Cooperative wireless networking beyond store-and-forward: Perspectives for PHY and MAC design

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***Abstract*— In future wireless networks end-user terminals 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 *user cooperative diversity* increases the robustness of the link vs. fading and interference. After surveying approaches in cooperative diversity we focus on the consequences of these new methods for resource allocation. We discuss which additional factors are introduced by user cooperation and how resource allocation can be combined with cooperative diversity schemes. When it comes to implementation, the question arises how cooperation can be integrated efficiently into existing WLAN standards or wireless mesh networks. A case study of the 802.11 standard reveals the issues that need to be solved in order to deploy cooperative techniques. We provide an overview of the state of the art in implementing cooperative 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 WLAN standards and mesh networks.**

I. 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 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.

In the intermediate situation (which is the nearest to reality), several techniques for error correction and channel coding have been studied. In this field, a relatively new area is attracting the research community: *cooperative networking/diversity*.

Cooperative networking takes advantage of the openness of the radio channel, so far viewed as a drawback. Instead of merely forwarding received packets, i.e. Store-and-Forward (S&F), in cooperative networks stations help each other by mutually combining and error correcting these packets prior to forwarding. Such mechanisms require research on the coding schemes used for combining, on multiple access methods to limit interference, on routing methods (e.g., helper selection), as well as on information theoretic aspects of cooperative diversity. In this paper we provide a survey of the various problems of and approaches for user cooperation and show how they were treated so far by the community. Furthermore, we discuss how resources may be allocated and shared among the cooperating users and which additional factors have to be considered for optimizing cooperative transmission.

To provide a benefit to the user, a cooperative scheme has to be implemented. Hence, the question arises how cooperation can be integrated efficiently into existing WLAN standards and wireless mesh networks. To answer this question we provide case studies which reveal the issues that need to be solved in order to deploy cooperative techniques. Furthermore, we give an overview of the state of the art in solving practical issues with cooperative networking. We further summarize

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how appropriate these issues are solved and which problems are still open.

The paper is structured as follows. In Section II we introduce user cooperative approaches and discuss the performance and functional details of the current schemes. Section III is focused on resource allocation approaches and the factors which are specific for cooperative networking. Section IV discusses practical aspects such as implementation and integration in current Wireless Local Area Network (WLAN) and future mesh standards. Finally, we conclude this paper with a road map for future research, which defines the open problems of integrating user cooperation in next-generation WLAN and mesh networks.

II. User cooperative diversity – New approaches in physical layer relaying

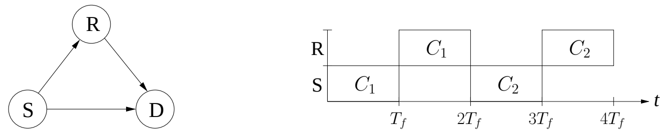
User cooperative diversity is a promising approach for relaying data at the Physical layer (PHY). In this section, we will introduce this approach and several classes of schemes which realize cooperative diversity. Furthermore, we provide a detailed description of the recent schemes and illustrate their performance gains compared to direct transmission and Multiple Input Multiple Output (MIMO) systems.

A. User cooperative diversity

The concept of user cooperative diversity goes back to the work of Van der Meulen [1], Cover and El Gamal [2], and Gallager [3] on the relay channel. 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 (Figure 1(a)). Forwarding and the direct transmission from S to D is performed on orthogonal channels. This orthogonality may be achieved in time by using an Time Division Multiple Access (TDMA) scheme, frequency (FDMA), or code (CDMA). Figure 1(b) shows a simple example of TDMA-based relaying in which T_f denotes the frame time. In this case the frames of all neighboring terminals must be synchronized by the multiple access scheme to be sent within the correct time slot. Furthermore, in order to avoid the need for dedicated relays, any terminal may become a relay if the need arises to.

Based on the work on the relay channel, Sendonaris et al. proposed user cooperation diversity [4], where user cooperation allows users to share their resources during the transmission of their independent data streams. A typical scenario is illustrated in Figure 2. In contrast to relaying, with user cooperation *each* user u 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.

By cooperating, users act as a distributed multiple antenna system by sharing their antennas during the transmission. In contrast to relaying, here the data of a single user is relayed via *multiple* channels between these antennas. Using multiple channels/antennas provides spatial diversity even if each user node is equipped with only one antenna. However, the varying



(a) Channel scenario (b) TDMA transmission of S and R to D

Fig. 1. Simple three-terminal relay channel and a TDMA example

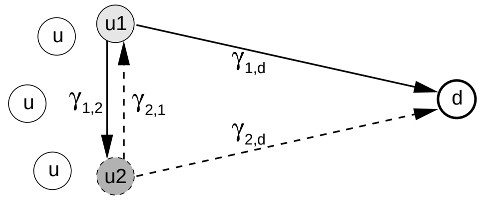


Fig. 2. Basic coded cooperation scenario where u_1 and u_2 (out of a number of users) may cooperate to reach d. The figure shows the *instantaneous* SNR/ channel state values $\gamma_{i,j}$ for all 4 considered channels.

channels need to be independent. In the shown example, user cooperative diversity is provided if the channel states $\gamma_{1,d}$ and $\gamma_{2,d}$ are independent. Spatial independent channels can be assumed if the users are spatially separated.

A further resource, shared by cooperating users is transmission time. In contrast to conventional relaying, also called Store-and-Forward (S&F), the mutual relaying of user cooperative diversity may be performed on a much smaller timescale. With S&F the relay needs to receive and store the *complete* packet before forwarding can start, whereas cooperative diversity allows forwarding if 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 channels provide diversity if these changes are independent. This is comparable to standard diversity coding for multiple antenna systems [5]. Furthermore, users can mutually cooperate on packet level since one packet may contain bits of several users. Hence, on packet level, each user may "simultaneously" act as a helper for another user which may provide an equal diversity gain for all cooperating users.

The interest attracted by the work of Sendonaris et al. has lead to the development of several user cooperative diversity schemes [6–9] which will be discussed in the following section.

