Wireless Pers Commun (2009) 48:49–68
DOI 10.1007/s11277-007-9429-2

Cooperative Wireless Networking Beyond Store-and-Forward

Perspectives in PHY and MAC design

**Stefan Valentin · Hermann S. Lichte · Holger Karl ·
Guillaume Vivier · Sébastien Simoens · Josep Vidal ·
Adrian Agustin**

Abstract In future wireless networks devices may cooperate to form logical links. Each of these links may consist of several independent physical channels which are shared by the cooperating partners. Even without multiple antennas this cooperation provides diversity in time and space. This so-called *cooperation diversity* increases the robustness of the link vs. fading and interference. After surveying approaches in cooperation diversity we focus on optimizing its performance by combining several cooperation schemes and by integrating cooperation into space-time coding. For multiple scenarios, we further discuss the factors and benefits introduced by user cooperation and how cooperation-aware resource allocation can be employed to further increase the performance of cooperative networks. When it comes to implementation, the question arises how cooperation can be integrated efficiently into existing wireless networks. A case study for 802.11-based WLANs reveals the issues that need to

---

S. Valentin (✉) · H. S. Lichte · H. Karl
University of Paderborn, Warburger Str. 100, Paderborn 33098, Germany
e-mail: stefanv@upb.de

H. S. Lichte
e-mail: hermann.lichte@upb.de

H. Karl
e-mail: holger.karl@upb.de

G. Vivier · S. Simoens
Motorola Labs, Rennes, France

G. Vivier
e-mail: guillaume.vivier@motorola.com

S. Simoens
e-mail: simoens@motorola.com

J. Vidal · A. Agustin
Technical University of Catalonia, Barcelona, Spain

J. Vidal
e-mail: pepe@gps.tsc.upc.edu

A. Agustin
e-mail: agustin@gps.tsc.upc.edu

be solved in order to deploy cooperative techniques. We provide an overview of the state of the art in implementing cooperation approaches, analyze how appropriate these approaches solve the issues, and, where appropriate, point out their deficiencies. We conclude with a road map for future research necessary to tackle these deficiencies for the practical implementation of cooperation in next generation mesh, WLAN, WMAN, and cellular standards.

Keywords Cooperative networks · Cooperation diversity · Resource allocation

1 Introduction

Wireless communication has a tremendous success and progressive spread in our daily life. Major factors of this success are the use of voice and multimedia applications that are rapidly migrating from wired to wireless networks.

Most of the advantages of wireless networks are due to practical aspects such as the low cost of deployment and mobility. The drawbacks, however, lie on the technical side: attenuation and fading of radio signals may cause disconnections and the "open" aspect of the medium makes it prone to noise, interference, and security attacks. On a very abstract level we can distinguish the state of the radio channel as follows:

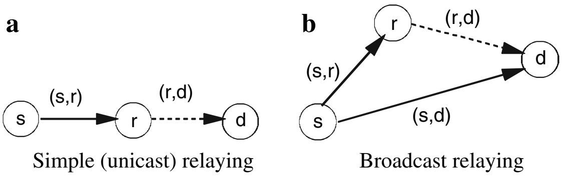
- Very good signal quality received at the destination,
- Very bad (or no) signal quality received at the destination,
- An intermediate situation where the received signal quality is between the former two cases.

In the first case, where the destination is reachable directly, research issues usually focus on the Medium Access Control (MAC) mechanisms for fair and efficient use of the network. This research area has been extensively explored in the past.

In the second case, where the destination is "out of direct reach", route discovery (IP layer) and packet forwarding come into the picture, revealing new research aspects in multi-hop networks.

For the intermediate situation (which is the nearest to reality), advanced channel coding schemes have been intensively investigated for wireless communication to ensure reliable reception of the information without spending too much power or overhead to mitigate the channel impairments. In this field, a relatively new area is attracting the research community: *cooperative networking*.

Cooperative networking takes advantage of the openness of the radio channel, so far viewed as a drawback. Instead of merely forwarding received packets, in cooperative networks devices help each other by mutually combining and error correcting these packets prior to forwarding. Such mechanisms require research on coding schemes used for combining, on relaying techniques used for mutually exchanging data, on multiple access methods to limit interference and overhead, on cooperation-aware resource allocation (e.g. selecting partners and cooperation level), on routing methods in multi-hop cooperative networks, and on the additional scenario factors introduced by cooperation. In this article we provide a survey of these various problems arising with cooperation. We focus on centralized, i.e. cellular and Wireless Metropolitan Area Network (WMAN), and decentralized, i.e. Wireless Local Area Network (WLAN) or mesh, scenarios where either the base stations/access points or the end-user terminals may cooperate. We discuss, exemplarily for these scenarios, how the theoretical problems were treated so far by the community and point out future work.



Simple (unicast) relaying

Broadcast relaying

Fig. 1 Unicast relaying and, specific to the wireless case, broadcast relaying. Each figure shows the utilized half-duplex channels in the first (solid line) and second phase (dashed line). (**a**) Simple (unicast) relaying, (**b**) Broadcast relaying

Finally, to assess the concrete benefits of cooperation, the schemes have to be *implemented* and tested. Hence, the question arises how cooperation can be integrated efficiently into existing mesh, WLAN, WMAN, and cellular standards. To answer this question we provide case studies which reveal the issues that need to be solved for deploying cooperative techniques. Furthermore, we give an overview of the state of the art in solving practical issues with cooperative networking and discuss which problems are still open.

The article is structured as follows. In Sect. 2 we introduce cooperation approaches, discuss the performance and functional details of the current schemes and discuss combined schemes. Section 3 is focused on resource allocation and the factors which are specific for cooperative networking. Section 4 discusses practical aspects such as implementation and integration in current WLAN and future mesh standards. Finally, we conclude with a road map for future research.

2 User Cooperation Diversity: New Approaches in Cooperative Relaying

Cooperation diversity is a promising approach to provide multiple antenna gains in single antenna scenarios. In this section, we will introduce this approach and classify basic protocols to realize cooperation diversity. Finally, we discuss current combined cooperation strategies and show performance results.

2.1 Cooperation Diversity

With unicast transmission the relay channel represents the simplest cooperative scenario, in which a nearby terminal, called relay r, forwards messages from a source s to the destination d (Fig. 1a).

Although this scenario is rather simple, it includes two basic elements of more complex cooperative relaying schemes. At first, relaying requires two time phases. In the first phase (solid line in Fig. 1) the relay has to receive the data from the source. Then, in the second phase, it forwards the source's data to the destination (dashed line). The second basic element is that a relay permanently or temporarily lends its channel to other nodes.

However, this simple relaying scheme ignores one specific attribute of the radio channel – its broadcast nature. This was taken into account by Van der Meulen [29], Cover and El Gamal [5], and Gallager [7]. In their early work, they extended the above simple unicast relaying by a broadcast transmission (Fig. 1b). Assuming that relay and destination are in range, in the first phase the source's data equally reaches the relay *and* the destination before it is conventionally relayed in the second phase. Compared to simple unicast relaying, this broadcast introduces a redundant transmission in the first phase via the so-far unutilized (s, d) channel. If this transmission is affected differently by fading then diversity is introduced. Here, this is the case if the two channels (s, d) and (r, d) fade independently in both phases.

