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Resource-Efficient Relay Selection in Cooperative Wireless Networks

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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.

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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.

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Kurzfassung

Die vorliegende Arbeit beschäftigt sich mit Protokollen zum kooperativen Relaying. Dabei bedient man sich eines Relayknotens, der Daten bei einer drahtlose Übertragung von einem Sender zu einem Empfänger “mithört”, um diese ebenfalls an den Empfänger zu senden. Die so erzielte Signaldiversität verbessert die Kommunikationszuverlässigkeit in störungsanfälligen Kanälen.

Während kooperatives Relaying den Durchsatz für einen Kanal verbessert, kann sich der Gesamtdurchsatz in einem Netzwerk durch dabei entstehende Interferenzen auf anderen Übertragungen gleichzeitig verringern. Darauf wird in Kapitel 3 eingegangen. Es wird daher ein Relayauswahlverfahren vorgeschlagen, welches zusätzlich entstandene Interferenz reduziert.

Für die Auswahl des Relayknotens fällt allerdings Overhead an, welcher die erzielten Performanzgewinne zumindest teilweise zunichte machen kann. Kapitel 4 stellt ein analytisches Framework für die Modellierung eines kooperativen Relayings mit Hilfe von Semi-Markov-Prozessen vor. Es wird untersucht, inwieweit der zeitliche Aspekt in der Relayauswahl in kooperativen Protokollen eine Rolle spielt. Vier Relay-Update-Methoden werden verglichen, und es zeigt sich, dass der Selektionsoverhead den Durchsatz und die Energieeffizienz in hohem Maße reduzieren kann. Es wird daher vorgeschlagen, eine adaptive Auswahlregelung anzuwenden, wonach ein neues Relay nur dann ausgewählt wird, wenn die kooperative Verbindung ausfällt.

Kapitel 5 enthält Messergebnisse in industriellen drahtlosen Sensornetzwerken von kooperativem Relaying mit drei Relay-Auswahlmethoden. Implementiert wurden sie auf serienmässige IEEE 802.15.4 Hardware. Die Messungen haben gezeigt, dass alle kooperativen Protokolle dem nicht-kooperativen Ansatz, sowohl bezüglich Übertragungsrate als auch Verzögerung, überlegen sind. Protolemulationen basierend auf Trace-Dateien zeigen, wie Systemparameter eingestellt werden sollen, um die Zuverlässigkeit der Übertragungen zu verbessern und die Zahl der Relayauswahlprozesse zu minimieren.

Abstract

This thesis focuses on cooperative relaying protocols employing a relay node that overhears data transmissions between a source and a destination nodes and retransmits the data when necessary. The achieved signal diversity at the destination improves the data recovery in fading-rich environments.

While cooperative relay can improve communication on one link, the induced relay interference can decrease the overall network capacity. In Chapter 3 of this thesis a contention-based relay selection method is proposed that assigns a relay which retransmissions have low impact on neighboring nodes. By using one of the proposed contention and selection functions, a higher spatial channel reuse in uniform and clustered networks is achieved.

The main role of relay selection is to timely provide a relay that maximizes certain performance metrics. However, the required coordination overhead can diminish performance benefits anticipated from cooperation. Chapter 4 presents an analytical framework for modeling cooperative relaying with relay selection using semi-Markov processes. The comparison of four relay update schemes shows that the required selection overhead can significantly decrease throughput and energy efficiency of cooperative relaying when selections are performed frequently and overhead is large. A proposed adaptive selection scheme, which triggers a new selection only when the cooperative link fails, is shown to have the lowest selection rate among the compared schemes in slow-fading channels.

Chapter 5 provides an experimental study of cooperative relaying in industrial wireless sensor networks. Cooperative relaying with three relay selection schemes is implemented in off-the-shelf IEEE 802.15.4 devices. Measurements show that all cooperative protocols outperform non-cooperative transmissions in terms of delivery ratio and delay. A trace-based analysis is used to demonstrate how system parameters can be adjusted to improve the delivery ratio and reduce the number of triggered selections.

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It all started in January 2008, after Professor Dr.-Ing. Christian Bettstetter offered me an opportunity to join his research group at the Institute of Networked and Embedded Systems (NES) at University of Klagenfurt. This thesis is the result of my research activities during these years. I am very grateful to him for the chance to conduct research in an excellent work environment. His strong support and competent guidance played a major role in accomplishing this dissertation.

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I would like to thank my parents Irena and Valery, and my twin brother Vladimir, who support and encourage me throughout my life. My very special thanks is to my girlfriend Margot who filled my last five years with joy and love.

Klagenfurt, August 2013 — Nikolaj Marchenko

Contents

CHAPTER 1 Introduction

Wireless communication networks have been experiencing an extraordinary growth in last two decades. As in numerous other industries, the expansion became possible thanks to tremendous technological advances in microprocessor electronics. On one side, the boost of the computational power enables the use of advanced signal processing techniques and increases the communication data rate. On the other side, the concurrent decrease of the chip area, allows the production of smaller wireless devices.

Wireless broadband networks for voice and data communication quickly became omnipresent in our lives. Internet of Things is another fast growing industry of wireless sensor networks and Radio Frequency Identification (RFID) tags that connect real physical objects to Internet. And with further shrinkage in size, wireless devices of only few cubic millimeters (called Smart Dust [KKP99]) are envisioned as one of the next frontiers for wireless networks.

Researchers in academia and industry are striving to overcome diverse technological obstacles for future wireless networks. One of the main challenges for reliable wireless communication is posed by the wireless medium itself. This thesis explores how nodes in a wireless network can cooperate with each other to mitigate negative effects of wireless fading, and how this cooperation can be efficiently coordinated.

1.1 Wireless Channel and Signal Diversity

A wireless signal x sent by a transmitter s (source) propagates through the environment as a wavefront with a certain carrier frequency f_c. Only part of the transmitted signal energy from this wavefront can be sensed by an antenna at the receiver d (destination). The amount of the signal energy received at d depends on the transmission power p_{tx}, the distance between s and d, propagation environment, antennas, and f_c. The received signal y also entails the thermal noise from the propagation channel and receiver circuits.

The quality of the received signal is assessed as the ratio between the received signal power p_{rx} and induced noise and interference power p_{n},

$$\gamma_{sd} = \frac{p_{\mathrm{rx}}}{p_{\mathrm{n}}}, \tag{1.1}$$

and is known as Signal-to-Noise Ratio (SNR). A receiver can reconstruct the received signal correctly as long as its SNR is above a certain threshold level γ_{thr}. If $\gamma_{sd} < \gamma_{\mathrm{thr}}$, the signal cannot be recovered correctly and the communication channel is considered to be in *outage*.

While propagating, some of the signal energy can be dispersed by the objects on its way, such as walls, people, and trees. This effect is called *shadowing*, and depends on the propagation environment and the carrier frequency f_c. Since surrounding objects are typically larger than communicating devices, significant changes in shadowing effects can be seen only when a device is moved at a large distance. Therefore, shadowing is sometimes also referred to as *large-scale fading*. SNR decrease due to shadowing can be mitigated by proportional increase of the transmission power.

A propagating signal can also be reflected from surrounding objects and create other wavefronts. All signal wavefronts are then superimposed at the receiver. But due to differences in traveled distances, signals arrive at different times with different powers and phase offsets. As a result, their superposition can lead to strong decrease in the signal SNR, which makes the recovery of the initially modulated signal very difficult. This effect is called *multi-path fading* or *small-scale fading*, since already very small changes in the environment lead to different phase offsets and strong fluctuations in the received signal power. Therefore, countering such fading is particularly challenging and cannot be done with simple boost of transmission power. Further details on signal propagation in wireless radio channels can be found e.g., in [Skl97a, Skl97b, Pro01, Rap02, Gol05, SA05]. The referenced work also includes detailed descriptions of various techniques to overcome multi-path fading. Next, only a brief overview of some of them is given.

Sophisticated signal processing techniques can be used at transmitter and receiver to mitigate multi-path fading. One technique that can be employed is signal *equalization*, where s, first, transmits a signal sequence known to the receiver. Based on the received signal, d can evaluate the effect of multi-path fading on following unknown transmissions. However, at mobile nodes or in dynamic environments, multi-path fading becomes difficult to predict and equalization less reliable. Furthermore, in small low-power devices sophisticated signal processing can hardly be applied since computational power is very limited due to strict size and complexity constraints.

Several *diversity* techniques are proposed to counter multi-path fading employing intrinsic properties of the wireless medium. A common idea behind these techniques is to provide to d multiple copies of the same data signal x. If the received copies experienced different multi-path fading while propagating to d, one of them or their combination can lead to successful data recovery.

Following diversity techniques are commonly used [Gol05, TV05]:

- *Time diversity*: Source transmits copies of data on the same frequency channel in separated time slots. Due to small changes in the environment or movements of s and d between transmissions, received signals have different multi-path fading at d. However, when additional data copies come with very similar fading, they do not provide any new information for signal recovery. This can be the case e.g., in environments with low mobility, where fading channels are strongly correlated in time. Time diversity is employed by Automatic Repeat-reQuest (ARQ) and Hybrid-ARQ protocols [LCM84, ZRM97, LC04].

- *Frequency diversity*: Source transmits copies of data on different frequency channels. Since radio waves propagate differently on different carrier frequencies, they arrive to d with different multi-path fading, which again can be exploited. However, this is possible only when fading on the used frequencies is uncorrelated, i.e., the difference between used frequencies is larger than the corresponding coherence bandwidth. Frequency diversity is employed e.g., in frequency spread-spectrum and Orthogonal Frequency-Division Multiplexing (OFDM) [TV05, vNP00, PBZ95].

- *Antenna diversity*: Diversity techniques based on the usage of more than one antenna for transmitting or/and receiving fall into this category [Gol05]. The main idea behind *transmitter diversity* is the use multiple antennas to transmit several data copies. Due to a spatial separation of antennas, the received copies experience different multi-path fading and provide signal diversity at the receiver. In *receiver diversity*, multiple antennas are used for receiving data. If orthogonal space-time codes are applied, transmitter can send either the same or different data on its antennas simultaneously, and provide better diversity or transmission rate, respectively. Such systems are known as Multiple Input Multiple Output (MIMO) [TV05, BCC+10]. Finally, in *polarization diversity*, transmitting antennas send signals with different polarization, which then reflect from surrounding objects with different phase offsets.

However, the use of multiple antennas requires their minimal physical separation to guarantee that incoming signals at the receiver experience uncorrelated multi-path fading. This requirement cannot be fulfilled on small devices.

- *Cooperative diversity*: Source broadcasts data to d and another node called *relay*. After receiving the data, the relay retransmits its copy to d. In this way, two copies of the same data arrive to destination via different paths — directly from source, and from the retransmitting relay. Due to spatial separation of the source and relay, signals coming from these nodes experiences different multi-path fading, which can be exploited by destination for reliably data recovery [LTW04, SEA03a, SEA03b]. Multiple relays can also be used to increase signal diversity. Since cooperative diversity relies on antennas of other nodes in the network, it can be seen as distributed antenna diversity.

  However, use of cooperative diversity implies the availability of a node willing to act as relay. Furthermore, coordination of source and relay transmissions in a wireless network is challenging and can diminish performance benefits gained through cooperation.

Since both antenna and cooperative diversity require certain spatial separation of employed antennas, a common term *spatial diversity* for both schemes can also be used.

The focus of the thesis at hand is on the cooperative diversity and its efficient coordination in wireless networks. Retransmission protocols that employ cooperative diversity are also called *cooperative relaying* protocols. If not otherwise mentioned, the use of single cooperative relay is considered.

1.2 Cooperative Diversity and Relay Selection

In their seminal work, Laneman et al. [LTW04] show that cooperative diversity outperforms non-cooperative direct transmissions and the resulting outage probability at d declines proportionally to $1/\gamma_{sd}^2$ when γ_{sd} is high and one relay is used. The power with which the outage probability declines is called *diversity order*. The same diversity order of two can be achieved in a multiple antenna system where either transmitter or receiver use two antennas.

However, there can be multiple nodes in a network that can be used as a relay for a given s-d pair. *Relay selection* is required to identify and assign one of this nodes to assist on s-d transmissions. In the seminal work by Bletsas et al. [BKRL06], a cooperative diversity with relay selection called *opportunistic relaying* is introduced. According to the proposed proactive relay selection, a node in the network is a relay candidate if it receives signaling messages from both s and d. Based on the channel estimation obtained from these messages, a node with the best end-to-end channel is assigned as relay before each data transmission from s. The authors show that if there are M relay candidates during the selection procedure, cooperative retransmission with the selected relay provides diversity order of $M + 1$. This corresponds to the diversity order of a Multiple Input Single Output (MISO) system with $M + 1$ antennas, or cooperative relaying with all M nodes retransmitting to d with orthogonal Distributed Space-Time Code (DSTC) [LW03].

The results in [BKRL06] and related work (see an overview later in Section 2.4) show that cooperative diversity with relay selection can be effective means to improve reliability of wireless transmissions in fading-rich environments. However, efficient application of such cooperative relaying protocols in real-world networks remains challenging. Here is only a short list of challenges relevant to this thesis.

- *Local selection metrics:* Relay selection is performed based on certain local metrics obtained from potential relays. These metrics are used to select a relay that provides maximum performance gain e.g., in outage probability or energy efficiency. If there are several metrics considered jointly (e.g., SNR, distance, and battery life), they should mapped into a single utility metric, which defines the value of each potential relay. However, finding such a utility mapping function to maximizes the required performance in variety of conditions can be difficult.

  Since a relay is assigned for cooperation on subsequent data packet(s), there is another challenge for accurate relay selection: after a relay is selected, such local metrics as Channel State Information (CSI) can become quickly outdated. As a result, not an optimal relay is used. Finally, some metrics can be incomplete or erroneous.

- *Resource Allocation:* The use of another node for data retransmission opens possibilities for optimized allocation of spectrum and energy resources. However, it also implies that additional interference is induced into the network. This means that a relay retransmission creates additional interferences at other receivers, which can lead to outages on certain links and decrease of the overall network throughput.
- *Selection overhead:* Local metrics have to be exchanged either among potential relays, or communicated to the "selecting" node, which is typically either s or d. In distributed wireless networks, where the access to the spectrum is not controlled centrally, communication of multiple nodes requires certain coordination overhead. Such overhead implies additional delays before data can be transmitted by s. Furthermore, extra energy is used for listening and transmitting signaling messages. As a result, introduced selection overhead can significantly reduce benefits in throughput and energy efficiency gained through selection. Finally, due to occasional collisions of signaling messages, it is possible that none of the available relay candidates is selected.
- *Integration into the protocol stack:* Cooperative relaying has to be integrated into the communication protocol stack. This implies that additional coordination with other layers needs to be specified. Some modifications can include a) coding techniques and optimization of transmission power and rate on the physical layer, b) channel reservation and integrated link error control on the data link layer, and c) joint optimized selection of cooperative relay and multi-hop routing on the network layer. However, cooperative relaying and its cross-layer optimization should not harm other aspects of communication.

1.3 Thesis Contributions and Outline

The thesis at hand investigates some of the aforementioned challenges and focuses in particular on practical relay selection aspects. Chapter 2 provides an overview of cooperative relaying with literature survey. The main contributions of this thesis are done in three following chapters:

Chapter 3: Spatial Channel Reuse in Cooperative Relaying

On a simple five-node setup, the impact of relay interference on overall network throughput is investigated. We show that cooperative relaying, indeed, can decrease network performance. We propose several contention-based relay selection procedures for selection of spatially efficient relay nodes, i.e., a relay node which prevents fewer other nodes from channel access is preferred. The selection procedure introduces utility and selection functions that can use the node degree and relative location information to choose suitable relays. The comparison of the introduced schemes in uniform and clustered networks shows that significant improvements in spatial efficiency can be achieved when a proper relay selection is performed.

Chapter 4: Selective Cooperative ARQ: An Analytical Framework
We introduce an analytical framework based on semi-Markov processes that enables comparative analysis of cooperative ARQ protocols with relay selection in time-correlated channels. It takes into account selection overhead and energy consumption. Four practical relay selection schemes are modeled and compared in throughput and energy efficiency. The results show a tradeoff between the required relay selection overhead and the resulting throughput, and suggest that less frequent relay selections can be more efficient than the use of selection diversity at each transmitted packet.

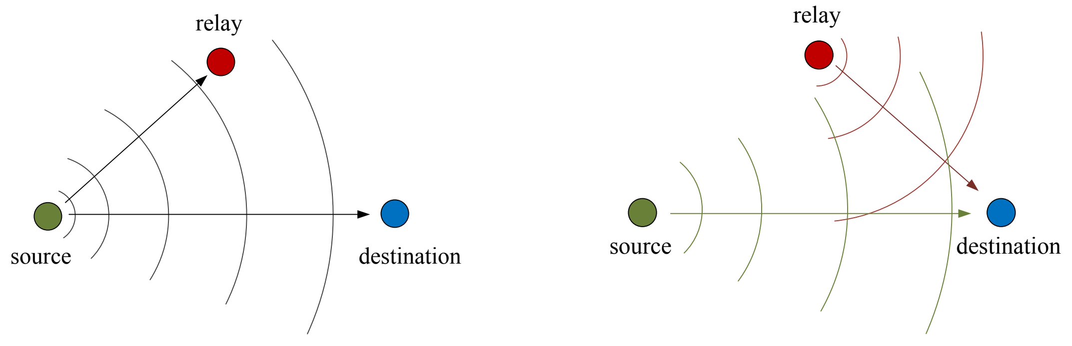
Chapter 5: Cooperative ARQ in Industrial WSN: An Experimental Study
We present an experimental study of three cooperative relaying protocols for industrial wireless sensor networks. In highly dynamic and heavily cluttered industrial environments, cooperative relaying is particularly beneficial for providing reliable and timely communication. We implemented three relaying schemes in off-the-shelf devices compliant with IEEE 802.15.4 [IEE06] and deployed them in a factory environment. The protocol performance measurements show that cooperative relaying outperforms time diversity in mean delivery ratio and delay. Additionally, cooperative relaying is particularly beneficial in mitigating short-term outages which can be harmful in time-critical control applications. We employ trace-based analysis to investigate how system parameters can be adjusted to balance the delivery ratio and selection rate.

Some of the work presented in this thesis has been performed in cooperation with H. Adam, T. Andre, C. Bettstetter, G. Brandner, W. Masood, and E. Yanmaz. Some parts of the thesis have been published in [2]-[11] and are still under review in [1]. Note that those publications are referenced numerically, while all other references are alphanumerical.

CHAPTER 2 Cooperative Relaying: Background and Literature Survey

2.1 Introduction

The idea of a three-terminal communication channel is introduced by van der Meulen in 1971 [vdM71]. The concept is shown in Figure 2.1 and is known as relay channel. The setup consists of three nodes: a source node s, a destination node d, and a relay node r. Communication between the three nodes is performed in two phases: *broadcast phase* and *retransmission phase*. In the broadcast phase, s broadcasts a signal to r and d. Both receiving nodes store incoming versions of the signal locally. In the retransmission phase, s and r send their copies of the signal to d.



(a) Broadcast phase (b) Retransmission phase

Figure 2.1: Concept of a relay channel.

First studies of the relay channel provided general theoretical capacity bounds in Gaussian channels with the use of full-duplex radios [vdM77, CG79]. In early

2000's the topic of relay channel communication was revived as a result of substantial advances in signal processing techniques such as MIMO, and since then has been receiving significant attention in the wireless research community.

In their seminal work [LWT01, LTW04] Laneman et al. coin the term *cooperative diversity* to describe the use of relay channel to overcome negative effects of multipath fading on direct *s*-*d* transmissions. The authors study orthogonal cooperative diversity protocols where in the retransmission phase only r forwards its signal copy to d. The combination of the signal from s in the broadcast phase and the signal from r in the retransmission phase is used by d for demodulation and decoding. Since s and r are located at some distance from each other, multi-path fading is considered to be uncorrelated on *s*-*d* and *r*-*d* channels. As a result, two copies of the same signal with uncorrelated disturbance arrive to d and provide signal diversity.

Due to its wide spread across various wireless research topics, use of cooperative diversity can be found under different names. Here are few examples: *cooperative relaying* is used to emphasize the use of relaying protocol on data link level [DH05, MMMZ08]; *cooperative (H)-ARQ* is referred to specific cooperative relaying protocols where relay retransmission is a part of the error control (similar to point-to-point (H)-ARQ) [ZV05, DLNS06]; *virtual MIMO* and *virtual antenna array* are used when multiple relays are employed as distributed MIMO or distributed beamforming [Jay06, Doh03].

In this thesis, the term *cooperative relaying* is used to refer to a protocol employing cooperative diversity in general, and *cooperative ARQ* is used to refer to a protocol with ARQ retransmissions by relay without soft information combining at d.

Despite its seeming simplicity, cooperative relaying turned out to be a very fruitful and multifarious research topic. This chapter gives a brief overview of some major aspects of cooperative relaying and should help the reader to get a broader perspective on the topic.

The discussed aspects are grouped according to the layer in the protocol stack architecture shown in Figure 2.2. PHY represents the physical layer which is responsible for physical signal transmission and reception. The Medium Access Control (MAC) sublayer defines how the medium is accessed by communicating nodes in the network. Together with the Logic Link Control (LLC) sublayer — an error control specification on how data are retransmitted when errors on the PHY layer occur, they build a data link layer in the conceptual Open Systems Interconnection (OSI) model. The network layer defines routing functions such

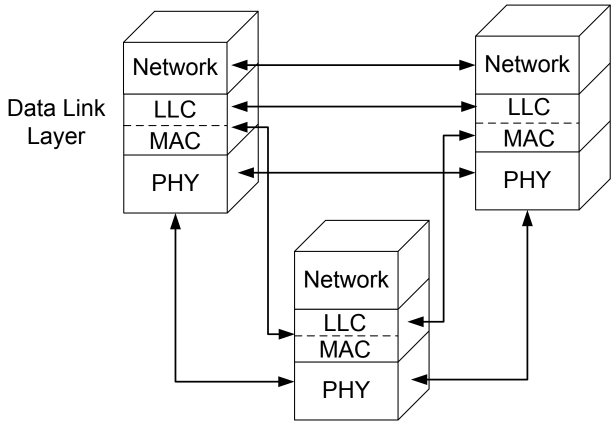


Figure 2.2: A protocol stack incorporating cooperative relaying.

as optimal route discovery and its maintenance in multi-hop networks. In its simplest form, cooperative relaying can be performed using PHY and MAC layers and remains "invisible" to the higher layers in the protocol stack. However, use of certain information from the network layer for cooperative communication has also been proposed in the literature and is discussed in Section 2.5.

A major part of this thesis addresses relay selection aspects on the data link layer. There, the data coming from the network layer at s is transmitted to d in chunks. Throughout this thesis such a transmission is referred to as a `DATA` packet, `DATA`, or simply a packet. The use of related terms such as data frame, datagram, or data message is also common in the literature. Messages generated by the data link for coordination activities are referred to as signaling messages, and are also typeset in a typewriter font, e.g., `ACK`.

2.2 Physical Layer

2.2.1 Retransmission by Relay

First, let us address the question *how the received information is processed by the relay*. The main options are defined as following [LTW04, RW06]:

- *Amplify-and-Forward (AF)*: Relay does not decode `DATA` packets from s and simply retransmits the amplified version of `DATA` it receives in the broadcast phase. The benefit of this scheme is in its simplicity since demodulation and packet decoding at r are not needed. However, together with the useful information from s, noise and interference on the s-r channel are also amplified and retransmitted to d. Thus, a signal received at d from r cannot have a higher SNR than the corresponding signal received at r from s.

- *Decode-and-Forward (DF)*: Relay decodes `DATA` packets from s before forwarding them to d. Typically, only when a `DATA` packet is decoded correctly, it can be retransmitted to d. After decoding a `DATA`, r can encode it in the same way as s, or it can use a different encoding scheme appropriate for the r-d channel. In contrast to AF scheme, decoding takes additional processing time but then only useful information is retransmitted to d. However, when decoding fails, no information is relayed at all, while with AF some information is always delivered from r to d.
- *Compress-and-Forward (CF)*: Relay retransmits a quantized and compressed version of `DATA` packet without decoding it. In this way, the r-d channel is used more efficiently than by simple AF.

Other retransmission schemes, typically modifications of the presented ones, have been proposed as well [KDMT08]. In this thesis only the DF scheme is considered since it is the most common one in practical systems.

Another important design question is *when relay retransmits received* ***DATA***. Following common options can be considered [LTW04]:

- *Fixed relaying*: Relay always retransmits the received `DATA` packet to d. This is the simplest method that does not require any feedback from other nodes, but it can become very inefficient when the s-d channel is rarely in outage and relaying is performed unnecessary.
- *Incremental relaying*: Relay retransmits its copy of `DATA` only when the direct s-d transmission fails, i.e., d cannot decode the `DATA` packet from s. An explicit or implicit notification to the relay is required for incremental relaying.
- *Selection relaying*: Relay retransmits even when it fails to decode the `DATA` packet from s, but only if the s-r channel quality is above a certain threshold. In this way, some quality of the relayed information is guaranteed.

In their seminal article [LTW04] Laneman et al. show that selection and incremental relaying schemes achieve the maximum diversity order of two. This means that outage probability is proportional to $1/\gamma_{sd}^2$ for high SNR γ_{sd}, whereas for direct transmission it is proportional to $1/\gamma_{sd}$. In that sense, cooperative diversity resembles a MIMO system with the total of three antennas. Further details on the outage probability analysis can be found in following highly cited articles [SEA03a, SEA03b, AEGS05].

2.2.2 Diversity Combining

DATA from s arrives to d via two independent paths with different channel characteristics: as a direct transmission, and as a retransmission from r. An important design question arises: *how these copies of the same DATA packet received from two nodes (branches) are processed at the destination*? Following common options also used for other diversity techniques can be considered [Bre59, Gol05]:

- *Selection combining*: Destination uses the signal (branch) with the highest SNR and ignores information from the other branch.
- *Switched combining*: Destination selects a branch with SNR higher than a certain threshold, and uses its signal to decode the packet. If the signal SNR on the selected branch drops below the threshold, d switches to another branch.
- *Equal-gain combining*: Signals from both branches are combined with equal weights and then decoded by destination. This scheme results in the perceived signal SNR of $0.5(\gamma_{sd} + \gamma_{rd})$ when r received DATA.
- *Maximal Ratio Combining (MRC)*: Signals from both branches are combined with weights proportional to the corresponding channel SNRs. The resulting perceived SNR is $\gamma_{sd}+\gamma_{rd}$. Although MRC is the optimal combining scheme, it also requires precise channel knowledge from both branches, which can be difficult to obtain in time-varying environments.

A major part of this thesis considers selection combining on the packet level. In combination with DF incremental relaying, this means that r retransmits the DATA packet received from s only when it decodes the packet correctly but d does not. Then, the DATA packet received from r is processed by d independently from the failed s-d transmission. Such implementation of cooperative relaying can also be referred to as *cooperative ARQ* due to its similarity to conventional ARQ retransmission.

2.2.3 Channel Coding

A source node can encode information bits to decrease transmission errors induced by the radio channel. A straightforward approach for cooperative relaying is to employ encoding schemes widely used for point-to-point transmissions such as block, convolutional or Low-Density Parity-Check (LDPC) codes [LC04]. *Repetition coding* takes place when relay decodes the received DATA packet correctly, and then encodes it in the same way as the source, i.e., simply retransmits the incoming bits. Although the method benefits from its simplicity, it is not the most efficient way of utilizing cooperative diversity [HSN06].

In *coded cooperation* relay re-encodes information bits of the received packet instead of simply retransmitting them. For that it can use a code with a different rate. In that way, additional information to each retransmission can be added in a form of incremental redundancy as also used in Hybrid-ARQ schemes. As a result, relay retransmissions are used more efficiently, which further reduces bit error rates perceived at destination [SE04, HSN06, HN06].

Finally, *DSTC* allow simultaneous data streaming in the retransmission phase by the source and relay (or multiple relays) [LW03, NBK04, AK06]. The idea comes from MIMO systems where source uses different coding schemes to stream data with multiple antennas. The superimposed signal received at destination can be efficiently decoded using orthogonal nature of space-time codes [TJC99]. Although DSTC shows a higher efficiency of spectrum usage than repetition-based methods, additional challenges in its implementation come along: the codes have to be carefully designed and distributed among communicating nodes, channel gains on parallel channels have to be known precisely to each relay, and symbol-level synchronization is required. These aspects are challenging in dynamic environments and networks with distributed coordination.

2.2.4 Transmission Rate and Power

Setting of the transmission power and rate is also performed on the PHY layer. For a cooperative relay, a straightforward option is to use the same power and rate as the source [LTW04]. However, since radio channels in a network have different characteristics, more efficient allocation schemes for energy and bandwidth resources have been developed [HHCK07, ZAL07]. Optimized resource allocation strongly depends on the availability of CSI at communicating nodes. In [SSRL08] authors study cooperative relaying under assumption of full CSI availability, and show that DF performs better in terms of Symbol Error Rate (SER) than AF. However, obtaining full CSI is challenging in distributed dynamic networks. Still, suboptimal power allocation schemes for setups with partially available CSI (e.g., only mean CSI, or CSI not from all channels) can be beneficial [DH05, LBC+07].

By changing its modulation scheme, a transmitter is able to adjust signal robustness and modify bit transmission rate. Various modulation schemes have been developed for cooperative relaying protocols [TMB05, LV05, CL06, WCGL07], where demodulators can take into account information about other channels in the three-terminal setup. Furthermore, in [HH07] hierarchical modulation is proposed that allows source to transmit data simultaneously to relay and destination with different rates according to corresponding channel quality.

2.2.5 Multiple Relays

So far cooperative relaying with only one relay node has been discussed. However, as shown in Figure 2.3, there can be multiple nodes that overhear a `DATA` packet in the broadcast phase and forward it in the retransmission phase.

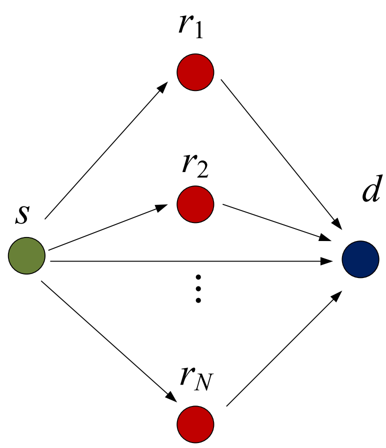


Figure 2.3: Use of multiple relays to assist *s*-*d* transmissions.

In [LW03] authors show that by using multiple retransmitting relays full system diversity of $M+1$ can be achieved, where M is the number of cooperating relays. Use of DSTC is particularly beneficial in such a setup and allows simultaneous retransmission by all relays. The system in Figure 2.3 mimics a MISO system where a transmitter uses $M+1$ antennas to stream data to a receiver with a single antenna. Therefore, such use of multiple cooperative relays is sometimes referred to as *virtual MIMO*. Further details on performance of cooperative relaying with multiple relay nodes can be found in [MOT05, JJ07].

If relay nodes can be synchronized in phase and frequency, their antennas can be used in coordination to form a particular signal superposition at the receiver and achieve an SNR gain higher than with MRC. The technique is referred to as *distributed beamforming* [MBM07] or *virtual antenna array* [Doh03]. Such schemes, however, require very precise synchronization and sophisticated signal processing techniques. With the use of multiple relays, cooperative relaying can benefit from additional network layer information, as is discussed in Section 2.5.

2.3 Medium Access Control

The general goal of MAC is to provide nodes in a network efficient and fair access to the shared wireless medium. In cooperative relaying, a major challenge for MAC is to efficiently use an opportunistic transmission of the relaying node, i.e., to define when a relay listens to and when it retransmits `DATA` packets. Numerous MAC protocols incorporating cooperative relaying functionality have been developed. Here, only a brief overview of some of them is given. Detailed surveys on existing cooperative MAC protocols can be found in [Ju12, KK13, JSZ, ZZ].

Most of the proposed cooperative MAC protocols are extensions of Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA), widely spread as a part of IEEE 802.11 Distributed Coordination Function (DCF) MAC [IEE07]. In IEEE 802.11 DCF, a source and a destination exchange Request-To-Send (`RTS`) and Clear-To-Send (`CTS`) packets before the source starts transmitting a `DATA` packet. This allows the s-d pair to reserve the channel and warn other nodes about the prepared `DATA` transmission. If the `RTS-CTS` handshake is unsuccessful, the `DATA` transmission is postponed.

In [ZC06, LTN$^+$07a] relay-DCF (rDCF) and CoopMAC extensions to IEEE 802.11 DCF are proposed that allow two-hop high-rate communication on MAC layer instead of low-rate one-hop transmissions. For that a third packet `Relay-CTS` from a cooperating relay is included into the handshake. However, strictly speaking, this scheme can only exploit the SNR advantage of a relay located closer to d, and does not make use of cooperative diversity. Similar extensions that do exploit cooperative diversity are suggested in [CYW07a, GG08, GC09, ZZJ09, SCZ11, AYB13b].