B. Realizing cooperative diversity

Several schemes were proposed to realize cooperative diversity. Table I lists and compares the most common approaches. Although all these schemes employ different algorithms to process the relayed data they follow the same general procedure. In all schemes, each cooperation cycle is structured in two phases. In the first phase, each user transmits parts of its own data *and* receives data or, generally, signals of other users. While transmission and reception is performed on separate channels, this does not necessarily mean that it is performed simultaneously. For example, a TDMA scheme may structure the first phase in separate time slots per user. In the second phase, the users help each other by relaying the data/signal

TABLE I
CLASSIFICATION OF RELAYING APPROACHES

Approach	Data regeneration	Cooperative diversity	Coding scheme
Store-and-Forward (S&F)	Yes	No	–
Amplify & F (A&F)	No	Yes	–
Compress & F (C&F)	No	Yes	Compression
Decode & F (D&F)	Yes	Yes	Repetition
Coded Cooperation (CC)	Yes	Yes	FEC
Space-time CC	Yes	Yes	Space-time & FEC

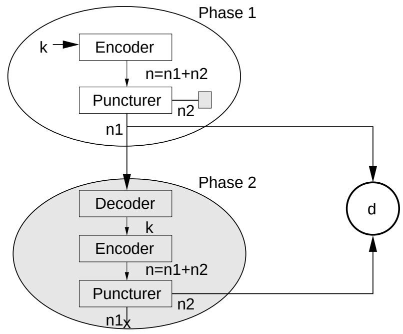


Fig. 3. Encoding/decoding functions and the resulting bits transmitted in both phases of coded cooperation. The functions, illustrated per phase, are performed by *each* cooperating user individually.

received in the first phase. The cooperative diversity scheme defines how relaying is performed in the second phase and how the partner's data is represented (Table I).

In reference [8] 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 helper 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 helper. After receiving the signal, both helpers 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. Here, the partner's data can be checked for errors, e.g., by using Cyclic Redundancy Check (CRC), prior to the relaying, and more powerful codes may be employed.

While the basic D&F approach [8] considers only the repetition of the regenerated data, Hunter et al. [9] proposed a scheme called Coded Cooperation (CC) which encodes the relayed data more efficiently. CC provides cooperative diversity by distributed Forward Error Correction (FEC) coding and considers the result of the error check for its relaying decision. A simple protocol avoids the retransmission of erroneous data without wasting resources. Furthermore, even with single antenna transmitters, CC can be combined with space-time coding [10]. By space-time coding the data of both users may be multiplexed to a single data stream simultaneously transmitted by both shared user antennas. Details of the CC protocol and space-time CC are discussed later in this section, a very informative tutorial on cooperative diversity schemes is provided in reference [11], and detailed analyses of the common approaches are presented in references [12, 13].

The Compress-and-Forward (C&F) cooperative relaying strategy was initially suggested in Theorem 6 of [2]. This scheme strikes a balance between the regenerative and non-regenerative methods. On the one hand, the received signal is only demodulated to digital symbols instead of being decoded to bits. On the other hand, these symbols are not directly repeated as a signal in phase 2. In order to reduce redundancy, the symbols are compressed and included in the relayed packet.

Cooperative coding enables to adjust the level of cooperation by controlling the amount of redundancy in both phases. This offers to optimize the transmission by adjusting the cooperation level and code rate. 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 user cooperation diversity gain dramatically. This adaptation and the relevant scenario factors are further discussed in Section III. In the following, we describe further details of the recent cooperative coding schemes CC, space-time CC and C&F.

1) Coded cooperation: This scheme enables cooperative diversity *only* by distributed FEC coding. Considering two cooperating users transmitting to a single destination, both users divide the transmission of a single packet in two phases. As illustrated in Figure 3 each user prepares the transmission by encoding a packet of length k bits to a block of $n = n_1 + n_2$ bits. This is performed by FEC coding using the overall coding rate $R = k/n$ with $R < 1$. From the coded block n_2 bits are removed according to the defined phase length and stored at the user.[1] This leaves n_1 bits that consist of the k data bits and redundancy, which leads to $k < n_1 < n$. As above, this can be expressed in terms of coding rate, i.e., $R_1 = k/n_1$ with $R < R_1 < 1$.

As illustrated, in the first phase each user sends its own n_1 bits. Due to the broadcast character of the wireless medium each user transmits its n_1 bits via the uplink channel to the destination as well as via the inter-user channel to the cooperating partner. From the bits received in the first phase each user decodes k data bits of the partner. If the decoded data is correct, determined by a CRC code, the user cooperates by restoring the n_2 removed bits of the partner. As shown in Figure 3, this can be done by re-encoding and puncturing the partner's data but this time saving the n_2 punctured bits. Finally, the n_2 restored partner bits are transmitted in the second phase, which provides diversity for the partner at the destination. Spatial diversity results from using the partner's antenna, and temporal diversity is provided if both phases transmitted during independently faded time intervals. The four resulting diversity branches, provided if both users fully

[1] Although in the original proposal [9] this is assumed to be done by puncturing with Rate-Compatible Punctured Convolutional (RCPC) codes [14], other methods and codes such as concatenation and block or turbo codes [10] can be used here as well.

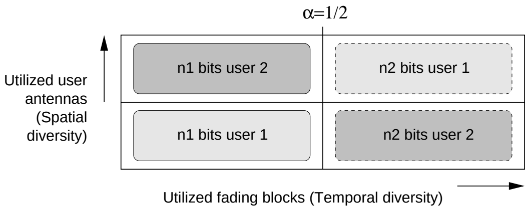


Fig. 4. The 4 diversity branches utilized in both phases of standard coded cooperation if two users fully cooperate.