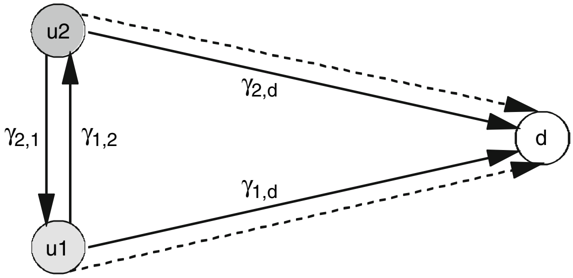


Fig. 2 Basic two-user cooperation scenario where u_1 and u_2 may cooperate to reach d. The figure shows the instantaneous SNR/channel state values γ for all 4 half-duplex channels used during phase 1 (solid line) and 2 (dashed line) of a cooperation cycle

Based on the work on the relay channel, Sendonaris et al. proposed *user cooperation diversity* [23], where cooperation allows users[1] to share their resources, antennas, and time slots, during the transmission. A typical scenario is illustrated in Fig. 2. In contrast to relaying, with cooperation *each* user may act as source of own data *and* as a relay for other users. In this example, both cooperating users u_1 and u_2 aim to transmit data to the destination d and both users may forward data for the respective cooperation partner.

The first resource cooperating users share, are their antennas. In contrast to relaying, with cooperation the data of a single user is relayed via *multiple* channels between these antennas. Using multiple channels provides spatial diversity even if each user node is equipped with only one antenna. However, the varying channels need to be independent. In the shown example, cooperation diversity is provided if the channel states $\gamma_{1,d}$ and $\gamma_{2,d}$ are spatially independent. This can be assumed if the user antennas are separated in space.

A further resource shared by cooperating users is transmission time. In contrast to Store-and-Forward (S&F) schemes, where a *complete* packet must be received before it can be forwarded, cooperative relaying may be performed on a much smaller time-scale. Here, forwarding can start as soon as only a few bits, symbols, or parts of the signal are received. In addition to spatial diversity, this enables temporal diversity since even short-time changes of the channel states γ provide diversity if these changes are independent.

As space-time coded Multiple Input Multiple Output (MIMO) systems cooperative networks employ multiple antennas to profit from space-time diversity. For this reason cooperative networks are sometimes called *virtual* MIMO or virtual antenna arrays. However, compared to "real" multiple antenna systems, cooperation has several fundamental differences. The first difference to MIMO is that cooperation does not rely on multiple antennas per node. Cooperation is possible with single antenna devices but can also be combined with space-time coding techniques if multiple antennas are available. Secondly, the antennas of cooperating partners are, naturally, further apart than antennas of a MIMO device. This assures that the shared channels stay spatially independent and provide diversity gains even with severe spatial effects, e.g. shadow fading, which dramatically affect MIMO systems. However, in contrast to MIMO, creating *virtual* MIMO by cooperation comes at the cost of unreliable channels *between* the antennas of the cooperating devices. Furthermore, additional effort to achieve and synchronize cooperation is required.

One important part of this effort are *cooperation protocols* defining the exchange of data between the cooperating nodes and the destination. The interest attracted by cooperation diversity has led to the development of many cooperation protocols [24,13,10], which will be discussed in the following.

---

[1] Here, the term *user* is a simple shorthand for any type of device, e.g. a cellular base station or an end-user terminal.

Table 1 Classification of relaying approaches

Approach	Data regeneration	Diversity order	Coding scheme
Store-and-Forward (S&F)	Yes	1	n.a.
Amplify & F. (A&F)	No	N	n.a.
Compress & F. (C&F)	No	N	Compression
Decode & F. (D&F)	Yes	$[1,N]$	Repetition
Coded Cooperation (CC)	Yes	N	FEC
Space-time CC	Yes	N	Space-time & FEC

2.2 Basic Cooperation Protocols

Table 1 lists and compares the most common approaches to realize cooperation diversity.

Although all these approaches employ different methods to process the relayed data, they all follow the basic relaying principles. Each scheme employs two phases per cooperation cycle, e.g. separated by Time Division Multiple Access (TDMA) or Code Division Multiple Access (CDMA). While in the first phase the users exchange their data, in the second phase the users help each other by relaying the data/signal. The cooperation diversity protocol defines how relaying is performed in the second phase, how the partner's data is represented (Table 1), and, finally, which order of diversity can be reached. Here, a diversity order of N means that a scheme can exploit the *full* diversity provided by N users. With smaller diversity order the cooperation scheme limits the resulting performance.

In reference [13] Laneman et al. introduced the schemes Amplify-and-Forward (A&F), Decode-and-Forward (D&F), and a hybrid scheme that switches between these two. A&F is non-regenerative which means that the relay does not extract data from the signal received in phase 1. The signal is amplified and relayed in phase 2 of A&F. In contrast to this non-regenerative relaying, with D&F the data is *regenerated* at the relay. After receiving the signal, both partners extract symbols which are demodulated to code words and decode these code words to data bits. These bits are re-encoded and retransmitted in phase 2. Static D&F does not reach full diversity, while dynamic schemes, where the relay checks the source's data for errors, e.g. by using a Cyclic Redundancy Check (CRC), and reacts to the result of this check, may reach full diversity order of N. This reaction can be, e.g. to remain silent or forward own data instead of the erroneous partner's data during phase 2. Such selective D&F protocols [13] perform best with good channels between source and relay but lack performance, compared to A&F schemes, if these channels degrade [26].

The Compress-and-Forward (C&F) cooperative relaying protocol was initially suggested in Theorem 6 of [5]. This scheme strikes a balance between the regenerative and non-regenerative methods. On the one hand, the received signal is only quantized instead of being fully decoded to bits. On the other hand, the quantized symbols are not directly repeated in phase 2 as with A&F relaying. In order to reduce redundancy, the symbols are compressed by Wyner-Ziv coding prior to relaying.

While the basic D&F approach [13] considers only the repetition of the regenerated data, Hunter et al. [10] proposed a scheme called Coded Cooperation (CC) which encodes the relayed data more efficiently. CC provides cooperation diversity by distributed Forward Error Correction (FEC) coding and considers the result of the error check for its relaying decision. If a user is not able to correctly decode the partner's bits it forwards its own data during the second phase. Using this simple protocol a user still provides redundancy for its own without wasting resources by retransmitting erroneous data. CC can be easily combined with space-time coding schemes [12], which is discussed in detail in Sect. 2.3. An informative tutorial on cooperative coding techniques is provided in reference [22] and detailed analyses of the common approaches are presented in references [11,14].

In CC the amount of redundancy in each of the phases controls the cooperation level $\alpha = n_1/(n_1+n_2)$. This level defines the portion of the n_1 bits transmitted non-cooperatively during phase 1 relative to the n_2 bits transmitted cooperatively in the second phase. Hence, adjusting α allows to trade off the number of cooperatively and non-cooperatively transmitted bits per cooperation cycle, e.g. to optimize the transmission's error performance. However, the optimal parameter set and even the choice of the coding scheme strongly depend on the scenario. Hence, there is no single optimal scheme and parameter set. Switching between several coding schemes and scenario-aware adaptation of the parameters can increase the cooperation diversity gain dramatically. This adaptation and the relevant scenario factors are further discussed in Sect. 3.