Mentioned above MAC protocols rely on successful `RTS-CTS` exchanges between the source and destination. A commonly made assumption is that such signaling messages are more robust due to better encoding and smaller size. However, in real-world networks they still can be lost when channels experience strong fading, which also implies that cooperative diversity can be particularly beneficial. In [MYP$^+$07] authors introduce cooperative diversity MAC (CD-MAC) — an adaptation of 802.11 DCF which allows cooperative relaying with simultaneous transmission by two nodes using DSTC. There, cooperative relays also assist on transmissions of `RTS`, `CTS`, and `ACK` signaling messages. In [VKES10] a more general MAC protocol for simultaneous use of multiple relays is proposed. In [LMS09] authors introduce a detailed MAC protocol to employ multiple frequency channels to separate data and control message exchange. Further, they allow neighboring nodes to notify receivers about scheduled incoming DATA packets.

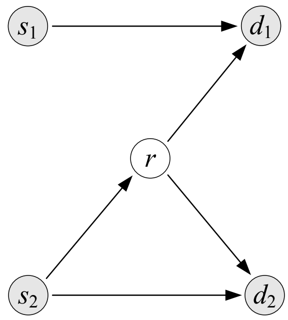


Figure 2.4: Interference at d_2 introduce by the cooperative relay.

Another problem observed in [ZC06, LMS09] is the additional interference introduced by relay. An example is given in Figure 2.4, where source nodes s_1 and s_2 communicate to destination nodes d_1 and d_2, respectively. Both links are positioned in such a way that transmissions can co-exist without disturbing each other. However, a selected cooperative relay r, when retransmitting, can create interference at the other destination or prevent the other source node from transmitting. As a result, r might disturb one link more than help another. A cooperative MAC in [SWZW08] utilizes Cooperative Triple-Busy-Tone Multiple Access (CTBTMA) to coordinate medium usage more efficiently than discussed CSMA/CA protocols but cannot solve the problem completely. Chapter 3 of this thesis is devoted to this problem and discusses in detail spatial channel reuse of cooperative relaying and the selection of spatially efficient relays. Relay selection procedure can be efficiently incorporated into the MAC since some signaling messages can be reused to identify potential relay nodes.

2.4 Relay Selection

The aim of a relay selection procedure is to identify one relay node out of multiple candidates and assign it to a given source-destination pair. The overview here is limited to the selection of a single relay. Selection of multiple relays for virtual MIMO can be found e.g., in [JJ09, VKES10]. Relay selection should provide efficiently a relay that optimizes required performance characteristics and, therefore, is critical for the performance of cooperative relaying. Most commonly this means a relay minimizing outage probability (in Bit Error Rate (BER) or Packet Error Rate (PER)) at the destination should be preferred. However, other aspects as energy efficiency, network throughput and network lifetime can also be considered [MMMZ08, ZZCC08, HSHL07].

Following questions have to be examined for efficient relay selection:

1. *Which metrics determine the optimal relay candidate?* Most important metrics to consider are s-r and r-d channel quality since they determine the successful packet delivery to d [BSW07]. Other local parameters, such as residual energy of the nodes [CJL11, WYS10] or spatial efficiency [9], can also be considered to optimize network performance.

2. *When is a relay selection to be performed?* In a dynamic environment timely relay selections are required to guarantee that an optimal relay is used. However, the required signaling overhead can also decrease benefits of cooperative relaying when selections are performed too frequently. A new relay selection can be triggered by certain events, e.g., a failed packet, an expired timer, etc. In *Proactive selection* methods, a relay is assigned anew before each `DATA` packet transmission [BKRL06].*Reactive selection* is performed only when the direct transmission fails [ZV05]. A new selection can also be triggered when the currently assigned relay does not provide the required performance [MLKS10], [2]. Chapter 4 of this thesis discusses the question of relay selection timing in detail.

3. *How is a relay selected?* Finally, one should consider carefully the message exchange between nodes in a network that results in a successful relay selection for a given s-d pair. First, a node deciding which candidate node to select as a relay needs to be defined. It can be either s, d, or a candidate node itself [BKRL06]. Second, local metrics of potential relays has to be shared to the node making the selection. Most relay selection proposals are contention-based, i.e., surrounding nodes contend in a distributed manner either using timers [BKRL06] or transmitting short messages in a slotted contention window [QB04, SMY10b]. The particular message exchange depends on application goals and the wireless technology. In Chapter 5 of this thesis an implementation of cooperative relaying with various relay selection schemes for IEEE 802.15.4 is proposed.

As mentioned in the previous section, relay selection can be efficiently incorporated into the MAC with the reuse of some coordination messages. Bletsas et al. in their seminal publication [BKRL06] propose a simple method, called opportunistic relaying, where nodes in a network listen to `RTS` and `CTS` messages to obtain SNR on channels from s and d, respectively. Using this information, each node sets a local timer. The timer function is common for all nodes and is adjusted in a way that the timer of a node with the best end-to-end SNR expires first. When its timer expires, the node broadcasts a message to d. Other nodes overhear this message and stop their timers. The authors show that when there are M potential relays for a given s-d pair in the network, the diversity order of cooperative relaying with the suggested relay selection at each transmitted packet is $M+1$. This corresponds to the diversity order of a system when all M relays retransmit simultaneously using DSTC [LW03].

However, the use of a distributed timer function is challenging and can cause collisions and delays. In [TN08] authors propose to use 1-bit feedback from d for additional coordination among the nodes and confirm performance results of [BKRL06]. A contention-based approach is used in [QB04, SMY10b], where the contention window is divided into time slots. Based on local information, a relay candidate randomly selects a time slot and transmits a short contention message in it. The receiver can collect contention messages from multiple candidates and choose a node (or several nodes) with the best characteristics. Numerous variations of these two contention methods have been developed to improve contention success probability [YMM09, SMY10b], [9].

Joint cross-layer optimization of relay selection, medium access, and physical layer settings can be employed to efficiently coordinate wireless spectrum usage [CDLC08, MRMS09, VRW10, SCZ11].

2.5 Network Layer

The main role of the network layer is to discover a route between the source and destination when multiple hops are used. Such criteria as number of hops, end-to-end PER, round-trip-time, or energy per delivered packet are typically used for selection of an optimal route. In its simplest form, cooperative relay is performed on PHY and MAC layers and remains invisible for networking protocols as illustrated in Figure 2.2. This means that an end-to-end route is established in a standard way without awareness of cooperative relaying. In such a case, s and d in Figure 2.1 represent one hop in the established route, and a relay is used only per packet-basis similar to ARQ retransmissions. The advantage is in the local cooperative retransmission control at the MAC level. A link that falls temporally in outage does not require new route discovery.

However, information exchange between the network layer and other layers can have some benefits for cooperative relaying. For example, a cooperative relay can obtain information about the other nodes on the route before and after its immediate s-d pair. As a result, it can listen to transmissions on preceding hops and also transmit DATA to following nodes on the route as well [BFY04, ABS09, GDC09]. Such methods allow to further exploit benefits of cooperative diversity over multiple hops but keep routing protocols unchanged.

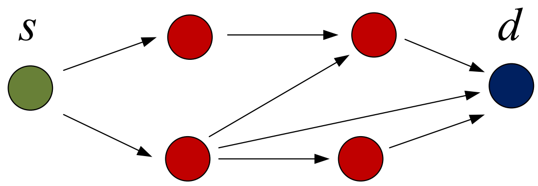


Figure 2.5: An example of routing with cooperative relaying.

Cooperative relaying can also be fully incorporated into a routing protocol, e.g., as illustratively shown in Figure 2.5. In [KMAZ07, SSL07] optimal routes are established with consideration of cooperative transmissions between the nodes. The transmission of a DATA packet along such a route resembles a cascade of activated nodes retransmitting the same packet simultaneously. The problem of optimal route calculation can become extremely difficult when number of nodes is large. Simplified heuristic algorithms for cooperative routing have been suggested in [ZV05, KWM08, IHL08, LH08].

Since cooperative relaying improves link quality, it can also be seen as a technique to extend the node communication range. This implies that fewer nodes are needed to keep the same route or network connected. Some works have been devoted to studying network connectivity with cooperative relaying schemes [SH03, WLG$^+$08, GLT$^+$09, LZL10].

Besides end-to-end delivery to a single destination, cooperative relaying can be employed to assist packet multicast or broadcast, i.e., a packet from one source has to be delivered to multiple destination nodes. In such a setting, multiple channels are affected by fading and cooperative diversity can be particularly useful [SH03, SMSM06, JKFK07, ZS10].

On a network level, cooperative relaying can be naturally coupled with network coding [Lan04], i.e., packets from several sources can be combined into one packet of the same size and then retransmitted by a relay. The benefit of such combination is twofold: a) only one packet instead of two is relayed, and b) spatial diversity is employed. Studies with implementation details and performance results can be found in e.g., [CKL06, XFKC07, MRZ09, DLGT09].

2.6 Experimental Studies

All works presented above are obtained analytically or with the help of computer simulations. This implies that certain simplifications have to be made to model the communication system in an analytical way. For example, mutual information is used, perfect channel knowledge is assumed, or uncorrelated fading channels are considered. Experimental verification of cooperative relaying in actual testbeds is important for its advancement into real-world networks. This section provides an overview of published experimental studies of cooperative relaying. Two classes of implementations can be differentiated: a) testbeds based on IEEE 802.11-compliant hardware, typically used for high-rate Wireless Local Area Network (WLAN), and b) testbeds based on IEEE 802.15.4-compliant hardware, typically used for cheap low-power and low-rate Wireless Sensor Network (WSN).

2.6.1 WLAN Testbeds

Miu et al. in [MBK05] study multi-radio diversity with packet combining. In their setup, a single IEEE 802.11-compatible source transmits wirelessly data to several receivers wired to a PC, where final combining of the received erroneous versions on the packet is performed. The bit errors in the received copies of a `DATA` packet are uncorrelated due to spatial diversity. Authors propose to split each faulty packet into several blocks some of which can be assumed to be correct. Therefore, it is possible that one combination of those blocks from different packets provides the correct `DATA` packet. The proposed setup requires only software modifications in wireless WiFi drivers. Performance gains in throughput and delay are shown.

In [BW05, HZBW05] authors performed real-world indoor measurements of OFDM at 5.25 GHz in a network with eight nodes. Based on these measurements, the resulting bit rate is emulated for cooperative relaying with single and multiple relays employing DSTC.

Mentioned earlier CoopMAC [LTN+07a] protocol has been tested in hardware implementation in [KNBP06]. The implemented protocol exploits only the advantage of a high-rate two-hop transmission over a low-rate one-hop transmission without information combining at the destination. For their implementation authors modified open source wireless drivers for IEEE 802.11. In the article a discussion on confronted limitations of control over time-sensitive tasks is given, since not all aspects of wireless firmware could be changed.

For implementation of full cooperative relaying on both PHY and MAC layers, use of Software-Defined Radio (SDR) is necessary [KKEP09, BL10]. SDR is typically based on Field-Programmable Gate Array (FPGA) hardware and provides developers with programmable control to all aspects of hardware implementation such as access to analog signal processing before symbol demodulation. Two OFDM-based SDR platforms are commonly used: Wireless Open Access Research Platform (WARP) [WAR], where all processing is done on the board, and open-source GNU radio [GNU], where digital signal processing is done on a computer connected to a separate analog front-end (e.g., Universal Software Radio Peripheral (USRP) [USR]).

Based on their first findings, authors of [KKEP09] present an improved version of CoopMAC implemented in WARP boards [SGS+08], but cooperation still remained limited to the MAC only.

Authors in [WKK+07] use USRP GNU radio platform to investigate experimentally information combining of faulty packets in a WLAN setup similar to [MBK05], where multiple receives are connected through wires to a PC for final packet combining. A combination technique with the use of soft confidence information for each bit is proposed and compared with hard-combining algorithms. Benefits of the proposed combining scheme are shown in delivery rate and the expected number of retransmissions required for packet recovery.

In [Bra08, BL09] authors use GNU radio to implement DF cooperative relaying. Results show that cooperative relaying provides diversity gain in a fixed three-node setup that moves in a linear direction in office environment. However, only SNR values are measured. The resulting BER is obtained through simulations.

A different testbed implementation in mobile environments is explained in [VLW+08]. It shows clear benefits for cooperative relaying even though no MRC at the destination is done. In the related article [VWVK09] authors provide a comparison of cooperative relaying with MRC and with selection combining at d in slow fading channels. From the observed results they claim that combining gain obtained with MRC provides only marginal benefit on resulting PER in addition to the diversity gain already available with selection combining. Another experimental study in mobile environments is done in [BSAB12], where cooperative relaying is used for car-to-car communication. Performance gains in BER for cooperative relaying with selection combining are shown in different urban environments.

In [MHS09, MSA09, Mur10, MS11] authors provide a detailed study of AF and DF cooperative diversity implemented in WARP platforms. In their PHY layer, a cooperative relay and a source simultaneously transmit data to a destination using a simple DSTC. Authors discuss in detail some implementation challenges, e.g., time synchronization and carrier frequency offset. To obtain experimental results over a range of node topologies and channel characteristics, a channel emulator is used. The results show that DF protocol in general outperforms AF, and both schemes show better BER than direct transmissions. Another implementation in WARP boards is presented in [KE10], where authors implement PHY layer for a three-node setup with coded cooperation and MRC combining at the destination. The results show clear improvement in BER over direct non-cooperative transmissions.

In [HMS10] authors implement cooperative relaying on PHY and MAC layers and perform relaying only when direct transmissions fail. They show that the cooperative scheme exploits diversity gain but still performs worse than a simple MISO link, i.e., when a source uses two transmitting antennas instead of a relay. The same group of authors provides an in-depth study on how communication energy efficiency in a network can be improved with cooperative relaying [HZS13]. According to the proposed Distributed Energy-Conserving Cooperation (DECC) each node can individually decide based on its local information how much it participates in cooperative relaying for other nodes. The implementation on the WARP platform is performed across PHY and MAC layers to adjust transmission powers and medium access by relays. DF cooperative relaying with MRC at the destination is performed. The empirical results in different topologies show that when some nodes are ready to contribute altruistically certain amount of energy for cooperation (e.g., 5 % loss is tolerable), energy efficiency of overall network communication can be doubled.

Another MAC layer implementation is presented in [ZMLM09], where a Digital Signal Processor (DSP)-based platform is used. Following implementations are compared: AF and DF with single relay; DF protocol with two relays using DSTC; DF with relay selection at each packet. A comparison of empirical and theoretical results is given. All schemes show improved performance in BER compared to direct transmissions.

A combination of a routing protocol with cooperative relaying is evaluated in [LVK+08] using IEEE 802.11-compatible SDR. There, cooperative relays can receive from and transmit to nodes several hops away. The results show up to 66 % improvement in the end-to-end PER.

Authors of [JCI10] present an experimental study of the transmission range extension at a certain PER constraint. Four relay nodes transmit simultaneously to a single destination using orthogonal frequencies. GNU radio and USRP front-end hardware are used. Performance extension in coverage area and directional reach are investigated in different network topologies in office environment. An extension to virtual MIMO routing is experimentally approached in [CIF10, GCI10, CJI11], where the corresponding end-to-end PER and round-trip times are shown to improve when compared to conventional multi-hop transmissions.

Using newest advances in signal processing authors of [MMBB11, RBWMD12, QMRM12] claim to implement in SDR beamforming with multiple distributed relay nodes. This means that signals transmitted from relays are synchronized not only in frequency but also in phase. The coordinated use of such distributed antenna arrays results in perceived SNR at the destination higher than with MRC.

Finally, integration of cooperative relaying with cognitive radio in SDR is experimentally done in [JZZ09, ZJZ09], where cooperative relaying, spectrum sensing, and spectrum allocation are performed jointly.

2.6.2 WSN Testbeds

Most of the experimental studies presented above rely on the use of sophisticated hardware which allows precise channel estimation, symbol-level synchronization, frequency adjustment, and analogue information combining before demodulation and decoding. However, the use of cooperative relaying can be particularly beneficial in low-cost small-size radios [BKW08], where use of multiple antennas and advanced signal processing techniques for fading mitigation is not possible due to strict cost and hardware constraints. The studies discussed below are performed using commodity off-the-shelf hardware compatible with IEEE 802.15.4, and only software changes in the protocol stack have been done.

Bletsas et al. in [BL06] discuss the implementation of their opportunistic relaying protocol [BKRL06] in simple radios with 8-bit microcontrollers without information combining at the destination. Although authors provide some interesting implementation details of their testbed, no performance results are given.

In [DFEV05] authors propose a simple packet combining scheme (SPaC) that can be used in low-cost wireless sensor nodes. In SPaC, the difference between two erroneous copies of the same `DATA` packet received from source and relay is used to identify an error pattern. Going through all possible combinations of bits in the error pattern in a brute-force manner, a packet can be correctly recovered. Benefits in the BER for individual links and in the end-to-end packet delivery rate for multi-hop routing is shown. Authors of [OB12] extend SPaC to reduce required computational effort. They also provide an in-depth study of cooperative relaying on the link level for IEEE 802.15.4 networks. As a result of the improved performance, energy consumption at nodes is shown to be reduced.

In [IKR09, IKR11] authors provide an experimental study where several IEEE 802.15.4 nodes have to receive information from a single source. If a `DATA` packet at one of the receivers cannot be decoded, a copy from other receivers is requested. Variations of selection diversity, equal gain combining and MRC algorithms for demodulated packets are developed and benefits in delivery ratio and energy consumption are shown.

In cooperation with his colleagues, the author of this thesis investigates cooperative relaying in industrial wireless sensor networks in [1, 3, 4]. Such networks are deployed in cluttered highly dynamic factory environments and have strict reliability requirements. Different cooperative relay selection techniques are experimentally studied using IEEE 802.15.4 nodes and the tradeoff between the selection overhead and link reliability is shown. Chapter 5 of the thesis discusses the topic in detail.

2.7 Summary

Although three-terminal relay channel has been introduced in 1970's, its real breakthrough into wireless research community came in 2000's following significant advances in signal processing such as discovery of Space-Time Codes (STC) and MIMO. Despite its conceptual simplicity, cooperative relaying turned out to be a very fruitful research topic. This chapter gave only a brief overview of main design an implementation issues associated with cooperative relaying.

On PHY layer, relay retransmission protocols such as AF, DF, CF, and their variations can be used. Information combining at the receiver and channel coding techniques such as coded cooperation or DSTC are also performed on PHY layer. On MAC, the medium access for a cooperative relay needs to be coordinated to improve performance on individual links without reducing the overall network performance. Relay selection can be included into MAC to allow quick and efficient relay switching. Joint cross-layer optimization of PHY and MAC layer is widely investigated and promises additional efficiency in resource utilization. Finally, cooperative relaying can be extended to the network layer and used by routing protocols. There, it can also be naturally coupled with network coding.

Protocol implementation in testbeds is important to provide additional insight into the performance of cooperative relaying under real-world technological hardware constraints. However, in contrast to theoretical work, only limited number of experimental studies on cooperative relaying has been done. Use of SDR hardware with full control over PHY and MAC layers allows analog information processing before demodulation. Cooperative relaying with some advanced signal processing techniques such as MRC and DSTC are successfully implemented in SDR and benefits in PER, range extension, delay, and energy efficiency are shown. Only few studies with empirical evaluation of cooperative relaying for low-cost low-power devices have been performed. Although sophisticated signal processing is not possible in such devices, experiments using off-the-shelf hardware show that even limited use of cooperative diversity increases communication reliability and can be beneficial in time-critical applications.

Cooperative relaying has to be considered jointly with other diversity techniques when efficient and cost-effective real-world system engineering is desired. Depending on the system requirements, other methods can provide sufficient performance and replace cooperative relaying. Time diversity in form of (Hybrid)-ARQ is a standard retransmission technique and does not require a third node to improve source-destination link. Frequency diversity can be effectively used for mitigation of frequency selective fading. Conventional multi-hop routing without cooperative diversity may be sufficient in most static environments. Finally, MIMO systems also exploit spatial diversity with multiple antennas and can be used when hardware constrains comply.

CHAPTER

3 Spatial Channel Reuse in Cooperative Relaying

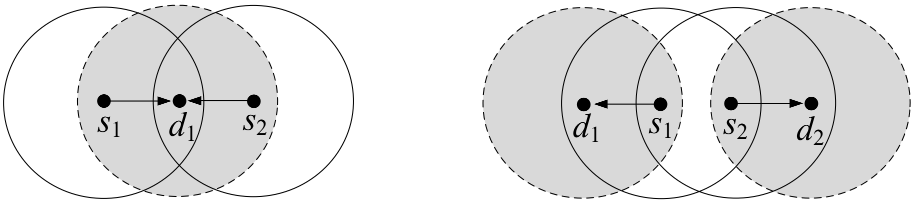
3.1 Introduction and Motivation

3.1.1 Medium Access Control: CSMA and CSMA/CA

To avoid interference, coordinated use of shared wireless spectrum among transmitters is required. Numerous MAC protocols have been developed to optimize resource allocation in temporal and spatial domains. The analysis in this chapter explores two widely used MAC protocol types:

- *Carrier Sense Multiple Access* (CSMA): Before transmitting a `DATA` packet, each node listens to the channel and proceeds with the transmission if and only if the channel is free. If the node senses that there is another ongoing transmission, it reschedules the transmission of the packet according to certain rule [KT75].
- *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA): In addition to CSMA, collision avoidance through four-way handshake is accomplished [Kar90, BDSZ94, Gol05]. Before starting a transmission, each node senses the channel. If the channel is occupied, the node backs off. If it is idle, the node sends, a `Request-To-Send` (`RTS`) message to the destination. If the destination receives the `RTS` message, and there are no other transmissions in its range, it sends a `Clear-To-Send` (`CTS`) message back to the source. Only after a successful `RTS-CTS` handshake, the source can proceed with the `DATA` transmission.

CSMA protocol, while providing simple distributed coordination among the nodes, experiences a so called *hidden terminal problem* illustrated in Figure 3.1a. Here, a common disc model is used, which approximates signal propagation in homogeneous environment: packet transmitted by s can be successfully received only



(a) Hidden terminal problem (b) Exposed terminal problem

Figure 3.1: Medium access problems.

within its transmission range R_{tx}. Two nodes, s_1 and s_2, out of channel sensing range of each other start simultaneous transmissions to the same destination node d resulting in mutual interference and failed reception at d.

CSMA/CA protocol, in turn, solves the hidden terminal problem with `RTS-CTS` handshake. However, it experiences a so called *exposed terminal problem* shown in Figure 3.1b. Here, two source nodes s_1 and s_2 want to communicate with destination nodes d_1 and d_2, respectively. Destination nodes are in the transmission range of each other, but d_1 is out of range of s_2 and cannot be disturbed by its transmissions. After s_1 and d_1 exchange `RTS-CTS` messages, d_2 cannot respond with its `CTS` to s_2 because it assumes s_2 can disturb the already initiated transmission of s_1 even when it is not the case.

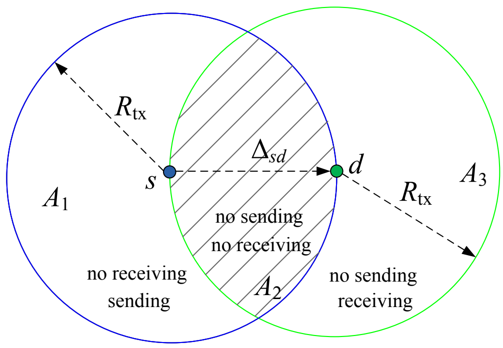
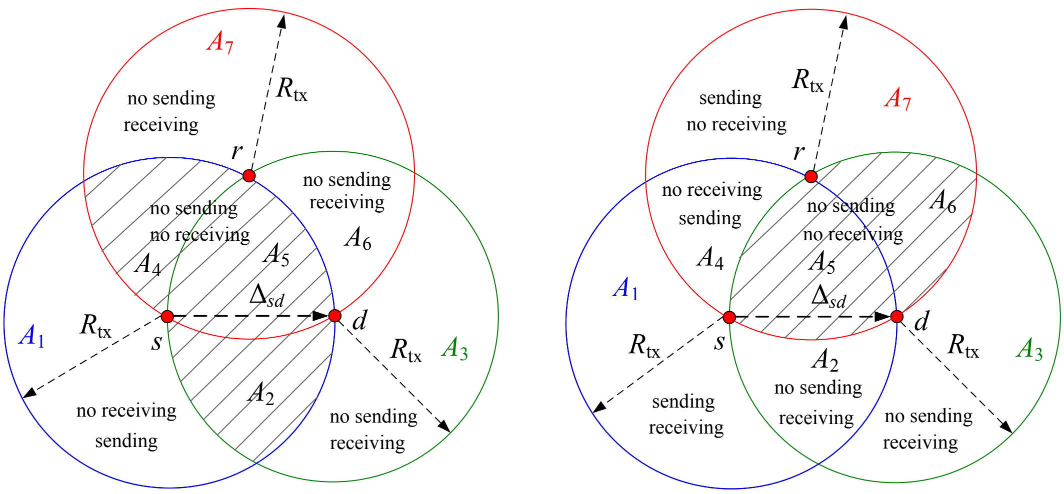


Figure 3.2: Ideal spatial resource allocation for s-d transmission.

Figure 3.2 visualizes the use of spatial resources for a communicating s-d pair with omni-directional antennas. In conventional CSMA/CA, all nodes that are in range of either s or d (areas A_1, A_2, and A_3) are blocked from receiving and transmitting because they are assumed to either disturb ongoing s-d transmission, or be disturbed by it. With the ideal spatial resource use, when the exposed terminal problem is avoided, nodes in area A_1 can send `DATA` because they are out of range of d and, thus, will not disturb s-d transmissions. However, they cannot receive `DATA` when s is transmitting due to created interference. Nodes in A_3 are allowed to receive but not to transmit `DATA`. In area A_2 other nodes can neither transmit nor receive `DATA`. A commonly known dual busy tone multiple access (DBTMA) protocol is proposed in [HD02] to realize such resource allocation. However, such sophisticated MAC requires timely coordination and tight synchronization of nodes, particularly when acknowledgments are sent back by receivers.

3.1.2 Cooperative MAC Protocols

The discussed MAC protocols can be enhanced to cooperative relaying transmissions as well. E.g., [CYW07a],[ABS08] and [SCZ11] propose extensions of CSMA/CA for cooperative transmissions. And in [SWZW08] authors propose cooperative triple busy tone multiple access (CTBTMA) to coordinate medium usage and solve exposed terminal problem. In this chapter the implementation details of cooperative MAC protocols are omitted, and the focus is made on the resulting allocation of spatial resources. In the following, the extended MAC protocols are referred to as *cooperative CSMA* and *cooperative CSMA/CA*, respectively. Cooperative MAC with solved exposed terminal problem is referred to as *ideal cooperative MAC*.



(a) Transmission by source s (b) Retransmission by relay r

Figure 3.3: Spatial resource allocation with ideal cooperative MAC.

Figure 3.3 visualizes the required spatial resources for a cooperative transmission with ideal cooperative MAC. In the first slot, s sends `DATA` to d and r. In the second time slot, r relays the received `DATA` to d. The figure shows the most efficient allocation of resources at each time slot to avoid interference with the ongoing cooperative transmission. Although the representation of protocols is simplified, it is used here to motivate the study of spatial use of cooperative relays without going into sophisticated channel models and implementation details. For cooperative CSMA/CA the area within the range of any the nodes s, d, and r needs to be reserved when s is transmitting. As it can be observed from the figure, cooperative transmissions might require additional space-time resources which can degrade the overall network capacity. In the worst case scenario, up to 60 % resources are needed just in the first time slot to ensure that no interference occurs at r and d.

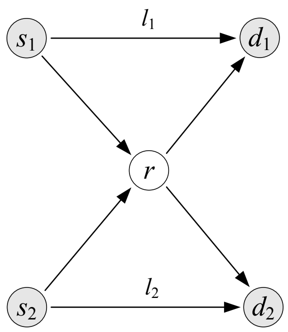
The contribution of this chapter is twofold:

1. Impact of relay spatial use on the overall network performance is analyzed in Section 3.2. In two simple network setups with symmetrical and non-symmetrical relay exposure various cooperative MAC protocols are studied. It is shown that under certain conditions cooperative relaying may reduce overall network throughput in comparison to non-cooperative transmissions. Regions where cooperative relaying is beneficial are also identified.
2. A method to increase spatial efficiency of cooperative transmissions through relay selection is proposed and investigated in Section 3.3. It is based on the assumption that relays that require less additional spatial resources should be preferred. The developed contention-based selection scheme increases probability of selection of spatially more efficient nodes.

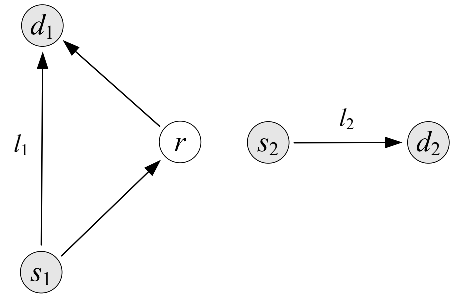
The results presented in this chapter are partially published in [9] and [10] and have been achieved in cooperation with the corresponding coauthors.

3.2 Network Throughput with Cooperative Relaying

Figure 3.4 shows two simple scenarios where communicating pairs are located at such distances that transmissions on links l_1 and l_2 can take place simultaneously without disturbing each other if cooperative relaying is not employed. In Figure 3.4a node r is in range of all other nodes, and can serve as cooperative relay for both communicating pairs. In Figure 3.4b node r is in range of s_1, d_1, and s_2, but out of range of d_2. There, it can assist only s_1-d_1 transmissions.



(a) Symmetrical relay exposure



(b) Non-symmetrical relay exposure

Figure 3.4: Two considered network scenarios.

It is assumed that communication channels are slotted in time according to the `DATA` packet duration. The probability that at a given time slot i a new `DATA` packet arrives for transmission is p_1 and p_2 for nodes s_1 and s_2, respectively. The queue at each node does not accumulate packets, i.e., if a packet is not transmitted within the same time slot, it is dropped. The same result is achieved when the queue size is limited to one `DATA` packet. In such a case, if a `DATA` packet is not transmitted due to the busy channel, the source node backs off and tries to transmit the packet in the next free time slot with probability p_1 for s_1, and p_2 for s_2. This method corresponds to p-persistent CSMA [KT75].

The probability of a packet error is ε_1 and ε_2 for channels s_1-d_1 and s_2-d_2, respectively. The channels are assumed to be uncorrelated in time.

If no cooperative relaying is employed in the network, CSMA and CSMA/CA provide the same throughput if signaling overhead is neglected. The overall throughput η in both network scenarios is calculated by

$$\eta = p_1 \left(1 - \varepsilon_1\right) + p_2 \left(1 - \varepsilon_2\right). \tag{3.1}$$

If cooperative relaying is employed, node r can be used as a cooperative relay for the nodes in its range. Following assumptions on the relaying protocol operation are made:

1. Relay r operates in the decode-and-forward mode, i.e., r can retransmit a `DATA` packet only when r has correctly decoded it upon reception from s.
2. Relay r retransmits `DATA` packet to d only if the direct transmission of the packet from s to d failed.

3. No information combining on signal level is performed at d.
4. Relay transmission has a priority over other transmissions. That means when a direct transmission fails, r retransmits the decoded packet first. Both s_1 and s_2 sense the ongoing relay retransmission and back off with their transmissions.
5. Cooperative relay r transmits with the same power and rate as s_1 and s_2.

Error probabilities on links s_1-r, s_2-r, r-d_1, and r-d_2 are denoted by ε_{s_1r}, ε_{s_2r}, ε_{rd_1}, and ε_{rd_2}, respectively. To simplify some mathematical expressions, end-to-end packet error probability on path s_j-r-d_j, where $j \in \{1, 2\}$, is introduced:

$$\varepsilon_{R_j} = 1 - \left(1 - \varepsilon_{s_jr}\right)\left(1 - \varepsilon_{rd_j}\right). \tag{3.2}$$

3.2.1 Symmetrical Relay Exposure

For symmetrical relay exposure in Figure 3.4a, node r can be used as cooperative relay for both communicating pairs. However, the resulting overall throughput depends on the used cooperative MAC protocol.

Cooperative CSMA

A cooperative relay can be used only when it has correctly received a `DATA` packet from either source. For cooperative CSMA, when $p_1 = p_2 = 1$, cooperative relaying is not possible, because a relay is never able to receive packets due to interfering packets sent at the same time. Therefore, cooperative and non-cooperative transmissions result in the same overall throughput. The differences start to appear when the nodes do no transmit at each time slot.

A time slot is available for transmission by source nodes only when there is no ongoing retransmission from r. In case the relay retransmits a packet to either d_1 or d_2, both source nodes sense the channel and back off. Assuming there are in total K available time slots for protocol operation, the number of time slots $\widetilde{K}$ available for source transmissions is

$$\widetilde{K} = K\Big[1 - p_1(1-p_2)\varepsilon_1(1-\varepsilon_{s_1r}) - p_2(1-p_1)\varepsilon_2(1-\varepsilon_{s_2s})\Big]. \tag{3.3}$$

Therefore, the probability q_s that a given time slot is available for source transmission is the ratio

$$q_s = \frac{\widetilde{K}}{K}. \tag{3.4}$$

Overall throughput can be calculated as the ratio of packets successfully received at d_1 and d_2 over K time slots:

$$\eta_{\text{co}} = q_s\Big(p_1(1-\varepsilon_1) + p_2(1-\varepsilon_2) \\ + p_1(1-p_2)\varepsilon_1(1-\varepsilon_{R_1}) + p_2(1-p_1)\varepsilon_2(1-\varepsilon_{R_2})\Big). \tag{3.5}$$

The first two summands in the brackets correspond to the probability that a packet is available at the source and is successfully delivered to the corresponding destination directly. The third and fourth summands correspond to the cases when a retransmission by relay is performed. This is only the case when all three following points are true: a) the direct transmission fails, and b) the other source did not transmitted any packet, and c) r received the packet from s. In such a case, the packet is delivered to the destination when the corresponding two-hop path over the relay is good.