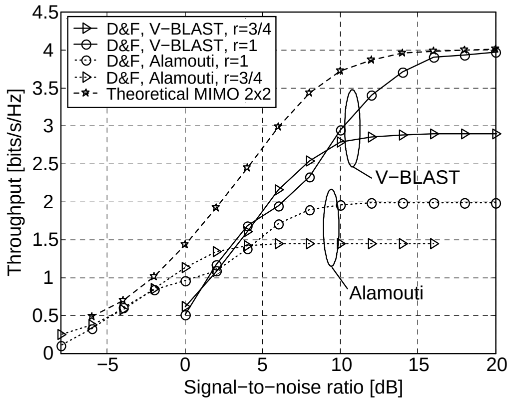


Fig. 5. Throughput for coded cooperation with RCPTC of rates 3/4 and 1, using V-BLAST and Alamouti space-time block codes. Source and relay terminals feature two antennas and the destination terminal has one antenna. Modulation is 4-QAM. (Results from [17])

cooperate, are illustrated in Figure 4.

However, full cooperation is not always possible. Due to transmission errors on the inter-user channel during the first phase, one or both user(s) may not be able to decode the partner's data. In these cases, either one or both user(s) transmit its/their own n_2 bits, which were removed and stored before the first phase. Although this does not lead to spatial diversity, it may provide temporal diversity for each user.

Coded cooperation enables controlling the level of cooperation by adjusting the amount of bits transmitted in the first phase. With coded cooperation the level of cooperation is defined as $\alpha = n_1/n$ [12]. If both users employ the same modulation scheme during the two phases, α also defines their duration. For example, with $\alpha = 1/2$ both phases are equally long (Figure 4). In Section III we will show how the performance of CC depends on adjusting the phase times by α.

2) Space-time coded cooperation: In order to get all the benefits of user cooperative diversity and space-time coding a combination of these methods is possible. The gains of virtual MIMO systems (the source and the assisting relay antennas form a distributed array) are achieved by a proper selection of distributed space-time codes [15]. When combined with FEC codes at the source and relay terminals, significant gains are observed [16]. In reference [17] results are obtained when the assisting relays transmit under the half-duplex constraint. In two orthogonal phases, the source transmits first to the destination and the relay, and afterwards the assisting relay transmits to the destination. This transmission mode offers an increase in virtual receiving antennas at the destination by multiplexing them to streams simultaneously transmitted on different orthogonal channels. In case the source and relay are equipped with 2 antennas, and the destination provides a single antenna, the equivalent channel behaves like a 2×2 MIMO system. However, transmitting two streams reduces the spectral efficiency to one-half of that experienced by an equivalent MIMO system. This reduction can be alleviated through efficient MAC strategies that either optimize the assignment of resources to every cooperative link [18] or force multiple cooperative users to reuse the relay slot [19].

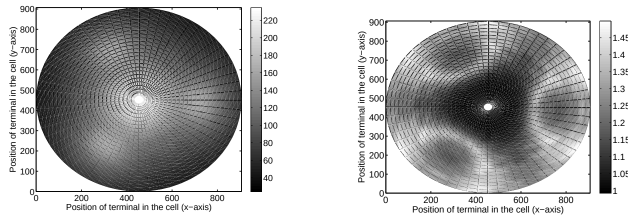
Combination of space-time block codes and FEC in an Automatic Repeat Request (ARQ) system, where erroneous packets are retransmitted, has been studied in reference [17]. Rate Compatible Punctured Turbo Codes (RCPTC) [20] have been considered along with different H-ARQ (hybrid automatic repeat request) techniques: Pure ARQ and code combining. In the last case, source and relay puncture codewords that relate to the same message differently in each retransmission. Moreover, two modes of operation are considered at the relay: *incremental transmission* (the relay only transmits if the packet at the destination is received with error) and *selective transmission* (the relay only transmits if it has correctly decoded the packet). Figure 5 presents the throughput obtained by a cooperating user and equal average SNR (signal-to-noise ratio) in the three links. 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. The source and the assisting relay are equipped with two antennas, while the destination only has one antenna. The throughput is compared with the direct transmission assuming that the destination has two antennas. Distributed versions of Alamouti and V-BLAST have been considered as space-time codes, which are used by both the source and the relay. In general, the source and the relay can use different columns of a given space-time coding matrix. RCPTC codes allow selecting the rate of the codeword in the first and subsequent transmissions, but the retransmission is based on code combining which adds redundancy each time a packet has to be retransmitted.

The main conclusion in reference [17] is 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.

3) Compress-and-Forward: In order to illustrate the behavior of a Compress-and-Forward (C&F) relay, let us assume Time Division Duplex (TDD) operation since half-duplex relays are easier to implement. Similar to A&F, the C&F relay quantizes the signal received during the source-transmit phase of the protocol. However, in the relay-transmit phase, it does not generate an analog replica of its observation. Instead, it compresses the digitized samples, encodes them into a new packet as if they were information bits, and forwards the packet to the destination. The latter decodes the packet, extracts the samples, and jointly processes them with those that it has observed during the first phase already. Thus, a virtual MIMO channel is created. The compression at the relay exploits the fact that the signals observed at the relay and destination during the first phase of the protocol are correlated, since they correspond to the same signal sent on two different noisy channels. The problem of source coding with side information at the destination was investigated by Wyner [21] who derived the rate-distortion trade-off in the scalar Gaussian case. Wyner's results were applied to C&F [22], deriving the compression rate/distortion trade-off, which maximizes mutual information (i.e., achievable rate). Because the durations of the first and second phase can be optimized, C&F outperforms A&F in many practical scenarios. Efficient practical implementation [23] and extension to vector channels [24, 25] are ongoing research topics.