2.3 Combined Cooperation Approaches

To get all the benefits of cooperation diversity and space-time coding a combination of these methods is possible. Figure 3 shows the throughput obtained by combining CC and space-time coding in the two-user cooperation scenario of Fig. 2. A TDMA scheme is assumed and that a high reuse of the relay slot is possible and, hence, there is no reduction in spectral efficiency due to orthogonal relaying. Both cooperating partners are fixed and equipped with two antennas, while the fixed destination only has one antenna. The throughput is compared with the direct transmission assuming that the destination has two antennas. In addition to cooperation the partners employ Alamouti and V-BLAST space-time codes.

The results show that the best throughput is obtained when code combining is selected as the retransmission scheme and source and relay are transmitting different parity bits in each retransmission. Additionally, the throughput depends on the space-time code selected for a given quality of the channel: lower rate space-time codes seem to be more effective in a low SNR scenario.

In addition to combining space-time and cooperative coding we can trade off regenerative and non-regenerative relaying techniques. Rather than considering regenerative and non-regenerative relaying as competing approaches, it makes sense to design adaptive multi-mode cooperative relays that would select the best protocol, i.e. the one which maximizes the throughput under Quality of Service (QoS) constraints. Let us illustrate this

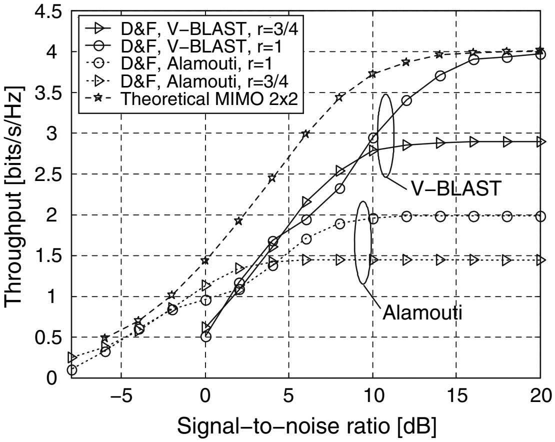


Fig. 3 Combining cooperative and space-time coding: Throughput for CC with 4-QAM, RCPTC of rates 3/4 and 1 using V-BLAST and Alamouti space-time block codes. Source and relay terminals have two antennas and the destination terminal has one antenna

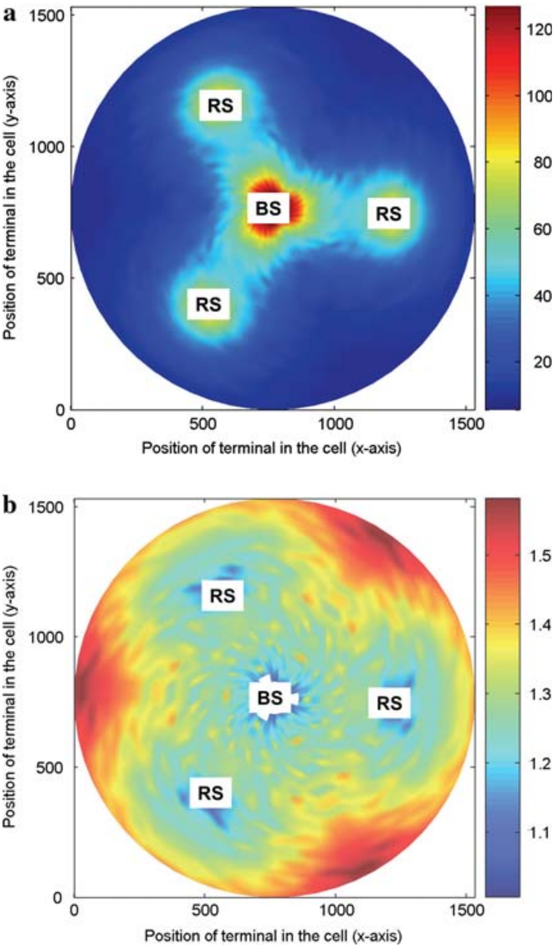


Fig. 4 Maximum throughput and gain with cooperative relaying support in the downlink of an IEEE 802.16e-like WMAN. Shown as a function of the terminal location within the cell. (**a**) Maximum throughput, (**b**) Cooperation gain

exemplarily for a cellular WMAN scenario similar to IEEE 802.16 e which employs MIMO-OFDMA. The Base Station (BS) at the center of the cell is equipped with 3 antenna sectors and supported by a fixed Relay Station (RS) in each sector. Let us assume that each RS is located on lamp poles or roof tops letting it benefit from Line-Of-Sight (LOS) propagation and high SNR to the BS. The mobile terminals are assumed to be not in line-of-sight (NLOS), which is typical in urban and sub-urban environments.

Let us now study how cooperative D&F can improve the downlink throughput and coverage. Here, we consider a space-time coded cooperation scheme where source (BS) and relay (RS) transmit simultaneously during the second cooperative phase via spatially uncorrelated channels. In Fig. 4a, the downlink throughput (more precisely, the ergodic mutual information) for cooperative D&F at 90% coverage probability is plotted as a function of the terminal location within the cell. It can be verified that in a given cell the cooperation gain – which we define as the throughput ratio of cooperative D&F to the best non-cooperative strategy – is on average around 20%. However, at certain locations the improvement can be as high as 50%.

We can study this further by plotting the cooperative gain at 90% coverage probability as in Fig. 4b. We see that direct transmission from the BS remains the best strategy to serve mobile terminals at the center of the cell. Around the RS, hot spots are created in which non-cooperative D&F relaying is quite efficient. The largest cooperative gains are achieved when the path loss and shadowing lead to low and similar SNR at the BS and RS. Here, cooperation diversity maximizes capacity. This happens in areas which are far away from both the BS and RS. When looking at the uplink, the situation changes because now the most robust link is between the relay (RS) and destination (BS). In this case C&F is optimal [25] and provides a similar cooperation gain in the uplink as D&F does in the downlink for the same areas (i.e. far from the BS and RS). This highlights the need for implementing multi-mode relays that maximize uplink *and* downlink capacity by selecting the optimal cooperation protocol.

3 Optimizing Cooperation: Resource Allocation for Cooperating Users

Not only selecting the best cooperation protocol can optimize the performance of cooperative networks. Furthermore, adjusting the cooperation partner, the employed code, or the level of cooperation may be beneficial. In this section we introduce factors which are relevant for optimizing cooperative communication, discuss optimization approaches, and show performance results for such optimized cooperation schemes.