Cooperative CSMA/CA

In case of cooperative CSMA/CA, before transmitting a `DATA` packet, the radio channel for the transmission and reception at r and the corresponding destination is reserved. In such a case, simultaneous transmissions by s_1 and s_2 are impossible. It is assumed that when one of the sources reserves the channels first, the other one backs off. Both sources have equal probability to win the reservation when they have a packet to transmit.

If there are K time slots for packet transmissions, on average only $\widetilde{K}$ of them can be used as transmissions by either source node:

$$\begin{aligned}\widetilde{K} &= K\Big[1 - \Big(0.5p_1p_2 + p_1(1-p_2)\Big)\varepsilon_1(1-\varepsilon_{s_1r}) \\ &\quad - \Big(0.5p_1p_2 + p_2(1-p_1)\Big)\varepsilon_2(1-\varepsilon_{s_2r})\Big] \\ &= K\Big[1 - (1-0.5p_2)p_1\varepsilon_1(1-\varepsilon_{s_1r}) - (1-0.5p_1)p_2\varepsilon_2(1-\varepsilon_{s_2r})\Big].\end{aligned} \tag{3.6}$$

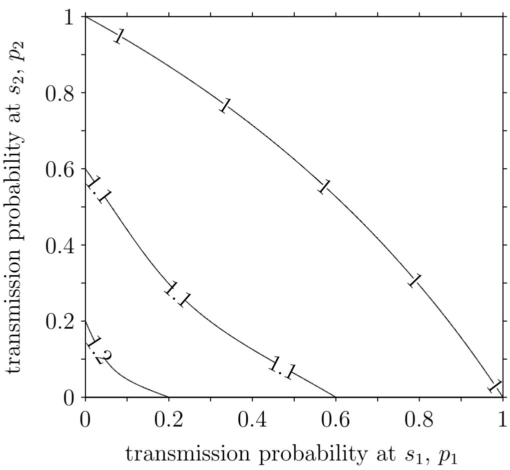
The resulting expected overall throughput η_{co} in the network is

$$\begin{aligned}\eta_{\text{co}} &= q_s\Big[\Big(0.5p_1p_2 + p_1(1-p_2)\Big)\Big((1-\varepsilon_1) + \varepsilon_1(1-\varepsilon_{R_1})\Big) \\ &\quad + \Big(0.5p_1p_2 + p_2(1-p_1)\Big)\Big((1-\varepsilon_2) + \varepsilon_2(1-\varepsilon_{R_2})\Big)\Big] \\ &= q_s\Big[p_1 + p_2 - p_1p_2 - p_1(1-0.5p_2)\varepsilon_1\varepsilon_{R_1} - p_2(1-0.5p_1)\varepsilon_2\varepsilon_{R_2}\Big].\end{aligned} \tag{3.7}$$

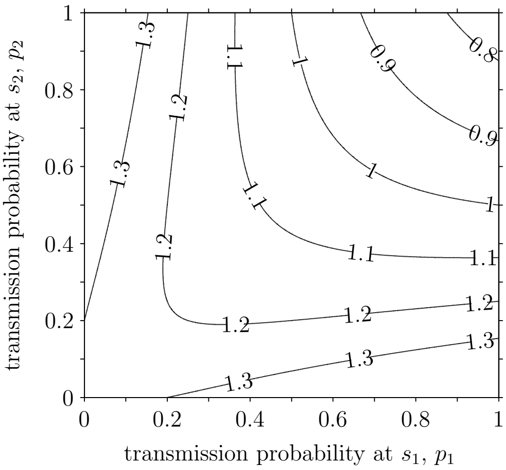
Throughput Comparison

Figure 3.5a shows the contour lines of the ratio η_{co}/η as a function of transmission probabilities p_1 and p_2 when cooperative CSMA is employed. Here, $\varepsilon_{R_1} = \varepsilon_{R_2} = 0$ (optimal relaying); $\varepsilon_1 = \varepsilon_2 = 0.2$. The area below the contour line $\eta_{co}/\eta = 1$ indicates pairs of values (p_1, p_2) where the overall network throughput gains with the use of cooperative relaying. The area above that line corresponds to the loss in throughput. However, the decrease is not that significant since even the contour line 0.95 does not lie within the parameter range $p_1, p_2 \in [0, 1]$. This can be explained by the lower number of relay retransmissions when p_1 and p_2 are high.

Figure 3.5b shows in a similar manner the contour lines for η_{co}/η as a function of transmission loads (p_1, p_2) for cooperative CSMA/CA. The contour line $\eta_{co}/\eta = 1$ marks the border where cooperative and non-cooperative schemes perform the same. The area above this line contains all possible values of (p_1, p_2)-pairs where cooperative relaying reduces overall network throughput. In contrast to cooperative CSMA in Figure 3.5a, a faster decline in overall throughput with cooperation can be observed. The area below the line denotes the combination of p_1 and p_2 where cooperative relaying is beneficial for overall capacity. Here, the ratio is significantly higher than with cooperative CSMA.



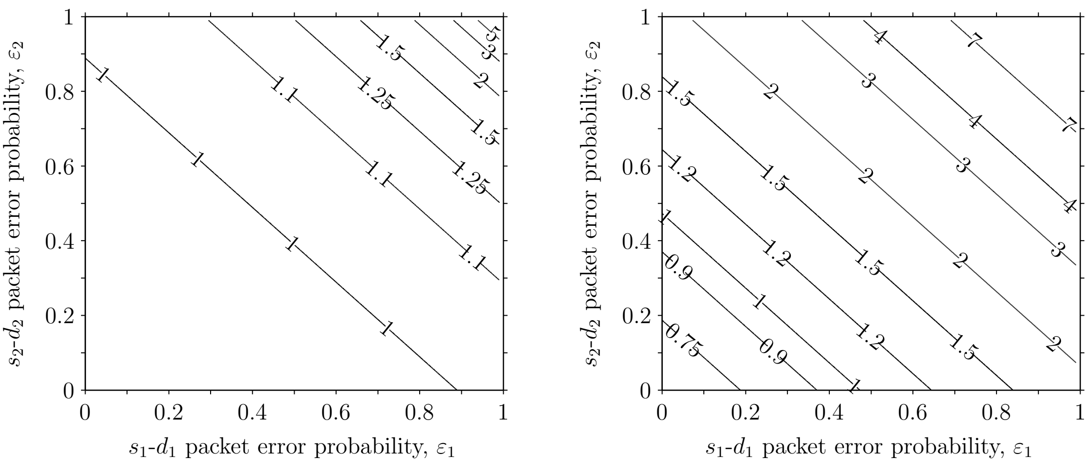
(a) Cooperative CSMA



(b) Cooperative CSMA/CA

Figure 3.5: Ratio of overall network throughput with cooperation to that without cooperation, η_{co}/η, as a function of transmission loads p_1 and p_2 in the symmetrical network scenario; $\varepsilon_1 = \varepsilon_2 = 0.2$, $p_{R_1} = p_{R_2} = 0$.

Figure 3.6a shows the contour lines for η_{co}/η as a function of packet error rates



(a) Cooperative CSMA (b) Cooperative CSMA/CA

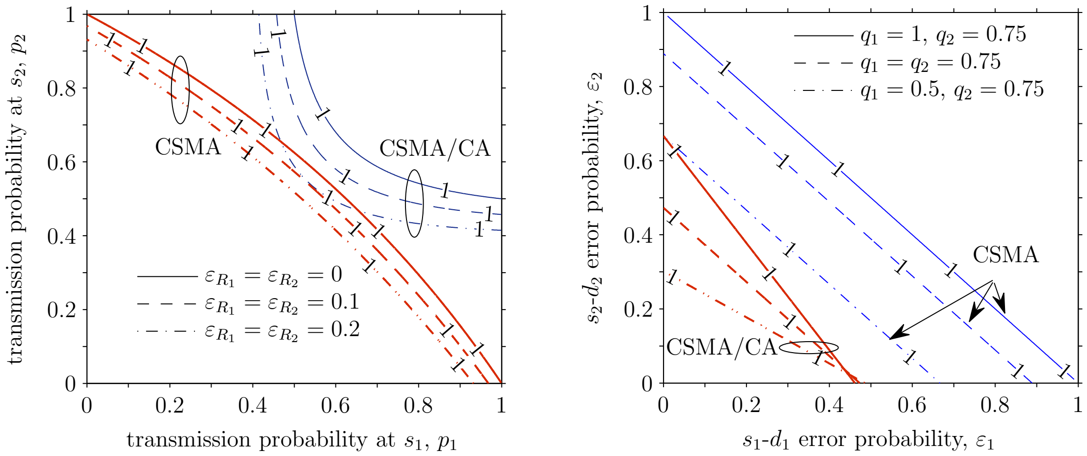
Figure 3.6: Ratio of overall network throughput with and without cooperation, η_{co}/η, as a function of packet error rates ε_1 and ε_2 in the symmetrical network scenario; $p_1 = p_2 = 0.75$, $p_{R_1} = p_{R_2} = 0$.

$(\varepsilon_1, \varepsilon_2)$ for cooperative CSMA. Here, $\varepsilon_{R_1} = \varepsilon_{R_2} = 0$, and $p_1 = p_2 = 0.75$. Cooperative relaying becomes beneficial only when packet error rates ε_1 and ε_2 take certain values above the contour line $\eta_{\text{co}/\eta} = 1$. However, the performance remains similar to non-cooperative transmissions when error rates are lower.

Figure 3.6b shows the corresponding contour lines for cooperative CSMA/CA with the same parameters. Again, the corresponding area and the gain in throughput with cooperative CSMA/CA are larger than with CSMA in Figure 3.6a. However, in the area below the line, the overall throughput for cooperative relaying with cooperative CSMA/CA declines faster than with simple CSMA, where it remains almost the same.

Figure 3.7 shows the change in contour line $\eta_{\text{co}}/\eta = 1$ with increasing error rates on the end-to-end relaying path. As expected, it decreases the area where cooperative relaying improves the overall throughput.

One can conclude that cooperative relaying is not always beneficial for the overall network throughput due to the exposed terminal problem. When direct channels tend to be good and traffic load in the network is high, direct transmissions can provide better usage of the space-time resources and achieve higher throughput. However, when the traffic load is rather low and the packet error rates on direct channels increase, usage of cooperative relaying is beneficial for the overall network throughput. In such cases, cooperative CSMA/CA performs better than



(a) $\eta_{co}/\eta = 1$ as a function of (p_1, p_2); $\varepsilon_1 = \varepsilon_2 = 0.2$;

(b) $\eta_{co}/\eta = 1$ as a function of $(\varepsilon_1, \varepsilon_2)$; $\varepsilon_{R_1} = \varepsilon_{R_2} = 0$;

Figure 3.7: Equal overall throughput with and without cooperation, $\eta_{co}/\eta = 1$, in the symmetrical network scenario.

cooperative CSMA in terms of throughput, as the presented symmetrical scenario shows.

3.2.2 Non-Symmetrical Relay Exposure

In the non-symmetrical network scenario in Figure 3.4b, differences between cooperative relaying with cooperative CSMA/CA and ideal cooperative MAC can be studied. Here, as in Figure 3.4a, direct links l_1 and l_2 can be used simultaneously without disturbing each other. Relay node r and s_1, d_1, are in transmission range of each other. Node r is also in range of s_2, but, in contrast to the butterfly scenario, d_2 is out of the transmission range for r. Therefore, node r can be used as cooperative relay only to assist s_1-d_1 transmissions. In case, cooperative relaying is employed, simultaneous transmissions by both sources will result in decoding failure at the relay.

Overall throughput without cooperative relaying is calculated in the same way as in the butterfly scenario in (3.1).

Cooperative CSMA/CA

With the cooperative CSMA/CA, when s_2 starts transmitting first, s_1 cannot use the relay r anymore, but direct transmission to d_1 is still possible. When s_1 starts transmitting first, r also reserves the channel in its range. Therefore, s_2 cannot start its transmission until s_1 finishes transmitting, and, if necessary, r retransmits to d_1. The resulting throughput is calculated by

$$\begin{aligned}\eta_{\text{co}} = q_s\Big[&\Big((0.5p_1p_2 + p_1(1-p_2)\Big)\Big((1-\varepsilon_1) + \varepsilon_1(1-\varepsilon_{R_1})\Big)\\ &+ \Big(0.5p_1p_2 + p_2(1-p_1)\Big)(1-\varepsilon_2) + 0.5p_1p_2(1-\varepsilon_1)\Big].\end{aligned} \tag{3.8}$$

Here, the summands in the first row correspond to the packet transmissions when s_1 reserves the cooperative link for its transmissions. The summands in the second row correspond to the case when s_2 starts transmitting first. Finally, q_s is the ratio of the slots that can be used for direct transmissions:

$$\begin{aligned}q_s &= 1 - \Big(0.5p_1p_2 + p_1(1-p_2)\Big)\varepsilon_1(1-\varepsilon_{s_1r})\\ &= 1 - p_1(1-0.5p_2)\varepsilon_1(1-\varepsilon_{s_1r}).\end{aligned} \tag{3.9}$$

Ideal Cooperative MAC

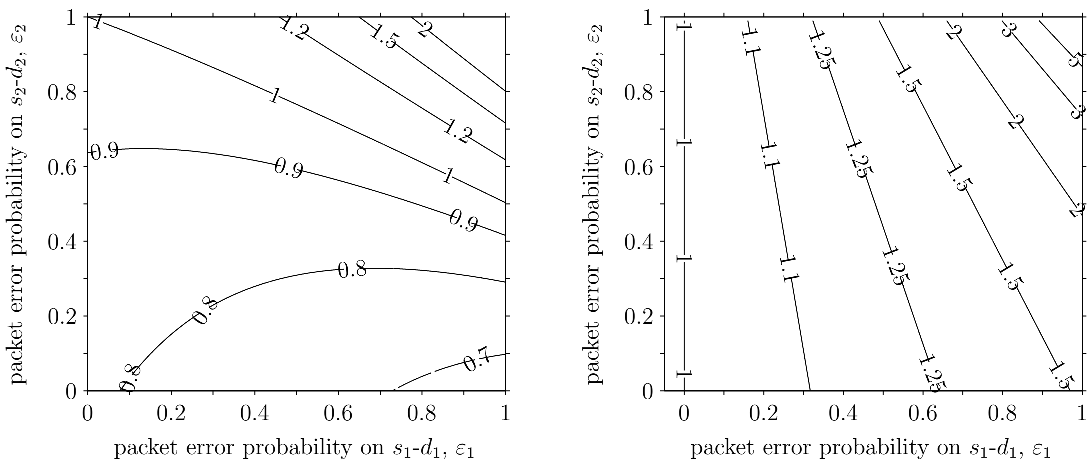
For the ideal cooperative MAC, s_2 can also transmit to d_2 even when r is retransmitting `DATA` to s_1. The two transmissions do no disturb each other since d_1 is out of range of s_2, and d_2 is out of range of r. The resulting throughput is calculated by

$$\begin{aligned}\eta_{\text{co}} &= q_sp_1\Big((1-\varepsilon_1) + \varepsilon_1(1-\varepsilon_{R_1})\Big) + p_2(1-\varepsilon_2)\\ &= q_sp_1(1-\varepsilon_1\varepsilon_{R_1}) + p_2(1-\varepsilon_2).\end{aligned} \tag{3.10}$$

Ideal cooperative MAC improves performance of s_1-r-d_1 link and does not affect performance on the s_2-d_2 link.

Throughput Comparison

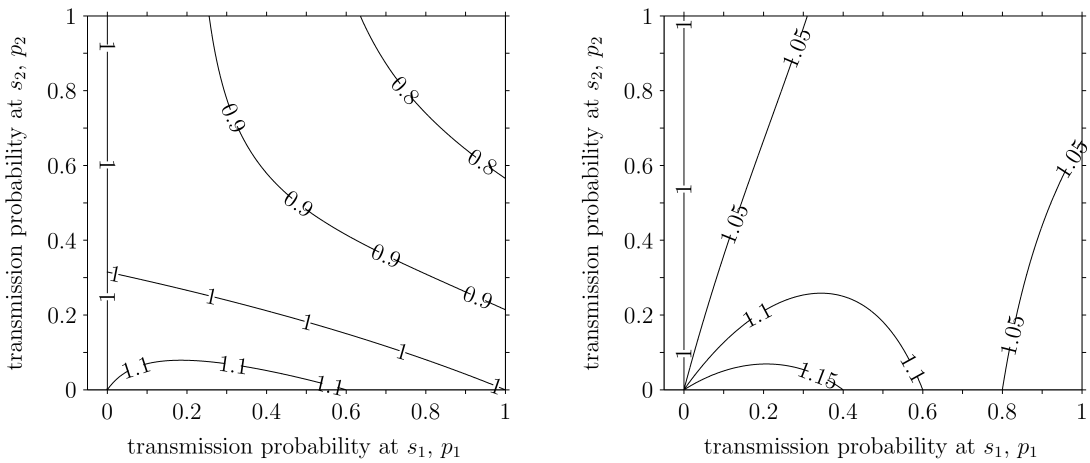
Figures 3.8 and 3.9 show contour lines of the ratio η_{co}/η as a function of (p_1, p_2) and $(\varepsilon_1, \varepsilon_2)$, respectively. Relaying path s_1-r-d_1 is assumed error-free, $\varepsilon_{R_1} = 0$. From both figures it can be observed that ideal cooperative MAC performs better than cooperative CSMA/CA and non-cooperative scheme. However, as mentioned



(a) Cooperative CSMA/CA

(b) Ideal cooperative MAC

Figure 3.8: Ratio of overall network throughput with and without cooperation, η_{co}/η, as a function of packet error rates ε_1 and ε_2 in the non-symmetrical network scenario; $p_{R_1} = 0$, $p_1 = p_2 = 0.75$.



(a) Cooperative CSMA/CA

(b) Ideal cooperative MAC

Figure 3.9: Ratio of overall network throughput with and without cooperation, η_{co}/η, as a function of transmission loads p_1 and p_2 in the non-symmetrical network scenario; $\varepsilon_1 = \varepsilon_2 = 0.2$, $\varepsilon_{R_1} = 0$.

before, its realization requires strict synchronization among nodes to guarantee delivery of acknowledgments back to source nodes.

3.3 Selecting a Spatially Efficient Relay

Cooperative relaying aims to increase the reliability of wireless links in fading-rich environments. However, as was shown above, due to the shared wireless medium, cooperative relaying can also prevent other nodes from transmitting, or cause additional interference at receivers.

Ideally, in addition to the traffic already blocked by the communicating source-destination pair, an assisting relay should interfere with as less traffic (outgoing and incoming) as possible. However, the traffic situation around a node can change very quickly in wireless distributed networks. Furthermore, it is nearly impossible for a relay to estimate with which links it interferes for each s-d pair. In an ideal cooperative MAC, a relay would need to differentiate additionally between incoming and outgoing traffic on each neighboring link, see Figure 3.3.

Alternatively, simply the number of nodes a relay prevents from transmission or reception can be considered. This assumes that traffic load is distributed equally among the nodes, and a relay with the minimum number of blocked nodes also blocks less traffic in its range. Additionally, nodes in range of s or d back off from channel access and are not considered as blocked by the selected relay.

As shown in Figure 3.3, cooperative retransmission consists of two time steps. In the first step, s is transmitting to d and relay r. The second step is probabilistic and is performed only when direct transmission fails. Furthermore, it depends on particular MAC implementation which nodes back off from channel reuse during first and second time slots. To simplify the further analysis, it is assumed that same nodes are blocked during both time slots, and in further only first time slot is considered, since it always takes place when s is transmitting. The number of nodes which are prevented by relay r from transmitting or receiving during the first time slot is named *relay spatial use* a_r.

If there are N nodes in the network indexed by $n \in \{1, 2, \ldots, N\}$, indices of all nodes in the transmission range R_{tx} of node n build a set S_n. The size of the set is denoted by $N_n = |S_n|$. For cooperative CSMA/CA, this corresponds to the nodes located in area A_7 in Figure 3.3a — nodes in the range of r and out of the range of given s and d. The resulting relay spatial use a_n of node n is

$$a_n = N_n - |S_n \cap S_s| - |S_n \cap S_d| + |S_n \cap S_s \cap S_d|. \tag{3.11}$$

For ideal cooperative MAC, nodes in areas A_4 and A_7 are counted as blocked. However, although the total blocked area is larger, nodes in A_7 still can receive

DATA without disturbing r. Resulting relay spatial use is defined by

$$a_n = N_n - |S_n \cap S_d| + |S_n \cap S_s \cap S_d|. \tag{3.12}$$

This section studies how nodes with lower relay spatial use can be preferred during the relay selection process. Relay selection is a critical part of any cooperative relaying protocol and can be used to identify and select nodes with best characteristics for relaying. A typical relay selection procedure consists of three distinctive phases:

- *Qualification phase*: A node can qualify itself as a relay candidate for the given s-d pair if it satisfies certain explicitly specified requirements, e.g., source-relay and relay-destination SNR thresholds.
- *Contention phase*: qualified relay candidates contend for being selected as relay. A *utility function* is used to combine and map local information into single value at each node.
- *Assignment phase*: single cooperative relay is selected among multiple relay candidates using a *selection function*.

For the further investigation, it is assumed that all nodes in range of both s and d pass the qualification phase and become relay candidates, and only the contention and assignment phases are studied.

3.3.1 Contention Phase

In the contention phase, qualified nodes contend to become relay. The contention is performed within a slotted contention window with w slots. A candidate relay node can send a contention message to either s or d, depending on a particular protocol realization. In this chapter, without loss of generality, it is assumed that contention messages are transmitted to d, where the selection decision is performed.

Contention is considered successful when at least one contention message from potential relays is successfully received at d. To select an optimal relay, d should receive contention messages from all candidate nodes. That requires, however, a sophisticated coordination algorithm and results in long selection delays if the number of potential relays is large. Moreover, in reality, d can hardly precisely know the number of candidate relays before the contention.

The goal of the contention phase is twofold: 1) to maximize the contention success probability, and 2) maximize number of contention messages received at d

from candidate nodes with lowest spatial usage. Next, several utility functions are discussed that can be used in the contention phase.

Maximum-Success Utility Function

Maximum-success utility function maximizes the probability of the contention success. It is assumed that there are M candidate relays for a given s-d pair, whose indices form set C_{sd}. Each potential relay $n \in C_{sd}$ chooses a random slot in the contention window of size w and transmits its contention message with probability q in this slot.

The probability that exactly m nodes select a given time slot is:

$$P_m = \binom{M}{m} \left(\frac{1}{w}\right)^m \left(1 - \frac{1}{w}\right)^{(M-m)}. \tag{3.13}$$

Then, probability that from those m nodes exactly one node transmits is:

$$P_{1|m} = mq\,(1-q)^{m-1}. \tag{3.14}$$

Summing up over all possible m, we obtain the probability that there is exactly one contention message in the given slot:

$$P_1 = \sum_{m=0}^{M} P_m \cdot P_{1|m} = \frac{(w-q)^{M-1}\, M \cdot q}{w^M}. \tag{3.15}$$

The probability that there is at least one non-collided message in the contention window is then given by:

$$P_s = 1 - (1 - P_1)^w. \tag{3.16}$$

Taking the derivative of (3.16) with respect to q and equating it to zero, one can find that q that maximizes P_s equals w/M. This is an expected result, and was also shown for slotted ALOHA protocols [Szp83, KS78].Using these findings, the following utility function to maximize contention success probability is used:

$$q = \begin{cases} 1, & M \leq w, \\ w/M, & M > w. \end{cases} \tag{3.17}$$

If $M > w$, on average w nodes send their application messages. Although in reality it is hard to estimate the exact number of current potential relays, the maximum-success utility function provides an upper bound on the success of the contention phase. The presented utility function, however, does not take into account spatial usage of candidate nodes.

Degree-Based Utility Function

For this utility function it is assumed that potential relays do not know the number of candidates M. Instead, each node n in the network can estimate its number of neighbors N_n (i.e., with N_n nodes in its transmission range) locally. Due to the broadcast nature of wireless networks, nodes constantly overhear the channel and over time can have an estimate about the number of nodes in their range. Special polling techniques for degree estimation are given in [KN06, HST$^+$10, AYB13a].

The degree-based utility function for potential relay $n \in C_{sd}$ provides transmission probability q_n of a contention message in a chosen time slot:

$$q_n = \begin{cases} 1, & (N_n - 2) \leq w, \\ \frac{w}{N_n-2}, & (N_n - 2) > w, \end{cases} \tag{3.18}$$

where s and d are discarded since they are neighbors of all potential relays by default. With this function, potential relays use their degree to get an estimate of the number of potential relays. Nodes with lower degree, which are also more likely to be spatially more efficient, have higher probability to transmit in the contention window.

Distance-and-Degree Utility Function

Distance-and-degree utility function, includes node degree N_n and information about its distances to s and d. Estimating distances between communicating nodes is trivial when they have GPS devices and can exchange their coordinates. But even without such hardware it would be possible to estimate local positioning of the nodes in the network [DPG01], [PHP$^+$03].

Intuitively, for cooperative CSMA/CA, a relay node that is located closer to either s or d should be preferred, since it shares a large part of spatial resources already allocated to the direct transmission. For ideal cooperative MAC in Figure 3.3, the potential relays that are closer to d should have a higher utility value for better resource utilization. The transmission probability q_n of a contention message for node $n \in C_{sd}$ is calculated by the following utility function:

$$q_n = \begin{cases} 1, & (N_n - 2) \leq w, \\ \min\left(\frac{1-\Delta_n}{\Delta_n}\frac{w}{N_n-2}; 1\right), & (N_n - 2) > w, \end{cases} \tag{3.19}$$

where Δ_n is given by:

$$\Delta_n = \begin{cases} \frac{\min(\Delta_{sn}, \Delta_{nd})}{R_{\text{tx}}}, & \text{cooperative CSMA/CA (I)}, \\ \frac{\Delta_{nd}}{R_{\text{tx}}}, & \text{ideal cooperative MAC (II)}. \end{cases} \tag{3.20}$$

Here, Δ_{sn} and Δ_{dn} are the distances from potential relay n to s and d, respectively, and R_{tx} is the transmission range.

3.3.2 Assignment Phase

In the assignment phase, d uses a selection function to find a single node out of the multiple candidates that went through the contention phase. Afterwards, the selected node is notified that it is assigned as the cooperative relay.

One selection function that does not require any other information besides contention messages is *random selection*: a relay node is randomly chosen from the successfully received contention messages. When a candidate node provides additional information in its contention message, a more effective selection method can be used. For instance, a cooperative relay with the highest contention probability q_n can be selected, which corresponds to *maximum-probability* selection function. In case there are several potential relays with the same q_n, a cooperative relay is chosen among them randomly. In addition to the random and maximum-probability, *minimum-degree* and *minimum-distance* selection functions are studied, which choose a potential relay with minimum N_n and minimum Δ_n, respectively.

3.3.3 Results and Discussions

For comparison of different utility and selection functions, two performance metrics are considered: the probability of successful contention P_s and relay spatial use a_r of the selected cooperative relay. Both metrics are studied for cooperative CSMA/CA and ideal cooperative MAC introduced in Section 3.1.

We assume that the normalized transmission range of all nodes is $R = 1$. Without loss of generality we assume that s and d are located at a distance of $\Delta_{sd}/R = 0.7$ from each other. Unless otherwise noted, the contention window size is set to $w = 5$ slots and the node density is seven nodes per square unit. The simulation area is set to include all nodes in the range of potential relays.

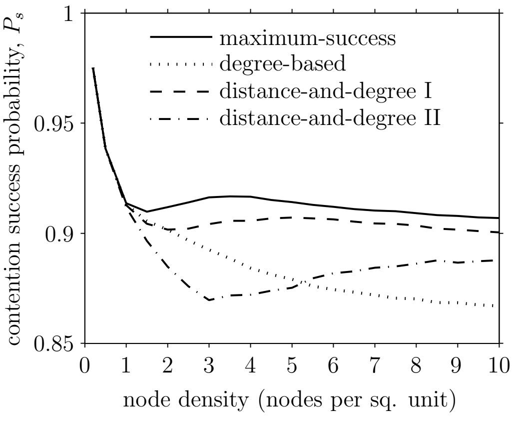
The performance results in two network scenarios are presented: a) network with random uniform node distribution, and b) network where one node has only s and d in its range.

Random Uniform Network

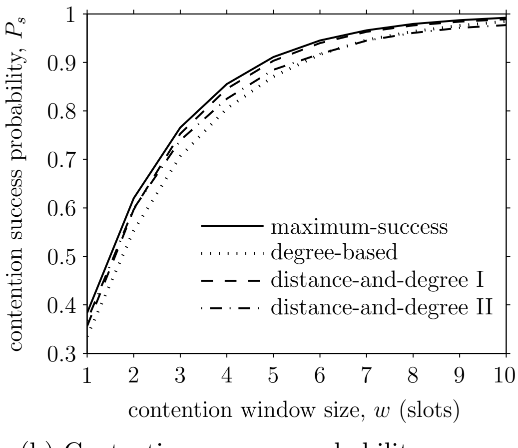
Nodes are randomly placed with uniform distribution at the area around communicating s-d pair. First, it is assumed that all nodes in the range of both s and d qualify as potential relays. The considered area is large enough to include all candidate relays and their neighbors, and avoid boundary effects.

Figure 3.10a shows contention success probability, i.e., the probability that at least one contention message is received without collision at d, versus the network node density. Maximum-success utility function represents the upper bound since the exact number of candidate nodes is used. However, other methods perform only slightly worse than the upper bound. Distance-and-degree utility functions with cooperative CSMA/CA (I) has slightly better success probability than with the ideal cooperative MAC (II), since in the former case more nodes are likely to participate in each contention.

As shown in Figure 3.10b, the contention window size w influences the outcome of the relay selection procedure significantly. A larger w results in lower number

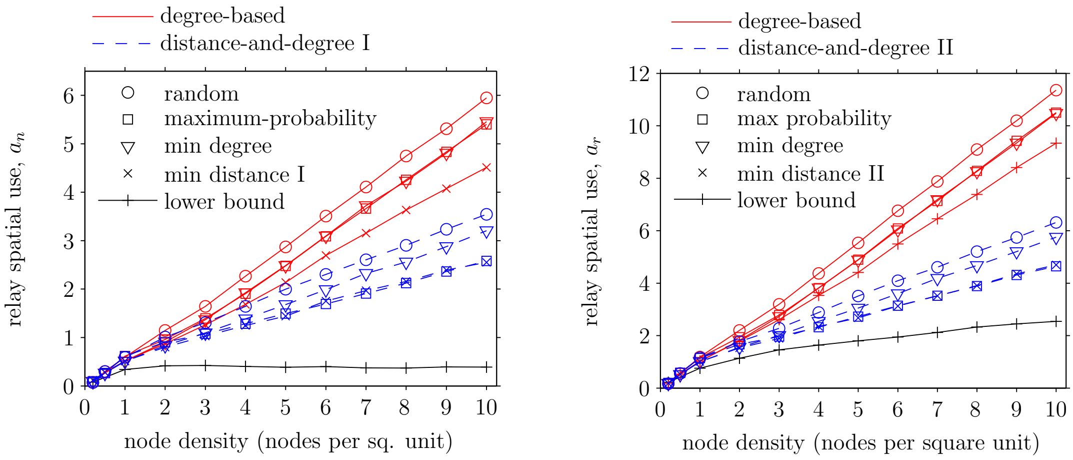


(a) Contention success probability vs. node density; $w = 5$.



(b) Contention success probability vs. contention window size; node density is seven nodes per sq. unit.

Figure 3.10: Contention success probability for different utility functions.



(a) Cooperative CSMA/CA

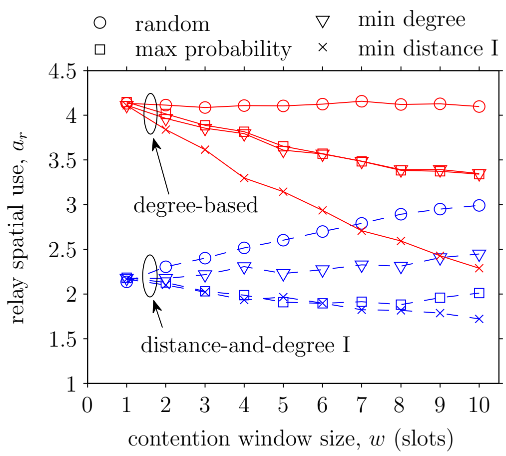
(b) Ideal cooperative MAC

Figure 3.11: Expected relay spatial use a_r versus node density in the network for different combinations of utility and selection functions; contention window size $w = 5$.

