerably higher than the contention window size. If the number of candidates is small, however, the estimation step might not bear any benefits but increases the cooperation delay. To this end, CoRe-MAC can optionally skip the estimation. Finally, CoRe-MAC skips the estimation if a prioritized candidate set is available. Commonly, the estimation step ends by S transmitting an `extend-channel-reservation` (`ECR`) packet.

Figure 5.8 and Figure 5.9 illustrate the packet exchange and node behaviors during the estimation step of CoRe-MAC.



(a) (b)

Figure 5.8: Packet exchange/channel reservation during estimation step: (a) a prioritized candidate is selected as relay and (b) $\{S, D\}$ perform a candidate estimation.

We differentiate three realizations of the estimation step based on the outcome of the feedback step.

1. Node D has utilized a prioritized candidate set and has chosen a relay R out of this set: S and R transmit simultaneously a `BUSY` after the `CACK` reception (see Figure 5.8a). These transmissions prevent other nodes to access the channel for t_{EIFS}. A candidate estimation is not needed and skipped.

2. Node D needs to choose a new relay, but is unaware of the number of candidates. From Section 3.4, we know that the accuracy demands for a successful relay selection are rather relaxed. For instance, for a contention window of size $s = 6$ and a selection success probability of 0.9 we need an estimation accuracy not better than 50 %.

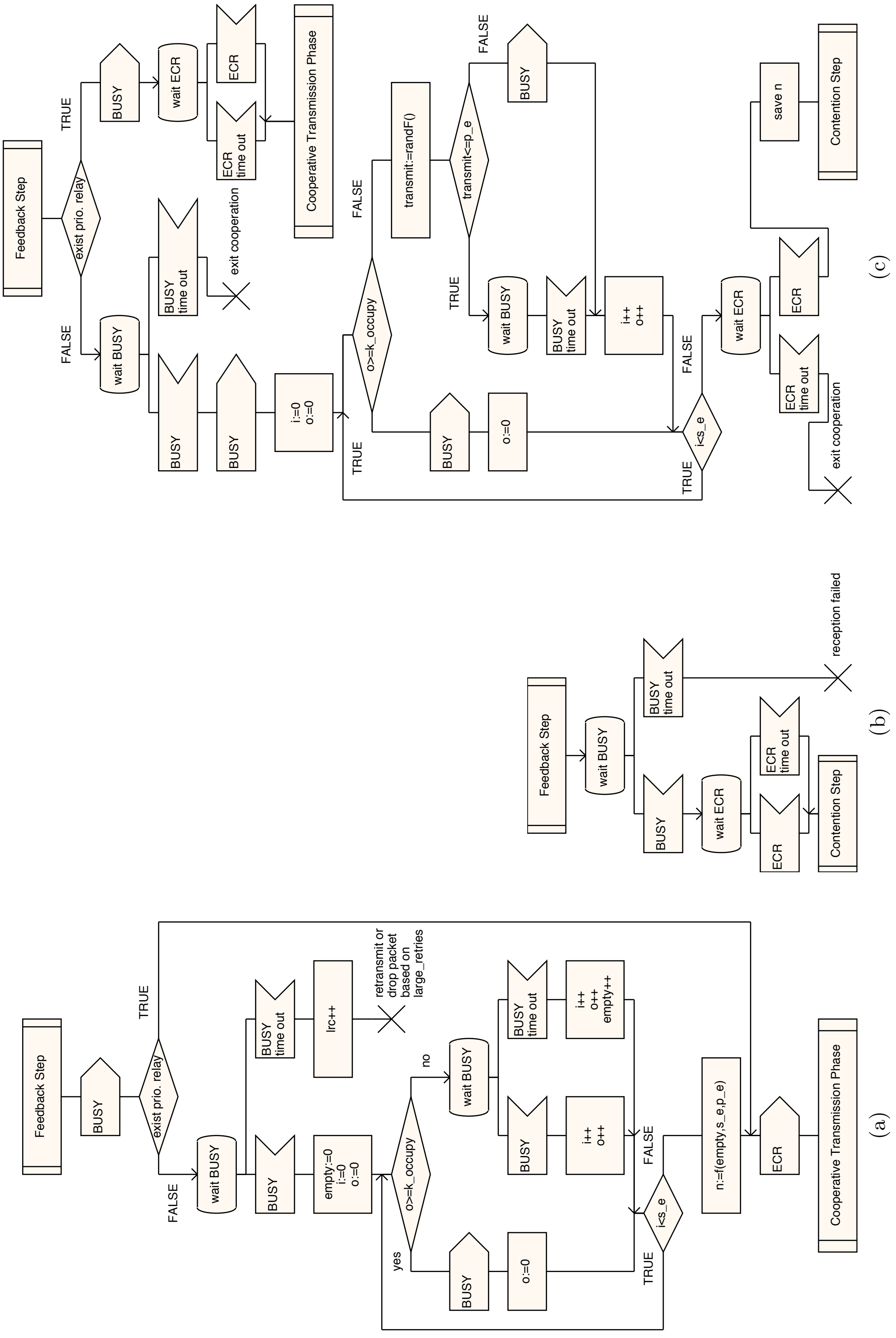


Figure 5.9: Behavior of nodes during estimation step: (a) source S, (b) destination D, and (c) relay candidates.

We choose the NAE (see Chapter 4) to estimate the relay candidate cardinality. This estimator does not require any data packet exchange during the estimation process, is simple, and is fast for relaxed accuracy demands. The NAE requires a certain operation range for the number of relaying candidates. After the feedback step we know that at least one candidate is available. Moreover, we know from Section 3.4 that the access probability for the relay contention is 1 as long as the number of candidates is less than s. That is why we fix the lower bound of the operation range to $s+1$. For a fixed lower bound, the upper bound of the operation range defines the number of required contention slots s_e. This number scales well with the upper bound. For instance, for $\alpha = 0.9$ and $\theta = 0.5$ the NAE requires for an operation range of $[9, 100]$ and $[9, 1\,000]$, 56 and 108 contention slots, respectively.

We point out that the actual upper bound of the estimation is a design parameter of CoRe-MAC. It can be chosen to be a fixed value at deployment time, or it can be adjusted dynamically based on observations like outcome of previous rounds of estimations or data traffic monitoring.

The actual estimation process looks as follows (see Figure 5.8b, Figure 5.9a, and Figure 5.9c). Node S transmits a `BUSY` right after the `CACK` transmission. This transmission serves two purposes. First, it reserves the channel in vicinity of S for $t_{\texttt{EIFS}}$. Second, it informs potential candidates that S is aware of the ongoing cooperation process. All candidates which do not receive the `BUSY` transmission of S exit the cooperation. Afterwards, all remaining candidates transmit one `BUSY` simultaneously to indicate their presence. If S and D do not observe any channel activity during this period they quit the communication attempt. Otherwise, the estimation process starts (see Chapter 4). Depending on the operation range, CoRe-MAC uses multiple contention frames of size s_{e_i} with $\sum_i s_{e_i} = s_e$. During each contention frame, each candidate transmits a `BUSY` in each slot with a certain probability p_{e_i}. Node S counts the slots without channel activity e_i and estimates based on s_{e_i}, p_{e_i} and e_i the number of candidates. During the estimation process, S has to transmit every $k_{\text{occupy}} = \lfloor t_{\text{EIFS}}/t_{\text{slot}} \rfloor$ slots a `BUSY` to keep other nodes in its vicinity from accessing the channel.

3. Optionally, it is possible to skip the estimation process and use a fixed access probability during the contention window of the relay selection. The intention to skip the estimation step needs to be signaled by the `CACK` transmission of D. Right after the `CACK` reception, S transmits an `ECR`-packet to inform all candidates to transmit in the contention step with a given probability.

Besides signaling the end of the estimation step and broadcasting the number of candidates, the `ECR`-packet reserves the channel in the vicinity of S for the remaining duration of the cooperation process. This duration depends on the feedback step. If a prioritized candidate is selected as relay, the contention period is skipped, and the remaining cooperation duration consists of the `DATA` transmission from R and following `ACK` transmission from D. If a relay has to be selected, S reserves the channel additionally for the duration of the contention step.

Contention Step

CoRe-MAC processes the contention step only if *D* has to select a new relay. Figure 5.10 and Figure 5.11 illustrate the packet exchange and the node behavior during the contention step.

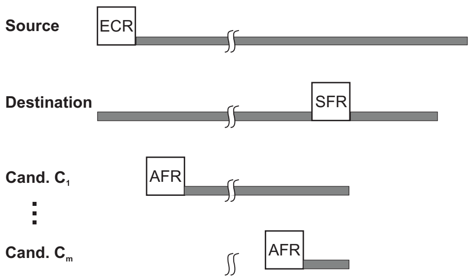
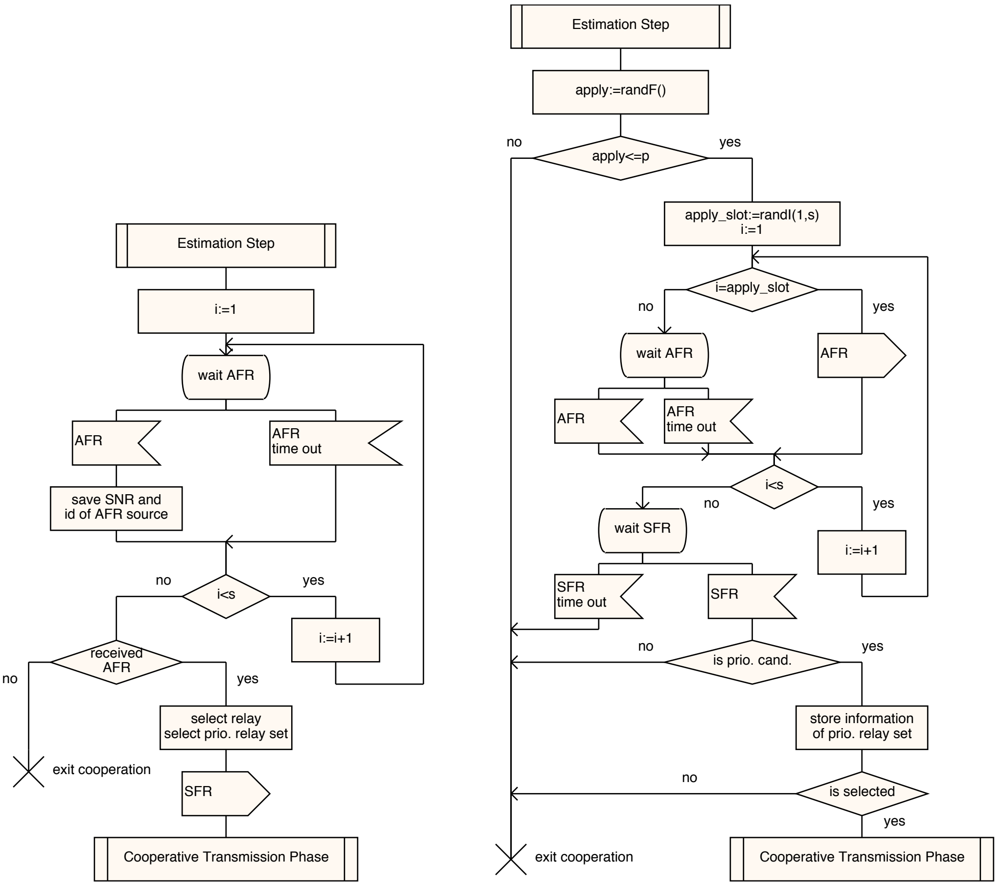


Figure 5.10: Packet exchange/channel reservation during contention step



(a) (b)

Figure 5.11: Behavior of nodes during contention step: (a) destination *D* and (b) relay candidates.

This step consists of s slots, where each slot can hold a complete `apply-for-relay` (`AFR`) transmission. Each candidate chooses randomly a slot and transmits during this slot with probability p (see Section 3.4)

$$p = \min\left(\frac{s}{\hat{n}}, 1\right) , \tag{5.1}$$

where $\hat{n}$ is the estimated candidate cardinality provided in the `ECR`-packet. Node D observes the channel during the contention window, and logs its error free `AFR` receptions together with the corresponding received SNR values (see Figure 5.11a).

The selection phase fails if D does not receive any `AFR`-packet during the contention step. Node D quits cooperation and S has to retransmit the `DATA`-packet.

The selection phase is a success if D receives one or more `AFR`-packets. In that case, D sorts the received `AFR`-packets according to their received SNR values at the end of the contention window. Node D chooses the node from which it has received the `AFR` with the highest SNR as relay for the current cooperation attempt. Node D selects all nodes from which it has received `AFR`-packets as prioritized candidates for future communication attempts with S. The contention step ends with an `select-for-relay` (`SFR`) transmission from D. This packet names the current relay and the prioritized candidate set for future attempts. Furthermore, it reserves the channel for the cooperative transmission step.

5.2.4 Cooperative Transmission Phase

The cooperative transmission contains the `DATA` transmission from the selected relay and if successful, the `ACK` transmission from D (see Figure 5.12 and Figure 5.13).

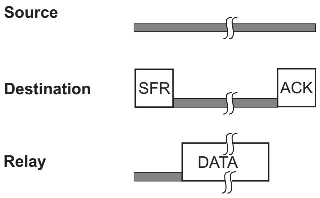
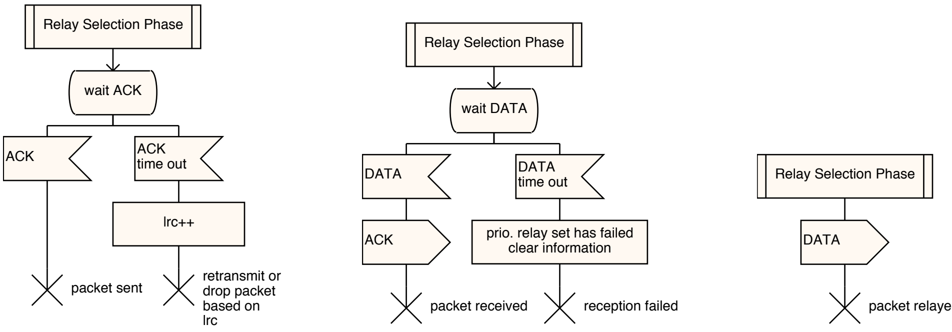


Figure 5.12: Packet exchange/channel reservation in cooperative transmission phase

The cooperation is successful, if D receives the `DATA`-packet correctly from R. Only then, D uses the relay set for future transmission attempts. As a last step of a successful communication attempt, D informs S about the transmission success via an `ACK` transmission. If the transmission from R is not successful or if R does not transmit at all, the cooperation fails and the communication attempt has to be repeated.