C. Capacity evaluation of several relaying schemes

Rather than considering regenerative and non-regenerative relaying as competing techniques, it makes sense to design adaptive multi-mode cooperative relays that would select the best strategy, i.e., the one which maximizes the throughput under QoS constraints. Let us consider the example of a MIMO-OFDM cellular system operating in a 10 MHz bandwidth around 2.5 GHz. We benchmark various non-cooperative strategies (direct transmission and non-cooperative D&F) with cooperative regenerative relaying (here, space-time coded cooperation with perfectly uncorrelated signals at the source and relay) and non-regenerative cooperative relaying (here C&F). The Base Station (BS) is equipped with 3 sectors and 4 antenna elements per sector. A fixed cooperative Relay Station (RS) is deployed in each sector and operates in TDD. The RS has no azimuthal gain to ease deployment but is equipped with 4 antenna elements. Let us assume that the RS is located on lamp poles or roof tops, and benefits from Line-Of-Sight (LOS) propagation to the BS and consequently from a high SNR. The mobile terminals are assumed to be not in line-of-sight. Such NLOS situation is typical in urban and sub-urban environments. In Figure 6(a), the maximum downlink throughput (more precisely, the ergodic mutual information) is plotted as a function of the terminal location within the cell. In Figure 6(b), the cooperation gain is plotted. We define this gain as the throughput ratio of the best cooperative strategy to the best non-cooperative strategy. Also note that we assume that BS and RS transmit in dynamic TDMA slots whose duration is adapted to maximize throughput. As expected, it can be observed 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 regenerative relaying is efficient. As shown, cooperative regenerative relaying always outperforms all other techniques, but the gain is only significant (up to 40 %) in areas which are far away from the BS and RS. Note that this gain would be even higher if simultaneous transmission from the BS and RS were allowed. When looking at the uplink, the situation changes because now the most robust link is between the relay (RS) and destination (BS). Figure 7 depicts the ratio of throughput obtained with non-regenerative vs. regenerative cooperation schemes. The regenerative strategy,



(a) Throughput (b) Cooperation Gain

Fig. 6. Maximum throughput in downlink (left) and gain brought by cooperative relaying (right) in a typical cellular system

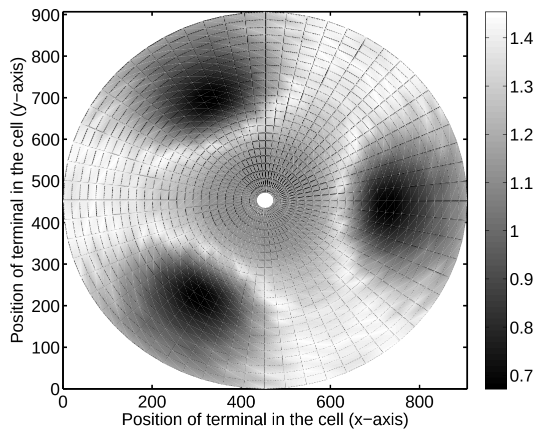


Fig. 7. Throughput gain of non-regenerative vs. regenerative cooperative relaying in the uplink of a typical cellular system

e.g. D&F, is optimal around the RS, i.e. when the source-to-relay link is good enough. However, non-regenerative C&F becomes optimal in other parts of the cell with gains up to 50 %. This highlights the need for implementing multi-mode relays with adaptive strategies in order to maximize capacity in both the downlink and uplink.

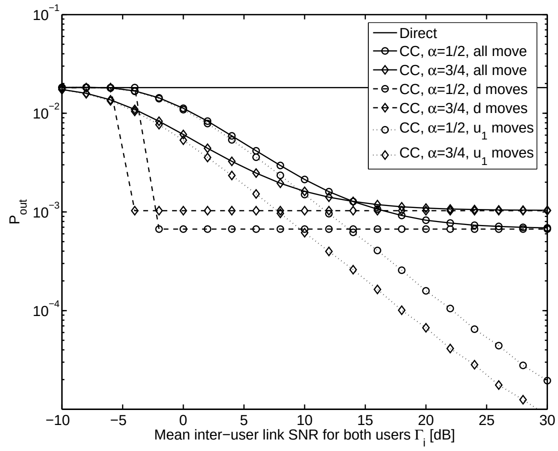
III. Optimizing cooperation – Resource allocation for cooperating users

With cooperative coding several codes and coding parameters may be used. Selecting the cooperation partner, the employed code, its overall rate, or its rate per phase according to scenario factors allows optimizing the performance gain due to cooperation. In this section we introduce factors which are relevant for cooperative diversity schemes, discuss optimization approaches, and show performance results for optimized cooperation schemes.

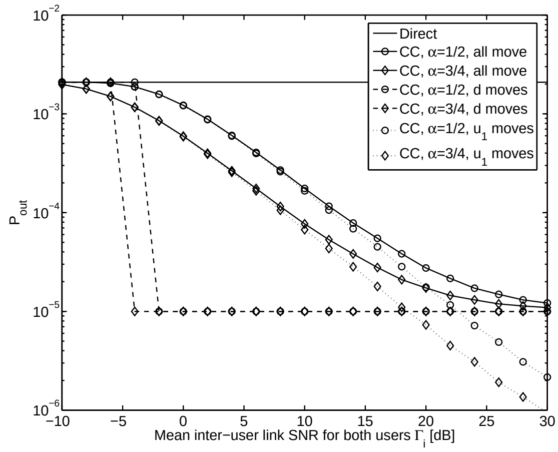
A. Scenario factors and decision metrics

The performance of cooperative 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 simplest scenario (Figure 2) only channel $(1, d)$ affects this transmission. With cooperative diversity the state of the inter-user channels $(1, 2)$ and $(2, 1)$ defines whether cooperation using *both* uplink channels is possible. Hence, even in this simple example, the performance of cooperative diversity depends on the states of the three additional channels $(1, 2)$, $(2, 1)$ and $(2, d)$. However, due to its frequent changes, in fading channels the instantaneous channel state cannot be directly considered as a decisive metric for selecting the appropriate cooperation scheme or parameters. We can classify the scenario factors on which the allocation decision is based as follows.