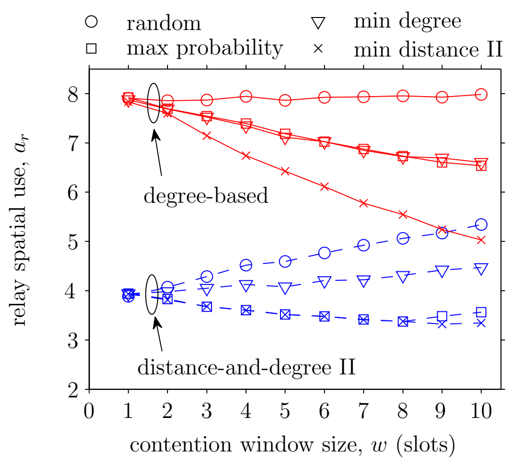
of collisions, and hence, a higher success rate for all utility functions. However, larger w also means a longer selection duration.

Figures 3.11a and 3.11b show the expected relay spatial use a_r, as declared at the beginning of Section 3.3, versus network density for cooperative CSMA/CA and ideal cooperative MAC, respectively. The performance of various combinations of utility and selection function can be observed. In both cases, a_r increases linearly with the node density. Distance-and-degree utility functions always outperform the degree-based one. A combination of distance-and-degree utility functions with the maximum-probability or with the minimum-distance selections provides spatially most efficient relays for both MAC protocols. However, comparison to the minimum bounds shows that there is still room for improvement in minimizing relay spatial use.

Figure 3.12 shows expected relay spatial use a_r as the function of contention window size w when node density is seven nodes per square unit. As above, contention success probability declines with decreasing w. However, a_r is calculated only for successful contentions. Therefore, degree-based utility function with random selection does not show any dependency on w, since qualified nodes have similar chances to go through contention and be selected due to the random uniform node distribution. For distance-and-degree utility functions with random selection, a_r increases with w. This is because at low w contention is likely to be successful when more efficient relays go successfully through contention. With increasing



(a) Cooperative CSMA/CA



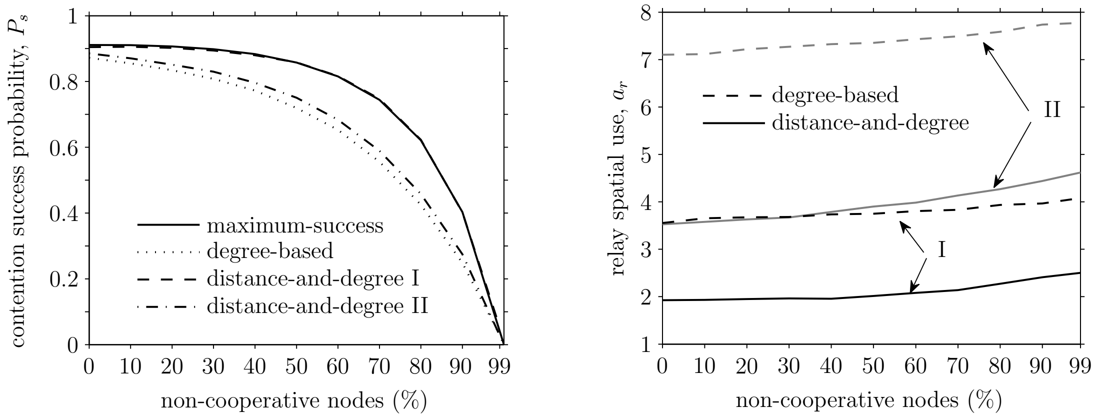
(b) Ideal cooperative MAC

Figure 3.12: Expected relay spatial use a_r versus contention window size w for different combinations of utility and selection functions; node density is seven nodes per sq. unit.

w, more nodes go through the contention phase and can be selected even if they are less spatially efficient. In both cooperative MACs, distance-and-degree utility functions with minimum-distance selection show best performance. And the maximum-probability selection performs only slightly worse at higher w.

So far it was assumed that all nodes in the range of s and d are qualified as potential relays and participate in the contention phase. In reality, not all nodes in range necessarily candidate for being relays. For instance, they might not satisfy SNR requirements, have low battery, or be in the sleep mode. Figure 3.13a illustrates the contention success probability versus the percentage of nodes that are not cooperating. Such nodes are chosen randomly in the given network. Observe that the success probability decreases sharply when the ratio becomes large. This is due to the fact that although fewer nodes enter the contention phase, contention probability q_n is not adjusted and uses same N_n as if every neighboring node qualifies as a potential relay. However, when contentions are successful, the expected relay spatial use is not significantly affected by the non-cooperative nodes (see Figure 3.13b) and increases only slightly.

One can conclude that with the use of utility and selection functions cooperative relay selection can provide spatially efficient relays in uniform networks even when not all nodes are willing to cooperate.



(a) Contention success probability versus percentage of non-cooperative nodes.

(b) Relay spatial use a_r versus percentage of non-cooperative nodes; maximum-probability selection function is used.

Figure 3.13: Impact of non-cooperating nodes on the contention success probability and expected relay spatial use; $w = 5$, node density is seven nodes per sq. unit.

Isolated Relay Scenario

Figure 3.14 illustrates a network consisting of an s-d pair, node r_1, and one cluster of nodes. The topology is setup so that r_1 is at the edge of the transmission ranges of s and d, and has no other nodes in its transmission range. A cluster of random uniform distributed nodes is located out of range of r_1 within the shaded area. Such cluster can e.g., represent nodes located in the same room. Some of the nodes in the cluster can be potential relays for the s-d pair and participate in the selection process. Clearly, if r_1 satisfies all other selection requirements, such as SNR thresholds, it should be selected as cooperative relay since it does not block any additional nodes.

Figure 3.15a shows the probability that r_1 is chosen with different contention utility functions versus the cluster size. Here, contention window size is $w = 5$, and the maximum-probability selection function is used in the assignment phase. If node r_1 is not selected, it means that either another node or none of the nodes are selected. When the cluster size is small all utility functions perform similar since nodes contend with probability of one. Observe that for the maximum-success utility function the probability of choosing r_1 significantly decreases with the increasing number of nodes. Here, all potential relays, including r_1, use the same

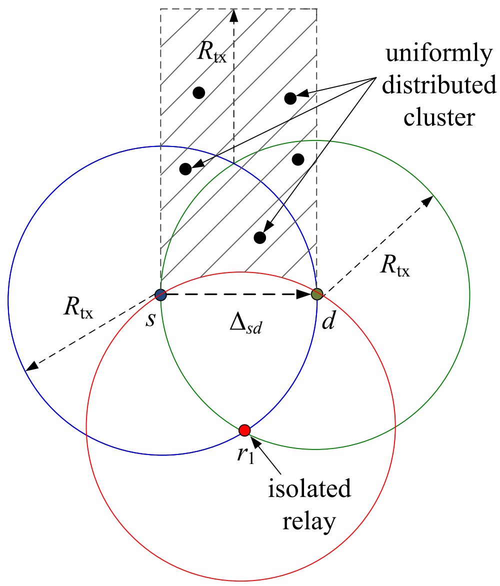
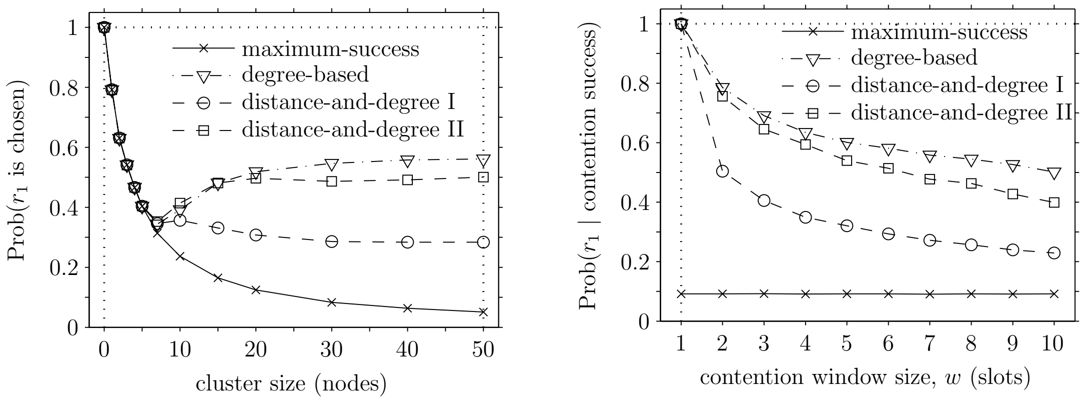


Figure 3.14: Network scenario with an isolated relay and a cluster of nodes.

contention probability, and have same chances to be chosen randomly in the assignment phase. With other utility functions, r_1 contends always with probability one. Degree-based utility function results in the highest probability for r_1 to be selected.

Figure 3.15b illustrates how the probability to select r_1 changes with the contention window size w given that the contention is successful. Again, maximum-probability selection function concludes each selection process. As expected, with maximum-success utility function, the probability of choosing r_1 does not change with w, since all nodes have the same contention probability. For other utility functions, when $w = 1$, a contention is successful when only r_1 transmits its contention message. The probability of choosing r_1 decreases with increasing w since when there is a collision with r_1, other nodes (with higher spatial use) can go through the contention and be selected.

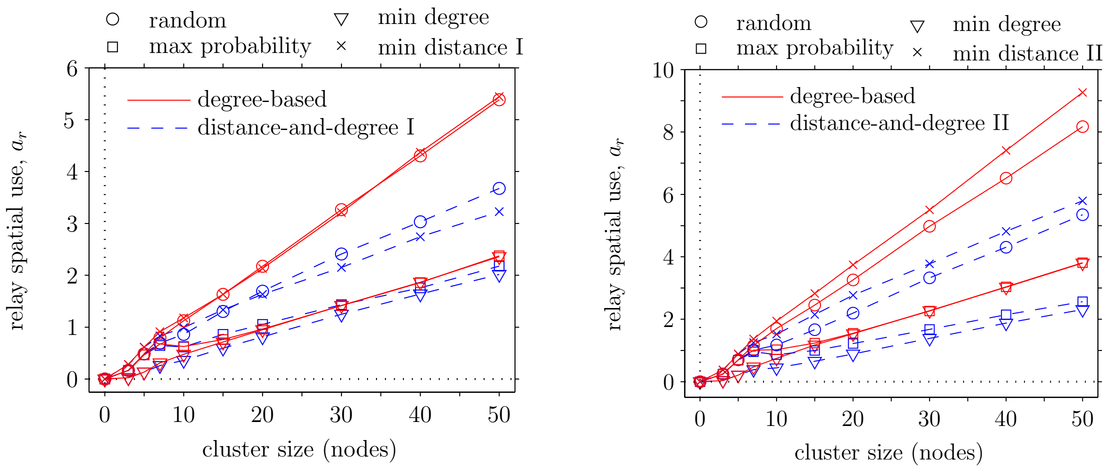
Figure 3.16 shows the expected relay spatial use a_r versus the cluster size. If r_1 could be selected as relay every time, zero nodes would be blocked for any cluster size. However, a_r grows with the increasing cluster size since more nodes are likely to cause collisions with contention messages from r_1, while other nodes go through contentions and become selected. Similar to a random uniform network, distance-and-degree utility functions on average perform better than the degree-based one when the same selection functions are used. When selecting nodes from the cluster, distance-and-degree utility functions are more likely to provide nodes



(a) Probability that r_1 is chosen versus the number of nodes in the cluster; $w = 5$.

(b) Probability that r_1 is chosen given contention is successful versus contention window size w; cluster size is 30 nodes.

Figure 3.15: Probability that an isolated node r_1 is selected (Figure 3.14). Maximum-probability selection function is employed.

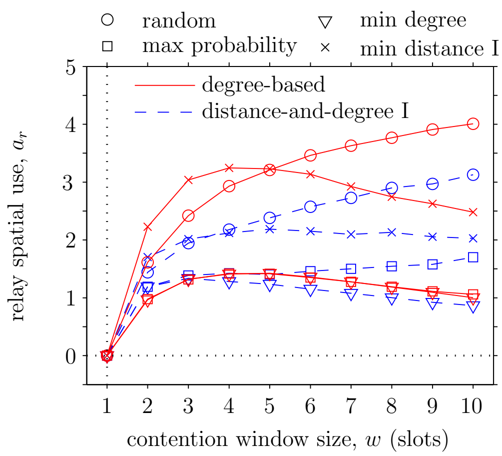


(a) Cooperative CSMA/CA

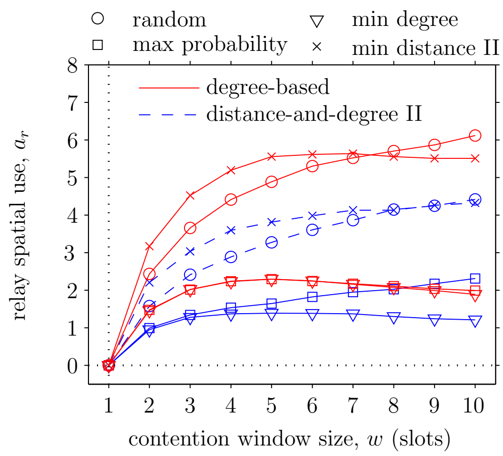
(b) Ideal cooperative MAC

Figure 3.16: Expected relay spatial use with different utility and selection functions versus the cluster size; $w = 5$.

with better relay spatial use for the assignment phase. However, in contrast to the uniform network, the minimum-distance selection function performs worst for both MAC protocols. The maximum-probability and minimum-degree functions always select node r_1 when it goes successfully through contention, and provide best spatial efficiency.



(a) Cooperative CSMA/CA



(b) Ideal cooperative MAC

Figure 3.17: Expected relay spatial use with different utility and selection functions versus contention window size; number of nodes in the cluster is 30.

Finally, Figure 3.17 shows the impact of the contention window size on relay spatial use a_r when the cluster contains 30 nodes. Minimum a_r is achieved at $w = 1$, when only r_1 goes successfully through contention. However, this also means that probability of successful contention is rather low (see Figure 3.10b). With growing w, also a_r increases since other nodes can go through contention and be selected instead of r_1. The random selection function performs worst with all utility functions since it does not take into account any information about spatial efficiency of the nodes. As already seen in Figure 3.16, the minimum-degree selection function performs best since it always chooses node r_1 if it goes through the contention. Naturally, maximum-probability and minimum-degree selections perform very similar for the degree-based utility function, while for degree-and-distance functions significant differences start to appear at larger w.

One can conclude that also in clustered networks utility and selection function in combination improve relay spatial use for cooperative relaying. Furthermore, adjustment of the contention window size provides tradeoff between contention success and spatial efficiency of the candidate relays.

3.4 Related Work

Efficient spatial reuse of spectrum resources in ad hoc networks is well studied and plays a critical role in the overall network performance [AZAM09]. Efficient scheduling of transmissions with MAC (e.g., with dual busy tone medium access [HD02]), control of sensing range and transmission power [DLV04], as well as use of directional antennas [CYRV02] are some common examples that significantly improve spatial reuse of ad hoc networks, and as a result their capacity. Theoretical capacity bounds of ad hoc networks are studied e.g., in [GK00, TG03, WAJ10]. In contrast, the spatial aspect of cooperative relaying has been studied only slightly.

A brief overview of cooperative MAC and relay selection schemes is given in Sections 2.3 and 2.4, respectively. Here, it is worth to mention that a large number of proposals extend the IEEE 802.11 DCF MAC and also use contention-based selection schemes [CYW07b, LTN+07b, ABS08, SCZ11]. An different MAC is proposed in [SWZW08], where authors enhance the idea of dual busy tones [HD02] to cooperative transmissions and develop a cooperative triple busy tone medium access (CTBTMA).

In [KWM08, AV08] authors propose an optimization of bandwidth and power allocation among the nodes in a network taking into account interference induced by relays. However, the proposed methods requires global network information and is relevant only for centralized networks. In [rCCH11] authors propose to select a node only from a specific geographical region and in this way improve spatial reuse and resulting outage probability in a network. Impact of node density and traffic load is analyzed.

Relay activation strategy that balances induced interference and outage probability is proposed in [AVPG13]. A relay node for a given source-destination pair in a network is selected based on CSI and its relative location to the source. Relay cooperation on a given link is either turned on or off by the global optimization algorithm. In [HS12] authors propose a binary network model to analyze how different cooperative scheme manage interference with incomplete view of a network.

The use of information about node locations in communication protocols is shown to be beneficial in number of works as well. Zorzi and Rao in [ZR03] use location of nodes for forwarding `DATA` from source to destination in multihop networks. At each hop a forwarding node closest to the destination is selected after the transmission. All nodes in the network build groups according to their distance to the destination. After receiving a message they participate in contention according to their group numbers. A contention resolution follows if necessary. In [BBM06] authors a spatial reuse ALOHA protocol that uses node locations to adjust transmission power and maximize the number of concurrent transmissions in a network. In [BBM10], the same group of authors proposes a relaying protocol where each next hop is selected opportunistically based on degree and location information of surrounding nodes. Significant improvement in the/ end-to-end delay compared to classical routing algorithms is shown. In [NJ07] authors propose an extension to the IEEE 802.11 DCF MAC that allows utilization of capture effects in ad hoc networks and increases overall network throughput by using local information of nodes location.

In contrast to the most of the publications above, the work presented in this chapter relies on relay selection that uses only local information at relays to improve spatial reuse of cooperative relaying. Some of the results have been also published in [10] and [9] in cooperation with corresponding co-authors.

3.5 Summary

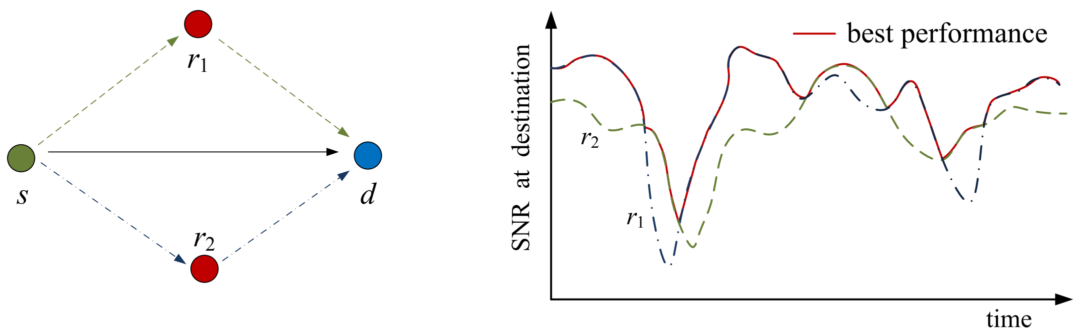
Cooperative relaying is used to improve reliability of wireless transmissions in fading-rich environments. However, it can also prevent other nodes from transmitting or receiving, and cause additional interference in the network. In the first part of this chapter, in a simple five-node setup, it is shown that cooperative relaying can decrease overall network throughput. Three different cooperative MAC protocols are explained and investigated. The results suggest that when cooperative relay prevents other nodes from communication, increase in overall throughput is possible when a) traffic load on the nodes is below certain threshold, and b) PER on direct links is rather high, and relaying can provide significant improvement.

In the second part, a relay selection mechanism is proposed that employs utility and selection functions to include degree and position information locally available of potential relays. With the presented selection procedure, relay nodes with lower spatial use are preferred. The performance of several selection algorithms is evaluated in terms of contention success probability and the amount of extra spatial resources used by selected cooperative relays. It is shown that while the proposed contention mechanism does not provide the best spatial efficiency, combined with a proper selection function a high success probability for relay selection ($> 90\%$) as well as significant reduction of blocked nodes ($> 50\%$) can be achieved in both random uniform and clustered networks.

CHAPTER 4 Selective Cooperative ARQ: An Analytical Framework

4.1 Introduction and Motivation

Cooperative relaying helps to mitigate negative effects of multi-path fading on the direct link between source and destination nodes and exploits a diversity path via a selected relay node. However, the diversity path can also suffer from fading. In such a case, a new relay selection can provide a relay node with better current channel characteristics.



(a) Network setup with two potential relays to assist source-destination transmissions

(b) Example of SNR perceived at destination

Figure 4.1: Impact of relay selection in cooperative relaying over time.

Figure 4.1a shows a simple setup where one of the two relays can be selected to assist s-d `DATA` transmissions. The corresponding SNR perceived at destination for cooperative relaying with the use of either r_1 or r_2 is shown illustratively in Figure 4.1b. In this example, neither of the relays can provide maximum SNR over the whole observation time. This can be the case when nodes r_1 and r_2 have rather similar channels to s and d. Therefore, it can be beneficial to switch from one relay to another and exploit cooperative diversity through timely relay selection.

The presented aspect reveals an important design question for cooperative relaying: *When has a new relay selection to be performed*? In Figure 4.1b the solid line shows the best SNR relay selection can provide. This can be achieved by proactive relay selection proposed by Bletsas et al. in their seminal work [BKRL06], where selection of a single relay is performed before each `DATA` transmission. The authors show that the achieved diversity order corresponds to that of a system with all potential relays retransmitting simultaneously using DSTC. However, in real-world, there may be no need to select a relay anew at each transmission. Furthermore, the required overhead for signaling can significantly reduce the performance benefits gained by relay selection.

The term *selective cooperative relaying* has been introduced by Michalopoulos et al. in [MLKS10] to emphasize that a particular cooperative relaying protocol employs timely relay updates. There, authors provide a performance comparison between opportunistic relaying and their relaying scheme with selection triggered only when the SNR perceived at d down-crosses a certain threshold. The authors show that their scheme performs far less relay selections than opportunistic relaying. However, the impact of selection overhead on throughput and energy efficiency is not investigated.

This chapter compares the performance of four different relay selection schemes, which define when and how a new relay selection is performed:

1) *Permanent* selection: A relay is selected for a long period of time (at least several magnitudes longer than the duration of a `DATA` packet).
2) *Proactive* selection: A relay is selected before each direct transmission [BKRL06, ISSL08].
3) *Reactive* selection: A relay is selected anew each time the destination fails to receive a `DATA` packet from the source directly [BSW07].
4) *Adaptive* selection: A relay is selected anew each time the destination fails to receive a `DATA` packet, i.e., neither the source nor the currently active relay could deliver the packet.

A relay node selected by one of the four schemes operates in the incremental relaying mode, i.e., relaying is performed when the destination is unable to decode the `DATA` sent by the source directly. If no signal combining [Pro01] is employed, such incremental relaying resembles an ARQ protocol, where the relay retransmits instead of the source [YZQ06]. The term *selective cooperative ARQ* is used throughout this chapter to refer to a corresponding cooperative relaying protocol that employs one of the introduced relay selections.

This chapter proposes an analytical framework based on semi-Markov processes [How07] to evaluate the performance of selective cooperative ARQ protocols with introduced selection schemes in time-correlated fading channels. The framework provides expected throughput and energy efficiency of relaying protocols taking into account relay selection overhead and energy required for transmitting and receiving `DATA` packets. Results are derived for a one-dimensional grid network with Rayleigh fading. They illustrate the tradeoff between throughput and selection overhead with reactive and adaptive selection. The throughput gain achieved through selection diversity can be diminished if selection delay is non-negligible and relay updates are triggered frequently. The chapter also studies the impact of temporal correlation of fading on throughput and energy efficiency, and derives closed-form throughput expressions for two channel correlation bounds (quasi-static and i.i.d. channels).

This topic is treated in a systematic manner using well-defined analytical methods. Although the analysis is limited to four selection schemes, the proposed framework is flexible enough to be extended to suit other cooperative retransmission schemes. The presented comparison yields novel insight into the relay selection process and can be used in the development of cooperative protocols.

4.2 Modeling Assumptions

4.2.1 Radio Channel

In the following, symmetrical wireless links with time-correlated block fading are considered. Time is divided into slots indexed by $k \in \mathbb{N}$ of duration T during which the signal level is assumed to be constant. It is assumed that T is also the transmission time of a `DATA` packet.

The SNR between nodes i and j over time is represented as a series of SNR samples $\{\gamma_{ij}(k)\}$. If the current SNR is higher than the decoding threshold, $\gamma_{ij}(k) > \gamma_{\text{thr}}$, the channel is in the *good* state, and can receive a `DATA` packet without errors. Otherwise, it is in the *bad* state, i.e., an outage event occurs, thus the `DATA` cannot be decoded by the receiver.

A binary random process $\{c_{ij}(k)\}$ describes the channel states between nodes i and j over time:

$$c_{ij}(k) = \begin{cases} \text{“Good” (G)}, & \gamma_{ij}(k) \geq \gamma_{\min}, \\ \text{“Bad” (B)}, & \gamma_{ij}(k) < \gamma_{\min}. \end{cases} \tag{4.1}$$

Generally, the process can be time-correlated, and can be modeled as a two-state Markov chain [ZRM97, ZRM98]. The corresponding transition probability matrix of the channel states,

$$\mathbf{C}_{ij} = \begin{bmatrix} \Pr(\mathrm{G}|\mathrm{G})_{ij} & \Pr(\mathrm{B}|\mathrm{G})_{ij} \\ \Pr(\mathrm{G}|\mathrm{B})_{ij} & \Pr(\mathrm{B}|\mathrm{B})_{ij} \end{bmatrix}, \tag{4.2}$$

defines the channel behavior. Here, $\Pr(b|a)_{ij}$, $a, b \in \{\mathrm{G}, \mathrm{B}\}$, is the probability that the next channel state is $c_{ij}(k+1) = b$ given that the current channel state is $c_{ij}(k) = a$.

The approach of [ZRM97, RCM02] is applied to obtain $\mathbf{C}_{ij}$ for Nakagami-m fading channels with given fading margin ψ_{ij}, Doppler spread f_D, and packet duration T. Fading is considered as slow if $f_D T < 0.1$ and fast if $f_D T > 0.2$ [ZRM97].

The fading margin ψ_{ij} characterizes the received signal power in relation to the receiver SNR threshold,

$$\psi_{ij} = \frac{\overline{\gamma}_{ij}}{\gamma_{\min}}. \tag{4.3}$$

The term $\overline{\gamma}_{ij}$ denotes the expected SNR at the receiver and is calculated according to a simple pathloss model by

$$\overline{\gamma}_{ij} = \frac{p_i}{p_n} \left(\frac{\Delta_{ij}}{\Delta_0} \right)^{-\alpha}, \tag{4.4}$$

where p_{tx} is the transmission power of node i, p_{n} is the noise power, Δ_{ij} is the distance between nodes, Δ_0 is a reference distance, and α is the pathloss exponent. Note that these values are linear and not in dB.

Since the results in this chapter are calculated for Rayleigh fading, here only the outage probability for this special case of Nakagami-m fading ($m = 1$) is given by:

$$\varepsilon_{ij} = \Pr[\gamma_{ij} < \overline{\gamma}_{\min}] = 1 - \exp\left(-\frac{1}{\psi_{ij}} \right). \tag{4.5}$$

For detailed information on Nakagami-m fading see [SA05].

If a conventional Stop-and-Wait (SW) ARQ protocol is employed on such a channel, i.e., s keeps retransmitting a `DATA` packet until it is received by d, with negligible and error-free feedback, the resulting normalized throughput at the receiver is $\eta = 1 - \varepsilon_{sd}$, which does not depend on channel time correlation [LC93].

4.2.2 Protocol Assumptions

The following assumptions are made on the operation of selective cooperative ARQ protocols with all four relay selection schemes:

- All transmissions are orthogonal in time.
- All nodes use the same transmission rate and power.
- All `DATA` packets have the same duration T.
- Signaling messages for relay selection and acknowledgments are error-free.
- Relays operate in decode-and-forward mode [ZV05].
- Receivers perform selection combining on packet level [Pro01]. Energy accumulation from different transmissions is not possible.
- A relay contention results in the selection of an optimal available relay candidate according to the selection requirements of a particular selection scheme.
- The selection overhead is expressed as the time interval T_{sel} needed for a relay selection procedure. Typically, it consists of the contention window size and the number of implementation-specific coordination messages from source and destination. It is assumed that this time remains constant for all four schemes. If a relay is not selected after the time T_{sel}, the source transmits the `DATA` packet without an assisting cooperative relay. In the rest of the chapter, the relay selection time T_{sel} is normalized to the `DATA` transmission time T. The duration of other signaling messages, such as `ACK`, is either ignored or included in the `DATA` packet duration.
- Energy for a `DATA` packet transmission is E_{tx}. At the receiver, energy is consumed only when a `DATA` packet is received correctly. The corresponding energy per packet is E_{rx}. If the channel is bad, the receiver can detect it at the beginning of the packet and stop receiving to save energy.
- Energy consumption during relay contention is not considered since it heavily depends on the particular implementation and network setup. However, the presented analytical framework can be easily extended to include this energy when it is known.

As mentioned before, it is assumed that relay selection is always successful as long as there is at least one available relay candidate, i.e., a node fulfilling selection requirements. Furthermore, always the nodes with best required characteristics is chosen. This implies that node contention is always successful. The intention here is to leave away implementation-specific details and keep the analytical framework generic and mathematical analysis more comprehensible. In spite of that the presented analytical framework can be extended to consider imperfect contention, e.g., one of the contention schemes introduced in the previous chapter.

4.3 Selective Cooperative ARQ as a Semi-Markov Process

4.3.1 Analytical Framework

A network consists of one source s, one destination d, and N surrounding nodes indexed by $n \in \{1, 2, \ldots, N\}$. The following notation is used to describe a selective cooperative ARQ protocol:

1. $c_{ij}(k)$ is the state of the radio channel between two nodes $i, j \in \{s, 1, 2, \ldots, N, d\}$. The channel behavior is defined by the channel state transition probability matrix $\mathbf{C}_{ij}$ as discussed in Section 4.2.1.
2. $Y = \{y_1, y_2, \ldots, y_L\}$ is a set of L operational states of a particular selective cooperative ARQ protocol. E.g., a protocol state can be a transmission of a new packet by s, retransmission by relay $r \in \{1, \ldots, N\}$, or relay selection procedure. The detailed description of protocol states for the four considered selective cooperative ARQ schemes is provided later in this section.
3. $y(k) \in Y$ is the protocol state at time slot k. Similar to a radio channel, the protocol states over time can be represented as a random process $\{y(k)\}$.
4. The tuple $\mathbf{z}(k)$ includes the protocol state and channel states at a given time step,

$$\begin{aligned}\mathbf{z}(k) = \Big(& y(k), c_{sd}(k), c_{s1}(k), c_{1d}(k), \\ & c_{s2}(k), c_{2d}(k), \ldots, c_{sN}(k), c_{Nd}(k)\Big).\end{aligned} \tag{4.6}$$

   Here, radio channels between nodes $n \in \{1, \ldots, N\}$ are not included since communication between potential relays is not considered in the proposed cooperative ARQ protocols.

5. Z is the set of all permitted unique tuples $\mathbf{z}(k)$ for a given protocol. The size of the set is
$$|Z|= L \cdot 2^{2N+1}. \tag{4.7}$$
In cases when the tuple set size becomes too large to handle, boundary cases have to be used as described later in this section.
6. The function $f : Z \to Y$ defines the protocol state transition from $y(k)$ to $y(k+1)$, which depends on the current channel states in the network and the protocol state.

Each tuple $\mathbf{z} \in Z$ can be seen as a state of a Markov chain incorporating protocol and channel transitions. The transition from tuple $\mathbf{z}_a$ to tuple $\mathbf{z}_b$ (both $\in Z$; $a, b \in \{1, \ldots, |Z|\}$) in one time step is only possible when $y^{(b)} = f(\mathbf{z}_a)$, and $y^{(b)}$ is the first element of $\mathbf{z}_b$, i.e., the protocol state of the next tuple is the same as defined by the function f for the current tuple $\mathbf{z}_a$. The transition probability is defined by the product of the corresponding channel state transitions from $\mathbf{z}_a$ to the ones in $\mathbf{z}_b$. The transition probability matrix $\mathbf{P}$ contains the probabilities of transitions between the tuples. Its elements are calculated by

$$P_{ab} = \begin{cases} \Pr(c_{sd}^{(b)}|c_{sd}^{(a)}) \prod_{n=1}^{N} \Pr(c_{sn}^{(b)}|c_{sn}^{(a)}) \Pr(c_{nd}^{(b)}|c_{nd}^{(a)}) & \text{for } y^{(b)} = f(\mathbf{z}_a), \\ 0 & \text{otherwise,} \end{cases} \tag{4.8}$$

where $c_{ij}^{(a)}$ is the corresponding channel state between nodes i and j in the tuple $\mathbf{z}_a$. Channel state transition probabilities are obtained from $\mathbf{C}_{sd}$, $\mathbf{C}_{sn}$, and $\mathbf{C}_{nd}$.

The vector $\boldsymbol{\pi} = \begin{bmatrix}\pi_1 \ \pi_2 \ \cdots \ \pi_{|Z|}\end{bmatrix}$ contains the limiting-state probabilities of the defined Markov process, i.e., element π_a is the probability that in its steady state after numerous transitions the Markov process will be in state $\mathbf{z}_a$.