5.2.5 Protocol Summary

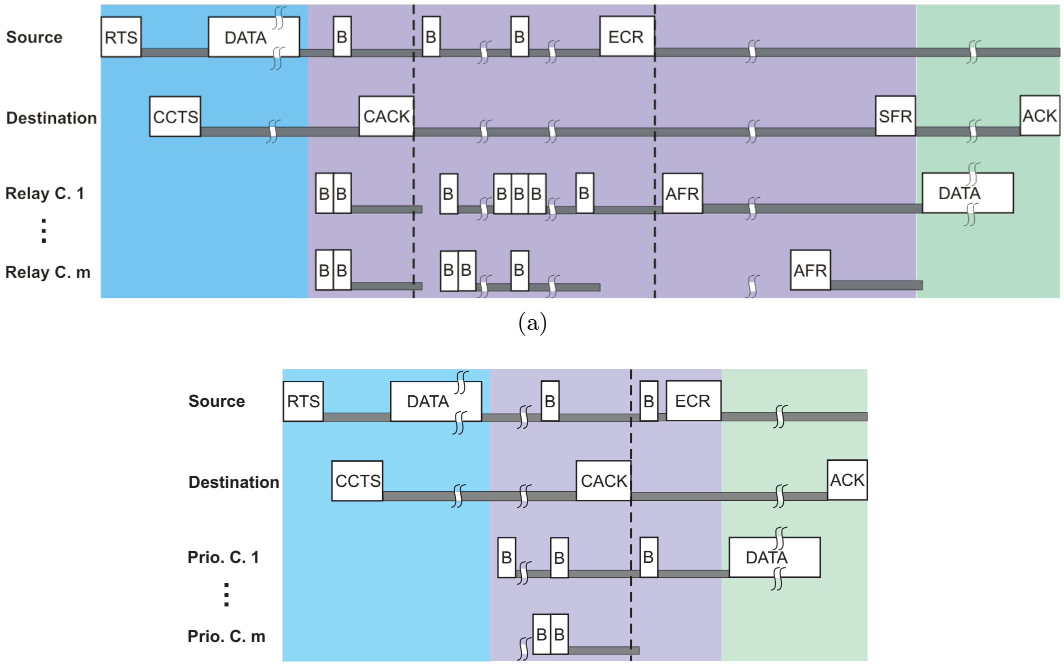
In Figure 5.14, we summarize the overall packet exchange of nodes using CoRe-MAC in case cooperation is enabled and required. The phases are illustrated by individual



(a) S (b) D (c) R

Figure 5.13: Behavior of nodes during cooperative transmission phase: (a) source S, (b) destination D, and (c) relay R.

background colors. Figure 5.14a illustrates the complete packet exchange of nodes in CoRe-MAC if no prioritized candidate set is yet available or is not used. The dashed lines indicate feedback, estimation, and contention step in the relay selection phase. If D reverts to a prioritized candidate set, the duration of the relay selection phase decreases significantly (see Figure 5.14b). In this case, the feedback step duration increases slightly to allow prioritized candidates to report their availability to D, the estimation phase duration shrinks significantly, whereas the contention phase is skipped completely.



(a)

(b)

Figure 5.14: Packet exchange/channel reservation of CoRe-MAC: (a) D selects a relay out of all potential candidates and (b) D uses a prioritized candidate set.

5.3 Evaluation

In the following, we evaluate CoRe-MAC by comparing its performance with standard CSMA/CA using the wireless sensor network simulator *JProwler* [SVML03]. We have chosen JProwler for its open source and its fast simulation performance. We have extended JProwler by the Rayleigh-Model-2 (see Section 1.3), and our implementations of CSMA/CA and CoRe-MAC.

In our simulations, we account for all control packets such as `RTS` and `CTS` as well as `DATA`-packets. For simplicity, we do not assume any channel coding. The simulation assumes low end radios with fixed symbol rate and a fixed energy per symbol value, i.e., it does not support power adjustment. The radio supports BPSK and QPSK modulation. BPSK-modulated-data experience a lower BER than QPSK-modulated-data due to the fixed energy per symbol assumption. Our protocol implementations use BPSK for signaling packets and QPSK for `DATA` transmissions. Hence, control packets to prepare communication and cooperation are less prone to transmission errors than `DATA`-packets.

Table 5.2 summarizes the main simulation parameters for our evaluations unless mentioned otherwise.

Figure 5.15 illustrates our basic simulation scenario. It consists of a dedicated pair of source and destination nodes, with potential relays distributed around them

Table 5.2: Simulation parameters

SNR at transmitter side	36 dB
average received SNR at D	15 dB
path loss exponent v	2.2
SNR detection threshold	1.5
coherence time	200 ms [1]
symbol rate	128 000 symbols/s
modulation	BPSK/QPSK
`DATA` size	500 byte
CW_{base}	4
CW_{max}	10
t_{SIFS}	$16\,\mu$s
t_{SLOT}	$8\,\mu$s
t_{DIFS}	$t_{\text{SIFS}} + 2\,t_{\text{SLOT}}$
t_{EIFS}	$t_{\text{SIFS}} + t_{\text{DIFS}} + t_{\text{ACK}}$ [2]
src_{max}	7
lrc_{max}	4
node density ρ	$50\,\text{m}^{-2}$
Θ	0.001
s	6

[1] see [MLC05] for indoor coherence time measurements

[2] t_{ACK} represents the transmission duration of an `ACK`-packet

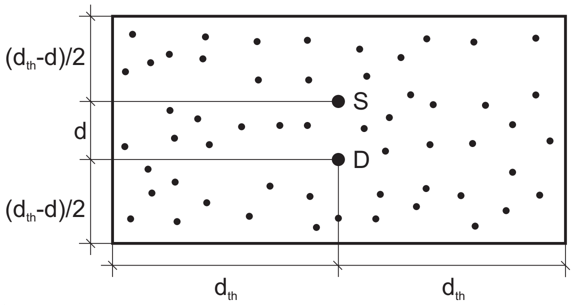


Figure 5.15: Simulation scenario: a single dedicated communication pair

Table 5.3: MAC protocols considered in the evaluation

CSMA/CA	standard non-cooperative CSMA/CA protocol
CoRe-MAC	CoRe-MAC as described in the previous section
CoRe-MAC-NE	CoRe-MAC without candidate estimation step: all candidates transmit during the contention window an `AFR`-packet.
CoRe-MAC-NPC	CoRe-MAC without candidate estimation step and prioritized candidate set: for each cooperative transmission, D selects a relay out of the complete candidate set.

uniformly randomly with node density ρ per transmission range. The distance d_{th} represents the maximum signal detection distance of a node in an AWGN channel model, i.e., the distance between S and D after which D experiences SNR $\leq \gamma_{\text{th}}$.

In our simulation scenario, S has constantly `DATA` to send. Each simulation run simulates 10 s of network communication. For each parameter set, we conduct 1 000 runs with different deployments of potential relay nodes and adopt the average values. We indicate the 90%-confidence interval of the obtained average values in the figures. For figures which present the gain of the cooperative protocols compared to CSMA/CA for certain criteria, we provide the corresponding true values including confidence intervals in the Appendix (see Figure C.1).

Besides the default CoRe-MAC scheme as described in the previous section, we present results of CoRe-MAC versions with different options/limitations. Our motivation is to show the gains offered by some of the features of CoRe-MAC and to elaborate on their benefits in certain settings. Table 5.3 summarizes the protocols we compare in our simulations and their basic behavior.

We use among others the following performance criteria in our analysis:

- The *retransmission rate of S* is the ratio of the number of sent `DATA`-packets by S minus the number of received `DATA`-packets at D to the number of sent `DATA`-packets by S.
- We define *throughput* as the number of received `DATA`-packets of D per second.

- We define the *costs of cooperation* as the average number of candidates that has to listen to each `DATA` transmission of S. In a non-cooperative scheme neighbors of S and D could save energy by avoiding listening to their `DATA`-packets, e.g., by switching their radio into sleep mode.
- `DATA` *dropping probability* is the ratio of the number of dropped to the total number of dropped and received `DATA`-packets. Node S drops a `DATA`-packet, if either its small retry counter rcs or its large retry counter rcl reaches its maximum value.
- The *relay selection periodicity* is the average number of `DATA` transmissions from S between two candidate contention steps. A larger number represents fewer selections and thus less overhead of CoRe-MAC.
- *Probability that cooperation succeeds* is the likelihood that D receives successfully a `DATA`-packet from its relay given that D has enabled cooperation and has not received the corresponding `DATA`-packet from S.

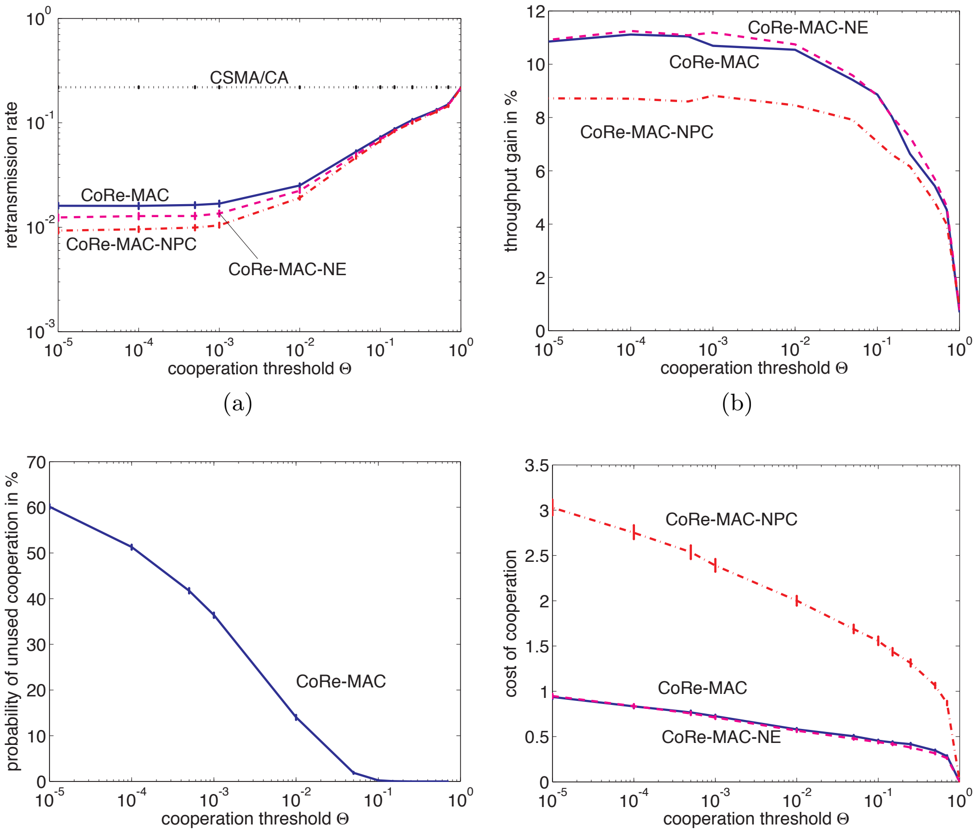
5.3.1 Impact of Parameters of CoRe-MAC

Let us first focus on the parameters of CoRe-MAC. To this end, we fix the distance d such that the average received SNR from S at D is 15 dB. We choose the remaining simulation parameters as listed in Table 5.2.

Cooperation Threshold Θ

Figure 5.16 illustrates various performance metrics of CoRe-MAC as a function of the cooperation threshold Θ. The value Θ represents the desired retransmission rate of S. If the expected PER of the direct link is higher than Θ, D enables cooperation with the intention to keep the retransmission rate below Θ. For $\Theta = 1$, CoRe-MAC never uses cooperation and hence becomes CSMA/CA. With decreasing Θ, D enables cooperation more often. For $\Theta \geq 0.001$, we observe a considerable impact of Θ on the retransmission rate (see Figure 5.16a) and the throughput performance (see Figure 5.16b). Smaller values of Θ improve neither the retransmission rate nor the throughput performance. For all CoRe-MAC versions, we observe a one-to-one relation between Θ and the retransmission rate for $\Theta \geq 0.1$. For $\Theta < 0.1$, relays cannot sustain the desired PER and the retransmission rate of S saturates for $\Theta \leq 10^{-3}$. The retransmission rate of CoRe-MAC and CoRe-MAC-NE is worse than the one of CoRe-MAC-NPC. The reason therefore is that CoRe-MAC-NPC chooses its relay always out of the entire set of candidates. A throughput comparison of the CoRe-MAC schemes reveals, however, that the schemes using the prioritized candidate set perform better. This performance difference is due to the faster selection process of prioritized candidates.

Figure 5.16c illustrates the probability that D has enabled cooperation but receives the `DATA`-packet already during the direct transmission phase as a function of



(a) (b)

(c) (d)

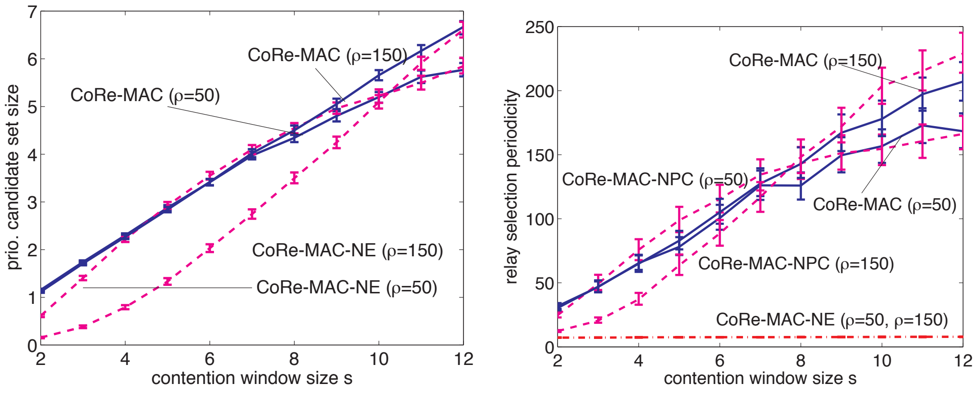
Figure 5.16: Performance metrics as a function of Θ: (a) retransmission rate of S, (b) throughput gain compared to CSMA/CA, (c) cooperation enabled but not needed, and (d) cost of cooperation.

Θ. For $\Theta \geq 0.1$, D uses cooperation most of the time if it has enabled it. For smaller Θ-values, the probability of enabling cooperation without needing it increases considerably. In this region, cooperative relaying using pro-active relay selection would lose some of its throughput gains, since the invested time of relay selection and channel reservation does not pay off and reduces the achievable throughput. The throughput gain of CoRe-MAC, however, does not worsen in this region.

Although a too small Θ value has hardly any negative impact on the throughput of CoRe-MAC we should nevertheless be careful in choosing it. The costs of enabling cooperation in a cooperative diversity scheme using re-active relay selection is mainly the additional number of candidates that have to listen to the `DATA` transmission of S. CoRe-MAC addresses this issue by using cooperation on demand, relay selection with early retreat, and a prioritized candidate set. Cooperation on demand is controlled by the Θ-value. For $\Theta = 1$, cooperation is never enabled and no candidate has to listen to the `DATA` transmission of S. For $\Theta = 0$, cooperation is always enabled. However, the number of candidates listening to the `DATA` transmission is kept low by using a prioritized relay set and relay selection with early retreat. Thus, while the cost of cooperation only gradually increases with decreasing Θ for CoRe-MAC using the prioritized candidate set, the number of candidates which has to listen to the `DATA` transmission of S increases much faster for CoRe-MAC-NPC (see Figure 5.16d). For instance, for $\Theta = 10^{-5}$ and CoRe-MAC one additional node besides D listens to each `DATA` transmission of S, while this number increases to 3 for CoRe-MAC-NPC. Note that all CoRe-MAC schemes here use cooperation on demand and relay selection with early retreat. Our observations regarding Θ motivate us to choose $\Theta = 0.001$ for the further analysis.