- *Channel-based allocation:* Factors introduced by the channel have an enormous effect on the performance of cooperative diversity schemes. As discussed in reference [26], high uplink channel correlation may degrade the performance, which is also affected by the fading distribution. However, these two factors cannot be determined easily.
  Another factor which highly affects the performance of the cooperative schemes is, naturally, the mean SNR of all related channels. This is illustrated in Figure 8, showing the simple two user scenario with three cases of user mobility and several cooperation levels α. In all these cases, a higher mean SNR on the inter-user channels increases the probability of cooperation. The probability that cooperation is successful is increased with rising uplink channel SNR. Since in most systems, the mean SNR of a channel can be measured easily, e.g. via the preamble of a Medium Access Control (MAC) frame, this provides an important metric for the optimization decision.
  A further important factor is the coherence time of the channel or, more precisely, its autocorrelation function. and parameterization. In most scenarios, the coherence time quickly decreases with rising relative speed between the transmitting and the receiving station. This effect is shown by the three mobility cases in Figure 8.
  For example, considering two cooperating users in the same moving train. Both users are relatively fixed to each other but move relative to the destination (case: “d moves”). As shown, in this case even a very low mean SNR is sufficient to decrease the outage probability for the overall transmission of both users to d. In contrast to the mean SNR, the motion speed of a user cannot be obtained easily. However, this information may be constructed from position or network topology information.
- *Position/topology-based allocation:* In reference [28] Lin et al. proposed a cooperation partner selection scheme based on geographical information. With known user locations, e.g. obtained via Global Positioning System (GPS), the distance can be considered for optimizing partner selection and/or cooperation level adjustment. This methods considers path loss which exponentially decreases the mean SNR with increasing distance.
  If the user locations are updated frequently even the user speed can be assumed to be known. Figure 9 shows how the mean SNR required to reach a helper relates to the speed. The faster the users move the better the helper needs to be reached to provide successful cooperation, i.e. to stay below a certain error bound. If both speed and mean inter-user SNR can be measured, this provides a guideline for selecting the cooperation partner. Furthermore, the cooperation level may be chosen in order to compensate for the degrading effect of the speed.



(a) Uplink channel SNR 10 dB



(b) Uplink channel SNR 20 dB

Fig. 8. Outage probabilities vs. mean inter-user SNR for the direct and coded cooperative (CC) transmission of two users u_1 and u_2 to the destination d. Shown for 2 different values of the mean uplink SNR (plot), 3 mobility scenarios (line style) and 2 cooperation levels α (marker type). Simulated for overall code rate $R = 1/4$ and mobile user speed $v = 10$ m/s. (Results from [27])

While one approach is the exact consideration of only one or a few factors, e.g., only the geographic positions of users may be considered, considering several factors may be more feasible. For example, in the scenario “moving train” users may only cooperate with relatively fixed helpers within the same train. This ensures high diversity gain which may be required to reach a base station outside of the moving train via the severely faded uplink channel. Another scenario occurs if the train stops or moves only slowly. In this case, the uplink channel quality may rise and even moving users with lower inter-user SNR may be considered as helpers.

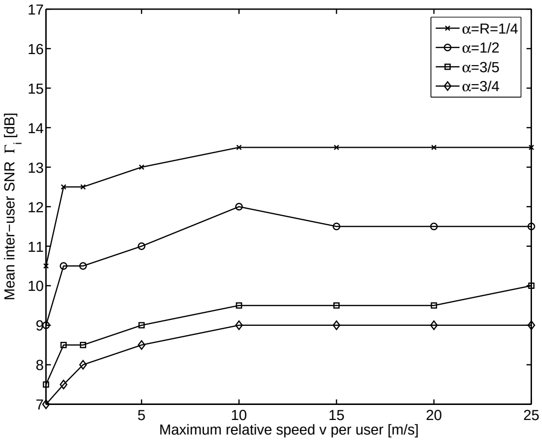


Fig. 9. Least mean SNR required to reach a helper to ensure an outage probability below 10^{-4} on the uplink. Shown vs. maximum relative speed btw. the cooperating users and several cooperation levels α. Simulated for 3 moving nodes, overall code rate $R = 1/4$, and uplink channel SNR 20 dB. (Results from [27])

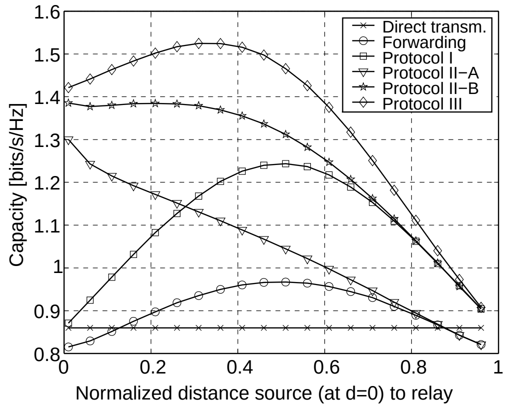


Fig. 10. Capacity of cooperative transmission for different orthogonal protocols optimized in terms of transmission time, as a function of the distance between the source and the relay terminals. The destination terminal is assumed to be placed at $d = 1$. All terminals have one antenna. The SNR between source and destination is 0 dB.

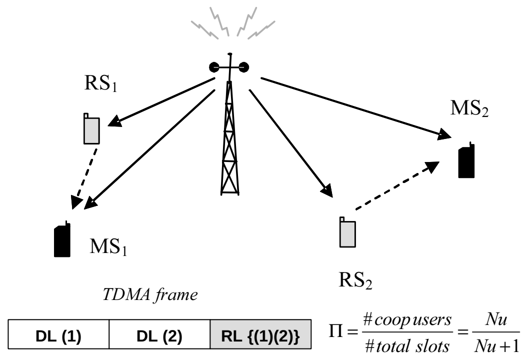


Fig. 11. Reuse of the relay slot for 2 cooperative users.

B. Optimization schemes and approaches

When the assisting relays work under the half-duplex constraint, different cooperative protocols are possible [29]. 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.