If the Markov chain is irreducible and aperiodic, $\boldsymbol{\pi}$ can be obtained by solving the following set of linear equations:

$$\boldsymbol{\pi}\mathbf{P} = \boldsymbol{\pi} \quad \text{with} \sum_{a=1}^{|Z|} \pi_a = 1. \tag{4.9}$$

In general, before making the transition from state $\mathbf{z}_a$ to $\mathbf{z}_b$ the protocol waits for a holding time H_{ab}. If this time is equal for all state transitions, the process is considered Markov. If H_{ab} varies for some pairs $(\mathbf{z}_a, \mathbf{z}_b)$, or it has some random distribution, the system is semi-Markov and is defined by two matrices: the transition probability matrix $\mathbf{P}$ of the embedded Markov chain and the holding time matrix $\mathbf{H}$.

To consider the relay selection overhead, holding times can vary among state transitions. The corresponding semi-Markov processes are defined later for each relay selection scheme.

Throughput

Next, a delivery reward $X_{ab} = 1$ is assigned to any transition from tuple $\mathbf{z}_a$ to tuple $\mathbf{z}_b$ that results in a successful packet delivery to the destination. Otherwise the reward is set to 0. The cumulative reward of the process at time τ is called reward function $X(\tau)$. In the long term, $X(\tau)/\tau$ corresponds to the *normalized throughput* of the protocol and is calculated according to the fundamental renewal-reward theorem [ZR96] by

$$\eta = \lim_{\tau \to \infty} \frac{X(\tau)}{\tau} = \frac{\sum_{a=1}^{|Z|} \pi_a \sum_{b=1}^{|Z|} P_{ab} X_{ab}}{\sum_{a=1}^{|Z|} \pi_a \sum_{b=1}^{|Z|} P_{ab} H_{ab}}. \tag{4.10}$$

In the enumerator, the inner sum $\sum_{b=1}^{|Z|} P_{ab} X_{ab}$ is the expected reward (delivered packets) gained by transitions starting in state $\mathbf{z}_a$. In the denominator, the inner sum $\sum_{b=1}^{|Z|} P_{ab} H_{ab}$ is the corresponding expected waiting time in the state $\mathbf{z}_a$ before a transition. The outer sums provide the expected reward and waiting time of the whole semi-Markov process in the steady state. More detailed explanations can be found in [ZR96].

Selection Rate

Another metric of interest is the *selection rate*. It corresponds to the expected number of relay selections performed in a time unit by a given cooperative ARQ protocol. A selection reward $S_{ab} = 1$ is assigned to each transition from tuple $\mathbf{z_a}$ to tuple $\mathbf{z_b}$ where a relay selection takes place. Otherwise, S_{ab} is set to zero. The corresponding selection reward matrix $\mathbf{S}$ for each studied relay selection scheme is defined later in this section. The resulting selection rate ρ is calculated in a similar way as throughput:

$$\rho = \lim_{\tau \to \infty} \frac{S(\tau)}{\tau} = \frac{\sum_{a=1}^{|Z|} \pi_a \sum_{b=1}^{|Z|} P_{ab} S_{ab}}{\sum_{a=1}^{|Z|} \pi_a \sum_{b=1}^{|Z|} P_{ab} H_{ab}}. \tag{4.11}$$

For any $T_{\text{sel}} > 0$, the resulting throughput η depends on ρ. If η_0 and ρ_0 denote the throughput and selection rate for $T_{\text{sel}} = 0$, the corresponding η for $T_{\text{sel}} \geq 0$ can also be calculated by

$$\eta = \frac{\eta_0}{1 + T_{\text{sel}}\rho_0}, \tag{4.12}$$

and can be used instead of (4.10) when only η_0, T_{sel}, and ρ_0 are known.

To better reflect the impact of various relay selection schemes on throughput, the *selection rate per delivered packet* ρ/η, which is independent of $\mathbf{H}$ and T_{sel}, is also used for performance comparison in Section 4.4.

Energy Efficiency

In a similar way, energy rewards E_{ab} are defined, which correspond to the energy consumed for `DATA` transmission and reception during the state transition from $\mathbf{z}_a$ to $\mathbf{z}_b$. The *expected energy per delivered packet* in the long run can be calculated similar to (4.10) with an additional division by throughput η,

$$\xi = \frac{1}{\eta} \lim_{\tau\to\infty} \frac{E(\tau)}{\tau} = \frac{\sum_{a=1}^{|Z|} \pi_a \sum_{b=1}^{|Z|} P_{ab}E_{ab}}{\sum_{a=1}^{|Z|} \pi_a \sum_{b=1}^{|Z|} P_{ab}X_{ab}}. \tag{4.13}$$

It is independent from holding times $\mathbf{H}$ and the selection overhead T_{sel}.

The expression above can be easily extended to include the energy usage during the relay selection phase. If the overall expected energy used during contention by all nodes is E_{sel}, then the resulting energy used per delivered packet is

$$\xi = \xi[E_{\text{sel}} = 0] + \frac{\rho}{\eta} E_{\text{sel}}. \tag{4.14}$$

Alternatively, E_{sel} can also be included into the energy rewards E_{ab}. The value E_{sel} strongly depends on the used wireless technology, protocol implementation, contention mechanism, number of nodes N and their locations. For example, if contention is performed through signaling messages, the resulting E_{sel} is the sum of the energy used for transmission and receiving these messages. It can be observed that the additional contribution of E_{sel} to ξ is proportional to ρ/η. To avoid speculations about E_{sel}, in the following it is assumed that $E_{\text{sel}} = 0$, which is the most energy efficient relay selection.

The computational complexity of using this analytical framework basically corresponds to the complexity of solving the system of linear equations (4.9). It varies from $O(n^3)$ floating point operations for a dense matrix to $O(n)$ for a sparse matrix [GvL96], where n equals $|Z|$.

Limiting Bounds of Time-Correlated Channels

Two channel time correlation boundaries can be used to simplify the analysis of the protocol performance: a) *independent and identically distributed* (*i.i.d.*) channels, and b) *quasi-static* channels.

In an i.i.d. channel, the next state of the channel between nodes i and j does not depend on the current state and is defined solely by the error rate ε_{ij}. The corresponding channel transition probability matrix is simply

$$\mathbf{C}_{ij} = \begin{bmatrix} 1-\varepsilon_{ij} & \varepsilon_{ij} \\ 1-\varepsilon_{ij} & \varepsilon_{ij} \end{bmatrix}. \tag{4.15}$$

If each channel is considered to be i.i.d., the system Markov chain can be drastically reduced to the number of protocol states so that $|Z| = |Y| = L$. The transition probabilities from protocol state $y^{(a)}$ to state $y^{(b)}$ can still be calculated by (4.8). Thus, taking into account (4.15), the resulting probabilities are independent of the current channel states. The corresponding throughput and energy efficiency are calculated by (4.10) and (4.13).

A quasi-static channel is the limiting bound when $f_D T \to 0$, and, as a result, the corresponding channel transition probability matrix approaches its limit

$$\lim_{f_D T \to 0} \mathbf{C}_{ij} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{4.16}$$

To calculate the throughput at this limit, one needs to identify all state transitions within the discussed semi-Markov model that can take place when channel states do not change. This means that transitions between tuples in Z become deterministic. Therefore, transitions between tuples that lead to changes of the channel states can be ignored. Taking this into account, the expected reward $\widetilde{X}$ and the overall mean time between transitions $\widetilde{H}$ are calculated on the remaining transitions when the semi-Markov process is in steady state. The resulting throughput boundary is then

$$\lim_{f_D T \to 0} \eta = \frac{\widetilde{X}}{\widetilde{H}}. \tag{4.17}$$

As shown later, the throughput in such channels can be derived as closed-form expression.

The throughput of time-correlated channels with $0 < f_D T < 0.35$ always lies between the throughput of these two bounds. Therefore, the bounds can be used to assess protocol throughput without the extensive calculations of full semi-Markov models.

4.3.2 Permanent Relay Selection

In permanent relay selection, a relay is selected once and serves as a single relay for a period of time at least several magnitudes longer than the duration of a `DATA` packet.

After the relay selection, the source s can send `DATA` packets to the destination d and the selected relay r. If d receives the packet correctly, it sends a positive acknowledgment (`ACK`), and a new `DATA` transmission can begin. The relay r retransmits `DATA` only if it has received it correctly and d has not. The retransmission can be triggered explicitly by a negative acknowledgment (`NACK`) from d, or implicitly if an `ACK` is missing. If the direct transmission fails but r receives the packet, r retransmits it to d until a successful reception occurs. If neither r nor d receive `DATA` from s, s retransmits it. This scheme slightly differs from the one presented in [7], where the relay retransmits only once and if it fails source retransmits again. The approach presented here shows better throughput at lower ψ_{sd} when the r-d distance is smaller than the s-d one, since the relay has higher chances to deliver the packet than s. Therefore, it represents an upper bound for permanent selection schemes. In a real-world implementation, the selected relay should have a limited number of retransmissions, after which s can retransmits the same packet itself or start a new packet transmission.

Since the selected relay is intended to assist on many s-d transmissions, it is better to employ certain long-term characteristics to select the best-suited relay. For the purpose of this study, the expected SNR values of the s-r and r-d channels are reasonable and sufficient. The selected relay should be statistically most capable of receiving packets from s and delivering them successfully to d. The signaling overhead can be neglected in comparison to the number of `DATA` packets sent over the cooperative link.

Figure 4.2 shows the embedded Markov chain of the protocol states and transitions between them for cooperative relaying with one preassigned relay. After a relay $r \in \{1, \dots, N\}$ has been selected, the cooperative ARQ protocol can be in one of the following states:

Tx: s transmits a packet to d and r. Depending on whether the previous packet was delivered successfully, it can be a new packet transmission or a retransmission of the failed packet.

R: r relays the source packet to d.

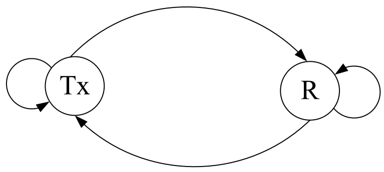


Figure 4.2: Markov chain for cooperative relaying with permanent relay selection

Only s-d, s-r, and r-d radio channels are needed to model the cooperative ARQ protocol operation. The set Z contains all valid combinations for the quadruple $\mathbf{z}_a = (y^{(a)}, c_{sd}^{(a)}, c_{sr}^{(a)}, c_{rd}^{(a)})$. In total, there are $|Z| = 16$ unique tuples that cover all possible state transitions in the system.

tuple	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$y^{(a)}$	Tx	Tx	Tx	Tx	Tx	Tx	Tx	Tx	R	R	R	R	R	R	R	R
$c_{sd}^{(a)}$	G	G	G	G	B	B	B	B	G	G	G	G	B	B	B	B
$c_{sr}^{(a)}$	G	G	B	B	G	G	B	B	G	G	B	B	G	G	B	B
$c_{rd}^{(a)}$	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B
$y^{(b)}$	Tx	Tx	Tx	Tx	R	R	Tx	Tx	Tx	R	Tx	R	Tx	R	Tx	R
X_{ab}	1	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0

Table 4.1: Transitions between protocol states depending on channel states for cooperative ARQ with a permanently assigned relay.

The function $y^{(b)} = f(\mathbf{z}_a)$ describing protocol state transitions of cooperative ARQ with a permanent relay can be written as:

$$y^{(b)} = \begin{cases} \text{Tx} & \text{for } y^{(a)} = \text{R},\ c_{rd}^{(a)} = \text{G}, \\ & \text{or } y^{(a)} = \text{Tx},\ c_{sd}^{(a)} = \text{G}, \\ & \text{or } y^{(a)} = \text{Tx},\ c_{sd}^{(a)} = \text{B}, c_{sr}^{(a)} = \text{B}, \\ \text{R} & \text{for } y^{(a)} = \text{R},\ c_{rd}^{(a)} = \text{B}, \\ & \text{or } y^{(a)} = \text{Tx},\ c_{sd}^{(a)} = \text{B},\ c_{sr}^{(a)} = \text{G}. \end{cases} \tag{4.18}$$

State transition probabilities from tuple $\mathbf{z}_a$ to tuple $\mathbf{z}_b$ are obtained according to (4.8).

Whenever a packet is successfully delivered to d, the protocol returns to the state Tx. The reward X_{ab} ($a, b \in \{1, 2, \ldots, 16\}$) is assigned in the following way

$$X_{ab} = \begin{cases} 1 & \text{for } y^{(a)} = \text{Tx}, c_{sd}^{(a)} = \text{G}, \\ & \text{ or } y^{(a)} = \text{R}, c_{rd}^{(a)} = \text{G}, \\ 0 & \text{otherwise}. \end{cases} \tag{4.19}$$

The holding time is the same for each state transition and corresponds to the duration of a single packet transmission, which is normalized to one. Since the duration of the relay selection can be neglected in the long run, selection rate $\rho = 0$. The resulting throughput is calculated by

$$\eta = \sum_{a=1}^{16} \pi_a \sum_{b=1}^{16} P_{ab} X_{ab}. \tag{4.20}$$

If all channels are i.i.d., the Markov process describing the tuple transition can be reduced to the chain in Figure 4.2 with transition probability matrix

$$\mathbf{P} = \begin{bmatrix} 1 - \varepsilon_{sd} + \varepsilon_{sd}\varepsilon_{sr} & \varepsilon_{sd}(1 - \varepsilon_{sr}) \\ 1 - \varepsilon_{rd} & \varepsilon_{rd} \end{bmatrix}. \tag{4.21}$$

The resulting throughput η is obtained by solving (4.9) and (4.10) and can be written as the closed-form expression

$$\eta = \Pr(\text{Tx}) = \pi_1 = \frac{1 + \varepsilon_{sd}\varepsilon_{sr}\varepsilon_{rd} - \varepsilon_{sd}\varepsilon_{sr} - \varepsilon_{rd}}{1 + \varepsilon_{sd} - \varepsilon_{sd}\varepsilon_{sr} - \varepsilon_{rd}}. \tag{4.22}$$

If all channels are approaching static states, the throughput reward $X_{ab} = 1$ is earned only when a) the s-d channel is good; or b) the s-d channel is bad AND both the s-r and r-d channels are good. In the second case, reward $X_{ab} = 1$ is assigned only when a protocol transition R$\to$Tx takes place, which makes up half of all transitions. Since all holding times are the same, $\widetilde{H} = 1$ and, therefore, the resulting limit for the throughput is

$$\lim_{f_D T \to 0} \eta = \widetilde{X} = 1 - \varepsilon_{sd} + 0.5\varepsilon_{sd}(1 - \varepsilon_{sr})(1 - \varepsilon_{rd}). \tag{4.23}$$

To shorten the next expressions, the indicator function for channel state c_{ij} is introduced:

$$\mathbb{1}_{\mathrm{G}}(c_{ij}) = \begin{cases} 1, & c_{ij} = \mathrm{G}, \\ 0, & c_{ij} = \mathrm{B}. \end{cases} \tag{4.24}$$

Using this indicator function, the energy consumed at state transition $\mathbf{z}_a \rightarrow \mathbf{z}_b$ is

$$E_{ab} = \begin{cases} E_{\mathrm{tx}} + E_{\mathrm{rx}}\Big(\mathbb{1}_{\mathrm{G}}(c_{sd}^{(a)}) + \mathbb{1}_{\mathrm{G}}(c_{sr}^{(a)})\Big) & \text{for } y^{(a)} = \mathrm{Tx}, \\ E_{\mathrm{tx}} + \mathbb{1}_{\mathrm{G}}(c_{rd}^{(a)})E_{\mathrm{rx}} & \text{for } y^{(a)} = \mathrm{R}. \end{cases} \tag{4.25}$$

The corresponding energy efficiency per delivered packet is calculated according to (4.13).

4.3.3 Proactive Relay Selection

In the proactive relay selection procedure, instantaneous CSI is obtained via signaling messages preceding each direct transmission (e.g., `RTS-CTS` message exchange [BKRL06]). A node n is a valid relay candidate if at the selection 1) its channel to s is in the good state, $c_{sn}^{(a)} = \mathrm{G}$, AND 2) its channel to d is also good, $c_{nd}^{(a)} = \mathrm{G}$. If node r is selected, it is assumed that the s-r channel remains in the good state in the subsequent time step when s is transmitting. This means that r always gets the packet correctly. Although at the selection point the r-d channel is also good, the channel state can change before relaying, since channel estimation takes place two slots before that. However, in time-correlated channels, the change becomes less probable.

If multiple nodes fulfill the selection requirements, the one closest to d is selected. In a real-world implementation this can correspond to the best n-d channel from available relay candidates. Without loss of generality, it is assumed that node indices $n \in \{1, 2, \ldots, N\}$ are assigned with ascending order according to the node distance to d. Finally, if the selection fails because there is no node having the required channel characteristics, s transmits the `DATA` without relay assistance and performs relay selection anew before transmitting the next `DATA` packet.

The discussed cooperative ARQ with proactive relay selection is described by the embedded Markov chain in Figure 4.3. The protocol states have following meanings:

- Tx: s transmits a packet. If the packet is delivered to d, a new packet transmission follows in the next time step. If no relay is selected and the packet is not delivered to d, s will retransmit the same packet again, and the protocol remains in state Tx.

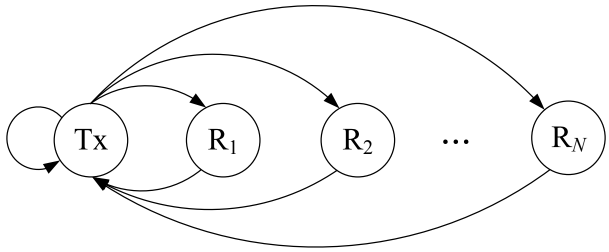


Figure 4.3: Protocol states and transitions for cooperative ARQ with proactive relay selection.

R_r: Relay r (selected at state Tx) retransmits the packet to d when an s-d transmission fails. Depending on the r-d channel state, relaying can be successful (the channel is good), or unsuccessful (the channel is bad).

Since channels to multiple potential relays are now considered, the size of the set Z with valid tuples according to (4.7) becomes $|Z| = (N+1) \cdot 2^{2N+1}$. The transitions between protocol states are defined as follows:

$$y^{(b)} = \begin{cases} \mathrm{Tx} & \text{for } y^{(a)} = \mathrm{Tx}, c_{sd}^{(a)} = \mathrm{G}, \\ & \quad \text{or } y^{(a)} = \mathrm{Tx}, c_{sd}^{(a)} = \mathrm{B}, \sum_{r=1}^{N} \mathbb{1}_{\mathrm{G}}(c_{sr}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{rd}^{(a)}) = 0, \\ & \quad \text{or } y^{(a)} = \mathrm{R}_r, \\ \mathrm{R}_r & \text{for } y^{(a)} = \mathrm{Tx}, c_{sd}^{(a)} = \mathrm{B}, \mathbb{1}_{\mathrm{G}}(c_{sr}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{rd}^{(a)}) = 1, \\ & \qquad \sum_{n=1}^{r-1} \mathbb{1}_{\mathrm{G}}(c_{sn}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{nd}^{(a)}) = 0. \end{cases} \tag{4.26}$$

Here, $r \in \{1, \dots, N\}$. The corresponding system state transition probabilities are calculated according to (4.8).

When a direct s-d transmission fails, the holding time of the process consists of the `DATA` packet duration and the time of relay selection overhead. If a direct transmission succeeds, the holding time equals only the `DATA` packet duration. The elements of the holding time matrix $\mathbf{H}$ are

$$H_{ab} = \begin{cases} 1 + T_{\mathrm{sel}} & \text{for } y^{(b)} = \mathrm{R}_r, \\ & \text{or } y^{(a)} = y^{(b)} = \mathrm{Tx}, \\ 1 & \text{otherwise.} \end{cases} \tag{4.27}$$

The resulting throughput is calculated according to (4.10).

For proactive relay selection, selection rewards S_{ab} are

$$S_{ab} = \begin{cases} 1 & \text{for } y^{(a)} = \text{Tx}, \\ 0 & \text{otherwise}, \end{cases} \tag{4.28}$$

and the selection rate is obtained according to (4.11).

Next, the throughput is obtained at the quasi-static channel correlation bound. First, the variable ε_R is introduced, which is the probability that no node satisfies the relay selection criteria,

$$\varepsilon_R = \prod_{n=1}^{N} \Big(1 - (1 - \varepsilon_{sn})\,(1 - \varepsilon_{nd})\Big). \tag{4.29}$$

Instantaneous channel knowledge becomes irrelevant in a quasi-static environment. The expected reward is calculated by

$$\widetilde{X} = 1 - \varepsilon_{sd} + 0.5\varepsilon_{sd}\,(1 - \varepsilon_R) = 1 - 0.5\varepsilon_{sd}(1 + \varepsilon_R). \tag{4.30}$$

To calculate the expected holding time between tuple state transitions, the probability of a state is multiplied with the time spent in this state before the transition assuming quasi-static channel states:

$$\begin{aligned} \widetilde{H} &= (1 + T_{\text{sel}})\Big(1 - \varepsilon_{sd} + \varepsilon_{sd}\varepsilon_R + 0.5\varepsilon_{sd}\,(1 - \varepsilon_R)\Big) + 0.5\varepsilon_{sd}\,(1 - \varepsilon_R) \\ &= 1 + T_{\text{sel}}\Big(1 - 0.5\varepsilon_{sd}(1 - \varepsilon_R)\Big). \end{aligned} \tag{4.31}$$

The resulting throughput in quasi-static channels approaches

$$\lim_{f_D T \to 0} \eta = \frac{\widetilde{X}}{\widetilde{H}} = \frac{1 - 0.5\varepsilon_{sd}(1 + \varepsilon_R)}{1 + T_{\text{sel}}\Big(1 - 0.5\varepsilon_{sd}(1 - \varepsilon_R)\Big)}. \tag{4.32}$$

Similar to permanent relay selection, for each transition from $\mathbf{z}_a$ to $\mathbf{z}_b$ energy rewards are assigned:

$$E_{ab} = \begin{cases} E_{\text{tx}} + 2E_{\text{rx}} & \text{for } y^{(a)} = \text{Tx}, c_{sd}^{(a)} = \text{G}, \sum_{r=1}^{N} \mathbb{1}_{\text{G}}(c_{sr}^{(a)})\mathbb{1}_{\text{G}}(c_{rd}^{(a)}) > 0, \\ E_{\text{tx}} + E_{\text{rx}} & \text{for } y^{(a)} = \text{R}_r, c_{rd}^{(a)} = \text{G}, \\ & \quad \text{or } y^{(a)} = \text{Tx}, c_{sd}^{(a)} = \text{G}, \sum_{r=1}^{N} \mathbb{1}_{\text{G}}(c_{sr}^{(a)})\mathbb{1}_{\text{G}}(c_{rd}^{(a)}) = 0, \\ & \quad \text{or } y^{(a)} = \text{Tx}, c_{sd}^{(a)} = \text{B}, \sum_{r=1}^{N} \mathbb{1}_{\text{G}}(c_{sr}^{(a)})\mathbb{1}_{\text{G}}(c_{rd}^{(a)}) > 0, \\ E_{\text{tx}} & \text{for } y^{(a)} = \text{R}_r, c_{rd}^{(a)} = \text{B}, \\ & \quad \text{or } y^{(a)} = \text{Tx}, c_{sd}^{(a)} = \text{B}, \sum_{r=1}^{N} \mathbb{1}_{\text{G}}(c_{sr}^{(a)})\mathbb{1}_{\text{G}}(c_{rd}^{(a)}) = 0, \\ 0 & \text{otherwise.} \end{cases} \tag{4.33}$$

The resulting average energy consumed per delivered packet is calculated according to (4.13).

4.3.4 Reactive Relay Selection

In reactive relay selection, s broadcasts a `DATA` packet to d and all nodes surrounding s. Relay selection takes place after each failed s-d transmission. A node n is an available candidate during selection procedure if: a) it receives the packet from s (i.e., the current s-n channel state is good), AND b) currently its channel to d is also good. The channel state information is obtained through a `NACK` from d, which in turn triggers a contention procedure. If a node fulfills the selection requirements it can always deliver the packet to d. It is thus not important which node out of the set of available candidates is chosen. If no candidates are available for relaying, s retransmits the `DATA` itself. To simplify the calculations, it is assumed that the nodes are sorted in order of preference, and a node with the lowest index in the candidate set is selected. This manipulation does not have any impact on the resulting throughput and energy efficiency of the protocol. In a real-world implementation, such as the one discussed in Chapter 5, the candidate with the best instantaneous channel quality to d at the time of selection should be taken.

Since all nodes overhear the direct transmissions, the advantage of reactive selection is in the usage of selection diversity at each failed packet.

Cooperative ARQ with reactive relay selection is described by an embedded Markov chain in Figure 4.4. It is similar to cooperative ARQ with a permanent relay, however, the protocol states have slightly different meanings:

Tx: s transmits a `DATA` packet. If the previous packet was not delivered and no relay was selected, s retransmits the same packet again. If the packet was successfully delivered, a new packet is transmitted.

R: A relay has been selected and delivers the packet to d.

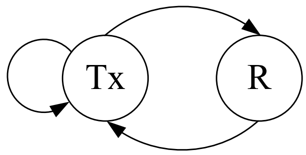


Figure 4.4: Protocol states and transitions for cooperative ARQ with reactive relay selection.

Since channels to multiple potential relays are considered now, the size of set Z with valid tuples according to (4.7) becomes $|Z| = 2^{2N+2}$. The states of s-r and r-d channels are obtained during the relay selection. Similar to proactive relay selection, it is assumed that the s-r channel does not change in the subsequent time step after the selection. The transitions between protocol states are defined as follows:

$$y^{(b)} = \begin{cases} \mathrm{R} & \text{for } y^{(a)} = \mathrm{Tx}, \sum_{n=1}^{N} \mathbb{1}_{\mathrm{G}}(c_{sn}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{nd}^{(a)}) > 0, \\ \mathrm{Tx} & \text{for } y^{(a)} = \mathrm{R}, \\ & \text{or } y^{(a)} = \mathrm{Tx}, c_{sd}^{(a)} = \mathrm{G}, \\ & \text{or } y^{(a)} = \mathrm{Tx}, \sum_{n=1}^{N} \mathbb{1}_{\mathrm{G}}(c_{sn}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{nd}^{(a)}) = 0. \end{cases} \tag{4.34}$$

The corresponding system state transition probabilities are calculated according to (4.8).

When a direct s-d transmission fails, the holding time of the process consists of the `DATA` packet duration and the time of relay selection overhead. If a direct transmission succeeds, the holding time equals only the `DATA` packet duration. The elements of the holding time matrix $\mathbf{H}$ are

$$H_{ab} = \begin{cases} 1 + T_{\mathrm{sel}} & \text{for } y^{(a)} = \mathrm{Tx}, c_{sr}^{(a)} = \mathrm{B}, \\ 1 & \text{otherwise.} \end{cases} \tag{4.35}$$

The resulting throughput is calculated according to (4.10).

For $N \to \infty$, the throughput approaches

$$\lim_{N \to \infty} \eta = 1 - \frac{1 + T_{\mathrm{sel}}}{2 + T_{\mathrm{sel}}} \varepsilon_{sd}, \tag{4.36}$$

as the selection of a relay is always possible. The consumed energy per delivered packet, however, goes to infinity for $E_{\mathrm{rx}} > 0$, since infinitely many nodes overhear the packet.

The selection reward S_{ab} is defined by

$$S_{ab} = \begin{cases} 1 & \text{for } y^{(a)} = \mathrm{Tx}, c_{sr}^{(a)} = \mathrm{B}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.37}$$

The selection rate is obtained according to (4.11).

Next, the throughput is obtained for quasi-static channels, where instantaneous channel knowledge becomes is the same as the expected CSI. The corresponding expected rewards are assigned in a similar manner as for permanent relay selection (4.23), but instead of a single relay state there are multiple relaying states that can be combined:

$$\widetilde{X} = 1 - \varepsilon_{sd} + 0.5\varepsilon_{sd}\,(1 - \varepsilon_R) = 1 - 0.5\varepsilon_{sd}(1 + \varepsilon_R). \tag{4.38}$$

To calculate the expected holding time between tuple state transitions, the probability of a state is multiplied with the time spent in this state before a transition assuming quasi-static channel states:

$$\begin{aligned} \widetilde{H} &= 1 - \varepsilon_{sd} + 0.5\varepsilon_{sd}\,(1 - \varepsilon_R) + \\ &\quad 0.5\varepsilon_{sd}\,(1 - \varepsilon_R)\,(1 + T_{\mathrm{sel}}) + \varepsilon_{sd}\varepsilon_R(1 + T_{\mathrm{sel}}) \\ &= 1 + 0.5\varepsilon_{sd}(1 + \varepsilon_R)w. \end{aligned} \tag{4.39}$$

The resulting throughput in quasi-static channels approaches

$$\lim_{f_D T \to 0} \eta = \frac{\widetilde{X}}{\widetilde{H}} = \frac{1 - 0.5\varepsilon_{sd}(1 + \varepsilon_R)}{1 + 0.5\varepsilon_{sd}(1 + \varepsilon_R)w}. \tag{4.40}$$

Similar to permanent and proactive relay selections, for each transition from $\mathbf{z}_a$ to $\mathbf{z}_b$ energy rewards are assigned by

$$E_{ab} = \begin{cases} E_{\mathrm{tx}} + E_{\mathrm{rx}}\Big(\mathbb{1}_{\mathrm{G}}(c_{sd}^{(a)}) + \sum_{r=1}^{N} \mathbb{1}_{\mathrm{G}}(c_{sr}^{(a)})\Big) & \text{for } y^{(a)} = \mathrm{Tx}, \\ E_{\mathrm{tx}} + E_{\mathrm{rx}} & \text{for } y^{(a)} = \mathrm{R}, y^{(b)} = \mathrm{Tx}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.41}$$

The resulting average energy consumed per delivered packet is calculated according to (4.13).

4.3.5 Adaptive Relay Selection

Adaptive relay selection is triggered when not only the direct transmission (as in reactive selection) but also the relay retransmission fails (i.e., either s-r or r-d channels are bad). If there is currently no assigned relay, s selects a relay proactively before starting a `DATA` transmission. However, in contrast to the proactive selection described above, if multiple nodes fulfill the requirement $c_{sn}^{(a)} = c_{nd}^{(a)} = \mathrm{G}$, the node with the best long-term channel characteristics such as for the permanent selection should be preferred. This means, a candidate node that provides the most reliable relaying path is preferred. Based on the received expected SNR values, s can estimate the most suitable relay node. Without loss of generality, but for simplicity of calculation, an index is assigned to each node to reflect the reliability of a two-hop path through this node. As in reactive relay selection, if multiple nodes fulfill selection requirements, the one with the lowest index is selected. This index is just used for analysis but is not required in a real protocol implementation.

After a relay r is selected, it assists s-d transmissions as long as the cooperative link remains good, i.e., as long as d receives `DATA` packets either from s or r. If both d and r are unable to decode the `DATA` packet, or if d fails to receive the forwarded `DATA` packet from r, s starts a new relay selection before transmitting `DATA`. If no relay can be selected, s transmits `DATA` packet, and starts a new selection again. The procedure is repeated until a suitable relay is assigned.

In [2] a slightly different version of adaptive relay selection is introduced. There a relay is selected in a reactive fashion instead of proactively as explained here. Each selection is preceded by broadcast of a Relay-Request (`RREQ`) message and retransmission of the failed `DATA` packet by s. After that a relay is selected from the nodes that have received `DATA` and have good channel to d. This approach provides a slightly better throughput since the relay can deliver the failed packet to d directly after the selection. However, it also implies lower energy efficiency at low ψ_{sd} since multiple nodes have to listen to `DATA` transmissions preceding selections. The testbed implementation of adaptive relay selection for IEEE 802.15.4 is introduced in Chapter 5.

Figure 4.5 shows the corresponding $L = 2N + 1$ protocol states and transitions between them.

Tx_r: s transmits a new packet. Node $r \in \{1, 2, \ldots, N\}$ is assigned as a cooperative relay.

R_r: The current relay r forwards the packet to d when it receives the packet from

s but d does not.

RS: A new relay selection is performed followed by a direct transmission. If relay r is selected and the direct transmission is successful, the process changes to state Tx_r in the subsequent time step. If relay r is selected, but direct transmission is unsuccessful, the protocol state changes to R_r. If no relay is found during relay selection, s retransmits the failed packet, or transmits a new packet, depending on the outcome of the preceding transmission; the protocol remains in state RS.

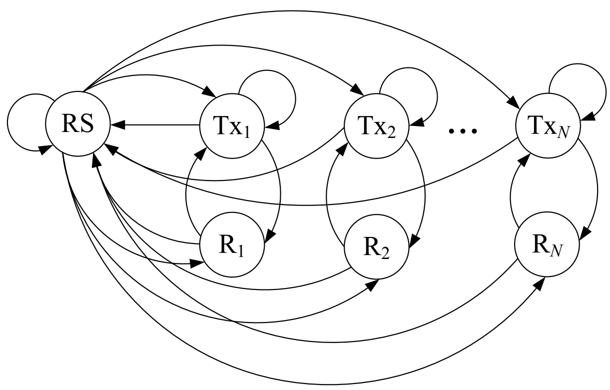


Figure 4.5: Protocol states and transitions for cooperative ARQ with adaptive relay selection.