Contention Window Size s

Let us now focus on the contention window size s of the relay selection phase. Figure 5.17 indicates the influence of s on the expected number of `AFR` receptions per candidate contention and the relay selection periodicity of CoRe-MAC for $\rho = \{50, 150\}\,\mathrm{m}^{-2}$. A large value of s increases the likelihood that D receives more `AFR`-packets. Intuitively, this increases also the probability of selecting a better relay and having a large prioritized candidate set. On the other hand, a large s increases the delay of the relay selection phase. The candidate estimation step of CoRe-MAC allows candidates to adjust their `AFR` transmission probability during the contention period such that the number of received `AFR`-packets at D is maximized. In CoRe-MAC-NE, all candidates transmit an `AFR`-packet in the contention step. For $\rho = 50\,\mathrm{m}^{-2}$, we observe a difference regarding the number of received `AFR`-packets between CoRe-MAC and CoRe-MAC-NE for $s < 4$ (see Figure 5.17a). In this scenario and $\rho = 50\,\mathrm{m}^{-2}$, the average number of candidates is 9. The closer s gets to 9 the smaller the difference between CoRe-MAC and CoRe-MAC-NE becomes. For $s \geq 9$, both schemes end up using an access probability of 1 and achieve similar selection results. For $\rho = 150\,\mathrm{m}^{-2}$, the average number of candidates increases to



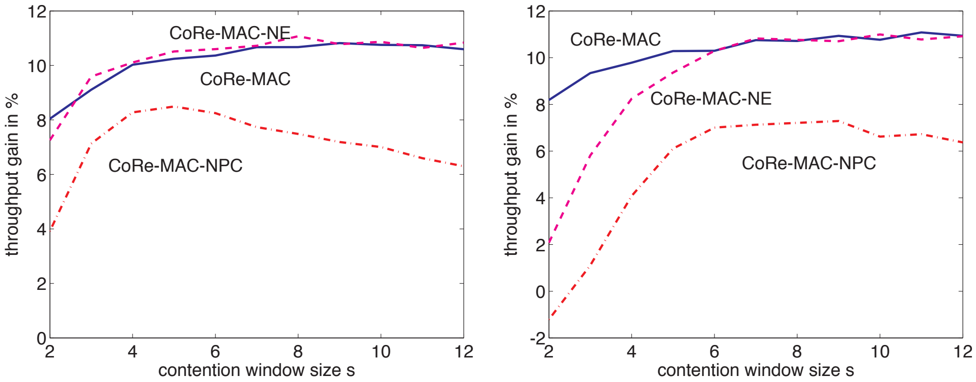
(a) (b)

Figure 5.17: Performance metrics as a function of s for $\rho = \{50, 150\}\,\mathrm{m}^{-2}$: (a) expected number of received `AFR` packets and (b) relay selection periodicity.

30. While the expected number of received `AFR`-packets of CoRe-MAC is similar for $\rho = 50\,\mathrm{m}^{-2}$ and $\rho = 150\,\mathrm{m}^{-2}$, this number drops considerably for CoRe-MAC-NE and small s-values. CoRe-MAC-NE hardly ever succeeds in selecting a relay for high node densities and small s-values, since most of the `AFR` transmissions collide. This holds also for CoRe-MAC-NPC.

The relay selection periodicity of CoRe-MAC is independent of ρ and increases with s (see Figure 5.17b). In layman terms, the larger the prioritized candidate set is the rarer the events that no member of this set can support D occur. Intuitively, the relay selection periodicity of CoRe-MAC-NE heavily depends on ρ. While CoRe-MAC-NE achieves a similar periodicity as CoRe-MAC for $\rho = 50\,\mathrm{m}^{-2}$ beyond $s = 2$, this number increases to 8 for $\rho = 150\,\mathrm{m}^{-2}$. For $s \geq 9$ and $\rho = 150\,\mathrm{m}^{-2}$, we observe that CoRe-MAC-NE achieves a higher relay selection periodicity than CoRe-MAC. This is due to the sloppy candidate estimation of CoRe-MAC which overestimates occasionally the number of potential relays and hence uses a too small transmission probability for the `AFR`-packets. Since CoRe-MAC-NPC has to select for each cooperative transmission a new relay its relay selection periodicity is the shortest and independent of ρ and s.

Figure 5.18 shows the throughput gain compared to CSMA/CA as a function of s. For $\rho = 50\,\mathrm{m}^{-2}$ (see Figure 5.18a), the candidate estimation pays off for $s < 3$ and results in a higher throughput gain than skipping the estimation step. For $s \geq 3$, the candidate estimation step imposes mainly an additional delay. The negative impact on the throughput, however, is small because of the large relay selection periodicity. The throughput gain saturates for CoRe-MAC and CoRe-MAC-NPC at 10.5 % (for $s \geq 6$) in the depicted range. Intuitively, larger values of s decrease the throughput gain again since CoRe-MAC spends more time in the relay selection process. We fail, however, to observe this trend in the given range due to the large relay selection periodicity. For higher node densities (see Figure 5.18b), the candidate estimation becomes more important and its benefits outweigh its overhead. CoRe-MAC-NPC



(a) (b)

Figure 5.18: Throughput gain compared to CSMA/CA as a function of s for (a) $\rho = 50\,\mathrm{m}^{-2}$ and (b) $\rho = 150\,\mathrm{m}^{-2}$.

performs regarding throughput always worse than the versions using the prioritized candidate set due to the frequent relay selections.

We draw the following conclusions regarding the contention window size s. CoRe-MAC needs a minimum value of s such that the relay selection of D is successful. The cardinality of the prioritized candidate set depends on s and the node density. The benefit of a large prioritized candidate set is a larger relay selection periodicity. The knowledge of the candidate cardinality bears definitely advantages. In situations where the number of candidates is similar to s, the candidate estimation step can be disabled to maximize the throughput gain. Alternatively, S could acquire its degree information (e.g., by monitoring the network activities), and use this information as an estimation of n. For dynamic networks and in the absence of any topology information regarding the average number of available relay candidates we recommend to perform the estimation step.

In the following, we aim to provide D with at least two candidate applications for each selection step. Therefore, we choose $s = 6$ hereafter (cf. Section 3.4).

5.3.2 Impact of Network Parameters on CoRe-MAC

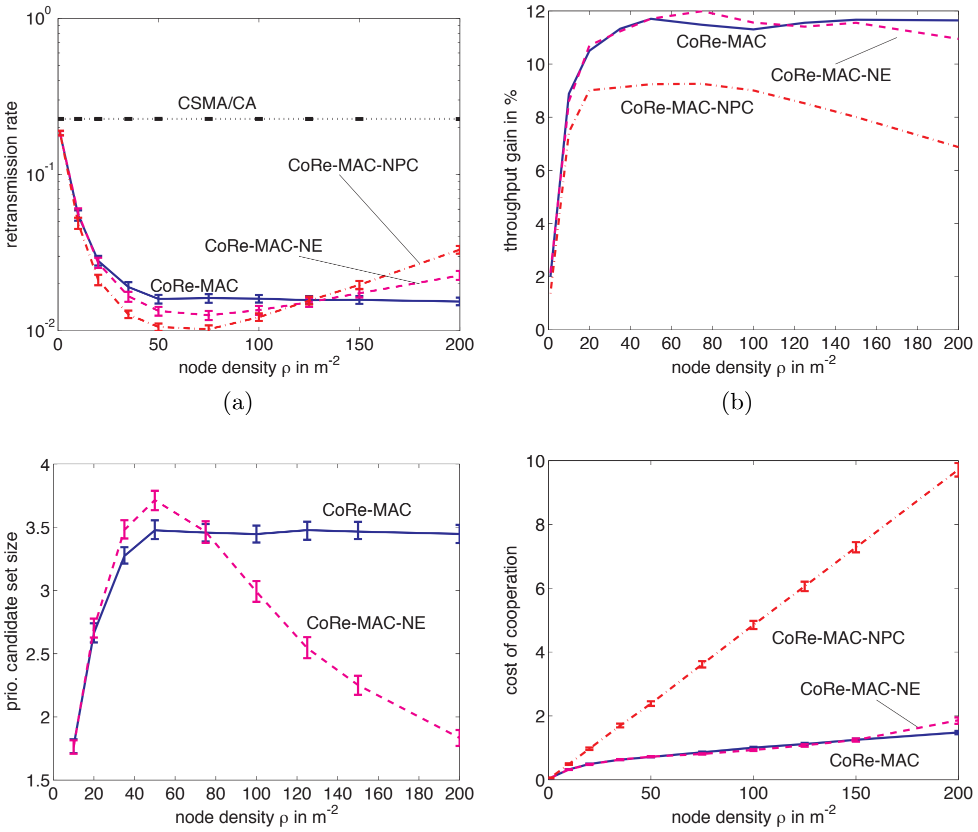
Let us in the following investigate the impact of different network parameters on the performance of CoRe-MAC.

Node Density ρ

First, we consider the impact of the node density ρ on various performance metrics of the CoRe-MAC schemes and CSMA/CA (see Figure 5.19). The retransmission rate of S (see Figure 5.19a) and the throughput (see Figure 5.19b) of the CoRe-MAC schemes improve with increasing ρ for $\rho \leq 50\,\mathrm{m}^{-2}$. For $\rho > 50\,\mathrm{m}^{-2}$, there exists a relay for each cooperation attempt of $\{S, D\}$. The retransmission rate and the throughput of CoRe-MAC saturates. The throughput gain of CoRe-NPC declines with further increasing ρ due to the increasing probability of failing relay selections. Although CoRe-MAC-NE experiences similar relay selection success probabilities as CoRe-MAC-NPC, its throughput does not decline as fast. CoRe-MAC-NE benefits from the fact that a once selected relay is re-used via the prioritized candidate set.

Figure 5.19c illustrates the cardinality of the prioritized candidate set of CoRe-MAC and CoRe-MAC-NE. For $\rho \leq 30\,\mathrm{m}^{-2}$, this value is similar for both schemes. For $30 \leq \rho \leq 70$, CoRe-MAC-NE can resort to a larger set size than CoRe-MAC. The sloppy node estimation of CoRe-MAC results occasionally in a too small transmission probability of `AFR`-packets. For $\rho > 70\,\mathrm{m}^{-2}$, however, the number of colliding `AFR`-packets increases for CoRe-MAC-NE which reduces the set size of prioritized candidates.

We observe the benefits of the prioritized candidate set in Figure 5.19d which illustrates the cost of cooperation. This value increases only gradually for CoRe-MAC



(a) (b)

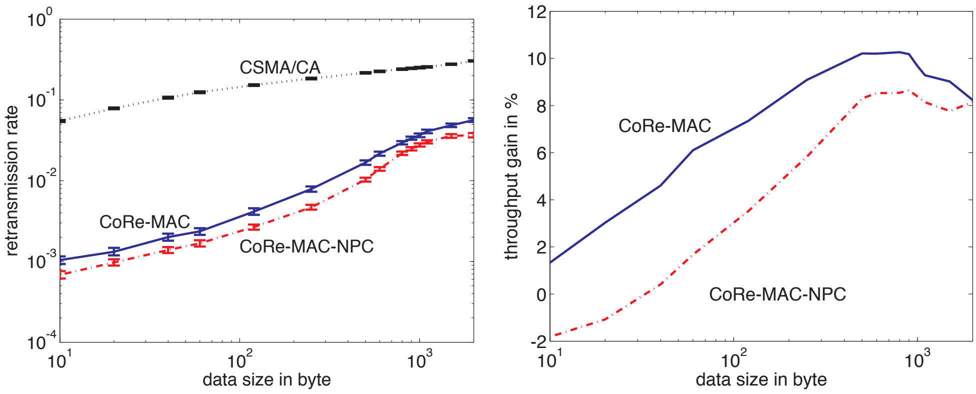
(c) (d)

Figure 5.19: Performance metrics as a function of ρ: (a) retransmission rate of S, (b) throughput gain compared to CSMA/CA, (c) cardinality of prioritized relay set, and (d) cost of cooperation.

using a prioritized candidate set while it increases linearly with ρ for CoRe-MAC-NPC. For CoRe-MAC-NE, we observe the negative impact of `AFR` collisions during the contention period for $\rho \geq 150\,\mathrm{m}^{-2}$. Due to the smaller number of received `AFR`s, D's prioritized candidate set is smaller. Moreover, there is a higher likelihood that a relay selection fails. The outcome is that CoRe-MAC-NE requires more often all candidates to listen to `DATA`-packets than CoRe-MAC.

`DATA`-Packet Size

Figure 5.20 summarizes the impact of the `DATA`-packet size on the retransmission rate and throughput performance of CoRe-MAC with and without prioritized candidate set. The retransmission rate increases for larger `DATA`-packet size (no channel coding is used). CoRe-MAC reduces the retransmission rate compared to CSMA/CA considerably. The difference, however, becomes smaller for increasing `DATA`-packet sizes. Again, the CoRe-MAC version which selects a relay out of the entire candidate set



(a) (b)

Figure 5.20: Performance metrics as a function of the `DATA` size: (a) retransmission rate of S and (b) throughput gain compared to CSMA/CA.

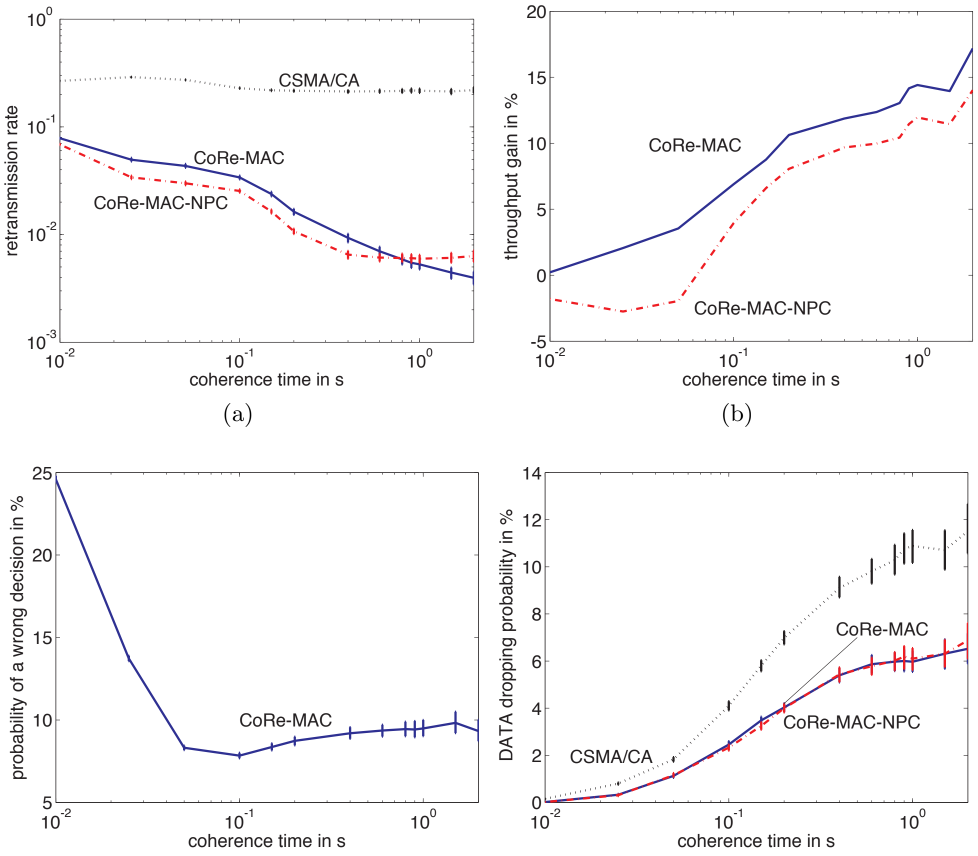
performs better than the one which restricts the relay selection to a prioritized set of candidates.