3.1 Factors and Metrics for Resource Allocation

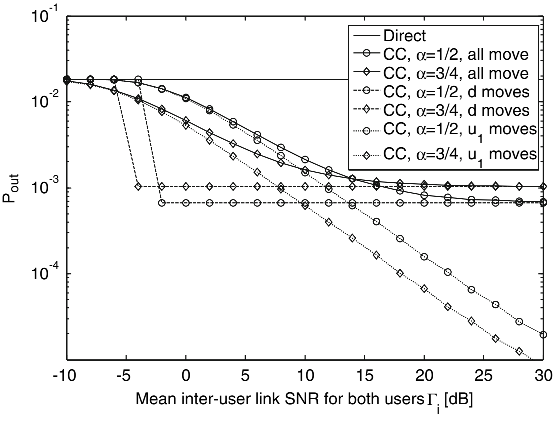
The performance of cooperation diversity schemes is affected by a higher number of parameters than with direct transmission. For example, if user 1 directly transmits to d in the most simple scenario (Fig. 2) only channel $(1, d)$ affects this transmission. With cooperation diversity the states of the inter-user channels $(1, 2)$ and $(2, 1)$ determine whether cooperation is possible. Hence, even in this simple example, the performance of cooperation diversity depends on the states of the three additional channels $(1, 2)$, $(2, 1)$, and $(2, d)$. In fading channels the instantaneous channel states may change very frequently which makes accurate measurements inappropriate. Here, the instantaneous channel state cannot be directly considered as a decisive metric for selecting the appropriate cooperation scheme or parameters. These channel-related factors highly depend on the position/topology of the cooperative nodes, and on their traffic demands. For this reason, we discuss these three classes of *channel*, *position/topology*, and *traffic*-related factors separately.

3.1.1 Channel-Based Allocation

Factors introduced by the channel have an enormous effect on the performance of cooperation diversity schemes. As discussed in reference [32], high spatial correlation and direct path components on both channels to the destination d significantly degrade the performance. However, these fading properties cannot be determined easily.

A further relevant factor is the mean SNR of all related channels. To illustrate its effect let us, again, consider the simple two-user cooperation scenario in Fig. 2. Figure 5 shows the outage probability vs. mean SNR of the inter-user links for three cases of user mobility and several cooperation levels α. In all cases, a higher mean SNR on the inter-user channels increases the probability of cooperation. The probability that this cooperation is successful increases with the SNR of the channels to d. Since in most systems the mean SNR of a channel can be measured easily, e.g. via the preamble of a MAC frame, this provides an important metric for the optimization decision.

Fig. 5 Outage probabilities vs. mean inter-user SNR for the direct and coded cooperative (CC) transmission with *mobile* partners and/or destination. Shown for 3 mobility cases (line style) and 2 cooperation levels α (marker type). Simulated for "moderate" channels to d (SNR 10 dB) and user velocity 10 m/s



As opposed to the above discussed scenarios in Fig. 5 we consider several cases of user mobility. This corresponds to a cellular, WMAN, WLAN, or mesh scenario where *both* cooperating users and even the base station may move. For example, let us consider two cooperating users in the same moving train. Both users are relatively fixed and close to each other but move relatively to the destination (case: "d moves"). As opposed to scenarios where only one ("u_1 moves") or both of the cooperating users move differently ("all move"), in the train scenario even a very low mean SNR shows to be sufficient to decrease the outage probability for the overall transmission of both users to d. In this scenario users may prefer partners which are relatively fixed within the same train. The good inter-user channels ensure high diversity gain which may be required to reach the base station outside of the moving train via a severely faded channel. Another scenario occurs if the train stops or moves only slowly. In this case, d may be better reached and even moving users with time-variant channels or lower mean inter-user SNR may be considered as partners. Although the users' motion velocity cannot be obtained easily, this information may be constructed from position or network topology information.

3.1.2 Position/Topology-based Allocation

Many partner selection schemes were proposed which rely on geographical information, e.g. [17,21]. Assuming known user locations, e.g. obtained via Global Positioning System (GPS), these schemes consider the distance between the nodes as metric for selecting the partner and/or cooperation level. While this approach has its analytical benefits its application scenario may be limited. Even if the node locations can be determined it relies on constant/known channel statistics in terms of fading Probability Density Function (PDF), fading autocorrelation function, and path-loss exponent. In scenarios with moving users and/or different propagation environments all these parameters are not likely to be known and require further adaptation.

However, if the user locations are updated frequently even the user's velocity can be assumed to be known. In reference [27] we illustrate the dependency of the velocity on the required mean SNR to reach a partner. The faster both users move the better the partner needs to be reached to provide successful cooperation, i.e. to stay below a certain error bound. If velocity and mean inter-user SNR can be measured, this provides a simple method for selecting the cooperation partner without requiring further channel knowledge [27].

Furthermore, selecting a higher cooperation level can compensate for the degrading effect of velocity.

3.1.3 Traffic-based Allocation

The traffic type may also be considered for adjusting cooperation parameters. For example, in reference [30] Xu et al. combine cooperative coding with code rate allocation according to multimedia traffic priority. In practical cooperative systems, the traffic class may be more relevant since it defines the optimization goal. For example, while with non-real time traffic, e.g. downloading a web page or file, the optimization goal is to maximize the data rate, with soft-real time traffic, e.g. VoIP telephony, the latency has to be minimized. In many systems, the type of traffic can be extracted from the packet allowing to consider it during selection of scheme, parameter, or partner.

While one approach is the exact consideration of only one factor, e.g. only the geographic positions of users, considering several factors may be more feasible. For example, in the "moving train with IP telephony" scenario a user may select a relatively fixed partner without real-time traffic of its own which does not require low latencies. Hence, a user can select a partner which provides the highest cooperation level by exploiting mobility and traffic information.

3.2 Optimization Schemes and Approaches

When the assisting relays work under the half-duplex constraint, different cooperative protocols are possible [20]. Every protocol exhibits different capacity properties, but the efficiency of the cooperative transmission also depends on the way resources are allocated to the source and relay terminals. Two, mutually not exclusive, options are possible to enhance efficiency: *optimization of resources* assigned for each phase depending on the channel state and *reuse of resources* by allowing multiple cooperating users access to the same resources.

3.2.1 Optimization of Resources

References [15,9,1] provide optimization methods of the resources for some of the protocols described in reference [20]. Let us, again, assume our two-user cooperation scenario (Fig. 2) with fixed single-antenna nodes. The effect of optimizing the transmission time for the D&F protocols from [20] is shown in Fig. 6. Properly balancing the allocated transmission time between the source and relay terminals significantly enhances the benefit compared to direct transmission and simple S&F. At the same time, the performance greatly depends on the geometry, with the most unfavorable cases being those where the relay terminal is close to the destination.