- *Optimization of resources:* References [18, 22, 30] provide optimization methods of the resources for some of the protocols described in reference [29] for single user transmissions. Figure 10 shows that the transmission rate can be enhanced with respect to direct transmission (or purely forwarding schemes) if the access time is properly balanced between the source and relay terminals. 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.
- *Reuse of resources:* A different approach to resource allocation is the reuse of transmissions in the relay slot. Let us consider a scheme where, in a first phase, the source transmits in orthogonal time slots to each destination and its associated relay. In the second phase, all assisting relays transmit to their associated destinations on a single and shared time slot. Assuming that there are K destination terminals to be served, time-orthogonal cooperative transmission needs $(1 + \frac{1}{K})$ time slots. Therefore, the efficiency of the cooperative transmission under TDMA is improved when K is high.
Interference is generated in the second phase due to the simultaneous transmission of all the relays, and some kind of power control may be required. Reference [19] shows that it is possible to obtain high reuse of the relay slot by maximizing the total cooperative mutual information through distributed control of the power transmitted by the relays based on game theory. Another possibility to deal with interference is to characterize its statistics and to control the outage generated by selecting the transmission rate. Reference [31] models the interfering power received when the terminals are uniformly distributed in the cell and the source randomly selects the terminals to be served without any priority. This way the interference patterns generated are homogeneous and completely random. Additionally, the averaged SNR in the relay-destination link is fixed to be the same for all served users. This application of cooperative transmission has shown significant gains in terms of throughput for the amplify-and-forward protocol, without centrally controlling the actual values of the interfering power.
Concerning multi-user cooperative transmissions, reference [30] studies resource optimization when multiple cooperating users want to transmit to the same destination (Figure 2). The allocation of the resources again 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, the problem of allocating resources to

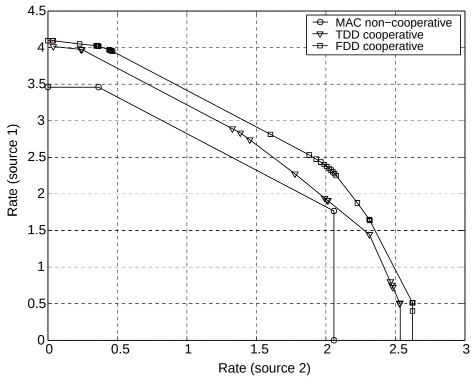


Fig. 12. Achievable rates for 2 cooperative users presented in Figure 2 (Results from [30])

multiple users may be shown to be a convex problem on a multi-access capacity region. Hence, there is an unique optimal solution which is simple to search. Note that the scheme in Figure 2 can be considered as a scheme where the resources in the second phase of the transmission protocol are being shared among various users and interference is dealt with a successive cancellation scheme [32]. In this respect, this scheme combines optimum resource allocation and spatial reuse of resources.

Figure 12 presents the achievable rate regions for two cooperating users with half-duplex assisting relays. The boundary of the capacity region is obtained by optimally selecting the fraction of resources for the different phases. Separation may be performed in time (TDD) or in frequency (FDD). The following configuration has been assumed: single antenna terminals, assisting relays with power limitation, and $\text{SNR}_{S-D,1} = 10\,\text{dB}$, $\text{SNR}_{S-R,1} = 15\,\text{dB}$, $\text{SNR}_{R-D,1} = 18\,\text{dB}$, for source 1, and $\text{SNR}_{S-D,2} = 5\,\text{dB}$, $\text{SNR}_{S-R,2} = 10\,\text{dB}$, $\text{SNR}_{R-D,2} = 10\,\text{dB}$, for source 2. 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.

IV. Cooperative networking – Towards feasibility

Based on the cooperative diversity schemes and optimization approaches discussed in Section II and III we now present two case studies. Section IV-A focuses on integrating user cooperative diversity schemes into WLANs and current amendments. In Section IV-B we extend our scope to multi-hop transmission by considering mesh networks. From these two case studies we derive open issues. In Section IV-C we present state-of-the-art approaches solving these issues. However, not all issues are solved in a way which allows cooperative diversity to be used in practice. These open issues are summarized in Section IV-D.

A. Case study: Cooperation in WLAN networks

Liu et al. proposed CoopMAC as an amendment to the 802.11 MAC protocol. CoopMAC applies the concept of cooperating relays to the 802.11 standard [33]. Every station maintains a list of possible helper stations as well as an estimate of the channel quality by overhearing ongoing transmissions. When a station has data to send, it picks a helper from its list and addresses the destination as well as the selected helper in the Request-to-Send (RTS) frame. The helper replies with a Helper-Ready-to-Send (HTS) frame if it participates in cooperation. The data frame is then transmitted to the destination via a two-hop path established by the relay instead of direct transmission.

CoopMAC merely exploits that the helper is selected such that both links have high transmission rates. CoopMAC considers cooperation only in the uplink direction and may similarly cooperate on the downlink. It does not employ cooperation in the sense of space and time diversity as coded cooperation offers. However, it already shows how the integration of cooperation into an existing WLAN standard impacts the MAC protocol design. Stations need to analyze ongoing transmissions to deduce channel quality and construct a list of helper stations. The estimated channel quality is a criterion to reduce the multi-user scenario to the well-known three-terminal case by selecting the station with the best channel quality as the relay. In the presence of many surrounding terminals, a cooperative MAC protocol must decide which terminals to cooperate with, i.e., select one or more partners. Such *partner selection* can either be centralized or decentralized. The estimated channel quality is a decentralized criterion that any station can deduce itself. A centralized approach has the potential to yield a better criterion but on the cost of additional signaling messages. The question is whether the benefit of a centralized criterion outweighs the associated signaling overhead. Therefore, suitable criteria for partner selection must be derived and analyzed both with and without centralized control.

A practical implementation of CoopMAC along with experimental results was carried out by Korakis et al. [34] Considering that modifications of the firmware of legacy devices are difficult or impossible, their implementation achieves backward compatibility to the 802.11 standard. Therefore, Korakis et al. describe the problems they had by implementing their CoopMAC extension in the 802.11 standard by modifying an open-source 802.11 device driver, and how they solved them. Up to our knowledge, cooperative diversity as a space-time diversity approach has not yet been implemented in WLAN scenarios.