Figure 5.20b represents the throughput gains of CoRe-MAC to CSMA/CA as a function of the `DATA`-packet size. In our analysis, we count the total additional overhead of CoRe-MAC required to setup and use cooperation. Intuitively, for small `DATA`-packets this overhead cannot be neglected. With increasing `DATA`-sizes this overhead gets less significant which explains why the throughput gain first increases with increasing `DATA`-packet size although the retransmission rate shows the opposite behavior. However, even for `DATA`-packets of the size of an `RTS`-packet, CoRe-MAC achieves a higher throughput than CSMA/CA. For the chosen parameter settings we observe the highest gains for `DATA`-packets of size 600 bytes. For larger `DATA`-packet sizes, the cooperation gain cannot any longer compensate the increasing PER of the `DATA`-packets. For large `DATA`-packet sizes, the throughput difference between the CoRe-MAC versions vanishes. The higher delay of the longer relay selection of CoRe-MAC-NPC becomes less significant because of the `DATA`-size and its lower retransmission rate gets more important.

Coherence Time

Let us in the following analyze the performance of CoRe-MAC with respect to the channel coherence time.

Figure 5.21a indicates the retransmission rate of CoRe-MAC, CoRe-MAC-NPC, and CSMA/CA as a function of the coherence time. While the retransmission rate of CSMA/CA is mainly independent of the coherence time, the retransmission rate of the CoRe-MAC schemes improve with increasing coherence time. Node D decides about enabling cooperation based on the channel state at `RTS` reception. This channel state, however, hardly ever represents the situation experienced during `DATA` transmission in case of short channel coherence times. For short coherence times, it



(a) (b)

(c) (d)

Figure 5.21: Performance metrics as a function of the channel coherence time: (a) retransmission rate of S, (b) throughput gain compared to CSMA/CA, (c) probability of a wrong decision, and (d) `DATA` dropping probability.

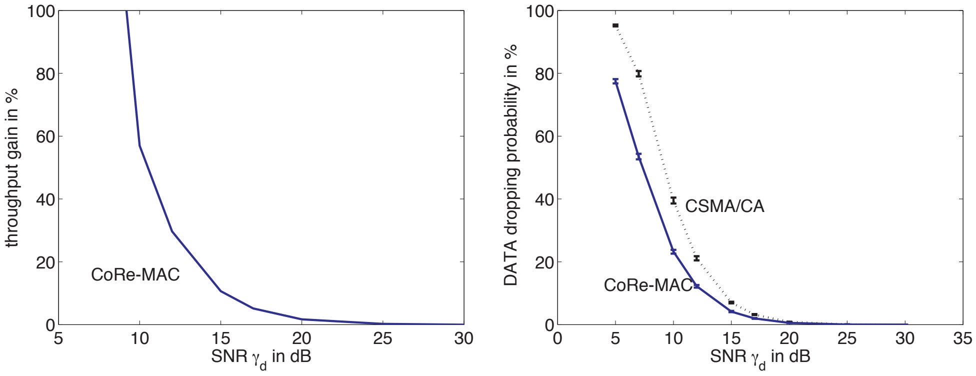
is likely that D disables/enables cooperation but requires/does not require it afterwards, i.e., makes a wrong decision (see Figure 5.21c). For short coherence times, the retransmission rate of CoRe-MAC-NPC is better than the one of CoRe-MAC since it chooses for each cooperative transmission a new relay from all available candidates. With increasing coherence time, this advantage to CoRe-MAC shrinks. The prioritized candidates' channel states to S and D stay longer in a good state. Beyond a coherence time of 1 s, the retransmission rate of CoRe-MAC is better than the one of CoRe-MAC-NPC. Selecting a relay out of the prioritized candidate set is in general more robust against signal packet failures. That is why CoRe-MAC-NPC's retransmission rate is worse due to occasionally occurring selection failures.

Looking at the throughput performance of CoRe-MAC in Figure 5.21b we see that CoRe-MAC hardly provides any gains compared to CSMA/CA for fast changing channel conditions. This is intuitive, since the channel for candidates may get worse during the direct transmission and that the channel between S and D gets considerably better during the retransmission. Hence, for fast changing channels, the time diversity effect of `DATA` retransmissions is as effective as cooperative diversity. Despite the wrong decision in fast changing channel conditions, CoRe-MAC does not perform worse than CSMA/CA. The reason therefore is that CoRe-MAC uses a re-active relay selection approach, and hence does not invest time to prepare cooperation in situations it does not need to. For a coherence time smaller than 0.06 s, the throughput of CoRe-MAC-NPC is worse than the one of CSMA/CA (negative gain). In this region, retransmissions from S are faster than selecting a new relay for each cooperative transmission attempt.

Figure 5.21d illustrates the probability of dropping a packet as a function of the channel coherence time. For fast varying channels, the probability of dropping a packet is for all considered schemes nearly 0. For increasing coherence time, the time the channel stays in a particular state — either good or bad — increases. Time diversity cannot mitigate bad channel states and the number of dropped `DATA`-packets increases. CoRe-MAC performs better than CSMA/CA. If the channel, however, is in a deep fade which does not allow any signaling between S and D, CoRe-MAC fails too.

Distance between S and D

Finally, we investigate the performance of CoRe-MAC for different distances d between S and D. We use the average received SNR γ_d as distance measure in Figure 5.22. At small distances between S and D, cooperation is hardly ever needed and hence is disabled by D. This results in similar throughputs of CoRe-MAC and CSMA/CA above 25 dB (see Figure 5.22a). With increasing distance, i.e., decreasing average received SNR, the throughput gain of CoRe-MAC increases. At low SNR values, the gain of CoRe-MAC is considerable. This region, however, is not suitable for any communication since most of the `DATA`-packets are dropped (see Figure 5.22b).



(a) (b)

Figure 5.22: Performance metrics as a function of average received SNR γ_d at D: (a) throughput gain compared to CSMA/CA and (b) `DATA` dropping probability.

Spatial Re-usability

Let us now focus on the spatial re-usability of the communication medium in CoRe-MAC. Our simulation results indicate a gain in throughput and a reduction of the retransmission rate of CoRe-MAC compared to CSMA/CA for a single communication pair $\{S, D\}$. In CoRe-MAC using cooperation and in cooperative relaying in general, at least one additional node besides S and D is invoked in their communication process. Moreover, during the cooperation setup, i.e., relay selection and additional channel reservation, even more nodes transmit signaling packets. It is not intuitive whether cooperation, even though it increases the throughput of a single link, is able to improve the overall network throughput compared to non-cooperative schemes.

We use the scenario illustrated in Figure 5.23 to elaborate on the overall network performance of CoRe-MAC. This scenario features two dedicated pairs of source and destination nodes with potential relays being distributed around them uniformly randomly with a node density ρ. The distance between source and destination node is for both pairs d and the distance between the two communication pairs is d_p. Nodes S_1 and S_2 have constantly `DATA` to send to D_1 and D_2, respectively. Each simulation run covers 10 s of network traffic. For each parameter setting, we simulate 1 000 runs with different potential relay nodes deployments and adopt the average values. We fix d to a value which corresponds to an average received SNR $\gamma_d = 15\,\text{dB}$ and vary the distance between the two communication pairs d_p.

Figure 5.24a illustrates the overall throughput, i.e., the average number of received `DATA`-packets per second at D_1 and D_2, of CSMA/CA and CoRe-MAC as a function of the average received SNR γ_{d_p} at S_2 transmitted from S_1. At first, we see that CoRe-MAC delivers more `DATA`-packets than CSMA/CA. For large distances between the communication pairs, i.e., for small γ_{d_p}-values, both communication pairs transmit simultaneously without interfering with each other. This is true for CSMA/CA and CoRe-MAC. For small distances between the communication pairs, the throughput of both schemes drop to values which are more than a half of their peak values. If the channel of one communication pair is in a bad state which does not allow any communication, the other one can utilize the channel more often and vice versa. The two communication pairs start interfering with each other around

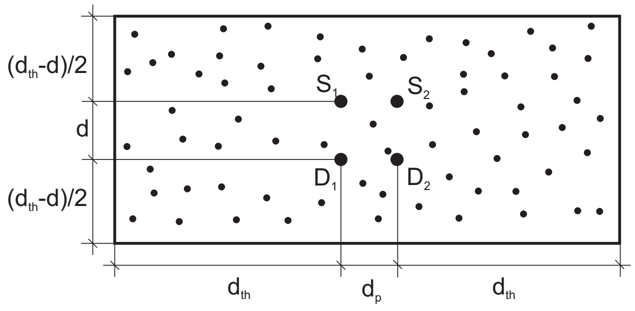
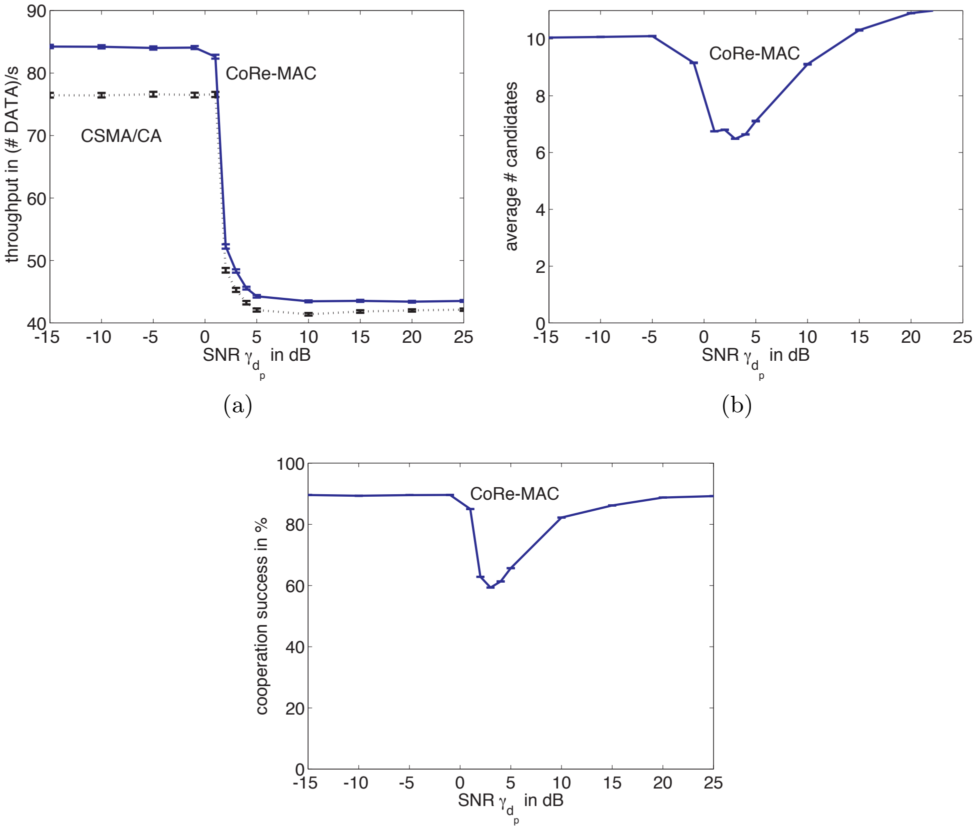


Figure 5.23: Simulation scenario: two dedicated communication pairs



(a)

(b)

(c)

Figure 5.24: Performance metrics as a function of γ_{d_p}: (a) throughput, (b) average number of candidates, and (c) probability that cooperation succeeds.

$\gamma_{d_p} = 1.5\,\text{dB}$. There, the impact on CoRe-MAC is higher than on CSMA/CA due to following reasons. First, the re-active relay selection of CoRe-MAC inherently prioritizes direct transmissions — candidates do not reserve resources until they are selected as relay. This results in a considerable reduction of available relay candidates in the region where both communication pairs are only in interference range of each other (see Figure 5.24b). Second, the mutual interference of the communication pairs reduces the cooperation success probability (see Figure 5.24c).

Regarding the average number of candidates, we observe that this number is higher for high γ_{d_p}-values than for low ones. For instance, at $\gamma_{d_p} = -10\,\text{dB}$ each communication pair can choose on average among 10 candidates its relay where else it can choose among 11 nodes at $\gamma_{d_p} = 25\,\text{dB}$. This is due to the fact that the communication pairs are potential relay candidates of each other for high γ_{d_p}-values.

We can draw the following conclusions from this simulation scenario. CoRe-MAC increases the throughput of single links in a network compared to CSMA/CA. If these links are not causing interference to each other, i.e., if the links are either far apart from each other or quite close such that they are aware of each other, CoRe-

MAC increases the throughput. Interference among communication pairs reduce the performance of CoRe-MAC. CoRe-MAC, however, does not negatively affect the overall network throughput.

5.4 Summary

In this chapter, we introduced and discussed CoRe-MAC, a MAC protocol based on CSMA/CA which facilitates cooperative relaying.

First, we elaborated on how cooperative relaying affects the wireless protocol stack and which layer would fit best to host the additional functionality needed to exploit its benefits. Since cooperative relaying requires information from the physical layer (e.g., link quality, battery level) and needs adjustments regarding the channel reservation of nodes, it is intuitive to include the necessary operations in the MAC protocol.

Motivated by this, we designed a new cooperative MAC protocol called CoRe-MAC which builds on CSMA/CA and extends the mechanisms for handling transmission failures by space/time diverse channels. We paid special attention to the feasibility of the protocol for low budget off-the-shelf hardware and its backward compatibility to standard CSMA/CA as used in IEEE 802.11. This allows the operation of heterogeneous networks, where some nodes use CoRe-MAC and others CSMA/CA, and hence facilitates easier integration of CoRe-MAC in existing networks. Moreover, we focused on keeping the overhead of CoRe-MAC compared to CSMA/CA at a minimum for good channel conditions. In CoRe-MAC, the destination of a transmission attempt decides to enable cooperation based on the quality of its link to the source (cf. cooperation on demand). Even if a destination enables cooperation and direct transmission succeeds, the overhead of CoRe-MAC is negligible. The expense of enabling cooperation is the energy consumption of candidates listening to the `DATA` transmission from the source. CoRe-MAC keeps this cost small by applying two concepts: *relay selection with early retreat* and *prioritized candidate set*. In relay selection with early retreat only those neighbors of source and destination which are likely to support the communication attempt by cooperation listen to the `DATA` transmission. A prioritized candidate set limits the number of nodes that listen to `DATA` transmissions to a previously selected subset of neighbors. The prioritized candidate set, however, does not only reduce the energy costs of cooperation but also reduces the relay selection delay.