3.2.2 Reuse of Resources

A different approach to resource allocation is the reuse of transmissions in the relay slot. For the simple two-user scenario (Fig. 2) this is studied in reference [1]. Here, the allocation of the resources depends on the cooperative protocol under consideration. When the source transmits to the relay in the first phase, and both source and relay transmit to the destination in the second phase, allocating resources to multiple users is a convex problem on a multi-access capacity region. Hence, there is a unique optimal solution which can be found easily. For this optimal resource allocation Fig. 7 shows the achievable rate regions for the two

Fig. 6 Capacity of cooperative transmission for different orthogonal D&F protocols optimized in terms of transmission time, as a function of the distance between the source and the relay terminals. The destination terminal is placed at $d = 1$. Mean SNR between source and destination is 0 dB and all terminals have one antenna

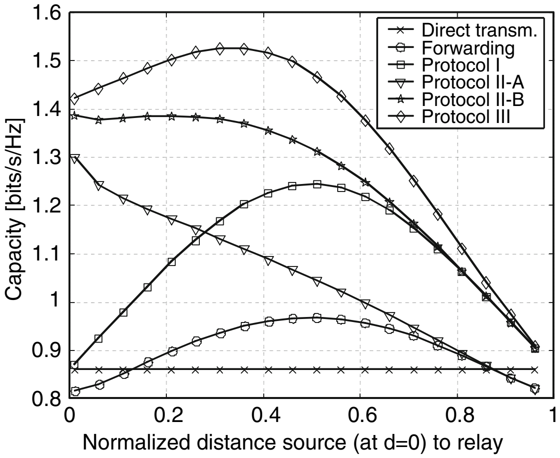
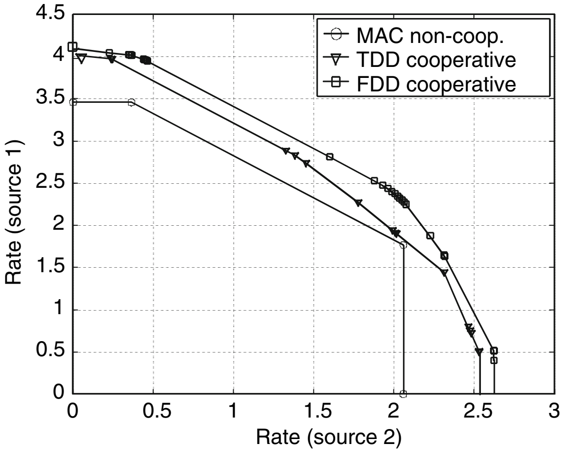


Fig. 7 Achievable rates with two fixed users and optimal resource allocation. Both users alternately relay without adding power



cooperating users. Both single antenna users are fixed and relay each other's data alternately. The separation of the channels may be performed in time (TDD) or in frequency (FDD). The boundary of the capacity region is obtained by optimally selecting the fraction of resources for the different phases. It shows that with both duplex schemes the multiple access capacity region is enlarged compared to the non-cooperative case. The gains strongly depend on the nominal SNRs for each link.

4 Cooperative Networking—Towards Feasibility

Based on the cooperation diversity schemes and the optimization approaches discussed in Sects. 2 and 3 we now emphasize issues arising when *practically* implementing these approaches. Section 4.1 begins with a case study of CoopMAC, a cooperative WLAN amendment already in existence. In Sect. 4.2 we summarize the most important practical issues partner selection, rate adaptation, traffic adaptation, and multi-hop cooperation.

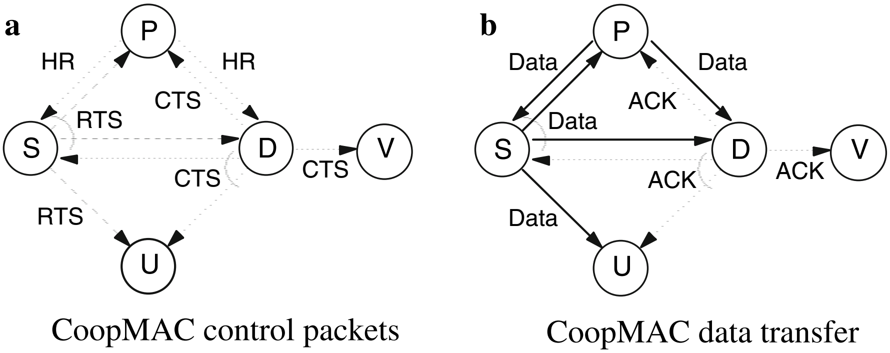


Fig. 8 The flow of control and data packets in CoopMAC. The source S communicates with the destination D on the direct path as well as on a two-hop path established by a partner P. The two adjacent nodes U and V are hidden. (**a**) CoopMAC control packets, (**b**) CoopMAC data transfer

4.1 Integrating Cooperative Relaying into WLANs–The CoopMAC Approach

CoopMAC is a cooperative relaying protocol for the IEEE 802.11 WLAN standard [19,18]. In CoopMAC every node maintains a list of potential partners and estimates data rates based on their channel states by overhearing ongoing transmissions. When a node has data to send, it picks the potential partner with the best data rate from its list. Then it addresses the destination as well as the selected partner in an extended RTS packet. We call CoopMAC a sender-initiated protocol because the source decides whether to cooperate and with whom. Reference [28] compares all three flavors of protocols, namely sender-initiated, destination-initiated, and partner-initiated.

Here, the extended RTS packets also carry the data rate estimated by the source. The addressed partner only replies with a Helper Ready (HR) packet if it can sustain the estimated data rate (Fig. 8a). The source then transmits its data to the destination via two paths, the direct path as well as the two-hop path established by the relay (Fig. 8b). When the original IEEE 802.11a physical layer (PHY) is used, packets can only be decoded “as is”. More capacity can be gained, however, by using receiver combining. If the destination PHY employs receiver combining it can reconstruct the data from the packets received on *both* paths leveraging cooperation diversity as well as coding gain [18].

4.2 Practical Issues for Cooperative Networking

Table 2 summarizes the issues that one is faced with when trying to apply cooperation in an existing WLAN standard, e.g. IEEE 802.11, and in mesh networks. Therefore, this section reviews state-of-the-art literature that already offers promising approaches for the issues listed in Table 2. If appropriate, it points out their deficiencies that prevent these approaches from being deployed straight away.

Table 2 Open issues for implementing coded cooperation

Issue	Required
Partner selection	Selection scheme, decision metrics
Rate adaptation	Multi-rates, allocation scheme
Traffic adaptation	Traffic classification, allocation scheme
Multi-hop cooperation	Cooperation-aware routing

4.2.1 Partner Selection

In a multi-user scenario it is not *a priori* clear with whom a node is cooperating. It is the goal of partner selection to find a suitable partner from the set of adjacent nodes. Partner selection can either be centralized, i.e. source or destination select the partner, or decentralized, i.e. the partners coordinate among themselves who cooperates [27,28]. Several factors determine partner selection, where the states of the inter-user *and* the uplink channel are most relevant. A good inter-user channel is necessary but not sufficient, e.g. a node with excellent inter-user channel is a bad choice when it does not provide an uplink to the destination. Thus, partner selection requires the availability of Channel State Information (CSI) for both inter-user and uplink channel that a partner provides. This information is generally easier obtained at the relay than at source or destination.

In reference [4], Bletsas et al. proposed *opportunistic relaying* as a decentralized partner selection scheme in which only one node is selected as a partner. Assuming that each potential partner can overhear the IEEE 802.11 RTS/CTS sequence between source and destination, indicating the start of a transmission, all potential partners estimate the channel state from the strength of the received RTS/CTS sequence and derive a timeout from it. The timeout is inversely proportional to the estimated channel state. Upon expiration of the timer, a node senses the channel and, if it is not busy, announces its help. Thus, the timeout serves as a back-off in which the node with the earliest timeout becomes the cooperating partner.