The protocol transitions are formally defined as

$$y^{(b)} = \begin{cases} \mathrm{Tx}_r & \text{for } y^{(a)} = \mathrm{Tx}_r, c_{sd}^{(a)} = \mathrm{G}, \\ & \quad \text{or } y^{(a)} = \mathrm{R}_r, c_{rd}^{(a)} = \mathrm{G}, \\ & \quad \text{or } y^{(a)} = \mathrm{RS}, c_{sd}^{(a)}, c_{sr}^{(a)}, c_{rd}^{(a)} = \mathrm{G}, \sum_{n=1}^{r-1} \mathbb{1}_{\mathrm{G}}(c_{sn}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{nd}^{(a)}) = 0, \\ \mathrm{R}_r & \text{for } y^{(a)} = \mathrm{Tx}_r, c_{sd}^{(a)} = \mathrm{B}, c_{sr}^{(a)} = \mathrm{G}, \\ & \quad \text{or } y^{(a)} = \mathrm{RS}, c_{sd}^{(a)} = \mathrm{B}, c_{sr}^{(a)}, c_{rd}^{(a)} = \mathrm{G}, \sum_{n=1}^{r-1} \mathbb{1}_{\mathrm{G}}(c_{sn}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{nd}^{(a)}) = 0, \\ \mathrm{RS} & \text{for } y^{(a)} = \mathrm{Tx}_r, c_{sd}^{(a)} = \mathrm{B}, c_{sr}^{(a)} = \mathrm{B}, \\ & \quad \text{or } y^{(a)} = \mathrm{R}_r, c_{rd}^{(a)} = \mathrm{B}, \\ & \quad \text{or } y^{(a)} = \mathrm{RS}, c_{sd}^{(a)} = \mathrm{G}, \sum_{n=1}^{N} \mathbb{1}_{\mathrm{G}}(c_{sn}^{(a)}) \mathbb{1}_{\mathrm{G}}(c_{nd}^{(a)}) = 0. \end{cases} \tag{4.42}$$

The transition probability matrix $\mathbf{P}$ is calculated by (4.10).

The holding times are assigned with consideration of selection overhead as follows:

$$H_{ab} = \begin{cases} 1 + T_{\text{sel}} & \text{for } y^{(a)} = \text{RS}, \\ 1 & \text{otherwise.} \end{cases} \tag{4.43}$$

The corresponding transition probability matrix $\mathbf{P}$ is calculated according to (4.10).

The throughput reward of one is assigned to transitions resulting in a successful packet delivery to d:

$$X_{ab} = \begin{cases} 1 & \text{for } y^{(b)} = \text{Tx}_r, \\ & \ \text{or } y^{(a)} = y^{(b)} = \text{RS}, c_{sd}^{(a)} = \text{G}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.44}$$

The resulting throughput and energy per delivered `DATA` packet are calculated according to (4.10), and (4.13), respectively.

In adaptive selection, a new selection is performed every time the protocol is in state RS. Therefore, selection reward S_{ab} is simply

$$S_{ab} = \begin{cases} 1 & \text{for } y^{(a)} = \text{RS}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.45}$$

The selection rate is obtained according to (4.11).

Similar to reactive relay selection instantaneous channel knowledge becomes irrelevant in a quasi-static environment. The mean reward per transition is calculated in the same way as in (4.38). The expected holding time between transitions is

$$\begin{aligned} \widetilde{H} &= (1-\varepsilon_{sd})(1-\varepsilon_R) + \varepsilon_{sd}\,(1-\varepsilon_R) \\ &\quad + (1-\varepsilon_R)(1-\varepsilon_{sd})\varepsilon_R + (1-\varepsilon_{sd})\varepsilon_R^2(1+T_{\text{sel}}) + \varepsilon_{sd}\varepsilon_R(1+T_{\text{sel}}) \\ &= 1 + \varepsilon_R(\varepsilon_{sd} + \varepsilon_R\,(1-\varepsilon_{sd})\,)w, \end{aligned} \tag{4.46}$$

and the throughput when all channels approach quasi-static states is

$$\lim_{f_D T \to 0} \eta = \frac{\widetilde{X}}{\widetilde{H}} = \frac{1 - 0.5\varepsilon_{sd}(1+\varepsilon_R)}{1 + \varepsilon_R(\varepsilon_{sd} + \varepsilon_R\,(1-\varepsilon_{sd})\,)w}. \tag{4.47}$$

Energy rewards for cooperative ARQ with the adaptive relay selection are:

$$E_{ab} = \begin{cases} E_{\mathrm{tx}} + E_{\mathrm{rx}}\Big(\mathbb{1}_{\mathrm{G}}(c_{sd}^{(a)}) + \mathbb{1}_{\mathrm{G}}(c_{sr}^{(a)})\Big) & \text{for } y^{(a)} \in \{\mathrm{Tx}_r, \mathrm{RS}\}, y^{(b)} \in \{\mathrm{Tx}_r, \mathrm{R}_r\}, \\ E_{\mathrm{tx}} + \mathbb{1}_{\mathrm{G}}(c_{rd}^{(a)})E_{\mathrm{rx}} & \text{for } y^{(a)} = \mathrm{R}_r, \\ E_{\mathrm{tx}} + \mathbb{1}_{\mathrm{G}}(c_{sd}^{(a)})E_{\mathrm{rx}} & \text{for } y^{(a)} = y^{(b)} = \mathrm{RS}, \\ 0 & \text{otherwise.} \end{cases} \tag{4.48}$$

4.4 Performance Analysis

4.4.1 Network Scenario

The presented framework can be used for performance analysis of arbitrary network topologies. In the following, performance in linear network topologies is evaluated. Networks in many transportation or production systems can be modeled as one-dimensional networks [NMA12]. Similar modeling is also performed in [ZV05] for studying cooperative Hybrid-ARQ in practical relay networks. Despite the topological simplicity, a linear network still enables to apprehend distinctively the differences among the relay selection schemes in all main aspects. A performance analysis with a two-dimensional or three-dimensional node placement would not necessarily give significant additional insight in the protocol behavior.

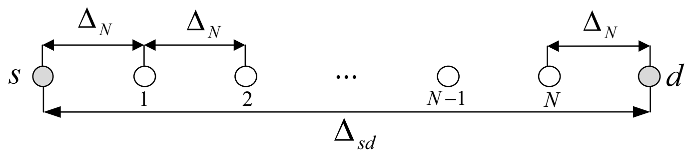


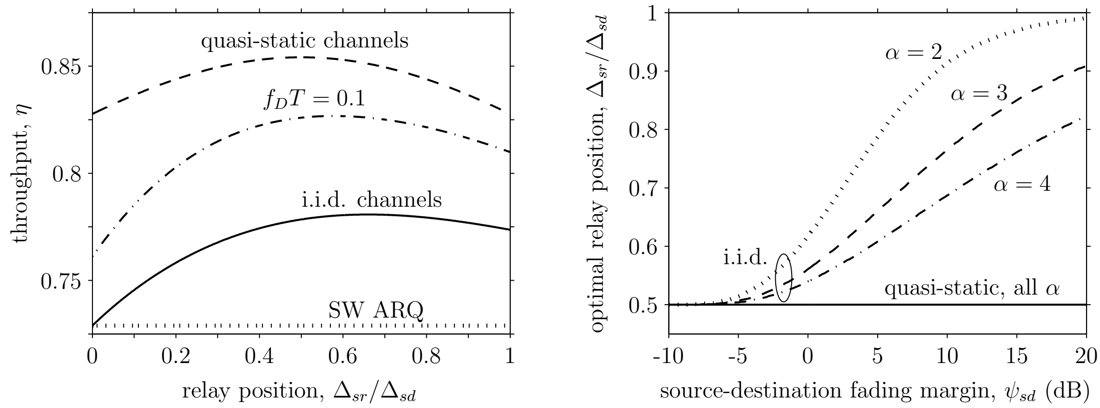
Figure 4.6: Network topology.

Figure 4.6 shows the used topology. There are N nodes located between source and destination at equal distances $\Delta_N = \Delta_{sd}/(N+1)$. These nodes can overhear the s-d communication if necessary and act as relays.

The pathloss exponent α is 3, and, for the sake of simplicity, it is assumed that all communication channels experience the same time correlation. All radio channels experience Rayleigh block fading. The corresponding channel state transition matrices are obtained according to [ZRM97].

4.4.2 Throughput

Figure 4.7a shows the impact of relay location on throughput at $\psi_{sd} = 5\,\text{dB}$. Relay r is located on the line between s and d at distance Δ_{sr} from source. For a given relay position and source-destination fading margin ψ_{sd}, throughput η in time-correlated Rayleigh channels is upper and lower bounded by the performance in quasi-static and i.i.d. fading channels. If the relay-to-destination distance is larger than the source-to-destination distance ($\Delta_{rd} > \Delta_{sd}$), cooperative relaying with a preassigned relay in i.i.d. channels performs worse than simple SW ARQ. Figure 4.7a also shows the throughput for moderately correlated channels with $f_D T = 0.1$.



(a) Impact of relay position at $\psi_{sd} = 5\,\text{dB}$, $\alpha = 3$.

(b) Optimal relay position to maximize expected throughput.

Figure 4.7: Performance of cooperative ARQ with permanent relay selection.

Numerical analysis shows that the maximum throughput of quasi-static channels is achieved when r is located in the middle between s and d. In contrast, for i.i.d. channels, the optimal relay placement depends on the fading margin and the pathloss exponent, as it is shown in Figure 4.7b. However, the gain at the optimal position to the throughput at the middle point is rather marginal. Therefore, to simplify analysis, it is assumed here that relay at the middle point between s and d should be selected, which is straightforward for network setup. The performance of cooperative ARQ with permanent relay selection is determined by the availability of such a node. To allow better comparison among schemes, in following all plotted results of cooperative relaying with permanent relay are calculated for a relay in the midpoint.

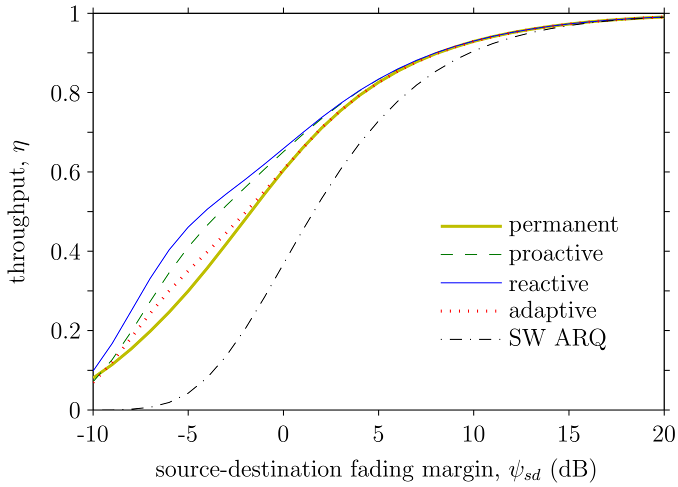
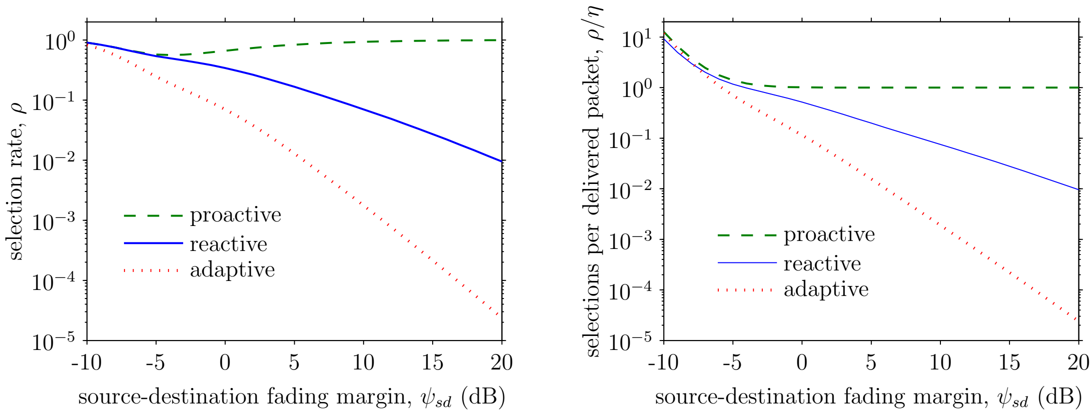


Figure 4.8: Throughput η as a function of source-destination fading margin ψ_{sd}. Number of potential relays $N = 5$, channel time correlation $f_D T = 0.1$, selection overhead sel $= 0$.

Figure 4.8 shows the throughput η versus the s-d fading margin ψ_{sd} for cooperative ARQ and SW ARQ when selection overhead is neglected, sel $= 0$, and the number of intermediate nodes is $N = 5$. All cooperative schemes perform better than SW ARQ. Reactive relay selection provides the highest throughput, since all N nodes overhear source transmissions, and in case of packet decoding failure at d, there is a higher probability of a successful relay retransmission. Adaptive selection outperforms permanent selection for $\psi_{sd} < 0\,\text{dB}$ for the same reasons. However, when a relay is selected, all nodes except the selected relay ignore s-d transmissions, and in case the cooperative link fails, a retransmission by s and a new relay selection are triggered. Therefore, the throughput for adaptive selection becomes lower than that of reactive and proactive relaying. Proactive relaying performs worse than reactive, since only one node is selected before each direct transmission. Even if the selected node receives `DATA` from source in the first time slot, there is a chance that it fails in retransmitting it to d, which is not the case for reactive relaying. For $\psi_{sd} > 5\,\text{dB}$ all schemes provide nearly the same throughput, since relay selection and relay transmission are almost always successful at such channel conditions.

In Figure 4.9a the selection rate ρ at sel $= 0$ is shown. It indicates how many selections are triggered per time unit. As expected, proactive selection is triggered most frequently, since with it a relay is selected before each direct transmission. Adaptive selection requires the least number of selections and significantly outperforms the reactive selection scheme for high ψ_{sd}. In Figure 4.9b the number of



(a) selection rate ρ, sel $= 0$

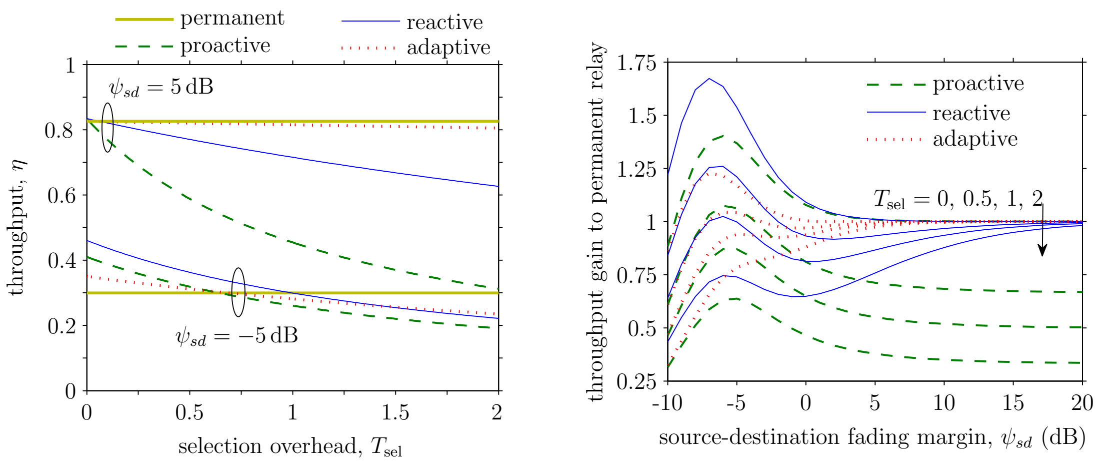
(b) selections per delivered packet ρ/η

Figure 4.9: Selection rate for proactive, reactive, and adaptive selections; $N = 5$, $f_D T = 0.1$.

selections per delivered packet is shown. The ratio ρ/η is independent of T_{sel}. It can be observed that reactive selection is only slightly more efficient at $\psi_{sd} < -5\,\text{dB}$. Otherwise, the adaptive selection is the most efficient in terms of triggered relay selections.

The impact of the relay selection overhead T_{sel} on the resulting throughput can be observed in Figure 4.10a. There, the throughput of reactive and proactive schemes decreases significantly with growing T_{sel}. Proactive selection always performs worse than reactive. Particularly, at $\psi_{sd} = 5\,\text{dB}$ a new proactive relay selection at each direct transmission becomes unnecessary and reduces the resulting throughput drastically. Adaptive selection can outperform reactive selection for certain T_{sel}. The throughput of cooperative ARQ with adaptive relay selection (dotted lines) is decreasing with an increase of T_{sel} as well. However, the impact of the overhead is smaller than that of reactive relaying. And since the throughput with a permanent relay is independent of T_{sel}, it can also perform better than all other schemes that utilize selection diversity but suffer from higher selection overhead T_{sel}.

This can also be seen in Figure 4.10b, which shows the resulting ratio of throughputs for proactive, reactive and adaptive selections to the throughput of cooperative ARQ with permanent relay. Again, the throughput of reactive and proactive relaying significantly suffers from the selection overhead. At some conditions it is even lower than the throughput of non-cooperative SW ARQ.



(a) Throughput as a function of overhead

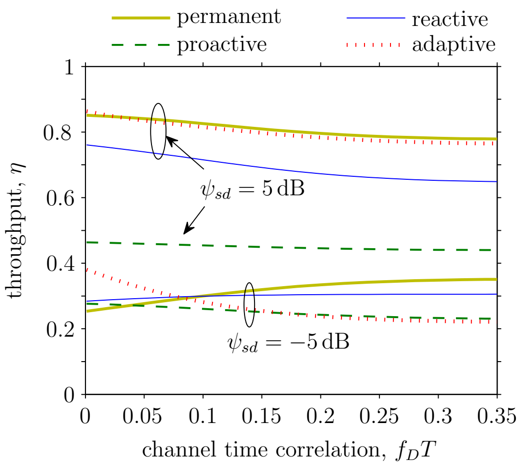
(b) Throughput gain to cooperative ARQ with permanent relay selection.

Figure 4.10: Impact of selection overhead on throughput; $N = 5$, $f_D T = 0.1$.

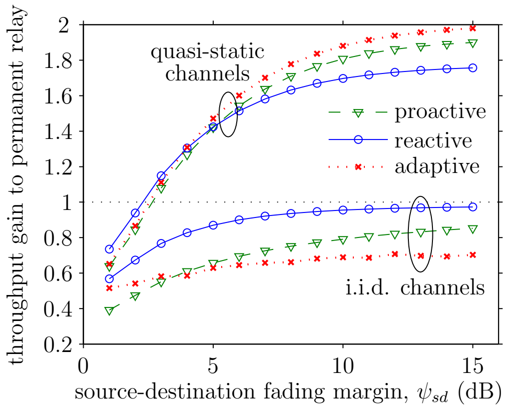
Next, the impact of channel time correlation on the throughput η is studied. Figure 4.11a shows the throughput for $f_D T \in (0, 0.35]$. As explained in Section 4.2.1, $f_D T \to 0$ corresponds to a quasi-static environment, where channel states do not change. The value $f_D T \approx 0.35$ corresponds to uncorrelated channels when the next channel state does not depend on the current state. Channel correlation can result in a difference of throughput performance from 10% to 35%. At $\psi_{sd} = 5\,\mathrm{dB}$, all selection schemes perform better in slower fading channels.

At an s-d margin $\psi_{sd} = -5\,\mathrm{dB}$ most transmissions require a retransmission by the relay. The s-r and r-d channels are now more prone to errors. As a result, in fast fading channels and given $N = 5$ relays, reactive and adaptive schemes often cannot select any relay since they require both s-r and r-d channels to be good. The probability can be improved by higher N, with the limiting case of $N \to \infty$, when a suitable relay node can always be found. In contrast, permanent relay selection allows the selected relay to retransmit `DATA` multiple times until the packet is delivered to d. Since selection overhead is negligible, higher throughput can be achieved. At slow fading channels, the channels to potential relays remain rather constant, and adaptive relay selection provides best throughput, since it makes use of various available relay nodes and keeps selection overhead at minimum.

Finally, the impact of the number of nodes N on throughput is shown in Figure 4.11b. Cooperative ARQ with a permanent relay at the midpoint between s and d is used as a baseline (independent of N) for comparison. For fading margins $\psi_{sd} > 5\,\mathrm{dB}$ the throughput of the three other schemes does not depend that



(a) Throughput η versus channel time correlation $f_D T$; $N = 5$.



(b) Throughput gain at correlation limits versus number of nodes N; $\psi_{sd} = -5$ dB.

Figure 4.11: Impact of fading time correlation and number of nodes on throughput; $f_D T \to 0$ — quasi-static channels, $f_D T \approx 0.35$ — i.i.d. channels; $T_{\text{sel}} = 1$.

much on N, since already with one or two available nodes the throughput is close to the achievable boundary. Figure 4.11b shows the throughput ratio of reactive and adaptive relay selection schemes to that of permanent relay selection at i.i.d. and quasi-static channel bounds and $\psi_{sd} = -5$ dB. Throughput ratios for other time-correlated channels lie within given bounds.

The results show that permanent relay selection performs better in i.i.d. channels, even when other schemes can make use of N available potential relays. The channel is too dynamic, which means selection of a good relay is less probable, and the selection overhead takes a lot of resources. For quasi-static channels, both adaptive and reactive selection schemes show significant benefits, since they can make use of more nodes and their stable channels. Particularly, adaptive relaying is highly beneficial in slow fading channels and high N, since a new relay selection is performed less frequently when using reactive relay selection.

4.4.3 Energy Efficiency

The total energy consumption per delivered `DATA` packet is used to evaluate the energy efficiency of the protocols. For comparison, the corresponding energy of

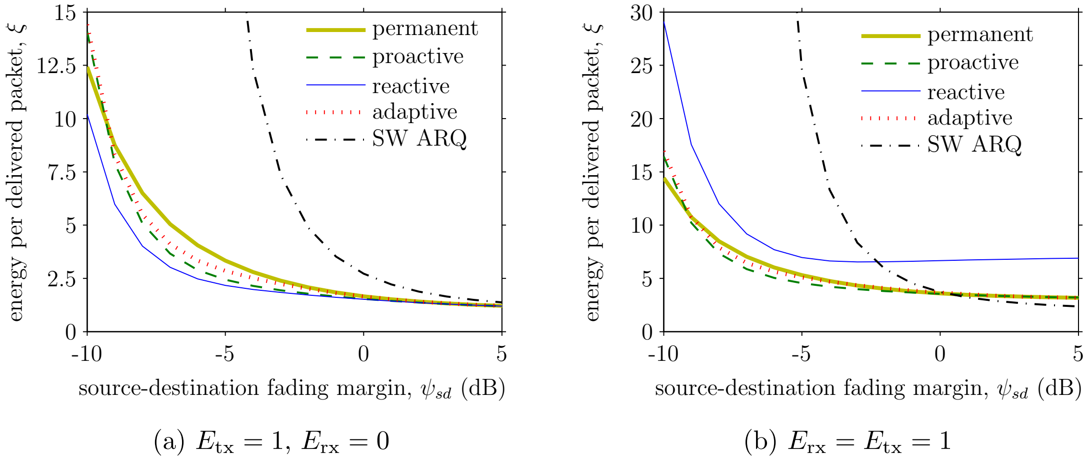


Figure 4.12: Expected energy per delivered packet ξ over source-destination fading margin ψ_{sd}; $N = 5$, $f_D T = 0.1$.

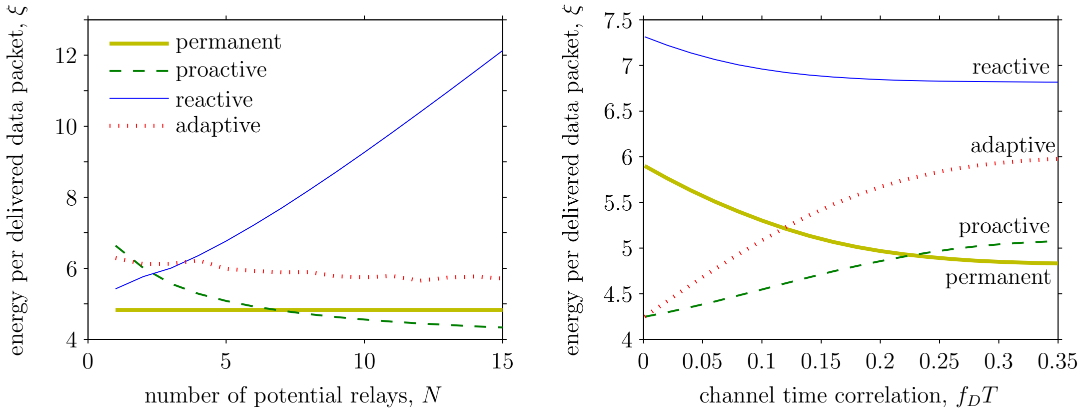
SW ARQ is also shown. It is calculated by

$$\xi = \frac{1}{\eta} E_{\mathrm{tx}} + E_{\mathrm{rx}}. \tag{4.49}$$

In the following, energy for transmission of a `DATA` packet is normalized, $E_{\mathrm{tx}} = 1$.

Figure 4.12a shows the expected energy per delivered `DATA` packet when energy consumption on the receiver side is neglected, i.e., $E_{\mathrm{rx}} = 0$. This corresponds to the inverse of the throughput η in Figure 4.8. As a result, reactive relay selection requires the least energy, since it provides the highest throughput. SW ARQ performs worst at low fading margins, since a packet delivery becomes nearly impossible. The energy consumption for $\psi_{sd} > 10\,\mathrm{dB}$ changes only insignificantly for all schemes and approaches one energy unit.

However, it is more practical to also consider the energy required for packet reception. Following results are obtained under a simplified assumption that the energy required to correctly receive a `DATA` packet is equal to the energy used for its transmission ($E_{\mathrm{rx}} = E_{\mathrm{tx}} = 1$) [FN01]. Figure 4.12b shows that, as a result, the energy efficiency changes significantly. Reactive relaying performs worst among all selective cooperative ARQ protocols. At $\psi_{sd} > 0\,\mathrm{dB}$ its energy per delivered packet is proportional to $N + 2$, since almost all overhearing nodes receive `DATA` packets with high probability. Permanent relay selection requires the lowest amount of energy, and, as shown in Figure 4.10b, provides best throughput. Adaptive relay



(a) Energy efficiency versus number of nodes; i.i.d. channels.

(b) Energy efficiency versus channel time correlation; $N = 5$.

Figure 4.13: Impact of number of nodes and channel time correlation on the energy per delivered DATA packet; $E_{\mathrm{rx}} = E_{\mathrm{tx}} = 1$, $\psi_{sd} = -5\,\mathrm{dB}$.

selection can adapt to the channel quality, and it requires the same amount of energy at higher ψ_{sd} as permanent relay selection. At lower fading margins, however, relay selection is triggered more and more frequently. This means that the source broadcasts its DATA to all surrounding nodes, and the energy efficiency of adaptive selection approaches that of reactive selection.

Figure 4.13b shows the impact of channel correlation on energy efficiency. Channels with higher correlation (lower $f_D T$) require more energy for relaying with permanent and reactive selection. This is due to the decreasing throughput (see Figure 4.11a), i.e., additional packet retransmissions decrease the energy efficiency. Adaptive relay selection, in contrast, performs significantly better in slow fading channels ($f_D T < 0.1$), as new relay selections occur less frequently, and mostly only one relay needs to overhear s-d transmissions.

4.5 Related Work

There are numerous relay selection methods studied in literature. Here, only a brief overview of some of them is given which discuss relay update rules and the impact of relay selection overhead.

The seminal publication of Bletsas et al. [BKRL06] introduces proactive relay selection before each DATA packet transmission. The resulting diversity order in a setup with N nodes is $N+1$ and corresponds to the diversity order of a system where all N nodes are used for retransmission. Authors stress the importance of relay selection within channel coherence time, which ensures that actual channel characteristics are used. In [BSW07] Bletsas et al. analyze proactive and reactive relay selection. There, reactive selection is performed after each `DATA` transmission and is shown to have the same outage performance as proactive relay selection. Authors mention that for reactive selection all nodes have to listen to `DATA` transmissions, which results in significant energy overhead. However, there are no results on energy consumption and impact of selection overhead. A reactive selection scheme is also studied by Yu et al. [YZQ06] for cooperative ARQ protocols with feedback from the destination. The resulting packet error rate after single retransmission is presented without consideration of the relay selection overhead.

Zhao et al. [ZV05] compare three practical selection schemes where a relay is selected based on the instantaneous Signal-to-Noise Ratio (SNR), average SNR, or randomly. Authors show potential benefits in throughput, energy, and latency for cooperative multi-hop transmissions. Although, the authors consider energy for receiving into their analysis, selection overhead and channel time correlation are not taken into account.

Michalopoulos et al. [MKTM06] study AF cooperative relay with an arbitrary number of relays selected out of multiple available candidates. Authors consider energy for signal transmission and reception and assume full CSI knowledge. Relay selection is modeled as a knapsack problem to optimize overall energy consumption, or improve BER under total power constraints. Authors also observe that relays selected with long-term channel statistics perform very similar to short-term selection. Another selection method for multiple relays is shown by Madan et al. [MMMZ08] and also aims to improve overall energy per packet. An optimal selection rule for DF relaying is derived where the destination chooses at each `DATA` packet which nodes retransmit.

System models with Markov processes have been successfully applied for performance analysis of probabilistic cooperative retransmissions. The authors of [LKW07] consider two-state Rayleigh channels which reflect overall system state. The resulting throughput of cooperative ARQ is analyzed but only a preassigned relay is considered. Dianti et al. [DLNS06] investigate a cooperative ARQ scheme where several permanently selected relay nodes can simultaneously retransmit `DATA` using distributed space-time codes (DSTC) if the source fails to deliver the packet to the destination directly. The authors consider time-correlated Rayleigh fading channels using Markov chains to model their cooperative ARQ scheme and obtain results for throughput and delay performance. Mahitan et al. [MRMS09] also use Markov models to model a cooperative ARQ protocol where a preassigned relay r always retransmits source packets to the destination as long as r is able to decode it. The authors consider error-correlated Nakagami-m fading, and do not take into account any relay selection aspects. The authors of [LT09] also assume correlated Nakagami-m fading, and derive guidelines for relay selection and optimal power allocation.

Shah et al. [SMY10a] analyze the tradeoff between selection duration and resulting throughput and energy benefits from cooperative transmission. They assume that a relay is selected after the source transmission and always retransmits data to the destination. It is shown that selection overhead can significantly decrease benefits of cooperation.

The topic of relay selection rate has also been studied from the perspective of switched diversity, which is typically used to switch spatially separated antennas at the receiver to use the strongest signal for demodulation [RYM73]. Two commonly studied switched diversity schemes are: *switch-and-examine* and *switch-and-stay* [RYM73, TAB01, YA04]. In the switch-and-examine scheme, the receiver switches to another diversity branch when the current SNR is below a given threshold. In switch-and-stay, the receiver switches to another branch only when the current SNR down-crosses the threshold, which avoids excessive switching. In contrast to diversity combining schemes such as selection combining and MRC, these two schemes do not require information from all branches to make decision about switching.

In relation to cooperative relaying, a Distributed Switch-and-Stay (DSSC) scheme is introduced by Michalopoulos and Karagiannidis in [MK07] where switching between a direct channel and a two-hop link is studied without diversity combining at the destination. Authors show that their scheme outperforms incremental relaying in terms of BER. Michalopoulos et al. [MLKS10] extend DSSC to selection from multiple relay candidates and diversity combining with direct transmission at the destination. The analysis in Rayleigh channels shows that DSSC significantly outperforms opportunistic relaying in terms of lower relay switching rate. In [XB12] Xiao et al. investigate DSSC in more general Nakagami-m channels. The resulting switching rates versus the SNR threshold and number of potential relays is presented. In relation to cooperative relaying, a DSSC scheme is introduced by Michalopoulos and Karagiannidis in [MK07] where switching between a direct channel and a two-hop link is studied without diversity combining at the destination. Authors show that their scheme outperforms incremental relaying in terms of BER. Michalopoulos et al. [MLKS10] extend DSSC to selection from multiple relay candidates and diversity combining with direct transmission at the destination. The analysis in Rayleigh channels shows that DSSC significantly outperforms opportunistic relaying in terms of lower relay switching rate. In [XB12] Xiao et al. investigate DSSC in more general Nakagami-m channels. The resulting switching rates versus the SNR threshold and number of potential relays is presented.

The analysis in this chapter was conducted independently from the work discussed in the paragraph above. It uses semi-Markov processes to model cooperative relaying with relay selection. In addition to selection rate and energy efficiency, the impact of relay selection overhead on throughput is studied for four different relay selection schemes. The results presented in this chapter are partially published in [7, 6, 5, 2] and have been achieved in cooperation with corresponding co-authors.

4.6 Summary

Early studies of relay selection showed that outage performance of cooperative relaying with a single relay selected at each `DATA` packet transmission is the same as cooperative relaying with multiple relays [BKRL06, BSW07, TN08]. However, relay selection at each `DATA` packet may not be necessary. Furthermore, in a real implementation, relay selection requires additional coordination overhead, which can reduce throughput benefits gained through diversity selection.