CoRe-MAC splits the relay selection phase into three steps. The *feedback step* allows the destination to collect information about the availability of candidates. In case no candidates are available, the destination aborts the cooperation process and requests a retransmission from the source. Hence, CoRe-MAC does not perform worse than CSMA/CA in sparse networks where nodes have hardly any neighbors which can act as relays. The *candidate estimation step* allows CoRe-MAC to estimate the number of available candidates of a communication attempt. With this knowledge, candidates can adjust their transmission probability in the *candidate* *contention step* to maximize the number of relay applications received by the destination. The destination chooses, based on the applications, the current relay and a set of prioritized candidates for further cooperations.

The candidate estimation imposes an additional overhead for cooperation which pays off mainly for dense networks. The overhead, however, is not significant and our results indicate that in absence of any topology information it is better to enable the candidate estimation option.

Our performance studies showed that CoRe-MAC performs in good channel conditions similar to CSMA/CA but offers for transmissions over unreliable communication links gains regarding the retransmission rate and throughput. The actual performance of CoRe-MAC depends on the node density, the coherence time of the channel and the data packet size. Our analyses revealed that CoRe-MAC does not only increase the throughput of a single link but also increases the network wide throughput.

Finally, it is important to point out that CoRe-MAC requires a link between source and destination to start the communication attempt. If the direct connection suffers from a severe deep fade which affects signaling packets, CoRe-MAC fails. The integration of a mechanism which facilitates cooperation in the absence of a direct signaling link can boost the gains of cooperation even further and represents an open research question.

Chapter 6

Conclusion

Cooperative diversity is an effective means to compensate the effects of small scale fading, where wireless communication devices cooperate to improve the reliability and the throughput in a wireless network. Especially highly dense networks (cf. WSNs, IoT) offer an ideal application area for cooperative diversity, where the devices are small, cheap, and likely incapable of supporting any sophisticated techniques to combat fading effects.

While the majority of research contributions in the field of cooperative relaying focus on its physical layer aspects — with known source, destination and relay nodes — this thesis focuses on networking layer aspects of cooperative relaying that cover packet flow control to setup and enable cooperation, relay selection, and resource reservation. Once these tasks are accomplished, cooperative diversity reduces to the well-studied physical layer aspects. We illustrate that obtaining the benefits of cooperative diversity as promised by theoretical research contributions in ad-hoc networks is not straightforward. The overhead of setting up cooperative diversity and the limitations imposed by radio architectures which would benefit from it have great impact on the achievable gains. Without adequately addressing the networking and protocol issues, successful deployment of cooperative diversity is impossible.

Summary

In Chapter 2, we elaborated on existing solutions to some of the challenges of cooperative diversity. We distinguished between physical layer and networking layer challenges and their existing solutions. We also summarized works on why nodes should cooperate, presented upcoming standards which include options for cooperative diversity, and clarified terms in context of cooperation and relaying.

In Chapter 3, we discussed the efficiency of cooperative relaying in the context of ad-hoc networks. First, we focused on the energy-efficiency of cooperative relaying and proposed methods to improve it via enabling cooperation on demand and discarding unreliable relay candidates. Second, we introduced the idea of exploiting routing information in the relay selection process such that a selected relay is in transmission range of three consecutive nodes of a routed packet. Our analysis indicates that multi-hop-aware cooperative relaying increases the achievable end-to-end throughput in a multi-hop network compared to hop-by-hop cooperative relaying. Finally, we elaborated on two basic strategies for slotted contention window based relay selection. In that context, we discussed the influence of imperfect knowledge of the relay candidate cardinality on the selection performance. Finally, we showed how to choose the parameters of the contention window to achieve a certain relay selection success.

In Chapter 4, we addressed the issue of how to estimate the number of neighbors of a node. Our motivation was to increase the success probability of the relay selection with this knowledge as illustrated in Section 3.4. There are numerous other application domains, however, which build on or benefit from the information about the number of neighbors of a node. A common constraint is the delay the estimation process needs to satisfy. In layman terms, the estimation should be as fast as possible and accurate enough to fulfill certain requirements. To this end, we proposed and evaluated different methods which utilize probabilistic trials to track the number of neighbors of a node.

In Chapter 5, we introduced a cooperative MAC protocol called CoRe-MAC. CoRe-MAC is based on CSMA/CA and combines ideas from Chapter 3 and Chapter 4 to efficiently handle relay selection, resource reservation, and cooperative packet flow. We rigorously evaluated the performance of CoRe-MAC with respect to network parameters like channel coherence time, node density, and data packet size. CoRe-MAC performs like CSMA/CA in good and sparse networks with negligible overhead. In bad channel conditions and in situations, where the communication pair can revert to a relay node, CoRe-MAC can deliver more packets than CSMA/CA. The throughput gain mainly depends on the aforementioned network parameters.

Contribution

Our main contributions in this thesis are:

- We improved the efficiency of cooperative relaying in terms of:
    - Energy:
        - We analyzed the energy consumption of cooperative relaying taking into account transmitting *and* receiving data and signaling packets, as well as idle listening.
        - We introduced and evaluated methods to increase the energy-efficiency of cooperative relaying by
            - enabling cooperation only if needed (cf. RSod), and
            - limiting the number of contending candidates to those nodes which are capable of making the direct transmission more reliable (cf. RSer).

  - Time:
    - We exploited routing information in the relay selection process to increase the end-to-end throughput of cooperative relaying.
    - We provided a system architecture for multi-hop-aware cooperative relaying.
    - We investigated different policies to select a multi-hop-aware cooperative relay.
  - Success:
    - We elaborated on relay selection using a slotted contention window.
    - We analyzed two contention strategies based on perfect knowledge of the number of competing nodes.
    - We illustrated the impact of imperfect candidate cardinality knowledge on the selection success.
    - We discussed on how to choose the parameters of contention based relay selection to achieve a desired selection result.

- We proposed methods based on probabilistic trials to estimate the number of neighbors of a node that optionally exhibit certain properties with minimum estimation delay:
  - We introduced methods with different levels of adaptivity and feedback and analyzed their performance in terms of the estimation delay.
  - We evaluated the methods with respect to different radio architectures, and illustrated their applicability in existing wireless networks.
- We proposed a cooperative MAC protocol which efficiently handles relay selection, resource reservation, and cooperative packet flow:
  - We employed a re-active relay selection scheme, where we considered the channel conditions and network density while enabling cooperation.
  - For time and energy-efficiency, we incorporated a prioritized candidate set into the relay selection process.
  - Taking into account the total overhead, we showed that cooperative relaying offers benefits even for simple radio architectures which operate with fixed transmission rates and powers.

Open Issues

Let us in the following discuss open issues and possible further research directions.

Regarding multi-hop-aware cooperative relaying, we proposed the basic idea, a potential systems architecture, and evaluated different selection policies. We, however, did not consider any signaling overhead or channel reservation issues in our analysis. Applying D-STC in the proposed multi-hop-aware scheme requires also more analysis. Furthermore, we did not elaborate on how the relay selection process accesses the routing information such that the new design does not violate the layering approach of the communication protocol stack. A potential extension is to integrate multi-hop-aware cooperative relaying in a wireless protocol stack and evaluate its performance with respect to different routing protocols.

An interesting topic of this thesis which is not limited to cooperative relaying is neighbor cardinality estimation. We believe that this research field will attract more interest in the future as the node densities in wireless networks increase. Further work is necessary to optimize the estimation process in terms of resources used for different technologies.

In the design of CoRe-MAC, we rely on an existing communication link between source and destination which at least needs to support the exchange of signaling packets. In the absence of such a channel CoRe-MAC — like other cooperative MAC proposals — does not provide any gains compared to non-cooperative schemes. This dependence on a direct signaling channel between source and destination needs to be removed in a further step. A possible solution is to extend CoRe-MAC to select a prioritized candidate set for each communication pair, regardless of the direct channel state. In case the direct channel fails to deliver signaling packets, the initiator of the communication attempt could invoke the help of the prioritized candidates. In such a situation all nodes in the candidate set could forward the request from the source to the intended destination, which selects the best candidate as relay.

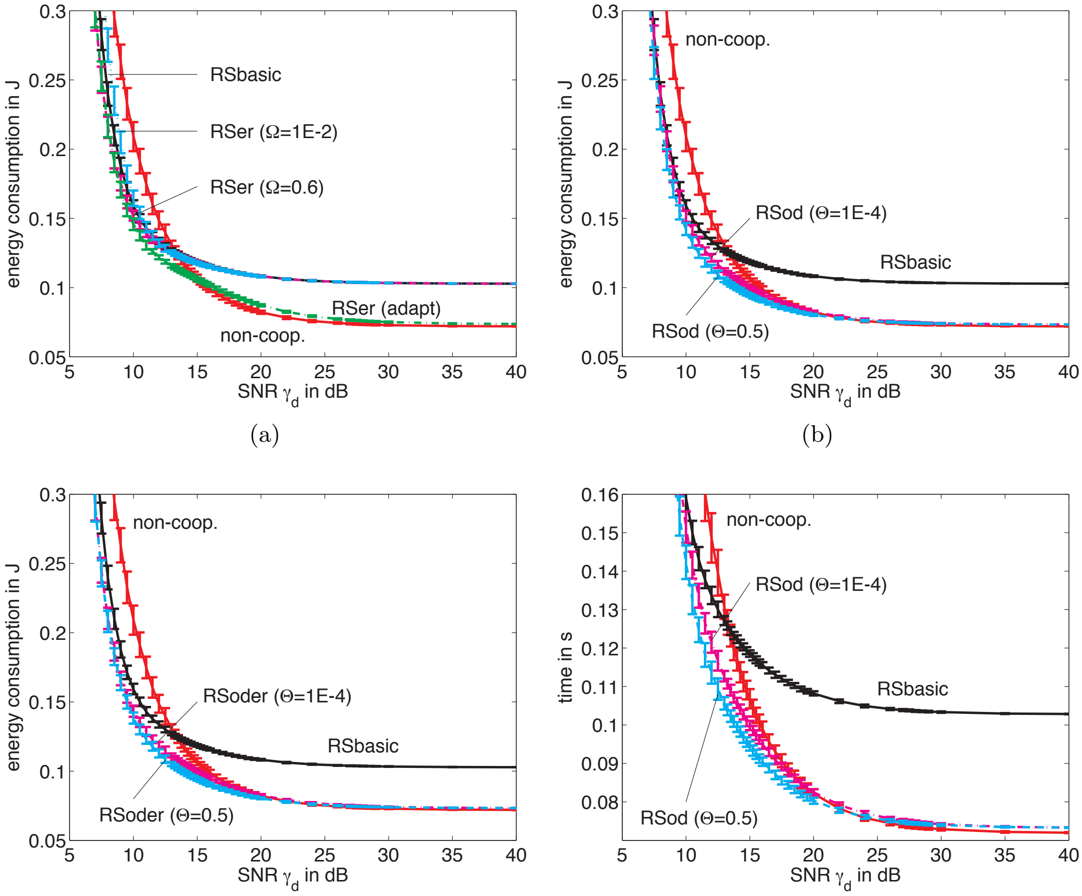
CoRe-MAC follows an approach, where the source needs to know the delivery success from the destination. Hence, if a cooperative transmission attempt is not successful or if the source has not received the corresponding `ACK` from the destination, the source node initiates a retransmission. As a side effect of this approach, the source node needs to reserve the channel for the overall duration of the cooperation process. An alternative is to hand over the responsibility of delivering the packet from the source to the relay node. This might have, however, implications on other layers of the protocol stack which needs to be investigated.

In this thesis, we limited the performance evaluation of CoRe-MAC to a comparison with standard CSMA/CA. Our motivation was to explore whether we could achieve any gains in the absence of a sophisticated radio architecture. Since other cooperative MAC proposals assume more capable radios (e.g., supporting D-STCs), a fair comparison is not possible. A next step could be to compare CoRe-MAC with those cooperative MAC protocols assuming identical hardware restrictions.

Appendix

Appendix A

Figures A.1(a-d) represent the true values corresponding to the relative gain results shown in Figure 3.5b, 3.6b, 3.7b, and 3.6c, respectively.



(a) (b)

(c) (d)

Figure A.1: Simulation results with 90%-confidence intervals: (a) energy consumption of RSer, (b) energy consumption of RSod, (c) energy consumption of RSoder, and (d) time consumption of RSod as a function of SNR.

Appendix B

Proof that (4.12) is a convex function in n

Ψ is a convex function of n if the second derivative of it is greater than 0 for all possible n values. For simplicity we substitute $(1-p)$ by x in (4.12). After taking the second derivative of Ψ for n and some rearrangements we get

$$g(x) := n \cdot \ln(x) \cdot (n \ \ln(x) + 4) + 6 \cdot (1 - x^n) \ .$$

For fixed x this function increases with n. Thus, we limit our examination to the case $n = 1$ which is the smallest number our estimator can handle. Since $g(x)$ is monotonically decreasing and has the value 0 for $x = 1$ the convexity of Ψ is shown.