B. Case study: Cooperation in wireless mesh networks

The IEEE Task Group TGs is working on a draft for multi-hop communications between 802.11 access points. The goal is to develop an Extended Service Set (ESS) *mesh* with a wireless distribution network that is based on 802.11 MAC and physical layers supporting broadcast, multi-cast and uni-cast delivery over self-configuring multi-hop topologies [35]. A Wireless Mesh Network (WMN) is a self-organizing and self-configuring ad hoc network consisting of mesh routers and mesh clients [36]. Mesh routers provide a wireless infrastructure. They are limited in mobility and dedicated to routing

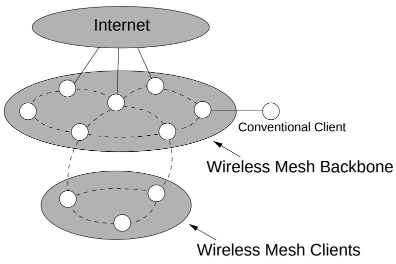


Fig. 13. Structure of a hybrid wireless mesh network

and configuration. Mesh routers may also provide gateway facilities in order to connect to other networks such as the Internet. Mesh clients typically connect to mesh routers but they also have routing abilities to form a link of several clients, although their hardware and software may be much simpler than that of mesh routers. Figure 13 illustrates a hybrid mesh network consisting of a wireless mesh infrastructure and a set of mesh clients.

The *wireless mesh backbone* consists of mesh routers with fixed locations and line-of-sight wireless links. For two mesh routers the attenuation of their wireless channel oscillates around a constant value, thus, large-scale fading is irrelevant. The fading conditions of the wireless links can be modeled by Rician fading. As a consequence, a mesh router will tend to cooperate with the same partners when channel state information is used as a criterion for cooperation. In contrast, the *wireless mesh clients* are mobile and may depart from an associated mesh router over time, thus, leading to an increase in attenuation. There may not exist a line-of-sight wireless link, so the fading conditions must be modeled by Rayleigh fading. The position of the clients with respect to each other is also subject to frequent changes, and so are their partners for cooperation.

Mesh scenarios require multi-hop communication as the destination may be out of the coverage area of the mesh router or client that wants to transmit data to it. Therefore, the selection of a partner for cooperation depends on the routing strategy that determines an intermediate station for the next hop. However, it would also be possible to let cooperation influence the routing strategy. *Cooperation-aware routing* might select an intermediate station such that there exists another station with suitable properties in terms of partnership. Figure 14 illustrates the principle of partner selection when routing is necessary. Out of a set of nodes that are reachable by S, a subset of nodes is selected according to a routing strategy. Then, this subset is reduced further to a pair $\{P_1, P_2\}$ that is optimal in terms of cooperation. We still need to specify what optimality means in this case. It should also be clear that the complexity of cooperation-aware routing cannot be arbitrarily large since routing decisions must take place online in a dynamic environment.

Although there exist several implementations of mesh networks, up to our knowledge none of these implementations consider *cooperative* diversity. Hence, the question of cooperation-aware routing might not have been raised before. Future research in cooperative mesh networks must analyze the impact of cooperation on routing and vice versa.

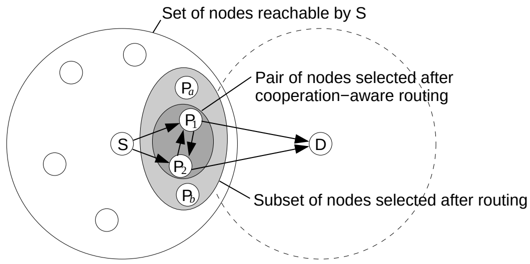


Fig. 14. Partner selection and routing in wireless mesh scenarios

TABLE II
OPEN ISSUES FOR IMPLEMENTING CODED COOPERATION

Issue	Priority	Required
Partner selection	high	Selection scheme, decision metrics
Rate adaptation	high	Many rates, allocation scheme
Routing	medium	Cooperation-aware scheme

C. State-of-the-art approaches to open problems

Table II summarizes the problems revealed by the above case studies for applying cooperation in an existing WLAN standard such as 802.11, and mesh networks. The following section reviews state-of-the-art literature that already yields promising approaches for the problems listed in Table II, and, if appropriate, it points out their deficiencies that prevent them from being deployed straight away. Note that the priorities in Table II are somewhat subjective but derived from current state-of-the-art.

1) Partner selection: Enhancing the simple relay channel to a multi-relay scenario as in Figure 15 raises two questions: Whom does the source cooperate with and how many partners does it need for cooperation? The latter question can be refined further: Is it sufficient to stick with one partner or would it be more beneficial to cooperate with two or even more?

Most analysis of cooperative diversity systems [12, 13] focuses on pairs of cooperating terminals only. However, in a multi-user scenario it is not a priori clear with whom a terminal is cooperating. In reference [37], Bletsas et al. consider it difficult to design a space-time-code that allows for an arbitrary number of partners and they identify this task as an open area of research. In the same paper, the authors propose a partner selection scheme in which only one terminal is selected. Allowing conventional coding schemes to still be used this selection scheme works as follows: Assuming that each potential partner can overhear the RTS/CTS sequence between source and destination indicating the start of a transmission,

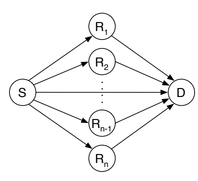
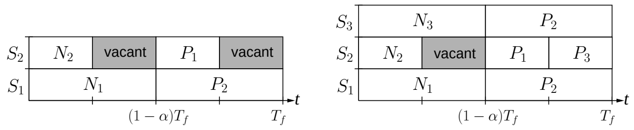


Fig. 15. Augmenting the simple relay channel with more relays



(a) The problem of rate adaptation (b) A triplet solution: Cooperating with two terminals

Fig. 16. Rate adaptation and coded cooperation

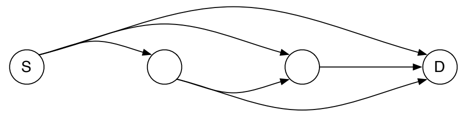


Fig. 17. Multi-hop node-to-node transmission

and further assuming that a potential partner can overhear all the others, all potential partners deduce the channel quality from the strength of the received RTS/CTS sequence and derive a timeout from it. The timeout serves as a back off in which the station with the earliest timeout becomes the cooperating partner. The back-off results in a decentralized scheme based on instantaneous channel measurements only. Bletsas shows that its achievable diversity is on the order of the number of cooperating terminals even though only one partner transmits [38]. Assuming that the potential partners may be hidden from each other, source and destination must announce the winner of the timeout period, therefore inducing additional signaling overhead.