This chapter discusses in detail the aspect of when a new relay selection should be triggered, and the tradeoff between selection overhead and resulting performance of cooperative relaying. Four relay selection schemes are studied: permanent, proactive, reactive, and adaptive. The focus in these schemes is on the timing of relay update, and the implementation details of relay contention are kept generic. A framework based on semi-Markov processes is introduced that enables the modeling of cooperative ARQ protocols with different relay selection schemes. Within this framework, the protocol performance is obtained in terms of throughput and energy efficiency taking into account relay selection overhead and temporal correlation of fading channels.

The results obtained in a one-dimensional network with Rayleigh fading show that there is a significant tradeoff between relay selection overhead and throughput for reactive and adaptive relay selection, which can devalue throughput gains achieved through selection diversity. In contrast, the selection overhead for cooperative ARQ with a permanent relay can be neglected, and its actual throughput can be higher compared to reactive and adaptive schemes.

It is shown that time correlation of a radio channel has significant impact on the performance of cooperative ARQ protocols, particularly at low fading margins. The framework also introduces two limiting channel correlation cases: quasi-static channels and i.i.d. channels, which can be used to obtain expected throughput bounds.

If the energy needed for packet reception is taken into account, reactive selection performs worst, since it requires all neighboring nodes to listen to source transmissions. In contrast, a permanent relay requires only a single listening relay. Adaptive selection adapts its behavior according to dynamics of radio channels, and is more energy efficient in slow time-correlated channels, where relay selections are less frequent.

Overall, these results show that relay selection is a critical part of cooperative relaying protocols, and that relay update rules have significant impact on the throughput and energy performance benefits. Adaptive relay selection methods should be considered in the design of new cooperative networking protocols.

CHAPTER 5 Cooperative ARQ in Industrial WSN: An Experimental Study

5.1 Introduction and Motivation

Wireless sensor networks are gaining interest for industrial automation to replace aging wired industrial communication networks [WMW05, DPMVZ06, GH09]. Wireless sensors can be placed in locations unreachable with cables, provide maintenance flexibility and cost benefits. Typical applications for industrial WSN are monitoring and control of production processes. Sensors measure physical or chemical parameters, monitor states of machinery, and report them wirelessly to a control center. Based on the received measurements, the control center can wirelessly send commands to machinery actuators. Communication standards such as WirelessHART [wir07] (released in 2007), ISA100.11a [ISA09] (released in 2009), and IEEE 802.15.4e [IEE12] (released in 2012) are used to facilitate the advancement of industrial WSNs [PC11]. All three standards are based on the physical layer of the IEEE 802.15.4 standard [IEE06] used for low-power low-rate wireless sensor networks.

Applications for industrial automation have very strict requirements on communication reliability and packet delivery time [GH09]. Mistakes such as irregular pressure reports, a delayed actuation of a valve, or a failure to deliver a warning about a potential hazard because of a lossy communication link can damage the equipment or disrupt the production process.

Achieving the required reliability levels with wireless transmissions is a serious challenge in heavily cluttered and quickly changing environments often found in industrial production plants. Due to the cluttered indoor environment, wireless signals suffer from strong and dynamic multi-path fading. Additionally, moving production machines, cranes, trucks, forklifts, and human workers induce severe dynamic signal shadowing and make communication even more unreliable. Detailed wireless channel measurements in industrial environments can be found e.g., in [WKHW02, SMLW05, TWHG07, TJV$^+$08].

The aforementioned industrial communication standards include some common diversity techniques to improve communication reliability in lossy wireless networks: a) *time diversity* — retransmission of failed packets later in time to mitigate short radio channel outages [Wil05], b) *frequency diversity* — retransmission on a different frequency channel to mitigate interference and frequency-selective fading [WLMP10], c) *path diversity* — packet retransmission on a different route to mitigate long channel outages [Ish09].

This chapter investigates the use of cooperative relaying to improve reliability of wireless transmissions in industrial WSN. As explained in previous chapters, neighboring nodes can overhear the direct transmissions between a communicating pair. A selected relay node can retransmit `DATA` packets to the destination node when a direct transmission fail. Such relaying protocols based on cooperative diversity are applied on the data link layer and can be triggered locally at each hop in a distributed fashion when the direct link is temporally in outage. Use of cooperative relaying in industrial wireless sensor networks is discussed by Willig in [Wil08a] and [Wil08b]. In contrast, WirelessHART and ISA100.11a make use of path diversity on the network layer, which requires centralized route discovery and maintenance [Ish09].

The potential benefits of selective cooperative relaying in industrial wireless sensor networks, on one side, and lack of its experimental evaluation and practical insight, on the other side, serve as motivation for this work. In this chapter, cooperative relaying with single DF relay is experimentally studied in an industrial setting. Three practical relay selection schemes are considered: a) *periodic selection*, triggered at constant time intervals; b) *adaptive selection*, triggered when the delivery ratio on the cooperative link is below the threshold; c) *reactive selection*, triggered after each failed direct transmission [2].

The aim of the presented work is to provide a case study that evaluates empirically selective cooperative ARQ and its benefits for timely packet delivery in industrial WSN. The detailed integration into a particular existing industrial standard is out of the scope of this thesis. The contribution of this chapter is threefold:

1. It presents an implementation of three selective cooperative ARQ protocols with aforementioned relay update schemes for the IEEE 802.15.4 software protocol stack.

2. It provides an empirical performance comparison of the selective cooperative ARQ protocols in terms of delivery ratio, delay, and selection overhead over a network of IEEE 802.15.4-compliant devices deployed in an industrial production plant.

3. It analyzes the tradeoff between communication reliability and selection overhead over a range of system settings using trace-based emulation on collected channel measurements.

Selective cooperative ARQ is studied analytically in the previous chapter. This chapter does not consider proactive selection as it requires significant selection overhead and has been shown to perform worse than other selection schemes. Permanent relay selection is substituted here with a more general periodic selection. Finally, a more general implementation of adaptive selection is used where multiple `DATA` packets can fail before a new relay selection is triggered.

Some results of this chapter are also included in [1] which was still under review at the time this thesis was submitted. The presented work extends the preliminary work published in [3, 4] and has been performed in cooperation with corresponding co-authors.

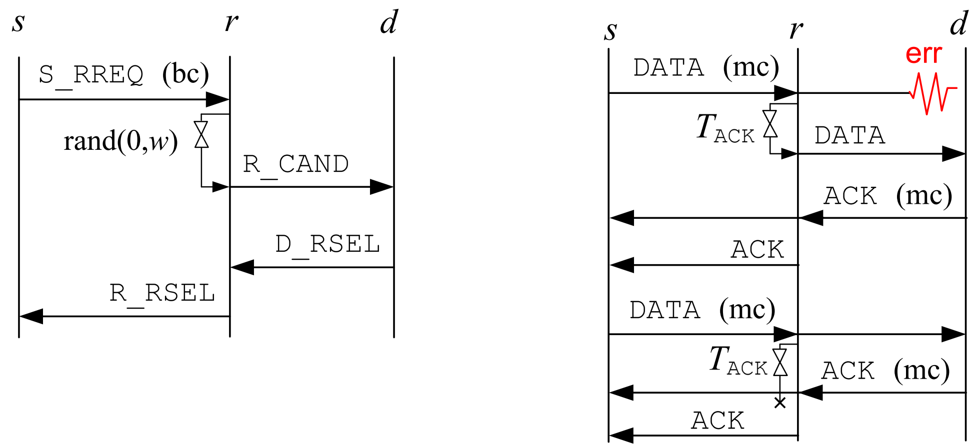
5.2 Selective Cooperative ARQ Protocols for WSN

As discussed in the previous chapter, relay selection requires knowledge of CSI on certain channels so that the selecting node can choose the relay with the best channel conditions. IEEE 802.15.4 off-the-shelve devices provide Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI) data for each received message. The RSSI value is expressed in dBm and corresponds to the average SNR computed over $128\,\mu$s. The LQI is computed over the first eight symbols of a frame and, additionally to the signal strength, also reflects its correlation. the IEEE 802.15.4 specifies that LQI has to be in the interval $[0, 255]$. The protocols discussed in this chapter use LQI since its better correlation with packet error rate has been shown [TWHG07]. Similar to the analysis presented in the previous chapter, only retransmission schemes without information combining of failed packets at d are considered. Therefore, the presented cooperative relaying protocols can also be referred to as cooperative ARQ protocols. Information combining can further increase the performance of cooperative relaying (see [DFEV05, WU08]) but it was shown that the gain achieved through combining is significantly smaller compared to the gain obtained through diversity transmission [OB12].

Next, the implementation of cooperative ARQ protocols with periodic, adaptive, and reactive relay update schemes is explained.

5.2.1 Periodic Relay Selection

As the name suggests, in this scheme a relay selection on a cooperative link is triggered strictly periodically at intervals T_{per} independent of the current relay performance. Figure 5.1a shows the implementation of this selection scheme. It



(a) Relay selection (b) Relay retransmission

Figure 5.1: Message flow for periodic and adaptive relay selection (a) and relay operation after it is selected (b). Here and later in the text, *bc* and *mc* stand for a broadcast and a multicast transmission, respectively.

is started by a source s that broadcasts a relay request message (S_RREQ). The message includes the ID of the destination node d. All nodes that receive this message (except d) start a random timer $T_{\text{w}} = \text{rand}(0, w)$ for a transmission in the following contention window of duration w. When the timer of a node expires, the node sends a message (R_CAND) to d. This message includes the LQI value measured on the S_RREQ packet received from s, and the value of $w - T_{\text{w}}$ so that d can identify the end of the contention window even if it does not receive S_RREQ itself. Nodes, whose R_CAND messages are received at, d form a relay candidate set C_{sd}. After the contention window ends, d evaluates the end-to-end link for each candidate node $c \in C_{sd}$ by taking the minimum of two LQI values

$$Q_c = \min(Q_{sc}, Q_{cd}), \tag{5.1}$$

where Q_{sc} and Q_{cd} are the LQI values from s to c and from c to d, respectively [BSW07]. A node r is selected as relay if it has the maximum Q_c among all candidate relays in C_{sd}. The destination sends a `D_RSEL` message to notify r that it has been selected. After receiving this message, r sends the message `R_RSEL` to s confirming the successful selection. Note that the introduced relay selection does not require any direct message exchange between s and d. This is different to other schemes in the literature which employ `Request-To-Send (RTS)` and `Clear-To-Send (CTS)` handshake [BKRL06, CYW07a, GG08] similar to the IEEE 802.11 DCF. However, such an exchange is not possible when the direct channel is in outage. As a result, the relay selection mechanism is likely to fail at times when involving a relay is most beneficial.

Figure 5.1b illustrates a relay retransmission when a direct `DATA` delivery fails. After the selected relay r receives the `DATA` packet from s, it starts a timer $T_{\mathtt{ACK}}$. If it does not receive an `ACK` from d within this time, it relays its copy of `DATA` to d. If d receives `DATA` correctly it multicasts an `ACK` to r and s. Regardless of whether r relayed `DATA` or not, whenever it receives an `ACK` from d, it always forwards it to s.

If s does not receive any confirmation `R_RSEL` within a certain time T_{conf} (Figure 5.1a), it assumes that relay selection failed and transmits the `DATA` packet without any assigned relay. The next relay selection is performed again directly before the next `DATA` transmission. If a relay is not selected after L of such selection attempts, s transmits its `DATA` packets without an assisting relay for the interval T_{per}. When the time T_{per} expires, a new relay selection process starts.

5.2.2 Adaptive Relay Selection

With adaptive relay selection, a new selection is triggered depending on the recent delivery ratio performance over the cooperative link. In this way, it exploits slowly changing channel conditions and minimizes the number of resulting relay selections. For such purpose, s keeps track of received acknowledgments from d for transmitted `DATA` packets. It assumes that if the `ACK` for a `DATA` packet is missing, the `DATA` packet is not delivered either by s or by the currently assigned relay r.

Only the W_{a} most recently transmitted packets are taken into account. If the ratio of missing `ACK`s from these W_{a} `DATA` packets is equal or higher than ε_a, a new relay selection is triggered, and a new recording of missing acknowledgments begins. The parameters W_{a} and ε_a define how sensitive the protocol is to losses on a cooperative communication link. If $\varepsilon_a = 1/W_a$, a new selection is triggered after each missing `ACK`. Another extreme is $\varepsilon_a = 1$, where a relay selection is triggered when all W_a packets are not acknowledged.

This version of adaptive relay selection differs from the one analyzed in the previous chapter, where a new relay selection is triggered when already one packet is not delivered to d. In the current implementation the selection is performed by s and the condition for a new relay selection can be modified to balance delivery ratio and selection overhead. The impact of the parameters W_a and ε_a on the delivery ratio and on the number of triggered selections is studied in Section 5.4.

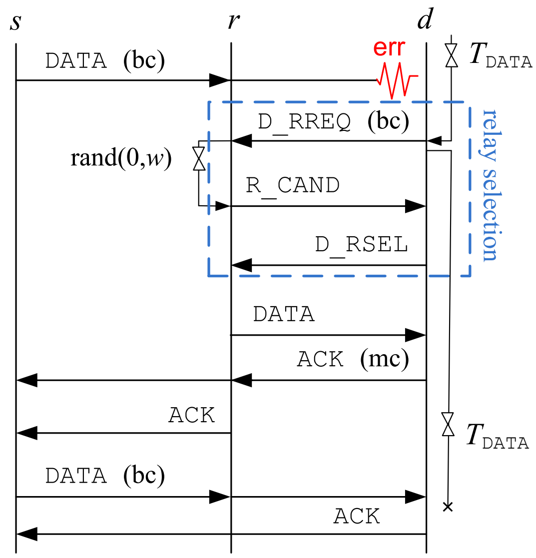


Figure 5.2: Message flow for cooperative ARQ with reactive relay selection.

The cooperative ARQ protocol with adaptive relay selection operates in the same way as shown in Figure 5.1.

5.2.3 Reactive Relay Selection

Reactive relay selection is triggered after each failed direct transmission of a `DATA` packet from s to d [BSW07]. Its clear benefit compared to other schemes adopted in this chapter is the full use of selection diversity among all potential relay candidates at each failed direct transmission.

Figure 5.2 shows the operation of cooperative ARQ with reactive relay selection initiated by d. Here, d broadcasts a relay request (`D_RREQ`) after the expiration of the timer T_{DATA} within which a new packet delivery is expected. This message includes the ID of s and the expected packet sequence ID. Only the nodes that have received both the DATA packet from s and the D_RREQ packet from d participate in the following contention. Similar to the contention procedure of periodic and adaptive relay selection, each of these relay candidates starts a random timer $T_w = \text{rand}(0, w)$, and upon its expiration sends a R_CAND message back to d. Nodes whose candidate messages are received by d form a set C_{sd} of relay candidates. A node $c \in C_{sd}$ is identified as the best relay if it has the highest Q_{cd} of all nodes in C_{sd}. After the best relay node r is identified, d sends a confirmation message D_RSEL to r to notify it about the selection. Afterwards, r starts retransmitting the stored DATA packet.

After the retransmission, the selected relay r waits for an ACK from d. Upon receiving it, it forwards the ACK to s. However, if a DATA packet is successfully delivered to d by s, no relay is selected, and the acknowledgment is not forwarded by any node.

The initiation of a relay selection by d is possible only in applications with periodic DATA transmissions. Alternatively, a selection can be initiated by s instead of d. In such a case, s broadcasts an S_RREQ message (instead of d) each time it does not receive an ACK for its direct transmission of DATA to d. The rest of the protocol remains the same.

One can also think of an implementation where each candidate relay node is set to retransmit the copy of DATA packet immediately after its timer T_w expires. When the first node starts retransmitting the packet, other candidates hear it and do not relay. In this way the additional signaling message exchange is avoided. However, a test implementation showed that it is difficult to avoid multiple retransmissions since nodes might miss the first transmission due to radio switching time or hidden terminal problems. A more reliable way is to let all candidates transmit a short message in a contention window as explained above. This also allows a fair comparison with the periodic and adaptive relay selection schemes.

5.3 Empirical Performance Comparison

The purpose of this experiment is to empirically evaluate and compare the performance of the proposed selective cooperative ARQ schemes in a real-world industrial setting.

5.3.1 Network Setup

Seven nodes are deployed inside a production plant of the package production company TEWA GmbH, Feldkirchen, Austria. The layout of the plant is shown schematically in Figure 5.3. The production environment consists of multiple shielded and unshielded machines (gray areas) that cut and transport cardboard packages. Dashed areas are the storage spaces for products, and the white space is the control room. Up to a dozen of human operators and three forklifts worked inside during the measurements. A part of the factory production floor can be seen in Figure 5.4.

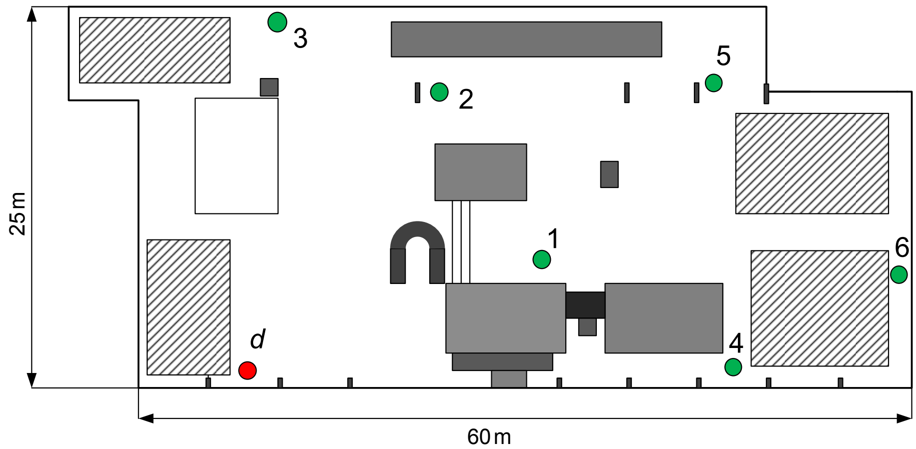


Figure 5.3: Factory layout and deployed sensor network.

There are six nodes (with IDs $i \in \{1, \dots, 6\}$) used as source nodes to send `DATA` packets to the destination node d. This reflects a typical setup of a wireless sensor network where remote sensors monitor the environment and report measured data to a single sink. Each source node generates and transmits $K = 60\,000$ `DATA` packets.

The presented selective ARQ protocols are implemented in off-the-shelf TelosB nodes from Crossbow [Tel04] shown in Figure 5.5. The devices are compatible with the IEEE 802.15.4 standard — a communication standard designed for networking of low-power devices. The physical layer of the IEEE 802.15.4 standard is also used in WirelessHART and ISA100.11a standards for industrial WSNs. The devices operate on unlicensed frequency bands at 2.4 GHz and provide a transmission rate of 250 kbit/s. Each node has an 8 MHz TI MSP430 microcontroller [MSP01], CC2420 radio transceiver [CC207], and 10 kB of internal flash RAM memory where the protocol stack with cooperative ARQ modifications is loaded.

Figure 5.4: Package production in TEWA GmbH where experiments were conducted.

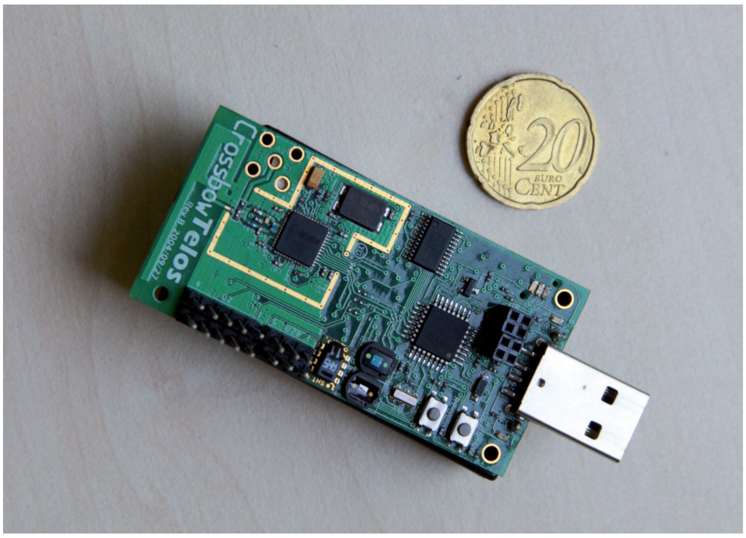


Figure 5.5: TelosB node [Tel04].

5.3.2 Experiment Description

For a better analysis of individual links, the operation of each source node is separated in time: i.e., source $i + 1$ starts transmitting its `DATA` packets only after node i finishes sending all its K packets. In this way, the performance of individual links is tested avoiding medium access and interference aspects, which are out of the scope of this work. For additional information on the topics, the interested reader is referred to [ACDF11] and [GHZ12].

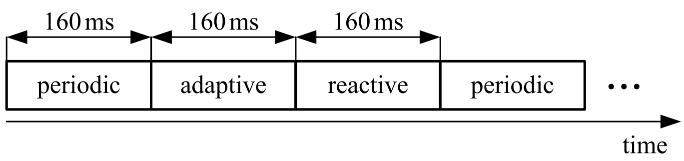


Figure 5.6: Sequential execution of cooperative ARQ protocols with different relay selection schemes.

To compare the three selective cooperative ARQ protocols explained earlier, they are executed sequentially as shown in Figure 5.6. A new `DATA` packet of 127 byte (including MAC and PHY overhead) is generated at the source every 160 ms. Depending on the sequence number $k \in \{1, 2, \dots\}$, packets are handled by a cooperative ARQ protocol with a different relay update policy:

- Periodic selection: packet IDs $1, 4, \dots, 1 + 3k, \dots, K - 2$,
- Adaptive selection: packet IDs $2, 5, \dots, 2 + 3k, \dots, K - 1$,
- Reactive selection: packet IDs $3, 6, \dots, 3 + 3k, \dots, K$.

Thus, the protocols are executed completely independent from each other within the allocated time frames of 160 ms. The window of 160 ms is selected to guarantee that the operation of one cooperative ARQ protocol (which can include relay selection, retransmissions and acknowledgment) for a given packet is finished and does not overlap with the next protocol operation.

From the point of view of a given protocol, packets are generated periodically every 480 ms, which may correspond to a typical application for a monitoring process. The execution of different protocols is just shifted in time with respect to each other by 160 and 320 ms. The main idea behind such sequential independent execution of protocols is to compare performance of all three schemes over relatively similar channel conditions. This means that eventual shadowing which causes several packets to fail would be observed in all schemes and reflected in performance results.

The experiment runtime of each selection scheme on each tested link is 2 hours 40 minutes, totaling in 16 hours of overall runtime. Periodic relay selection is performed $T_{\mathrm{per}} = 32\,\mathrm{s}$ after the previous successful selection. For convenience, it is also expressed as expected number of corresponding `DATA` packets transmitted with periodically selected relay, $K_{\mathrm{per}} = 66$. The maximum number of selection attempts L is five. Adaptive relay selection is triggered if more than five `ACK`s are not received by the source for the $W_a = 50$ most recent transmissions ($\varepsilon_a = 0.1$). The impact of these relay update parameters is discussed later in Section 5.4. The contention window w is set to 30 ms. The transmission power is $-4\,\mathrm{dBm}$ for all packets.

Implementation Overview

The control about which node $i \in \{1, 2, \ldots, 6\}$ is currently used as a source to transmit its K packets is performed by a central managing node co-located with node 1. The control node sends a short command to the node i, after which the test procedure of cooperative ARQ with three different selection schemes starts. After the node i finishes transmitting its messages, it sends a short message back to the control node, which then initiates a new test procedure on a different link. The central control node is connected to a PC, which runs a program for experiment configuration and its progress monitoring.

The protocol stack for cooperative ARQ is developed on the open-source TinyOS software [LMP+05] designed for use in low-power wireless embedded devices with small memory and processor capacities. The programs are written in nesC language — a dialect of C.

The current source periodically sends a `DATA` packet that includes also the packet ID and the relay selection type. This information is also added to all signaling messages. Based on these IDs, each node can differentiate an incoming message of each cooperative ARQ protocol, and process it accordingly. Periodic and adaptive selections are based on the same part of the code which is only triggered at different times as explained in the previous section. A request for reactive selection, in contrast, is performed every time the expected packet is not received within the expected time.

`ACK` messages are broadcast to the source and the relay and include packet IDs. Therefore, short and quickly processed point-to-point `ACK`s of IEEE 802.15.4 could not be used. Instead, all acknowledgments, as well as other signaling messages, are implemented as special information packets. The resulting size of an `ACK` message is

19 bytes, including MAC and PHY layer overhead. All other coordination messages are 24 bytes long. The use of multicast `ACK`s and their retransmission is one of the future changes in the existing standards required for efficient incorporation of cooperative relaying.

For data logging the 1 MB on-board external flash memory has been used, which posed severe constrains on the experiment runtime and amount of the stored data. Nodes $1, 2, \ldots, 6$ stored IDs of the `DATA` packets they transmitted or relayed. The information on the corresponding ACKs and participation in each relay selection procedure was also logged. Due to deployment constraints, only the node d was connected to a computer via a USB connection, and, thus, had no memory limitation. It logged all received messages with time and quality information, which could also be monitored in real-time. The post-processing of data logs was done in MATLAB.

5.3.3 Performance Metrics

Three main performance metrics for comparing the protocols are: 1) *delivery ratio* of `DATA` packets at d, 2) *packet delivery delay* for `DATA` packets from s to d, which together with delivery ratio reflects the communication reliability of cooperative links, and 3) *number of relay selection attempts*, which shows the overall selection overhead. In contrast to the previous chapter, here the delivery ratio is used instead of the throughput since packets are transmitted in regular intervals and their number per time unit is less important than delivery itself. Energy consumption is left out in this study, since for industrial WSN it has lower priority than reliable timely packet delivery. Estimating precisely the energy consumption is a difficult task. Typical approximate calculations of energy use are based on the current draw taken from the manufacturer's datasheet and on the measured/estimated time that the protocol spends in idle, transmitting, and receiving modes [YHE02, IKR11].

The three selective cooperative ARQ protocols are also compared with two non-cooperative protocols: a) *single direct transmission* by s, and b) *time diversity* where a retransmission by s is done when the first transmission does not succeed (i.e., an `ACK` from d is not received). The time diversity protocol is automatically incorporated within the sequential protocol execution in Figure 5.6: if the first direct transmission is performed within a time frame of a given cooperative protocol, the time diversity retransmission is simply the direct transmission in the time frame of the subsequent protocol.

Besides taking into account the time average of performance metrics over the whole duration of the experiment, it is important to consider short-term behavior as well. Such analysis is important to reveal short communication outages, which can be critical for monitoring and control applications in industrial processes.

For a given selection scheme, the sent packets are indexed according to their sequence number by $j \in \{1, \ldots, K_p\}$, where $K_p = K/3 = 20\,000$ is the number of `DATA` packets transmitted for each selection scheme. The binary sequence $X_i = \{X_i(j)\}_{j=1}^{K_p} = \{X_i(1), \ldots, X_i(K_p)\}$ describes the packet delivery from source $i \in \{1, 2, \ldots, 6\}$ to d using a given protocol:

$$X_i(j) = \begin{cases} 1, & \text{packet } j \text{ is delivered,} \\ 0, & \text{packet } j \text{ is not delivered.} \end{cases} \tag{5.2}$$

A subsequence $X_i(j_0, m) \subseteq X_i$ of length $m \in \{1, \ldots, K_p\}$ is defined as $X_i(j_0, m) = \{X_i(j)\}_{j=j_0}^{j_0+m-1}$, where j_0 is the starting index of the subsequence in X_i. In this chapter the subsequence $X_i(j_0, m)$ is also referred to as a sample.

The mean over the values in a sample is simply

$$\overline{X_i}(j_0, m) = \frac{1}{m} \sum_{j=j_0}^{j_0+m-1} X_i(j), \tag{5.3}$$

which corresponds to the packet delivery ratio in the sample for a given protocol. It also applies to the single direct transmission scheme and time diversity protocol. By incrementing j_0 from 0 to $K_p - m + 1$, i.e. sliding the sample window with given size m over the sequence X_i, data on delivery ratio over short-term intervals on the communication link i can be collected. In the presented results the sample size of $m = 100$ is used. This corresponds to a sample duration of $T_m = 48\,\mathrm{s}$.

For calculating the delay, it is assumed that a failed `DATA` packet is retransmitted again by the corresponding protocol in its time slots until the packet is delivered to d. Therefore, the delivery delay is defined as the communication outage duration (when $X_i(j) = 0$) between two consecutive successful packet deliveries ($X_i(j) = 1$).

5.3.4 Measurement Results

The mean measured values for delivery ratio and number of selections per 100 transmitted packets over all links are collected in Table 5.1. Furthermore, confidence intervals of 5 % and 95 % are obtained using the moving block bootstrap method suited for correlated time series [Pol03].

Table 5.1: Delivery ratio and protocol overhead

	delivery ratio			selections per 100 pkts		
	5 %	mean	95 %	5 %	mean	95 %
direct	0.809	0.820	0.824	—	—	—
time diversity	0.863	0.870	0.876	—	—	—
periodic	0.961	0.966	0.967	1.62	1.69	1.68
adaptive	0.965	0.970	0.970	1.29	1.33	1.61
reactive	0.984	0.985	0.986	17.6	18.1	19.0

All cooperative schemes provide a higher delivery ratio than non-cooperative ones. Particularly, cooperative ARQ with reactive selection provides a maximum delivery ratio of nearly 99 %. The number of relay selection attempts reflects how much coordination overhead was necessary during the protocol operation. Here, adaptive selection performs best among the cooperative schemes. For periodic relay selection, the number of selections in a sample varies from the expected constant $m/K_{\text{sel}} \approx 1.5$ since up to five relay selection attempts can be performed until a relay is successfully selected. Cooperative ARQ with reactive relay selection triggers a new relay selection at each failed packet. This means the mean number of relay selections per `DATA` packet equals simply the mean packet error rate on direct channels.

Table 5.2: Additional relay selection performance metrics

	periodic	adaptive	reactive
number of candidates	4.80	4.88	3.73
selection success	0.94	0.95	0.96
successful relaying (when selected)	0.80	0.82	0.96

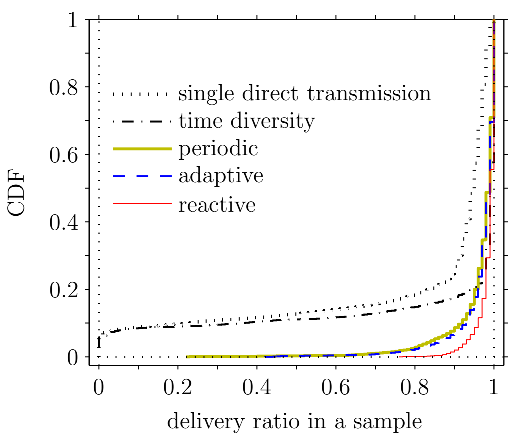
Table 5.2 shows some additional data on the relay selection process. On average, 3.7 nodes participated in the relay selection process for reactive relay update, which is less than the values obtained for periodic and adaptive relay selection (4.8 and 4.86, respectively). This is due to the fact that reactive relay selection is triggered by destination, and, as a result, only nodes that receive both packets from s and d participate in the contention. This is different for periodic and adaptive

selections, where, as shown in Figure 5.1, all nodes that receive S_RREQ message from s participate in the following contention.

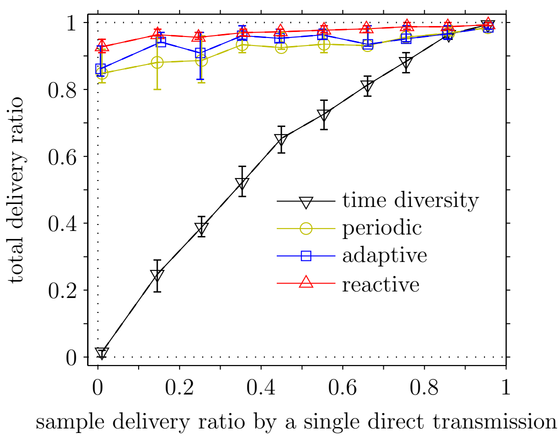
Despite having a different number of contending nodes, the success of relay selection is nearly the same — around 95 %. Here, a relay selection is counted as successful when the selected node receives the D_RSEL from d. This means that for periodic and adaptive selection the relay can retransmit DATA to d, even if s did not receive R_RSEL and assumes that no relay is selected.

Finally, the last row in Table 5.2 shows how successful relays are in retransmitting the DATA packets to the destination (when required). Adaptive and periodic relay selections provide similar performance. Reactive relay selection results in a significantly improved relaying delivery ratio, since it is performed at each failed direct transmission.

Figure 5.7a shows the Cumulative Distribution Function (CDF) for the delivery ratio using each retransmission protocol within a sample of $m = 100$ transmitted DATA packets according to (5.3).



(a) CDF of delivery ratio in a sample of 100 packets.



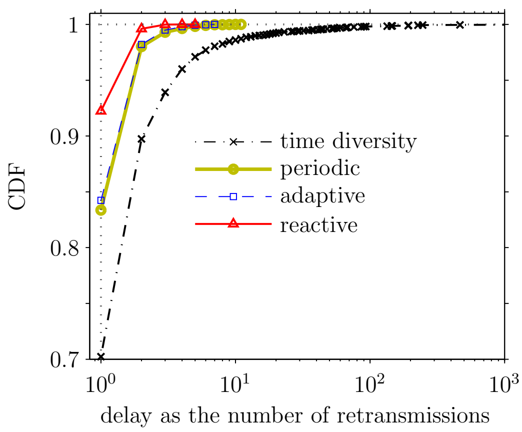
(b) Total delivery ratio versus delivery ratio using a single direct transmission for samples with 100 packets.