Derivation of (4.22)

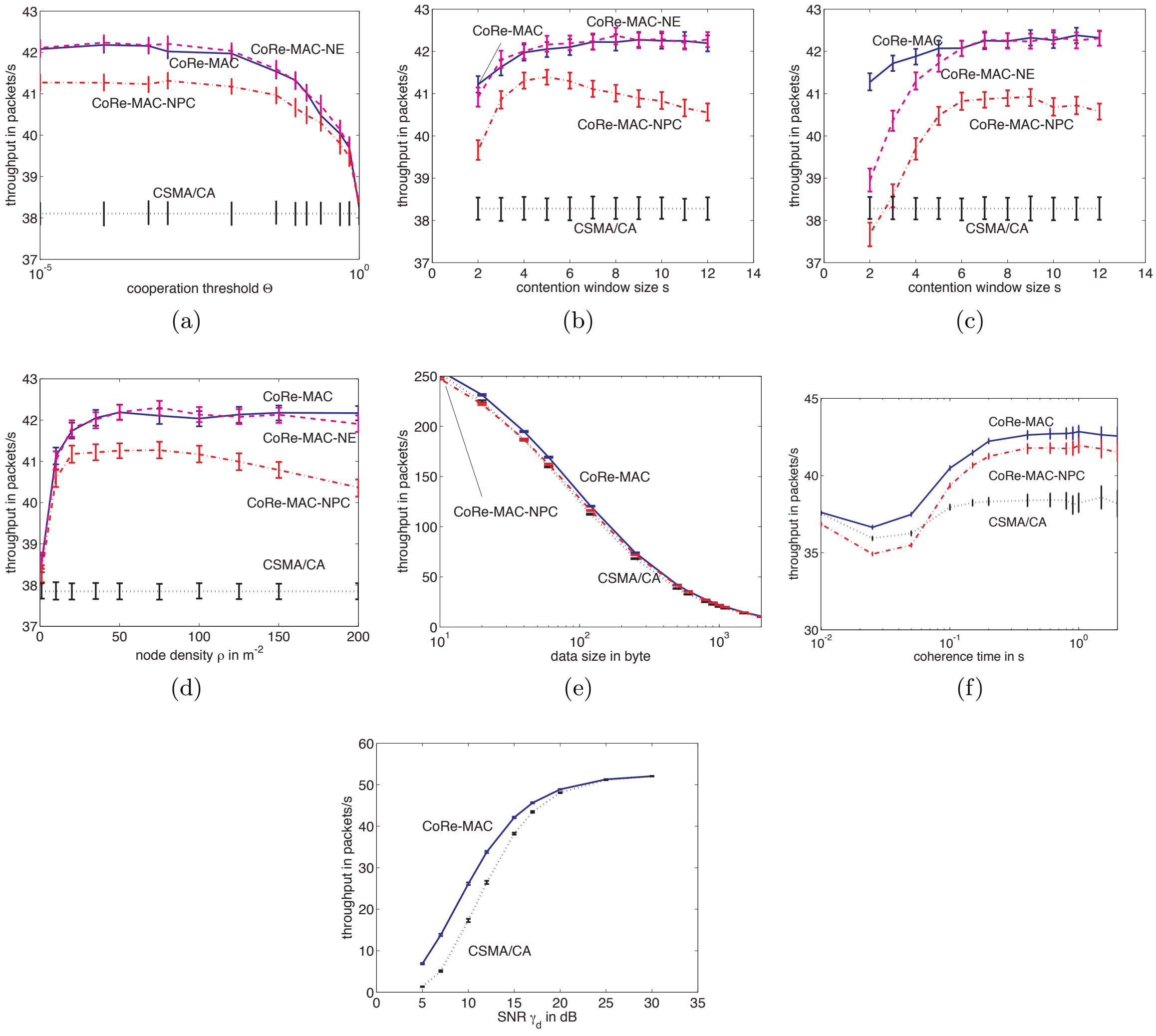
The variance of a maximum likelihood estimation is lower bounded by the inverse of the Fisher information [PP02]. For the derivation of this inequality we substitute $1 - p_i$ by q_i:

$$\begin{aligned}
\mathrm{Var}\left[\hat{n}\right] &\geq \frac{1}{I\left(z\right)} \\
I\left(z\right) &= -E\left[\frac{\mathrm{d}^2 \ln\left(L_z\right)}{\mathrm{d}z^2}\right] \\
\text{from equation (4.16):}& \\
L_z &= \prod_{i=1}^{m} \binom{s_i}{e_i} q_i^{z\,e_i} \ (1 - q_i^z)^{s_i - e_i} \\
\frac{\mathrm{d}^2 \ln\left(L_z\right)}{\mathrm{d}z^2} &= \sum_{i=1}^{m} \left(\frac{e_i - s_i}{\left(q_i^z - 1\right)^2} \cdot q_i^z \cdot \left(\ln\left(q_i\right)\right)^2 \right) \\
E\left[\frac{\mathrm{d}^2 \ln\left(L_z\right)}{\mathrm{d}z^2}\right] &= \sum_{i=1}^{m} \left(\frac{q_i^z \cdot \left(\ln\left(q_i\right)\right)^2}{\left(q_i^z - 1\right)^2} \cdot \mathrm{E}\left[e_i - s_i\right] \right) \\
E\left[\frac{\mathrm{d}^2 \ln\left(L_z\right)}{\mathrm{d}z^2}\right] &= \sum_{i=1}^{m} s_i \cdot \frac{q_i^z \cdot \left(\ln\left(q_i\right)\right)^2}{q_i^z - 1} \\
\mathrm{Var}\left[\hat{n}\right] &\geq \frac{1}{\sum_{i=1}^{m} \frac{s_i \ q_i^z \ \left(\ln(q_i)\right)^2}{1 - q_i^z}} \qquad \text{(B.1)}
\end{aligned}$$

In case enough statistics for the maximum likelihood estimation is available, the inequality of (B.1) becomes an equality. Furthermore, we observe that the summation terms in (B.1) equal the inverse of equation (4.10).

Appendix C

Figures C.1(a-g) represent the true values corresponding to the relative gain results shown in Figure 5.16b, 5.18a, 5.18b, 5.19b, 5.20b, 5.21b, and 5.22a, respectively.



(a) (b) (c)

(d) (e) (f)

(g)

Figure C.1: Throughput simulation results with 90%-confidence intervals: (a) as function of Θ, (b) as function of the contention window size for $\rho = 50\,\mathrm{m}^{-2}$, (c) as function of contention window size for $\rho = 150\,\mathrm{m}^{-2}$, (d) as function of ρ, (e) as function of the data size, (f) as function of the coherence time, and (g) as function of the average received SNR γ_d.

My Publications

Conference Papers

[1] H. Adam, C. Bettstetter, and S. M. Senouci. Adaptive relay selection in cooperative wireless networks. In *Proc. IEEE Intern. Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Cannes, France, Sep. 2008.

[2] M. Offner and H. Adam. Cooperative media access control in wireless networks. In *Proc. Junior Scientist Conf.*, pages 47–48, Vienna, Austria, Dec. 2008. Technische Universität Wien.

[3] H. Adam, C. Bettstetter, and S. M. Senouci. Multi-hop-aware cooperative relaying. In *Proc. IEEE Vehicular Techn. Conf. (VTC-spring)*, Barcelona, Spain, Apr. 2009.

[4] H. Adam, W. Elmenreich, C. Bettstetter, and S. M. Senouci. CoRe-MAC: A MAC-protocol for cooperative relaying in wireless networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Honolulu, US-HI, Dec. 2009.

[5] N. Marchenko, E. Yanmaz, H. Adam, and C. Bettstetter. Selecting a spatially efficient cooperative relay. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Honolulu, US-HI, Dec. 2009.

[6] H. Adam, E. Yanmaz, W. Elmenreich, and C. Bettstetter. Contention-based neighborhood estimation. In *Proc. IEEE Vehicular Techn. Conf. (VTC-spring)*, Taipei, Taiwan, May 2010.

Journal Papers

[1] W. Elmenreich, N. Marchenko, H. Adam, C. Hofbauer, G. Brandner, C. Bettstetter, and M. Huemer. Building blocks of cooperative relaying in wireless systems. *e & i*, Springer, 125(10):353–359, 2008.

[2] H. Adam, E. Yanmaz, and C. Bettstetter. Contention-based estimation of neighbor cardinality. Apr. 2011. submitted & under review.

Patents

[1] H. Adam, W. Elmenreich, and C. Bettstetter. Apparatus and method for cooperative relaying in wireless systems using an extended channel reservation. European Patent EP 2326030 (A1), published 25 May 2011, filed 23 Nov. 2009.

[2] H. Adam, W. Elmenreich, and C. Bettstetter. Cooperative relay scheme having backward compatibility. European Patent EP 2326029 (A1) , published 25 May 2011, filed 23 Nov. 2009.

List of Symbols

α	confidence level
b	packet size in bits
BER	bit error rate
BER_{xy}	BER of the link between node x and node y
$\bar{b}_{\mathrm{RX}}$	average number of received bits per correctly delivered packet
$\bar{b}_{\mathrm{TX}}$	average number of transmitted bits per correctly delivered packet
β	number of contention slots which would fit into the duration of a feedback data transmission
c	feedback interval of the MLE in the initial phase
C_i	relay candidate i
CW	exponent to determine the contention window size of the CSMA/CA backoff algorithm
CW_{base}	minimum value of CW
CW_{counter}	counting variable for the CSMA/CA backoff algorithm
CW_{max}	maximum value of CW
χ_i	relaying suitability of candidate i
D	destination node
d	distance between sender and receiver
d_0	reference distance
d_p	distance between two communication pairs
d_{max}	distance after which a receiver experiences a $BER \geq 0.001$ from a sender in an AWGN channel

d_{th}	signal detection threshold range in an AWGN channel model
e	number of empty slots
E_b	energy per bit
E_I	sum of interfering signal strengths
e_i	number of empty slots in the i^{th} contention round
E_{RX}	energy required to receive one bit
E_{TX}	energy required to transmit one bit
$\bar{E}$	average consumed energy
ϵ	relative estimation error
η	ratio of upper to lower bound of the operation range
η_c	ratio of upper to lower bound of a subrange in the coarse estimation phase
η_f	ratio of upper to lower bound of a subrange in the fine estimation phase
η_{sub}	ratio of upper to lower bound of the subrange
$G(C_i)$	end-to-end delivery value of C_i
γ	signal-to-noise ratio
γ_{d}	averaged received signal-to-noise ratio at distance d from the transmitter
γ_{th}	minimum signal-to-noise ratio that can be detected/received
γ_{tx}	signal-to-noise ratio at the transmitter
γ_{xy}	signal-to-noise ratio received at node y from transmitting node x
h	fading coefficient
$\mathcal{H}$	set of nodes that are connected to S, D_1, but not to D_2
I	electric current
$I\left(X;Y\right)$	Mutual information of two random variables X and Y
$I\left(z\right)$	Fisher information associated with the parameter z under a given pdf
k_c	number of partitions in the coarse estimation phase
k_f	number of partitions in the fine estimation phase
k_{occupy}	number of slots in the candidate cardinality estimation phase after which S has to transmit a `BUSY` to keep the channel occupied

L	path loss
L_z	likelihood value
lrc	large retry counter
$lrc_{\max}$	maximum retries for large packets
Λ	time constant for RSbasic
m	number of distinct `AFR` receptions
$\mathcal{M}$	set of nodes that are connected to S, D_1, and D_2
μ	mean value of the normal distribution
N_0	noise spectral density
n	number of neighbors/relay candidates
n_D	neighbors of D
n_S	neighbors of S
$n_{\max}$	upper bound of the operation range
$n_{\min}$	lower bound of the operation range
$\hat{n}$	estimation of n
$\hat{n}_c$	estimation result of the coarse estimation phase
$\hat{n}_j$	estimation results of the j^{th} main round of the MLE
o	number of rounds in the initial phase of the MLE
Ω	early retreat threshold
p	transmission probability
P_0	probability of having an empty slot
P_1	probability of having a singleton slot
p_i	transmission probability in the i^{th} contention round
P_k	probability that k candidates select the same slot
P_s	selection success probability
P_x	probability of having a colliding slot
$P_{1,k}$	probability that only one out of k nodes transmit in a given slot

$P_{1_{s1}}$	probability that there is exactly one `AFR` transmission in a given slot using strategy 1
$P_{1_{s2}}$	probability that there is exactly one `AFR` transmission in a given slot using strategy 2
p_{CTS}	CTS-early retreat probability
p_{er}	early retreat probability
P_{mode}	power consumption of a node in a specific operation mode, where the mode is either TX, RX, sleep, or idle
p_{relay}	probability of having a relay
p_{ret}	retransmission probability of S
p_{RTS}	RTS-early retreat probability
p_{e_i}	candidate transmission probability for the i^{th} partition of the candidate cardinality estimation
$p_{s1,max}$	transmission probability that maximizes $P_{S_{s1}}$
p_{s1}	transmission probability of a node in contention strategy 1
$p_{s2,max}$	transmission probability that maximizes $P_{S_{s2}}$
p_{s2}	transmission probability of a node in contention strategy 2
$P_{S_{s1}}$	selection success probability of contention strategy 1
$P_{S_{s2}}$	selection success probability of contention strategy 2
PER	packet error rate
$\hat{P}_0$	estimate of P_0
$\Phi\left(\cdot\right)$	cumulative density function of the standard normal distribution
Ψ	upper bound for the relative estimation error ϵ guaranteeing $\mathrm{P}\left[\epsilon \leq \Psi\right] = \alpha$
Ψ_j	error bound of the j^{th} round in the main phase of the MLE
q	probability of not transmitting
R	relay node
r	data rate
ρ	node density
S	source node

s	frame size of the contention window
s_e	number of total slots in the candidate estimation phase of CoRe-MAC
s_{b_i}	smallest number of slots required to finish estimation after the i^{th} round
s_{e_i}	number of slots in the i^{th} partition of the cardinality estimation
s_{np}	slots required for estimation process if no subrange partitioning is used
s_{w_i}	maximum number of slots required to finish estimation after the i^{th} round
src	small retry counter
$src_{\max}$	maximum retries for small packets
σ	deviation of the normal distribution
σ_R	parameter of the Rayleigh distribution
t_i	timer value of C_i in RSbasic
t_{DIFS}	duration of the distributed interframe space
t_{EIFS}	duration of the extended interframe space
t_{RxTx}	time to switch between transmit/receive mode
t_{SIFS}	duration of the short interframe space
t_{slot}	duration of a slot in the contention scheme of CSMA/CA
$t_{\text{time-out}}$	time out of RSer
$\bar{t}_{\text{waiting}}$	average contention time per packet of all nodes in RSbasic
$\mathcal{T}$	union set of $\mathcal{H}$ and $\mathcal{M}$
Θ	relay selection on demand threshold
θ	error threshold
θ_c	error threshold in the coarse estimation phase
U	electric voltage
u	number of prioritized candidates
v	path loss exponent
$\text{Var}\left[\hat{n}\right]$	variance of $\hat{n}$
w_{D_2}	weighting factor of the delivery-policy
z	result of the maximum likelihood estimation

List of Acronyms

ARQ	Automatic Repeat Query
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
A&F	Amplify and Forward
BER	bit error rate
BPSK	Binary Phase Shift Keying
cdf	cumulative distribution function
CDMA	Code Devision Multiple Access
CD-MAC	Cooperative Diversity Medium Access Control
CMAC/ARS	Cooperative Medium Access Control with Automatic Relay Selection
CoopMAC	Cooperative Medium Access Control
CSMA	Carrier Sensing Multiple Access
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
CoRe-MAC	Cooperative Relaying Medium Access Control
CSI	channel state information
C-MAC	Cooperative Medium Access Control
C&F	Compress and Forward
DSSS	Direct Sequence Spread-Spectrum
D-TC	Distributed Turbo Coding
D-STC	Distributed Space Time Code

D&F	Decode and Forward
FER	frame error rate
FHSS	Frequency Hoping Spread-Spectrum
FSK	Frequency Shift Keying
GSM	Global System for Mobile Communications
HbH-Coop-Relaying	hop-by-hop cooperative relaying
H-ARQ-II	Hybrid-Automatic Repeat Query Type II
ICSI	instantaneous channel state information
IMT-Advanced	International Mobile Telecommunications-Advanced
IoT	Internet of Things
ISI	inter symbol interference
ITU	International Telecommunication Union
LTE	Long Term Evolution
LTE-Advanced	Long Term Evolution-Advanced
MAC	Medium Access Control
MANET	mobile ad-hoc network
MFE	Multi-Feedback Neighbor Estimator
MHA-Coop-Relaying	multi-hop-aware cooperative relaying
MIMO	Multiple Input Multiple Output
MLE	maximum likelihood estimation
MRC	Maximal Ratio Combining
NAE	Non-Adaptive Neighbor Estimator
NPC	Non-Colliding Packet Counting
OFDM	Orthogonal Frequency-Division Multiplexing
pdf	probability density function
PER	packet error rate
QPSK	Quadrature Phase Shift Keying

RFID	Radio Frequency Identification
RSbasic	basic relay selection
RSer	relay selection with early retreat
RSod	relay selection on demand
RSoder	relay selection on demand with early retreat
SDL	Standard Description Language
SFE	Single-Feedback Neighbor Estimator
SNR	signal-to-noise ratio
SPaC	Simple Packet Combining
TC	Turbo Coding
UMTS	Universal Mobile Telecommunication System
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Network

Bibliography

[AAA05] A. Azgin, Y. Altunbasak, and G. AlRegib. Cooperative MAC and routing protocol for wireless ad hoc networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, St. Louis, US-MO, Nov. 2005.