4.2.2 Rate Adaptation

Rate adaptation, e.g. [8], aims to maximize the throughput by dynamically adjusting the transmission rate according to the current channel state. This method may be used in addition to a cooperation diversity scheme which introduces further channel states and rate constraints, e.g. due to the cooperation level α. Lin et al. analyzed the throughput of coded cooperation when rate adaptation is used [16]. Their analysis concludes that to achieve an optimal throughput in rate-adaptive coded cooperation, it does not suffice for source and relay to consider only their own channel quality to the destination. As with selecting the partner, selecting the transmission rate must be based on the states of *all* channels.

Figure 9 illustrates a typical problem with rate adaptation applied with coded cooperation. Suppose that one user is able to send with twice the data rate, the transmission obeys the scheme depicted in Fig. 9a. As shown, half of the transmission time of user S_2 is wasted due to vacant time slots. However, these vacant slots yield the possibility to assist another user with its transmission. Suppose that another neighboring user S_3 is available that also transmits with the same rate that S_1 uses. In this case, S_2 may become a partner of both users and accommodate the parity bits of S_3 in its second vacant slot as depicted in Fig. 9b. As a consequence,

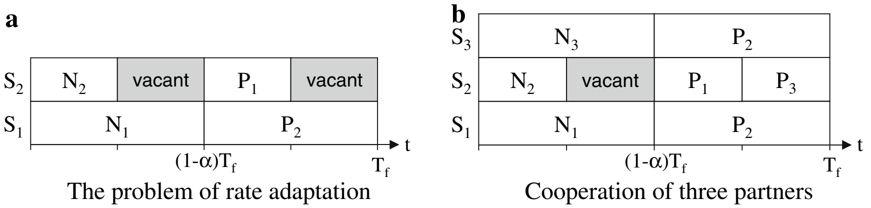


Fig. 9 Rate adaptation may cause vacant slots due to heterogeneous transmission times when applied to coded cooperation diversity schemes. Here, N_i refers to the encoded data originating at node S_i, and P_i refers to the additional parity bits of N_i. Vacant slots can be compensated for by accommodating more transmissions. (**a**) The problem of rate adaptation, (**b**) Cooperation of three partners

a rate adaptation protocol for coded cooperation should select the number of cooperating partners dependent on the used rate. Therefore, the overall transmission rate, which may in turn depend on the cooperation level α, is an important criterion for partner selection.

4.2.3 Traffic Adaptation

Xu et al. analyzed coded cooperation for increasing the quality for the transmission of multimedia streams consisting of bits with unequal importance [30]. They proposed layered cooperation which combines traffic adaptation with coded cooperation. The scheme employs Unequal Error Protection (UEP) of multimedia streams through coded cooperation. Instead of generating redundancy bits for the entire code word N_i, the code word is divided into two parts, N_{bi} and N_{ei}. The N_{bi} bits represent the more important bits of the code word for which redundancy is transmitted in the second phase, whereas the N_{ei} bits remain unprotected. The diversity benefit gained from cooperation is only applied to the more important bits of the multimedia stream. Figure 10 compares a standard coded cooperative transmission to the layered cooperative transmission of a multimedia stream using TDMA. The parity bits transmitted in the second phase of coded cooperation apply to all the punctured code bits transmitted in the first phase, whereas the parity bits transmitted in the second phase of layered cooperation apply to a fragment of the punctured code bits transmitted in the first phase only. The fragment N_{bi} contains the base-layer bits of the multimedia signal which are considered crucial for the reception of the signal and, thus, protected using cooperation. With the fragment N_{bi} having the same length α as the second phase, repetition coding may be used, i.e. $P_{bi} = N_{bi}$. The fragment N_{ei} contains the enhancement-layer bits of the multimedia signal for which transmission errors can be tolerated. Xu et al. derived a fragment length and cooperation level $\alpha = 1/3$ as an optimal value for minimizing the expected distortion using layered cooperation [30].

4.2.4 Multi-hop Cooperation

Zhang and Lok analyzed a very simple D&F strategy, in which a source node transmits its information to the destination node and all nodes in between forward the overheard transmission to the destination [31]. Unfortunately, this approach assumes that the source can adjust its transmission power such that it can reach the destination directly. Thus, it is not practical when source and destination are far apart. Furthermore, it uses a simple relaying strategy only and does not exploit the coding gain offered by coded cooperation.

Bao and Li use the same transmission idea, but they let intermediate nodes only transmit additional redundancy (similar to coded cooperation). In their proposed framework

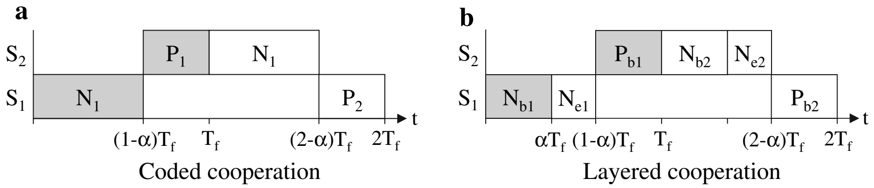


Fig. 10 TDMA transmission of coded and layered cooperation: While the parity bits in coded cooperation protect the entire first phase P_1 protects N_1, in layered cooperation only the more important bits in the first phase are protected (P_{b1} protects N_{b1}, but not N_{e1}). Such approach is feasible for multimedia streams. (**a**) Coded cooperation, (**b**) Layered cooperation

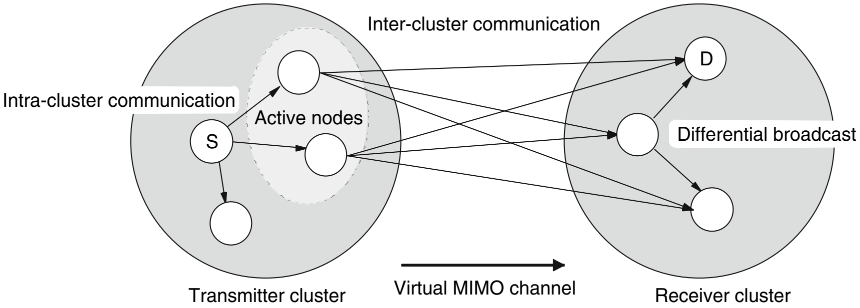


Fig. 11 Virtual MIMO transmission between cooperating clusters

progressive network coding [3], again, every intermediate node between source and destination combines all the signals received during previous hops to recover the initial information. It differs from Zhang and Lok's approach in that the intermediate nodes re-encode the extracted information with a specific code to yield a unique set of parity bits. This way, the FEC code is strengthened with each hop by including new parity bits. It should be noted that even in this approach the source still needs to transmit to the destination directly.