Figure 5.7: Delivery ratio in a sample of 100 packets.

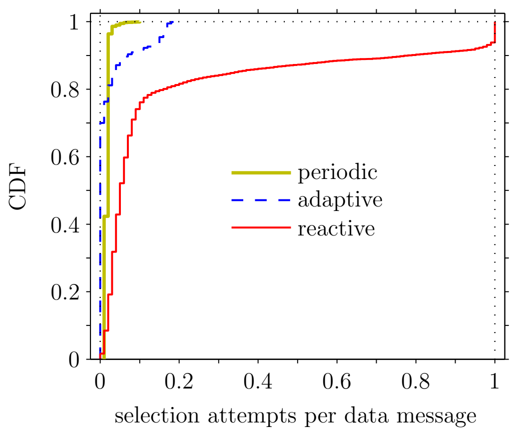
It can be seen that more than 10 % of all samples have a poor direct delivery ratio of less than 50 %. Time diversity retransmission improves the delivery ratio significantly only if the direct delivery ratio is higher than 90 %. When the direct delivery ratio is lower than 50 %, the direct channel remains bad most of the time, and the time diversity retransmission provides hardly any benefit. In contrast, all cooperative protocols achieve a significant gain in the delivery ratio. The reactive relay selection provides the best performance, while the adaptive update scheme performs only marginally better than the periodic one.

Figure 5.7b shows another comparison of the delivery ratio performance at the sample level. There, the delivery ratio of a given retransmission protocol in each sample is plotted versus the delivery ratio for single direct transmission in the same sample. However, to avoid plotting more than 300 000 scattered points on the graph, the points are collected according to the x-axis value into ten groups with boundaries $0.1(v-1) \leq x < 0.1v$, for $v = 1, \ldots, 9$, and $0.1(v-1) \leq x \leq 0.1v$ for $v = 10$. Within each such group arithmetic means over x and y values are calculated and plotted. In addition, the 25 % and 75 % quantiles of the data distribution are shown.

The performance of cooperative schemes changes only slightly compared to time diversity, which is clearly correlated with the direct delivery ratio on the x-axis. Therefore, cooperative ARQ proves to be particularly useful for short time intervals when the s-d channel suffers from a long outage. Reactive selection provides a slightly better delivery ratio than other relay update schemes. Particularly, its mean delivery ratio never falls below 90 %.



(a) Delivery delay CDF. Delay is the number of protocol retransmission cycles required for packet delivery.



(b) CDF of selection attempts per packet in a sample with 100 packets.

Figure 5.8: Delay CDF (a) and selections per `DATA` packet CDF (b).

Figure 5.8a shows the empirical CDF for the packet delivery delay. The delay is defined by the outage duration between two successful `DATA` packets delivered to d. A delay of k_Δ corresponds to a successful packet delivery at time frame $k_\Delta - 1$

after the `DATA` packet failed. Thus, a delay of one means that s failed to deliver the `DATA` packet itself at the first attempt, but the packet was delivered right after the failure with a retransmission. The figure shows that 70 % of all failed packets are successfully delivered by the following retransmission from s. However, there are also longer outages where time diversity is not helpful. Such outages can be particularly harmful for industrial control processes. All cooperative schemes outperform time diversity. Reactive relay selection performs best, and adaptive relay selection provides only marginally better delay distribution than periodic selection.

Finally, Figure 5.8b shows the CDF for the number of triggered relay selection per `DATA` packet within a sample of 100 packets. For periodic selection, most of the times $1/K_{\text{per}}$ selections are triggered per `DATA` packet. However, in a small fraction of samples, more selections are performed since some of the selection attempts fail. In adaptive selection, in approximately 70 % of samples no relay update is triggered at all. However, in comparison to periodic selection, the fraction of samples with a higher number of selections is also larger. This is due to more frequent selections when the cooperative link fails. Since reactive selection is triggered at each failed direct transmission, the corresponding number of selections per packet in Figure 5.8b is simply the inverse of the direct delivery ratio in Figure 5.7a, i.e., the delivery ratio curve is symmetrically reflected along the x and y axes. As it can be observed, the reactive selection procedure results in the highest number of selections as is also shown in Table 5.1.

The discussed results show that reactive relay selection provides the best performance by fully utilizing the selection diversity among surrounding nodes. However, that comes at significant costs — about 14 times more selections are required than by adopting adaptive relay selection. Although energy consumption is out of scope of this experimental work, as explained in the previous chapter, reactive relay selection requires other nodes to listen to all s-d transmissions, which can be energy inefficient. Adaptive relay selection provides similar delivery ratio to the periodic update rule but requires less overall selection overhead.

5.4 Trace-Based Analysis of System Parameters

In the previous section, the protocols are compared in a single real-world scenario. However, protocol performance also depends on network settings, such as number and location of potential relays, and protocol parameters. An experimental comparison similar to the one in Section 5.3 over a wide range of such parameters is hardly possible. A trace-based experiment was conducted for *emulating* the operation of cooperative ARQ with different parameters based on the logged data.

5.4.1 Experiment Description

The network setup is the same as in Figure 5.3. There is only one source node s (node 6), which sends a `DATA` packet to d every 160 ms. All other nodes $n \in \{1,2,3,4,5\}$ listen to that packet and, upon receiving it, log the corresponding LQI and packet ID. Then, each node that correctly received the packet relays it to d after $n \cdot 15$ ms, where the delay is selected to avoid collisions between nodes. All packets received at d are stored with their LQI values and the transmitter IDs n. In total, 50 000 `DATA` packets are transmitted by s.

Based on the stored traces, for each packet transmitted by s one can identify the following: a) whether a packet is delivered to d via relay node n or not, and b) the node that has the maximum Q_n according to (5.1) for periodic and adaptive selections, or maximum Q_{nd} for reactive selection.

As a result, one can emulate the operation of the protocols with the obtained traces and vary the protocol parameters arbitrarily [NSNK97]. The drawback of this method is that it does not involve real relay selection through contention, but follows rather idealistic assumptions based on available traces. The main advantage compared to computer simulation is that it is based on measurements in a real network in a specific environment.

5.4.2 Results and Discussions

Figure 5.9 shows the mean delivery ratio for cooperative ARQ protocols versus 31 possible combinations of nodes that can be relays. The combinations are grouped together according to the number of nodes $N \in \{1,2,3,4,5\}$ in them and assigned a node combination ID from 1 to 31. The node combination ID is calculated as follows. In a group of $N \in \{1,2,3,4,5\}$ nodes, the IDs of nodes in a combination serve as digits to form the smallest possible number. I.e., number 235 would correspond to nodes with IDs 2, 3, and 5 in the given combination. The resulting numbers are sorted in ascending order and assigned intermediate IDs $n_N \in \{1, 2, \ldots, \binom{5}{i}\}$ within the group of N nodes. The resulting unique combination ID is calculated according to $n_N \sum_{j=0}^{N-1} \binom{5}{j}$.

Here, relay selections are triggered in the same way as in the previous section: for periodic relay selection every $T_{\text{per}} = 32$ s (here, it corresponds to $K_{\text{per}} = 200$

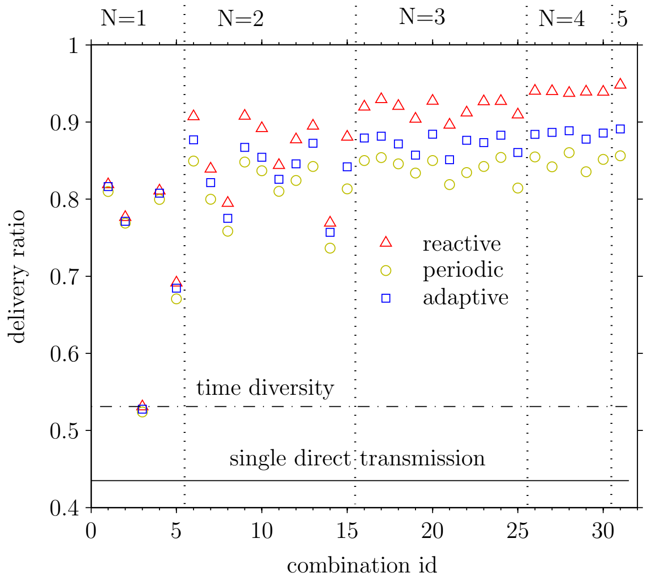


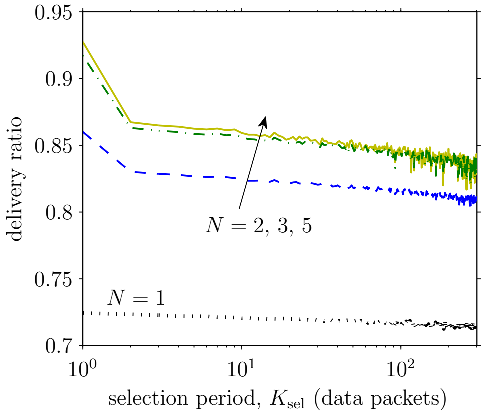
Figure 5.9: Delivery ratio of various retransmission protocols for different number of surrounding nodes and their combination.

packets), and for adaptive selection when a threshold of five lost `DATA` packets ($\varepsilon_a = 0.1$) in the window of $W_\mathrm{a} = 50$ most recently sent packets is reached.

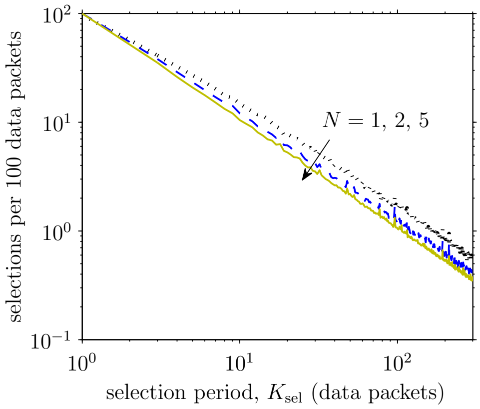
Figure 5.9 shows that all cooperative schemes perform better than non-cooperative ones, with one exception when only node 3 can serve as relay. In that case the delivery ratio achieved through cooperation is nearly the same as simple time diversity. Another important observation is that, for a given cooperative ARQ scheme, the difference in delivery ratio for node combinations with the same N is the highest for $N = 1$. It decreases for a growing number of neighbors and almost levels off for $N \geq 4$.

Next, the impact of the update interval K_per on the resulting delivery ratio for cooperative ARQ with periodic relay selection is shown in Figure 5.10a. The curves represent the mean values over all possible combinations of nodes with the same N. For example, for $N = 2$, an average over delivery ratios for all possible combinations of two different nodes is performed, i.e., $\{1, 2\}$, $\{1, 3\}$, $\{1, 4\}$, $\ldots$, $\{4, 5\}$.

As the figure shows, if only one relay is available, the delivery ratio does not change significantly. This is because a relay update results in the re-selection of the same relay. The slight degrade in delivery ratio for $N = 1$ can be explained by intervals when a relay is not selected after the limit of $L = 5$ attempts, and the protocol operates without an assisting relay for the time T_per.



(a) Total delivery ratio with periodic relay selection as a function of relay update interval.



(b) Number of selections per sample with 100 packets as a function of relay update interval.

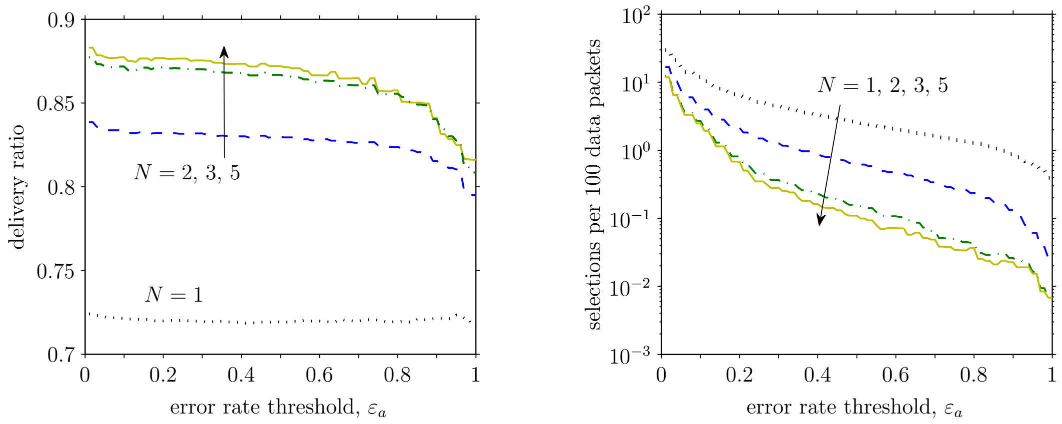
Figure 5.10: Impact of relay update interval K_{per} on delivery ratio and selection rate.

A significant gain in mean delivery ratio is seen between $N = 1$ and $N = 2$, and between $N = 2$ and $N = 3$. The performance difference between curves for $N = 4$ and $N = 5$ is hardly noticeable, and, therefore, only the curve for $N = 5$ is plotted. However, as seen in Figure 5.9, the difference can be larger for particular combinations of nodes.

If the selection period equals one `DATA` packet, the delivery ratio of periodic and reactive selection schemes becomes the same. However, for cases with $N > 1$, just changing the update period to two packets significantly reduces the delivery ratio. With a further increase of the selection period, the delivery ratio degrades only slowly (consider the logarithmic scale of the x-axis). The selection of a wrong relay or not selecting a relay at all can have significant impact on the delivery ratio for high K_{per} values. As a result, fluctuations in the delivery ratio can be seen.

The number of relay selections per `DATA` packet with periodic relay selection is shown in Figure 5.10b. It is proportional to $1/K_{\text{per}}$. For $N = 1$ and $N = 2$ slightly more attempts are required since nodes are more likely to be unavailable for selection. For $N > 2$ the difference in number of selections is negligible. It can be concluded that the overall selection overhead can be decreased significantly by increasing the selection period with only moderate degrade in delivery ratio.

Next, the impact of the threshold error rate ε_a within the window of the $W_a = 50$ most recently sent packets in adaptive relay selection is shown in Figure 5.11a.



(a) Total delivery ratio with adaptive relay selection as a function of the error rate threshold ε_a over a window W_a of recently transmitted `DATA` packets.

(b) Number of triggered relay selections per 100 transmitted `DATA` packets.

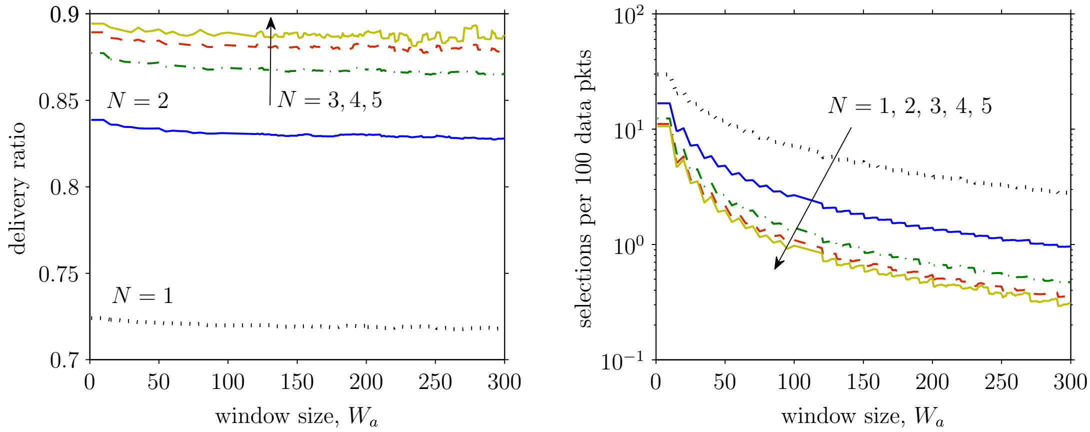
Figure 5.11: Impact of the error threshold ε_a on delivery ratio and selection rate in adaptive relay selection.

Here, the allowed error rate ε_a varies from $1/W_a$, where a relay is updated immediately after the first delivery failure on the cooperative link, to 1, where a relay is selected only when all W_a `DATA` packets fail. The delivery ratio is the highest when the triggering error rate is $1/W_a$, but it is still lower than that one provided by reactive selection (or periodic with $K_{\text{per}} = 1$). The delivery ratio decreases slowly for $N > 1$ since the window of 50 packets ensures that long periods of outage are not tolerated. However, when ε_a becomes roughly larger than 80 %, the delivery ratio starts dropping significantly, since relay selections become rare.

The number of selection attempts versus the tolerated error rate is plotted in Figure 5.11b. The observed results show that significantly less selections are triggered with growing ε_a and higher N. For $N > 1$, the number of updates for adaptive relay selection is always lower than that of periodic relay selection.

As shown in Figure 5.12a, the delivery ratio only slightly decreases with increasing W_a in the given setup. This is due to the fact that in general there are not that many long intervals where both s-d and selected s-r-d paths remain in outage. However, only in such intervals a larger W_a causes more tolerated errors and, therefore, the reduction in delivery ratio at the same ε_a.

Finally, Figure 5.12b shows the number of adaptively triggered relay selections as a function of the window size W_a. The threshold error rate is 0.1. When



(a) Number of triggered relay selections as a function of relay update interval.

(b) Number of triggered relay selections as a function of relay update interval.

Figure 5.12: Impact of the error window size W_a on throughput and selection rate; $\varepsilon_a = 0.1$.

W_a grows, the number of selections decreases significantly since more errors on the cooperative link have to take place to trigger a new relay selection. It can be concluded that increasing W_a and ε_a reduces significantly the overall selection overhead while introducing only a small degrade in the delivery ratio.

The presented results imply that network and protocol settings can be adjusted to fit the reliability and overhead requirements of various industrial WSN applications.

5.5 Related Work

Challenges in designing and using WSN for industrial automation are discussed in [WMW05, DPMVZ06, GH09]. Some experimental studies of industrial WSN have been conducted for radio channel characterization [SMLW05, TWHG07], architecture comparison [KAB+05], impact of interference [BGSV08], scheduling [YCK+10], frequency channel hopping [WMP09], and connectivity of mobile nodes [SPGO11].

Temporal properties of radio channels in WSN are experimentally assessed in e.g., [CWPE05, SKAL08, SDTL10]. According to these measurements, errors in wireless links in low-power networks can be very bursty even when the overall delivery ratio is high, which can be harmful in time-critical applications. Specific routing and scheduling protocols are proposed and implemented in [SBR10, MLH+10] to guarantee packet delivery under time constraints in office and industrial environments, respectively.

Use of cooperative relaying in industrial wireless sensor networks is first time discussed by Willig in [Wil08b] and [Wil08a]. In the joint work with Uhlemann, he also explores the capabilities of cooperative relaying with packet combining [WU08] and accurate relay placement [WU12]. The obtained results are based on mathematical analysis and do not consider relay update policies.

An experimental investigation of cooperative relaying in industrial setting is presented in [UGO11]. The authors study the performance of a cooperative protocol for networked control systems in IEEE 802.11 networks. The relay selection is performed at each `DATA` packet transmission based on the `RTS-CTS` message exchange between the source and the destination, which makes relay selection impossible when the direct channel is in an outage. Furthermore, the IEEE 802.11 technology is rarely used in wireless sensor networks, where relatively short messages with sensed data are transmitted.

Related analytical works on relay selection and relay update rules in cooperative relaying have been discussed previously in Sections 2.4 and 4.5. Experimental studies of cooperative relaying are discussed in Section 2.6. As mentioned there, only few works present empirical studies of cooperative relaying in WSN. In particular, packet combining aspects using IEEE 802.15.4 are addressed in [DFEV05, OB12]. In [IKR09, IKR11] cooperative multicast transmissions in WSN are studied experimentally.

This chapter presents an experimental study of selective cooperative ARQ in industrial WSN, and shows significant improvements in link reliability when time diversity techniques fail. To the best of our knowledge, selective relaying protocols have not been studied empirically.

Some results in this chapter are under review in [1] and have been obtained in cooperation with corresponding co-authors. This work extends the preliminary results published in [4, 3].

In [4] radio channel characteristics are evaluated and simplified analysis of cooperative ARQ is performed. In [3] periodic and adaptive relay selections are studied in a single network scenario. Relay selection is initialized by a message exchange between the source and the destination. Similar to [UGO11], this makes relay selection impossible when the direct channel is in an outage. The presented protocols show significant delivery ratio improvement to the ones in [3]. Furthermore, the impact of protocol parameters in various network topologies on the communication performance and the resulting tradeoff between reliability and overhead are studied.

5.6 Summary

The use of industrial wireless sensor networks has significant benefits for factory automation, since the deployment costs can be reduced, and sensors can also be placed in locations where cables cannot be wired. However, in factory settings, wireless transmissions are prone to severe dynamic multi-path fading and shadowing due to the cluttered environment and moving objects. Since applications for monitoring and control of production processes require very reliable transmissions under strict delay constraints, designing a reliable wireless communication system for WSN becomes indeed challenging [GH09].

This chapter analyzes the benefit of using selective cooperative ARQ protocols for providing additional signal diversity at receivers and improving link reliability in industrial WSN. Three cooperative ARQ protocols with different relay selection schemes, namely periodic, adaptive, and reactive, are studied. These protocols have been implemented in IEEE 802.15.4-compatible devices and deployed in an industrial production plant. Performance tests were conducted in a way to allows a direct comparison of cooperative and non-cooperative protocols for periodic monitoring processes in an industrial WSN.

Results show that selective cooperative ARQ outperforms conventional time-diversity-based retransmissions and can provide a mean delivery ratio close to 99 % over the whole network. The most significant performance increase takes place over short-term intervals when the direct delivery ratio is low. Here, the delivery ratio of cooperative ARQ does not fall below 80 % even when the direct delivery ratio approaches 0 % over the same intervals. The packet delivery delay is also significantly reduced by cooperative ARQ — nearly all failed `DATA` packets are delivered with three or less retransmissions.

Relay selection parameters are investigated in different network topologies via trace-based network emulation using empirical channel measurements. Typically, three available relay nodes are sufficient for a reliable relaying performance; only marginal gains in delivery ratio are achieved using more than three nodes. The delivery ratio can be also increased by setting a shorter selection interval T_{per}

for periodic selection and a lower error rate threshold ε_a for adaptive selection. However, even small gains impose a high increase in the number of relay updates. The tradeoff between delivery ratio and selection overhead must be adjusted based on the application requirements.

The presented results illustrate that selective cooperative relaying is a viable technique for improving the communication reliability in industrial wireless sensor networks. It can be efficiently employed when other diversity techniques fail. Open questions left out in this chapter are subjects for future research and include a) integration with MAC and routing protocols, b) performance evaluation in presence of interference, c) integration with energy efficient sleep scheduling.

CHAPTER 6 Conclusions

Cooperative relaying protocols employ retransmissions from surrounding nodes overhearing source-to-destination communication. The achieved signal diversity at the destination is shown to decrease outage probability in fading-rich environments [LW03, LTW04]. In a network of nodes an important task for successful cooperation is to efficiently identify which node (or nodes) can serve as a relay for a given source-destination link. Relay selection has to assign such a relay (or relays) that maximizes required performance metrics such as throughput, network capacity, or network lifetime.

Cooperative relaying has been extensively studied in the academic research community. However, its application in real-world networks and realization of anticipated performance gains remains challenging. Chapter 2 of this thesis provides a brief survey of the existing literature on PHY, MAC, and networking aspects of cooperative relaying. It also includes an overview of experimental studies on WLAN and WSN testbeds.

The main focus of the presented work is on the following two practical challenges:

1. While cooperative relaying can increase throughput on a given link, additional interference induced by the relay can disturb other transmissions in a network and decrease the overall network throughput [ZC06, LMS09],[9].

2. While relay selection can provide a relay with the best selection metrics, the required selection overhead can significantly decrease the resulting data throughput and energy efficiency [SMY10a, MLKS10],[2].

The thesis discusses how the undesired throughput decrease can be mitigated by proper relay selection mechanisms.

Summary of Contributions

Chapter 3 discusses in detail the spatial channel reuse with cooperative relaying. On a simple five-node setup it is shown that cooperative relaying can decrease overall network throughput when traffic load is high and packet error rates are low. Several contention-based relay selections are proposed for assigning a node with lower relay spatial use, i.e., fewer surrounding nodes are blocked by relay interference. The introduced selections schemes rely only on local information at potential relays such as the node degree and the relative distance to the source and destination. The simulation results obtained for uniform and clustered networks show that the relay spatial use in terms of blocked nodes can be significantly decreased when a proper selection scheme is used.

Impact of relay selection overhead on throughput and energy efficiency is studied in Chapter 4. The presented work investigates cooperative ARQ with four practical relay selection schemes: permanent, proactive, reactive, and adaptive. These schemes specify when a new relay selection procedure is triggered to assign a better-suited node than the active relay. An analytical framework based on semi-Markov processes is used to model and compare the selective cooperative ARQ protocols in time-correlated channels. The results show that the required coordination overhead can significantly reduce the data throughput gains anticipated from cooperation when selections are performed too frequently and the required overhead is large. In such conditions, the lowest selection rate and highest data throughput is achieved by the adaptive selection, where a relay update is performed if both the relay and source transmissions fail.

Lack of experimental studies of cooperative relaying in WSN served as the motivation for Chapter 5, which provides an empirical performance evaluation of cooperative ARQ in industrial WSN. Such networks are deployed in heavily cluttered dynamic environments and have to provide high communication reliability and low delay guarantees. Cooperative ARQ protocols with three relay selection schemes are implemented in IEEE 802.15.4 off-the-shelf devices and tested in a packaging production hall. The results show that cooperative relaying can provide the mean delivery ratio of up to 99 %. Furthermore, cooperative relaying helps to avoid short-term outages on a direct link, which are particularly harmful for time-critical applications. Trace-based analysis is used to demonstrate how cooperative protocols perform over a range of system parameters. By varying the periodic selection interval or adaptive PER threshold, one can improve the selection rate or the delivery ratio. However, it is shown that a small improvement in the delivery ratio requires significant increase in the selection rate.

Future Work

The presented work opens some directions for future research. Chapter 3 investigates overall network throughput in a simple five-node setup. Further studies in larger networks can be conducted for additional understanding of relay interference and its impact on the network behavior in terms of capacity, connectivity, and lifetime. The analytical framework in Chapter 4 does not consider signal combining, and can be extended to include MRC. Furthermore, sophisticated methods tracking SNR metrics and adapting to the network behavior can be developed and investigated. Timely updates of relay clusters can be a challenging research problem since multiple relaying nodes and their metrics have to be considered. The experimental study in Chapter 5 avoids MAC layer issues. Future integration of cooperative relaying into MAC with duty cycle and sleep schedules of wireless sensor networks is important for its incorporation into communication standards such as WirelessHART and ISA100.11a.

List of Symbols

$\lvert\cdot\rvert$	Cardinality of a set
$\mathbb{1}_{\mathrm{G}}(\,\cdot\,)$	Indicator function
A_i	Area
a_r	Relay spatial use for node r
C_{sd}	Set with indices of relay candidates for the s-d pair
$\mathbf{C}_{ij}$	Transition probability matrix for the channel between two nodes
c_{ij}	Channel state between two nodes
d, d_i	Destination node
E_{rx}	Energy required for receiving one data message
E_{sel}	Energy consumed during a relay selection procedure
E_{tx}	Energy required for transmitting one data message
E_{ab}	Energy consumption reward for the transition
$f(\,\cdot\,)$	Protocol state transition function
f_D	Doppler frequency spread
f_c	Carrier frequency
H_{ab}	Holding time before the transition
$\mathbf{H}$	Holding time matrix for a given semi-Markov process
$\widetilde{H}$	Expected holding time in quasi-static channels
K, K_p	Number of (allowed) data transmissions by the source
K_{per}	Periodic relay selection interval as a number of data packets
$\widetilde{K}$	Number of actual data transmissions (channel uses) by the source
k	Time step index
k_Δ	Delivery delay as the number of required retransmissions

L	Number of operational states for a given protocol
l_i	Communication link
M	Number of relay candidates
m	Sample size as a number of data packets
N	Number of nodes in a network
N_n	Number of nodes in the transmission range of the node n
P_1	Probability that there is at least one non-collided message in a contention window
P_m	Probability that m out of M nodes choose a given time slot
P_s	Probability of a successful contention procedure
$\mathbf{P}$	Transition probability matrix
$\Pr(\,\cdot\,)$	Probability of an event
p_i	Packet arrival probability at node i
p_{n}	Thermal noise power at the receiver
p_{rx}	Signal power at the receiver
p_{tx}	Transmission power
Q_c	Channel quality of the relay candidate c
Q_{ij}	Link quality between two nodes
q, q_n	Transmission probability in a given time slot
R_{tx}	Transmission range
r, r_i	Selected relay node
$S(\tau)$	Selection reward function
S_n	Set with indices of nodes in the transmission range of the node n
S_{ab}	Selection reward for a given transition in a semi-Markov process
$\mathbf{S}$	Selection reward matrix
s, s_i	Source node
T	Data packet transmission time
T_m	Sample duration with m data messages
$T_{\mathtt{ACK}}$	Waiting time for the acknowledgment message

T_{conf}	Waiting time for the selection confirmation message
T_{per}	Interval of periodic relay selections
T_{sel}	Relay selection time
T_w	Random contention time
W_{a}	Number of data messages in a window for error tracking
w	Contention window size in time slots
$X(\tau)$	Delivery reward function
X_i	Binary packet delivery sequence from node i
$X_i(j_0, m)$	Subsequence of length m and starting index j_0 in the sequence X_i
X_{ab}	Message delivery reward
$\widetilde{X}$	Expected delivery reward in quasi-static channels
Y	Set of operational states for a given protocol
y	Operational state of a protocol
$y^{(a)}$	Operational state of a protocol before a transition
$y^{(b)}$	Operational state of a protocol after a transition
Z	Set of all permitted unique tuples for a given protocol
$\mathbf{z}, \mathbf{z}_a, \mathbf{z}_b$	Tuple with the current operational protocol and channel states
α	Pathloss exponent
Δ_0	Reference distance
Δ_{ij}	Distance between two nodes i and j
η, η_{co}	Data throughput at the destination
ε_a	Packet error rate threshold for adaptive relay selection
ε_{R_i}	End-to-end packet error rate on the two-hop path via the relay i
ε_{ij}	Packet error rate from node i to node j
ε_i	Packet transmission error probability on the link i
γ_{thr}	SNR threshold below which channel is considered to be in outage
γ_{ij}	Receiver SNR of the signal sent from the node i to the node j
$\overline{\gamma}_{ij}$	Expected SNR of the signal sent from the node i to the node j

$\boldsymbol{\pi}$	A vector of limiting state-probabilities of a Markov chain
π_i	Limiting-state probability of the state i in a Markov chain
ψ_{ij}	Fading margin between two nodes i and j
ρ	Relay selection rate
ρ_0	Relay selection rate when the time for selection is neglected

List of Acronyms

ARQ	Automatic Repeat-reQuest
AF	Amplify-and-Forward
BER	Bit Error Rate
CDF	Cumulative Distribution Function
CF	Compress-and-Forward
CTBTMA	Cooperative Triple-Busy-Tone Multiple Access
CSMA	Carrier Sensing Multiple Access
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
CSI	Channel State Information
CTS	Clear-To-Send
DCF	Distributed Coordination Function
DSP	Digital Signal Processor
DSSC	Distributed Switch-and-Stay
DSTC	Distributed Space-Time Code
DF	Decode-and-Forward
FPGA	Field-Programmable Gate Array
GNU	GNU's Not Unix!
LDPC	Low-Density Parity-Check
LQI	Link Quality Indicator
LLC	Logic Link Control
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MRC	Maximal Ratio Combining

OFDM	Orthogonal Frequency-Division Multiplexing
OSI	Open Systems Interconnection
PC	Private Computer
PER	Packet Error Rate
PHY	Physical Layer
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
RTS	Request-To-Send
SDR	Software-Defined Radio
SER	Symbol Error Rate
SNR	Signal-to-Noise Ratio
SPaC	Simple Packet Combining
STC	Space-Time Codes
USRP	Universal Software Radio Peripheral
WARP	Wireless Open Access Research Platform
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

List of Own Publications

[1] N. Marchenko, T. Andre, G. Brandner, W. Masood, and C. Bettstetter. An experimental study of selective cooperative relaying in industrial wireless sensor networks. Under review in *IEEE Trans. on Industrial Informatics*.

[2] N. Marchenko and C. Bettstetter. Cooperative ARQ with relay selection: An analytical framework using semi-Markov processes. Accepted to *IEEE Trans. on Vehicular Technology*, Preprint(99):1–12, June 2013.

[3] T. Andre, N. Marchenko, G. Brandner, W. Masood, and C. Bettstetter. Measurement-based analysis of adaptive relay selection in industrial wireless sensor networks. In *Proc. Intern. Workshop on Wireless Network Measurements (WiNMee)*, Tsukuba, Japan, May 2013.

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