[ABS08] H. Adam, C. Bettstetter, and S. M. Senouci. Adaptive relay selection in cooperative wireless networks. In *Proc. IEEE Intern. Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Cannes, France, Sep. 2008.

[ABS09] H. Adam, C. Bettstetter, and S. M. Senouci. Multi-hop-aware cooperative relaying. In *Proc. IEEE Vehicular Techn. Conf. (VTC-spring)*, Barcelona, Spain, Apr. 2009.

[ACLY00] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W.-H. Yeung. Network information flow. *IEEE Trans. Inform. Theory*, 46:1204 – 1216, 2000.

[AEB09a] H. Adam, W. Elmenreich, and C. Bettstetter. Apparatus and method for cooperative relaying in wireless systems using an extended channel reservation. European Patent EP 2326030 (A1), published 25 May 2011, filed 23 Nov. 2009.

[AEB09b] H. Adam, W. Elmenreich, and C. Bettstetter. Cooperative relay scheme having backward compatibility. European Patent EP 2326029 (A1) , published 25 May 2011, filed 23 Nov. 2009.

[AEBS09] H. Adam, W. Elmenreich, C. Bettstetter, and S. M. Senouci. CoRe-MAC: A MAC-protocol for cooperative relaying in wireless networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Honolulu, US-HI, Dec. 2009.

[Ala98] S. M. Alamouti. A simple transmit diversity technique for wireless communications. *IEEE J. Select. Areas Commun.*, 16(8):1451 – 1458, 1998.

[AYB11] H. Adam, E. Yanmaz, and C. Bettstetter. Contention-based estimation of neighbor cardinality. Apr. 2011. submitted & under review.

[AYEB10] H. Adam, E. Yanmaz, W. Elmenreich, and C. Bettstetter. Contention-based neighborhood estimation. In *Proc. IEEE Vehicular Techn. Conf. (VTC-spring)*, Taipei, Taiwan, May 2010.

[BA06] E. Beres and R. Adve. On selection cooperation in distributed networks. In *Proc. Conf. on Information Sciences and Systems*, pages 1056 – 1061, Princeton, US-NJ, Mar. 2006.

[BA07] E. Beres and R. Adve. Cooperation and routing in multi-hop networks. In *Proc. IEEE Intern. Conf. on Commun. (ICC)*, Glasgow, UK, June 2007.

[BA08] E. Beres and R. Adve. Selection cooperation in multi-source cooperative networks. *IEEE Trans. Wireless Commun.*, 7(1):118–128, Jan. 2008.

[Bar01] H.-J. Bartsch. *Taschenbuch Mathematischer Formeln.* Fachbuchverlag Leipzig, 19th edition, 2001.

[BB03] A.-L. Barabási and E. Bonabeau. Scale-free networks. *Scientific American*, 288:60–69, Apr. 2003.

[Bet04] C. Bettstetter. On the connectivity of ad hoc networks. *The Computer Journal*, 47(4):443–447, July 2004.

[BKRL06] A. Bletsas, A. Khisti, D.P. Reed, and A. Lippman. A simple cooperative diversity method based on network path selection. *IEEE J. Select. Areas Commun.*, 24(3):659 – 672, Mar. 2006.

[Ble05] A. Bletsas. *Intelligent Antenna Sharing in Cooperative Diversity Wireless Networks.* PhD thesis, Massachusetts Institute of Technology, School of Architecture and Planning, Sep. 2005.

[BSTS10] R. Blasco-Serrano, R. Thobaben, and M. Skoglund. Compress-and-forward relaying based on symbol-wise joint source-channel coding. In *Proc. IEEE Intern. Conf. on Commun. (ICC)*, Capetown, South Africa, May 2010.

[BSW07] A. Bletsas, H. Shin, and M. Z. Win. Cooperative communications with outage-optimal opportunistic relaying. *IEEE Trans. Wireless Commun.*, 6(9):3450–3460, Sep. 2007.

[CE04] A. Cerpa and D. Estrin. ASCENT: Adaptive self-configuring sensor networks topologies. *IEEE Trans. Mobile Comput.*, 3(3):272 – 285, 2004.

[CFG07] I. Cerutti, A. Fumagalli, and P. Gupta. Delay model of single-relay cooperative ARQ protocols in slotted radio networks with non-instantaneous feedback and Poisson frame arrivals. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, pages 2276–2280, Anchorage, US-AK, May 2007.

[CGB04] S. Cui, A. J Goldsmith, and A. Bahai. Energy-efficiency of MIMO and coopeartive MIMO techniques in sensor networks. *IEEE J. Select. Areas Commun.*, 22(6):1089–1097, Aug. 2004.

[CJBM02] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. Span: An energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks. *Wireless Networks*, 8(5):481–494, Sep. 2002.

[CK08] J. Camp and E. Knightly. Modulation rate adaptation in urban and vehicular environments: Cross-layer implementation and experimental evaluation. *IEEE/ACM Trans. Networking*, 18(6):1949–1962, Dec. 2008.

[Cov72] T. M. Cover. Broadcast channels. *IEEE Trans. Inform. Theory*, 18(1):2–14, Jan. 1972.

[CYQZ06] Y. Chen, G. Yu, P. Qiu, and Z. Zhang. Power-aware cooperative relay selection strategies in wireless ad hoc networks. In *Proc. IEEE Intern. Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Helsinki, Finland, Sep. 2006.

[CYW07] C.-T. Chou, J. Yang, and D. Wang. Cooperative MAC protocol with automatic relay selection in distributed wireless networks. In *Proc. Pervasive Computing and Communications Workshops*, White Plains, US-NY, Mar. 2007.

[CZZY10] B. Chen, Z. Zhou, Y. Zhao, and H. Yu. Efficient error estimating coding: Feasibility and applications. In *Proc. ACM SIGCOMM*, New Delhi, India, Sep. 2010.

[DDA02] M. Dohler, J. Dominguez, and H. Aghvami. Link capacity analysis for virtual antenna arrays. In *Proc. IEEE Vehicular Techn. Conf. (VTC-spring)*, Vancouver, Canada, Sep. 2002.

[DFEV05] H. Dubois-Ferrière, D. Estrin, and M. Vetterli. Packet combining in sensor networks. In *Proc. ACM Conf. on Embedded Networked Sensor Systems (SenSys)*, San Diego, US-CA, Nov. 2005.

[DM08] S. Dehnie and N. Memon. Cooperative diversity with selfish users. In *Proc. Conf. on Inform. Sciences and Systems (CISS)*, Princeton, US-NJ, Mar. 2008.

[DM09] S. Dehnie and N. Memon. Modeling misbehavior in cooperative diversiy: A dynamic game approach. *EURASIP J. on Advances in Signal Processing, Special Issue on Game Theory in Signal Processing and Commun.*, Apr. 2009.

[DT10] S. Dehnie and S. Tomasin. Detection of selfish nodes in networks using CoopMAC protocol with ARQ. *IEEE Trans. Wireless Commun.*, 9(7):2328–2337, July 2010.

[EAK$^+$02] J.-P. Ebert, S. Aier, G. Kofahl, A. Becker, B. Burns, and A. Wolisz. Measurement and simulation of the enery consumption of an WLAN interface. Technical Report TKN Technical Report TKN-02-010, Technical University Berlin, Telecommunication Networks Group, June 2002.

[ED06] K. Egoh and S. De. Priority-based receiver-side relay election in wireless ad hoc sensor networks. In *Proc. ACM Intern. Conf. on Commun. and Mobile Computing (CMC)*, pages 1177–1182, Vancouver, Canada, July 2006.

[Elm07] W. Elmenreich. Fusion of continuous-valued sensor measurements using confidence-weighted averaging. *J. Vibration and Control*, 13(9-10):1303–1312, 2007.

[EMA$^+$08] W. Elmenreich, N. Marchenko, H. Adam, C. Hofbauer, G. Brandner, C. Bettstetter, and M. Huemer. Building blocks of cooperative relaying in wireless systems. *e & i*, Springer, 125(10):353–359, 2008.

[FN01] L. M. Feeney and M. Nilsson. Investigating the energy consumption of a wireless network interface in an ad hoc networking environment. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, volume 3, pages 1548–1557, Anchorage, US-AK, Apr. 2001.

[GK00] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Trans. Inform. Theory*, 46(2):388–404, Mar. 2000.

[GKJ$^+$07] D. Gesbert, M. Kountouris, R. W. Heath Jr., C.-B. Chae, and T. Sälzer. Shifting the MIMO paradigm. *IEEE Signal Processing Mag.*, 24(5):36 – 46, Sep. 2007.

[Gol05] Andrea Goldsmith. *Wireless Communications.* Cambridge University Press, 2005.

[GWL03] Y. Gao, K. Wu, and F. Li. Analysis on the redundancy of wireless sensor networks. In *Proc. ACM Intern. Conf. on Wireless Sensor Networks and Applications (WSNA)*, San Diego, US-CA, Sep. 2003.

[HH06] C. Hausl and J. Hagenauer. Iterative network and channel decoding for the two-way relay channel. In *Proc. IEEE Intern. Conf. on Commun. (ICC)*, Istanbul, Turkey, June 2006.

[HH07] C. Hausl and J. Hagenauer. Relay communication with hierarchical modulation. *IEEE Commun. Letter*, 11(1):64–66, Jan. 2007.

[HHL06] Z. J. Haas, J. Y. Halpern, and L. Li. Gossip-based ad hoc routing. *IEEE/ACM Trans. Networking*, 14(3):479–491, June 2006.

[HK07] K.-S. Hwang and Y.-C. Ko. An efficient relay selection algorithm for cooperative networks. In *Proc. IEEE Vehicular Techn. Conf. (VTC-fall)*, Baltimore, US-MD, Sep. 2007.

[HN04] T. E. Hunter and A. Nosratinia. Distributed protocols for user cooperation in multi-user wireless networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, volume 6, pages 3788 – 3792, Nov. 2004.

[HN06] T. E. Hunter and A. Nosratinia. Diversity through coded cooperation. *IEEE Trans. Wireless Commun.*, 52(2):283 – 289, Feb. 2006.

[HST$^+$10] H. Han, B. Sheng, C. C. Tan, Q. Li, W. Mao, and S. Lu. Counting RFID tags efficiently and anonymously. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, San Diego, US-CA, Mar. 2010.

[HZF04] P. Herhold, E. Zimmermann, and G. Fettweis. A simple cooperative extension to wireless relaying. In *Proc. Int. Zurich Seminar on Comm.*, Zurich, Switzerland, 2004.

[IEEE03] *IEEE Std 802.11g - Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band*, 2003.

[IEEE07] IEEE. *IEEE Std 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2007.

[IEEE09] *IEEE Std 802.16j - Amendment 1: Multihop Relay Specifications*, June 2009.

[IHL07] A. S. Ibrahim, Z. Han, and K. J. R. Liu. Distributed energy-efficient cooperative routing in wireless networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Washington D.C., USA, Nov. 2007.

[Inf02] Infineon. *TDA 5250 D2 Data Sheet*, July 2002.

[ITU11] International telecommunication union: Market information and statistics. `http://www.itu.int/ITU-D/ict/statistics/`, Jan. 2011.

[JH06] Y. Jing and B. Hassibi. Distributed space-time coding in wireless relay networks. *IEEE Trans. Wireless Commun.*, 5(12):3524 – 3536, Dec. 2006.

[JJ09] Y. Jing and H. Jafarkhani. Single and multiple relay selection schemes and their achievable diversity orders. *IEEE Trans. Wireless Commun.*, 8(3):1414–1423, Mar. 2009.

[Kam04] K. D. Kammeyer. *Nachrichtenübertragung*. Teubner, 3rd edition, 2004.

[KBW04] A. Krohn, M. Beigl, and S. Wendhack. SDJS: Efficient statistics in wireless networks. In *Proc. IEEE Intern. Conf. on Network Protocols (ICNP)*, Berlin, Germany, Oct. 2004.

[KFV06] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela. Network coordination for spectrally efficient communication in cellular systems. *IEEE Wireless Commun. Mag.*, 13:56–61, 2006.

[KGG05] G. Kramer, M. Gastpar, and P. Gupta. Cooperative strategies and capacity theorems for relay networks. *IEEE Trans. Inform. Theory*, 51(9):3037 – 3063, Sep. 2005.

[KK05] V. Kawadia and P. R. Kumar. A cautionary perspective on cross-layer design. *IEEE Wireless Commun. Mag.*, 12:3–11, Feb. 2005.

[KM07] K. Kredo II and P. Mohapatra. Medium access control in wireless sensor networks. *Comput. Networks*, 51(4):961–994, 2007.

[KMAZ07] A. E. Khandani, E. Modiano, J. Abounadi, and L. Zheng. Cooperative routing in static wireless networks. *IEEE Trans. Commun.*, 55(11):2185 – 2192, Nov. 2007.

[KN06] M. Kodialam and T. Nandgopal. Fast and reliable estimation schemes in RFID systems. In *Proc. ACM Intern. Conf. on Mobile Computing and Networking (MobiCom)*, Los Angeles, US-CA, Sep. 2006.

[KNL07] M. Kodialam, T. Nandgopal, and W. C. Lau. Anonymous tracking using RFID tags. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, Anchorage, US-AK, May 2007.

[KRD06] S. Kumar, V. S. Raghavan, and J. Deng. Medium access control protocols for ad hoc wireless networks: A survey. *Ad Hoc Networks (Elsevier)*, 4(3):326–358, 2006.

[KST04] K. Kar, S. Sarkar, and L. Tassiulas. Achieving proportional fairness using local information in ALOHA networks. *IEEE Trans. Automatic Control*, 49:1858 – 1863, Oct. 2004.

[KW05] H. Karl and A. Willig. *Protocols and Architectures for Wireless Sensor Networks*. Wiley, 2005.

[LC04] S. Lin and D. J. Costello. *Error Control Coding*. Prentice Hall, 2nd edition, 2004.