Del Coso et al. take a different approach to exploit cooperation in mesh networks [6]. They group several mesh nodes to clusters and apply the multi-hop transmission on a per-cluster basis. When all mesh nodes of a cluster transmit at the same time, virtual MIMO channels are created by cooperation. Figure 11 illustrates the flow of information in their cooperative cluster transmission scheme assuming that source and destination node do not reside within the same cluster. First, the source node broadcasts its information to all n_t nodes within the cluster that it belongs to intra-cluster communication. All nodes that successfully decode the information belong to the set of n_a active nodes and forward the information to the cluster containing the target node (inter-cluster communication). When the target cluster consists of n_r receiving nodes, this approach creates an $n_a \times n_r$ virtual MIMO channel with diversity order n_r. If the transmission is not in outage at least the node with the highest SNR of the receiving cluster has decoded the information correctly. Therefore, this node broadcasts the information within the cluster to reach the destination (differential broadcast). Opportunistic relaying lends itself for letting the node with the largest SNR broadcast (Sect. 4.2.1). If the target node is not within the cluster, all nodes transmit the information to the next cluster as in the first case, thus establishing a multi-hop cluster-to-cluster transmission.

5 Conclusion and Future Work

In the previous sections we have introduced cooperation diversity as a promising approach to increase transmission performance in wireless multi-user scenarios. We have provided a survey of cooperation diversity schemes which allow users to act as a multiple antenna system by sharing their antennas and time slots. We further discussed the optimization of cooperative networks by combining cooperation protocols, cooperation-aware resource allocation, and integrating cooperation into space-time coding. To enable such *cooperation-aware optimization* of transmission performance and to integrate it into practical cooperative networks we point out the following future work:

- *Factor and parameter studies:* Due to the enormous amount of new factors and system parameters in cooperative networks further studies are required. In addition to studies on the observable factors and controllable parameters in cooperative scenarios the effects of time-scale, measurement accuracy, and correlation of these factors has to be evaluated. Finally, the studies should provide suggestions for feasible control schemes and required accuracy and time-scale in practical scenarios. While for this evaluation abstract scenarios and metrics, as used in this article, provide a good starting point, further results for practical scenarios and metrics are required, e.g. the mean decrease of the web page download time vs. the number of cooperating partners for a certain cooperation scheme in an IEEE 802.11 WLAN. Testbed implementations may help to obtain accurate results and evaluate performance of cooperation diversity schemes under real-world constraints.
- *Optimization schemes and allocation:* In addition to the plain integration of cooperation diversity schemes into practical systems their combination with cooperation-aware optimization schemes may provide significant performance gains. In this case, optimization schemes and feasible control methods are required to optimize the selected partner, rate, and cooperation level. This requires functions to observe scenario factors, to define optimization objectives (e.g. by monitoring the traffic type), to solve the optimization problem, and to control the system parameters. With time-variant channel and traffic characteristics all these functions may have to be solved under strict timing constraints, since cooperation is done at local level and thus requires fast decision making. However, although running at local level, the optimization scheme should still provide a *global* optimal solution. Further important aspects are fairness, e.g. to prevent exhaustion of frequently used partners, and traffic-aware prioritization.
- *Protocols:* Efficient protocols are required to interconnect the functions of the optimization scheme, which may be distributed among nodes and layers. For example, for the optimal selection of a cooperating partner a user may need to know the mean SNR of the channels to all neighbors. In this case, the SNR has to be measured at each neighbor and these values have to be transferred back to the user. Additionally, this multi-access situation (all neighbors want to transmit measurements to one node) needs to be efficiently scheduled by a MAC protocol. The received values are then used to determine the solution of the optimization problem. This may be performed at higher layers to enable easy access to further parameters, e.g. network topology. This requires *cross-layer* communication (within a single node), which needs to be carefully synchronized. The achieved optimization result is used for selecting the partner and cooperation parameters. Transferring this selection to the partner and synchronizing the cooperation timing requires fast *cross-node* communication. Finally, this demands for protocols providing fast and efficient information exchange between multiple layers and nodes of a cooperative network.
- *Standard integration:* In order to provide transparent cooperation the above schemes have to be integrated into future mesh, WMAN, WLAN, or cellular network standards. These standards or amendments should define parameters and constraints for the PHY and MAC/DLC functions required for high-performance cooperation rather than provide detailed algorithms for solving optimization and cooperation problems. This ensures inter-node compatibility, while enabling the freedom for device manufacturers to choose the integrated optimization and cooperation algorithms.

Concentrating future research on these issues will enable users of future cellular, WMAN, WLAN, or mesh networks to benefit from the gain provided by cooperation.

References

1. Agustin, A., & Vidal, J. (2007). Radio resources optimization for the half-duplex relay-assisted multiple access channel. In *IEEE International conference on Acoustics, Speech and Signal Processing (ICASSP).*
2. Agustin, A., Vidal, J., & Muñoz, O. (2005). Hybrid turbo FEC/ARQ systems and distributed space-time coding for cooperative transmission. *International Journal of Wireless Information Networks (IJWIN), 12*(4), 263—280.
3. Bao, X., & Li, J. (2006). Progressive network coding for message-forwarding in ad-hoc wireless networks. In *Proceeding 3rd Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)* Vol. 1. (pp. 207—215).
4. Bletsas, A., Khisti, A., Reed, D. P., & Lippman, A. (2006). A simple cooperative diversity method based on network path selection. *IEEE Journal on Selected Areas in Communications, 24*(3), 659—672.
5. Cover, T. M., & Gamal, A. A. E. (1979). Capacity theorems for the relay channel. *IEEE Transaction on Information Theory, 25*(5), 572—584.
6. del Coso, A., Spagnolini, U., & Ibars, C. (2007). Cooperative distributed MIMO channels in wireless sensor networks. *IEEE Journal on Selected Areas in Communications, 25*(2).
7. Gallager, R. (1994). *Communications and cryptography: Two sides of one tapestry*, In Engineering & Computer Science, Kluwer.
8. Holland, G., Vaidya, N., & Bahl, P. (2001). A rate-adaptive MAC protocol for multi-hop wireless networks. In *Proceeding 7th Annual International Conference on Mobile Computing and Networking (MobiCom)* (pp. 236—251).
9. Host-Madsen, A., & Zhang, J. (2005). Capacity bounds and power allocation for wireless relay channels. *IEEE Transactions on Information Theory, 51*(6), 2020—2040.
10. Hunter, T. E., & Nosratinia, A. (2002). Cooperation diversity through coding. In *Proceeding IEEE International Symposium on Information Theory (ISIT).* p. 220.
11. Hunter, T. E., Sanayei, S., & Nosratinia, A. (2006). Outage analysis of coded cooperation. *IEEE Transactions on Information Theory, 52*(2), 375—391.
12. Janani, M., Hedayat, A., Hunter, T. E., & Nosratinia, A. (2004). Coded cooperation in wireless communications: space-time transmission and iterative decoding. *IEEE Transactions on Signal Processing, 52*(2), 362—371.
13. Laneman, J. N., Wornell, G. W., & Tse, D. N. C. (2001). An efficient protocol for realizing cooperative diversity in wireless networks. In *Proceeding IEEE International Symposium on Information Theory (ISIT).* p. 294.
14. Laneman, J. N., Wornell, G. W., & Tse, D. N. C. (2004). Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory, 50*(12), 3062—3080.
15. Liang, Y., & Veeravalli, V. V. (2005). Gaussian orthogonal relay channels: optimal resource allocation and capacity. *IEEE Transactions on Information Theory, 51*(9), 3284—3289.
16. Lin, Z., Erkip, E., & Ghosh, M. (2005). Adaptive modulation for coded cooperative systems. In *Proceeding IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC).*
17. Lin, Z., Erkip, E., & Stefanov, A. (2006). Cooperative regions and partner choice in coded cooperative systems. *IEEE Transactions on Communications, 54*(7), 1323—1334.
18. Liu, P., Tao, Z., Lin, Z., Erkip, E., & Panwar, S. (2006). Cooperative wireless communications: A cross-layer approach. *IEEE Wireless Communications Magazine, 13*, 84—92.
19. Liu, P., Tao, Z., & Panwar, S. (2005). A cooperative MAC protocol for wireless local area networks. In *Proceeding IEEE International Conference on Communications (ICC)*, Vol. 5. (pp. 2962—2968).
20. Nabar, R. U., Bölcskei, H., & Kneubüler, F. W. (2004). Fading relay channels: Performance limits and space-time signal design. *IEEE Journal on Selected Areas in Communications, 22*(6), 1099—1109.
21. Nosratinia, A., & Hunter, T. E. (2007). Grouping and partner selection in cooperative wireless networks. *IEEE Journal on Selected Areas in Communications, 25*(2), 369—378.
22. Nosratinia, A., Hunter, T. E., & Hedayat, A. (2004). Cooperative communication in wireless networks. *IEEE Communications Magazine, 42*(10), 74—80.
23. Sendonaris, A., Erkip, E., & Aazhang, B. (1998). Increasing uplink capacity via user cooperation diversity. In *Proceeding IEEE International Symposium on Information Theory (ISIT).* p. 156.
24. Sendonaris, A., Erkip, E., & Aazhang, B. (2003). User cooperation diversity. Part I. System description. *IEEE Transactions on Communications, 51*(11), 1927—1938.
25. Simoens, S., Muñoz, O., & Vidal, J. (2007). Achievable rates of compress-and-forward cooperative relaying on gaussian vector channels. In *Proceeding IEEE International Conference on Communications (ICC).*
26. Stankovic, V., Host-Madsen, A., & Xiong, Z. (2006). Cooperative diversity for wireless Ad Hoc networks. *IEEE Signal Processing Magazine, 23*(5), 37—49.

27. Valentin, S., & Karl, H. (2007). Effect of user mobility in coded cooperative systems with joint partner and cooperation level selection. In *Proceeding IEEE Wireless Communications and Networking Conference (WCNC)*.
28. Valentin, S., Lichte, H. S., Karl, H., Simoens, S., Vivier, G., Vidal, J., & Agustin, A. (2007). Implementing cooperative wireless networks – Towards feasibility and deployment. In F. H. P. Fitzek & M. D. Katz (Eds.), *Cognitive Wireless Networks: Concepts, Methodologies and Visions*, Springer.
29. van der Meulen, E. C. (1971). Three-terminal communication channels. In *Advances in Applied Probability*, Vol. 3. (pp. 120—154).
30. Xu, X., Erkip., Gunduz, D., & Wang, Y. (2005). Layered cooperative source and channel coding. In *Proceeding IEEE Conf. on Communications*, Vol. 2. (pp. 1200—1204).
31. Zhang, J., & Lok, T. M. (2006). Performance comparison of conventional and cooperative multihop transmission. In *Proceeding IEEE Wireless Communications and Networking Conf. (WCNC)*, Vol. 2. (pp. 897—901).
32. Zummo, S. A. (2006). Performance analysis of coded cooperation diversity in wireless networks. *Wireless Communications and Mobile Computing*.

Authors Biographies

Stefan Valentin studied communication technology and electrical engineering at the Technical University of Berlin. During his studies he worked on OFDMA subcarrier allocation algorithms at the Telecommunication Networks Group. Since 2005 he is Ph.D. student at the University of Paderborn. Here, Stefan Valentin works on resource allocation for cooperation diversity systems and on integrating these techniques into high-rate wireless networks.

Hermann S. Lichte received his diploma in computer science and electrical engineering at the University of Paderborn. He is now working on his Ph.D. in the field of cooperative MAC and routing protocols.

Holger Karl is professor of computer science and head of the computer networks research group at University Paderborn. His research interests are in mobile and wireless communication, wireless sensor networks, and Internet architecture.

Guillaume Vivier is graduated from the Ecole Nationale des Telecommunications, Paris, France and received his PhD degree from the University of Paris VI. He first worked with Alcatel in the design of digital communication systems. He joined Motorola in 1998 to contribute to the definition of Systems Beyond 3G and the Seamless Mobility areas, with the responsibility of the group "Radio System Optimization". He has been involved in European and National funded projects in these domains such as E^2R or Winner. Since early 2007, he moved to Beijing, China, to support the establishment of the newly created Motorola China Broadband Wireless Research Center.

Sébastien Simoens graduated in 1998 from Ecole National Supérieure des Télécommunications (ENST, Paris). Since then, he has been with Motorola Labs in Paris, currently working as a senior research engineer in radio systems optimization. His research activities included OFDM, MIMO, WLAN technologies and more recently cooperative relaying. He has been involved in standardization groups (ETSI HiperLAN/2, IEEE 802.11n) and E.U. projects (IST Broadway, IST Fireworks...). He holds several patents and published more than 20 papers/book chapters available at http://sebastien.simoens.free.fr

Josep Vidal received the Telecommunication Engineering and the Ph. D. degrees from the Technical University of Catalonia (UPC), Barcelona, in 1989 and 1993, respectively. From 1989 to 1990 he joined the LTS at the Ecole Polytechnique de Lausanne. In 1993, he became a Lecturer at UPC and since November 1996, he has been an Associate Professor at UPC. He has led UPC participation in the EC-funded project SATURN, ROMANTIK and FIREWORKS. He has authored 13 journal and 70 conference papers in various areas of signal processing and communications. His current research interests are in statistical signal processing and communication systems, as well as DSP implementation aspects. Dr. Vidal was awarded the UPC's Premio Extraordinario de Doctorado in 1996. He was the Co-Organizer of the IEEE Workshop on Higher-Order Statistics in 1995 and Co-Organizer of the IST Mobile Communications Summit 2001.

Adrian Agustin received the M.S. degree in Telecommunication engineering and M.S. degree in Electronic engineering from the Technical University of Catalonia (UPC), Barcelona, in 2000 and 2002 respectively. He is currently pursuing the Ph.D. degree in the Signal Theory and Communications Department, UPC. From 2000 to 2002 he joined Indra–Espacio, Barcelona, where he was engaged in the research and development of code synchronization techniques for DS-CDMA. His research interests are focused on wireless MIMO and multihop systems in terms of space-time coding, scheduling and cooperative transmissions. Mr. Agustin was the recipient of a Ministry of Catalonia grant to complete his Ph.D. degree in 2004.