[LHV07] C. K. Lo, R. W. Heath, and S. Vishwanath. Hybrid-ARQ in multihop networks with opportunistic relay selection. In *Proc. IEEE Intern. Conf. on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 3, pages 617–620, Honolulu, US-HI, Apr. 2007.

[LSM06] T. L. Lim, V. Srivastava, and M. Motani. Selective cooperation based on link distance estimations in wireless ad-hoc networks. In *Proc. IEEE Intern. Symp. on a World of Wireless, Mobile and Multimedia Networks (WOWMOM)*, Niagara-Falls/Buffalo, US-NY, June 2006.

[LSS05] R. Liu, P. Spasojević, and E. Soljanin. Cooperative diversity with incremental redundancy turbo coding for quasi-static wireless networks. In *Proc. IEEE Workshop on Signal Processing Advances in Wireless Communications*, New York, US-NY, June 2005.

[LT96] L. M. Leemis and K. S. Trivedi. A comparison of approximate interval estimators for the Bernoulli parameter. *The American Statistician*, 50:63–68, 1996.

[LTEA10] *3GPP TR 36.814 - Evolved Universal Terrestrial Radio Access (E-UTRA); Relay Architectures for E-UTRA (LTE-Advanced)*, Mar. 2010.

[LTN+07] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar. CoopMAC: a cooperative MAC for wireless LANs. *IEEE J. Select. Areas Commun.*, 25(2):340–354, Feb. 2007.

[LTW04] J. N. Laneman, D. N. C. Tse, and G. W. Wornell. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE J. Select. Areas Commun.*, 50(12):3062–3080, Dec. 2004.

[LVK+08] H. S. Lichte, S. Valentin, H. Karl, I. Aad, L. Loyola, and J. Widmer. Design and evaluation of a routing-informed cooperative MAC protocol for ad hoc networks. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, Phoenix, US-AZ, Apr. 2008.

[LVWD06] Y. Li, B. Vucetic, T. F. Wong, and M. Dohler. Distributed turbo coding with soft information relaying in multihop relay networks. *IEEE J. Select. Areas Commun.*, 24(11):2040–2050, Nov. 2006.

[LW03] J. N. Laneman and G. W. Wornell. Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Trans. Inform. Theory*, 49(10):2415–2425, Oct. 2003.

[LWCY10] T. Li, S. Wu, S. Chen, and M. Yang. Energy efficient algorithms for the RFID estimation problem. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, San Diego, US-CA, Mar. 2010.

[LWS+10] K. Loa, C.-C. Wu, S.-T. Sheu, Y. Yuan, M. Chion, D. Huo, and L. Xu. IMT-Advanced relay standards. *IEEE Commun. Magazine*, 48(8):40–48, Aug. 2010.

[MBM07] R. Mudumbai, G. Barriac, and U. Madhow. On the feasibility of distributed beamforming in wireless networks. *IEEE Trans. Wireless Commun.*, 6(5):1754 –1763, May 2007.

[MLC05] H. MacLeod, C. Loadman, and Z. Chen. Experimental studies of the 2.4-GHz ISM wireless indoor channel. In *Proc. IEEE Conf. on Communication Networks and Services Research*, pages 63–68, Halifax, Canda, May 2005.

[MM09] G. D. Menghwar and C. F. Mecklenbräuker. Outage performance of two users cooperative network coding. In *Proc. IEEE Intern. Symp. on Commun. and Inform. Techn. (ISCIT)*, Incheon, Korea, Sep. 2009.

[MMMZ08] R. Madan, N. B. Mehta, A. F. Molisch, and J. Zhang. Energy-efficient cooperative relaying over fading channels with simple relay selection. *IEEE Trans. Wireless Commun.*, 7(8):3010–3025, Aug. 2008.

[MWH01] M. Mauve, A. Widmer, and H. Hartenstein. A survey on position-based routing in mobile ad hoc networks. *IEEE Network*, 15(6):30–39, Nov. 2001.

[MYAB09] N. Marchenko, E. Yanmaz, H. Adam, and C. Bettstetter. Selecting a spatially efficient cooperative relay. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Honolulu, US-HI, Dec. 2009.

[MYPK07] S. Moh, C. Yu, S.-M. Park, and H.-N. Kim. CD-MAC: Cooperative diversity MAC for robust communication in wireless ad hoc networks. In *Proc. IEEE Intern. Conf. on Commun. (ICC)*, pages 3636–3641, Glasgow, UK, June 2007.

[OAF$^+$08] F. A. Onat, A. Adinoyi, Y. Fan, H. Yanikomeroglu, J. S. Thompson, and I. D. Marsland. Threshold selection for SNR-based selective digital relaying in cooperative wireless networks. *IEEE Trans. Wireless Commun.*, 7(11):4226–4237, Nov. 2008.

[PH09] S. W. Peters and R. W. Hearth. The future of WiMAX: Multihop relaying with IEEE 802.16j. *IEEE Commun. Magazine*, 47(1):104–111, Jan. 2009.

[Phi10] J. R. Phillips. Online curve fitting and surface fitting at zunzun.com. `http://zunzun.com/`, Sep. 2010.

[PNS00] R. J. Punnoose, P. V. Nikitin, and D. D. Stancil. Efficient simulation of Ricean fading within a packet simulator. In *Proc. IEEE Vehicular Techn. Conf. (VTC-fall)*, volume 2, pages 764–767, Boston, US-MA, Sep. 2000.

[PP02] A. Papoulis and S. U. Pillai. *Probability, Random Variables and Stochastic Processes.* McGraw-Hill, 4th edition, 2002.

[QNL10] C. Qian, H. Ngan, and Y. Liu. Cardinality estimation for large-scale RFID systems. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, San Diego, US-CA, Mar. 2010.

[Rao73] C. R. Rao. *Linear Statistical Inference and Its Applications.* John Wiley & Sons, 2nd edition, 1973.

[Rap02] T. S. Rappaport. *Wireless Communications: Principles and Practice.* Prentice Hall, 2nd edition, 2002.

[RF06] P. Rost and G. Fettweis. A cooperative relaying scheme without the need for modulation with increased spectral efficiency. In *Proc. IEEE Vehicular Techn. Conf. (VTC-fall)*, Montreal, Canada, Sep. 2006.

[SA06] N. Shastry and R. S. Adve. Stimulating cooperative diversity in wireless ad hoc networks through pricing. In *Proc. IEEE Intern. Conf. on Commun. (ICC)*, volume 8, pages 3747 – 3752, Istanbul, Turkey, June 2006.

[San05] P. Santi. Topology control in wireless ad hoc and sensor networks. *ACM Computing Surveys*, 37:164–194, Mar. 2005.

[SB05] G. Scutari and S. Barbarossa. Distributed space-time coding for regenerative relay networks. *IEEE Trans. Wireless Commun.*, 4(5):2387 – 2399, Sep. 2005.

[SCS03] Y. Sasson, D. Cavin, and A. Schiper. Probabilistic broadcast for flooding in wireless mobile ad hoc networks. In *Proc. IEEE Wireless Commun. & Networking Conf. (WCNC)*, pages 1124–1130, New Orleans, US-LA, Mar. 2003.

[SE04] A. Stefanov and E. Erkip. Cooperative coding for wireless networks. *IEEE Trans. Commun.*, 52(9):1470 – 1476, Sep. 2004.

[SEA98] A. Sendonaris, E. Erkip, and B. Aazhang. Increasing uplink capacity via user cooperation diversity. In *Proc. IEEE Intern. Symp. on Inform. Theory (ISIT)*, page 156, Cambridge, US-MA, Aug. 1998.

[SEA03a] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity – Part I: system description. *IEEE Trans. Commun.*, 51(11):1927–1938, Nov. 2003.

[SEA03b] A. Sendonaris, E. Erkip, and B. Aazhang. User cooperation diversity – Part II: Implementation aspects and performance analysis. *IEEE Trans. Commun.*, 51(11):1939–1948, Nov. 2003.

[SGL06] A. Scaglione, D. L. Goeckel, and J. N. Laneman. Cooperative communications in mobile ad hoc networks. *IEEE Signal Processing Mag.*, 23(5):18 – 29, Sep. 2006.

[SJR87] A. A. M. Saleh, A. J. Rustako Jr., and R. S. Roman. Distributed antennas for indoor radio communication. *IEEE Trans. Commun.*, 35(12):1245 – 1251, Dec. 1987.

[Skl97a] B. Sklar. Rayleigh fading channels in mobile digitial communication systems part I: Characterization. *IEEE Wireless Commun. Mag.*, 35(7):90–100, July 1997.

[Skl97b] B. Sklar. Rayleigh fading channels in mobile digitial communication systems part II: Mitigation. *IEEE Wireless Commun. Mag.*, 35(9):148–155, Sep. 1997.

[SLM10] B. Sheng, Q. Li, and W. Mao. Efficient continuous scanning in RFID systems. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, San Diego, US-CA, Mar. 2010.

[SLY09] W.-K. Sze, W.-C. Lau, and O.-C. Yue. Fast RFID counting under unreliable radio channels. In *Proc. IEEE Intern. Conf. on Commun. (ICC)*, Dresden, Germany, June 2009.

[SV06] M. R. Souryal and B. R. Vojcic. Performance of amplify-and-forward and decode-and-forward relaying in Rayleigh fading with turbo codes. In *Proc. IEEE Intern. Conf. on Acoustics, Speech, and Signal Processing (ICASSP)*, volume 4, pages 681 – 684, Toulouse, France, May 2006.

[SVML03] G. Simon, P. Völgyesi, M. Maróti, and Á. Lédeczi. Simulation-based optimization of communication protocols for large-scale wireless sensor networks. In *Proc. IEEE Aerospace Conf.*, volume 3, pages 1339 – 1346, Big Sky, US-MT, Mar. 2003.

[SWW04] J. M. Shea, T. F. Wong, and W.-H. Wong. Cooperative-diversity slotted ALOHA. In *Proc. Int. Conf. on Quality of Service in Heterogeneous Wired/Wireless Networks (QSHINE)*, Dallas, US-TX, Oct. 2004.

[TV05] D. Tse and P. Viswanath. *Fundamentals of Wireless Communication.* Cambridge University Press, 2005.

[VK10] S. Valentin and H. Karl. Cooperative feedback to improve capacity and error rate in multiuser diversity systems - An OFDM case study. *European Trans. on Telecomms.*, 21(8):714–724, Dec. 2010.

[VLK$^+$08] S. Valentin, H. S. Lichte, H. Karl, I. Aad, L. Loyola, and J. Widmer. Opportunistic relaying vs. selective cooperation: Analyzing the occurrence-conditioned outage capacity. In *Proc. ACM Intern. Conf. on Modeling, Analysis, and Simulation of Wireless and Mobile Systems (MSWiM)*, Vancouver, Canada, Oct. 2008.

[WC02] B. Williams and T. Camp. Comparison of broadcast techniques for mobile ad hoc networks. In *Proc. ACM Intern. Symp. on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pages 194–205, Lausanne, Switzerland, June 2002.

[WHL09] B. Wang, Z. Han, and K. J. R. Liu. Distributed relay selection and power control for multiuser cooperative communication networks using Stackelberg game. *IEEE Trans. Mobile Comput.*, 8(7):975 – 989, July 2009.

[WVK07] D. H. Woldegebreal, S. Valentin, and H. Karl. Outage probability analysis of cooperative transmission protocols without and with network coding: Inter-user channels based comparision. In *Proc. ACM Intern. Conf.*

on Modeling, Analysis, and Simulation of Wireless and Mobile Systems (MSWiM), pages 36–44, Crete Island, Greece, Oct. 2007.

[WZ76] A. Wyner and J. Ziv. The rate-distortion function for source coding with side information at the decoder. *IEEE Trans. Inform. Theory*, 22(1):1–10, Jan. 1976.

[XST$^+$10] L. Xie, B. Sheng, C. C. Tan, H. Han, Q. Li, and D. Chen. Efficient tag identification in mobile RFID systems. In *Proc. IEEE Intern. Conf. on Comput. Commun. (INFOCOM)*, San Diego, US-CA, Mar. 2010.

[XZQ06] L. Xie, X. Zhang, and P. Qiu. Relay selection strategies for distributed space-time cooperative systems over wireless ad-hoc networks. In *Proc. IEEE Intern. Conf. on Computer Commun. and Networks (ICCN)*, pages 213–218, Arlington, US-VA, Oct. 2006.

[Yan08] E. Yanmaz. Epidemic propagation in overlaid wireless networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, New Orleans, US-LA, Dec. 2008.

[YHXM09] Y. Yang, H. Hu, J. Xu, and G. Mao. Relay technologies for WiMAX and LTE-advanced mobile systems. *IEEE Commun. Magazine*, 47(10):100 – 105, Oct. 2009.

[ZAL07a] Y. Zhao, R. Adve, and T. J. Lim. Beamforming with limited feedback in amplify-and-forward cooperative networks. In *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, pages 3457–3461, Washington D.C., USA, Nov. 2007.

[ZAL07b] Y. Zhao, R. Adve, and T. J. Lim. Improving amplify-and-forward relay networks: Optimal power allocation versus selection. *IEEE Trans. Commun.*, 6(6):3114–3123, Aug. 2007.

[ZGLB10] M. Zorzi, A. Gluhak, S. Lange, and A. Bassi. From today's INTRAnet of things to a furture INTERnet of things: A wireless- and mobility-related view. *IEEE Commun. Magazine*, 17(6):44–51, Dec. 2010.

[ZHF04] E. Zimmermann, P. Herhold, and G. Fettweis. The impact of cooperation on diversity-exploiting protocols. In *Proc. IEEE Vehicular Techn. Conf. (VTC-spring)*, Milan, Italy, May 2004.

[ZK03] M. Zúñiga and B. Krishnamachari. Optimal transmission radius for flooding in large scale sensor networks. In *Proc. Intern. Conf. Distr. Comput. Sys. Workshops*, Providence, US-RI, May 2003.

[ZR94] M. Zorzi and R. R. Rao. Capture and retransmission control in mobile radio. *IEEE J. Select. Areas Commun.*, 12(8):1289–1298, Oct. 1994.

[ZV05] B. Zhao and M. C. Valenti. Practical relay networks: A generalization of hybrid-ARQ. *IEEE J. Select. Areas Commun.*, 23(1):7–18, Jan. 2005.

Curriculum Vitae

Helmut Adam

October 25th 1977	Born in Graz, Austria
September 1984 – June 1988	Elementary School in Kalsdorf
September 1988 – June 1992	High School Bundesrealgymnasium Oeversee Graz
October 1992 – June 1997	High School HTL Graz Gösting
October 1997 – May 1998	Military Service in Villach
October 1998 – February 2005	Studies of Telematics Technical University of Graz
April 2004 – February 2005	Internship Sense & Control Departement Infineon Technologies Graz
February 2005	Graduation (Telematics) with distinction
May 2005 – March 2006	Verification Engineer Sense & Control Departement Infineon Technologies Graz
since April 2006	PhD Studies and Research Assistant Institute of Networked and Embedded Systems Alpen-Adria-Universität Klagenfurt