Bletsas et al. proposed their partner selection scheme as an alternative to space-time-codes for multiple users. It simplifies the multi-user scenario by reducing it to the well-known three-terminal case with the instantaneous channel quality being the deciding factor. However, they do not consider the specifics of coded cooperation in which further criteria are relevant for partner selection. With coded cooperation it might be beneficial to cooperate with more than one partner due to varying channel qualities and varying levels of cooperation. The following section will make this point clearer.

2) Rate adaptation: The goal of rate adaptation is to maximize the throughput by dynamically allocating an appropriate transmission rate and transmit power that best suits the instantaneous channel quality. Popular rate adaptation algorithms for wireless networks are Automatic Rate Fallback (ARF) [39], Receiver-Based AutoRate (RBAR) [40], and variations thereof such as Adaptive Automatic Rate Fallback (AARF) [41]. Rate adaptation may be used in addition to a cooperative diversity scheme. However, in such a system cooperative systems introduce further channel states and rate constraints, e.g. for selecting the code rates of the cooperation phases according to the cooperation level α, which have to be considered by rate adaptation. Lin et al. have analyzed the throughput of coded cooperation in contrast to direct and multi-hop transmissions when rate adaptation is used [42]. Their analysis concludes that in order 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. Instead, the transmission rate must be chosen depending on the qualities of all channels.

Figure 16 illustrates the problem of rate adaptation within a coded cooperation framework. Supposing that one terminal is able to send with twice the data rate, the transmission obeys the scheme depicted in Figure 16(a). The capacity of station S_2's wireless channel is wasted since it is idle for half the time. However, these vacant slots yield the possibility to help out another terminal with its transmission. Suppose that another neighboring terminal 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 terminals and accommodate the parity bits of S_3 in its second vacant slot as depicted in Figure 16(b). As a consequence, a rate adaptive protocol for coded cooperation should select the number of cooperating partners in dependence of the rate used which in turn depends on the channel quality. Therefore, the overall transmission rate, which may in turn depend on the cooperation level α, is an important criterion for partner selection.

3) Multi-hop cooperation: How can multi-hop networks utilize cooperation to better transmit information? Zhang and Lok analyze a very simple decode-and-forward 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 [43]. Figure 17 illustrates this approach exemplarily for two intermediate nodes which overhear the transmission between S and D. Both of them adjust their power in order to reach D and retransmit the re-encoded data.

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 employ coded cooperation for multi-hop transmissions in their proposed framework *progressive network coding* [44]. Again, every intermediate node between source and destination combines all the signals received during previous hops to recover the initial information as depicted in Figure 17. It differs from Zhang and Lok's approach in that the intermediate stations re-encode the extracted information with a specific code to yield a unique set of parity bits. This way, the network code is strengthened with each hop by including new parity bits. For their practical experiments, Bao and Li focus on network coding, especially on a family of Low-Density Parity-Check (LDPC) codes [45]. However, the source still needs to transmit to the destination directly.

Del Coso et al. take a different approach to exploit cooperation in mesh networks [46]. They group several mesh nodes to clusters and apply the multi-hop transmission on a per-cluster basis. Virtual MIMO channels are created by letting all mesh nodes of a cluster transmit at the same time. Figure 18 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

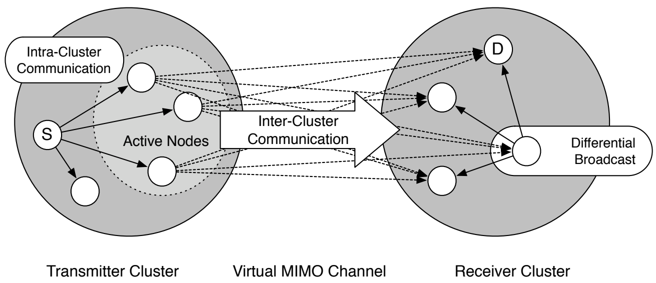


Fig. 18. Transmission between cooperating clusters

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. Since all nodes of the cluster possess some degraded copy of the information, the node with the highest SNR broadcasts the differential of mutual information required for the other nodes of the cluster to successfully decode the information, with the target node being among them (*differential broadcast*). 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.

Comparing to the previously mentioned cooperative multi-hop approaches shows the advantage of cluster communication mentioned previously. Since the source does not need to reach the destination directly it can send with less power. On the other hand this approach requires the management of clusters. The authors provide an analysis of outage probability of their transmission scheme as well as simulation results, but they leave the following questions open:

- Cluster assignment – Are clusters statically assigned, which may be feasible for mesh routers, or dynamically, which seems to be a must for mesh clients? What are the criteria for cluster assignment?
- Coded cooperation – Del Coso et al. used a simple decode-and-forward repetition coding strategy. What is the benefit of integrating coded cooperation into their scheme?
- Routing – How does the use of virtual MIMO channels and coded cooperation influence the routing of information?

The approach of Del Coso et al. offers cooperation benefits for communication in mesh networks, but the above questions need to be answered before their approach can be used in practice.

D. Open issues in implementing protocols for cooperative resource allocation

As discussed in Section II, cooperative diversity schemes provides substantial performance gain and may enable flexible resource allocation in practical systems. In order to integrate cooperative schemes to such a system the following problems need to be solved.

- *Partner selection* – Partner selection in coded cooperation must take the cooperation level α into account as well as the achievable rate. Stations with equal parameters would be ideal partners for cooperation. In this case, the problem of rate adaptation can be avoided in the first instance of an implementation. A first implementation should also consider one partner only as not to incur additional complexity. For multi-hop scenarios the routing strategy may impact partner selection. When coded cooperation is to be used in wireless mesh networks, two stations must be chosen for each hop instead of one.
- *Rate adaptation* – Even though channel adaptation can be a criteria for partner selection, adaptation can also be performed after a partner has been selected. The latter case is particularly interesting as it may reduce the complexity of finding a suitable partner, but it is more restrictive in terms of adaptation as it must cope with the chosen relationship.
- *Coding schemes* – Which coding schemes should be used for coded cooperation to yield best results? Multi-hop communications might perform better when a hop-dependent code is used.

While the cooperation level α provides a natural parameter which may be controlled for adaptation it is not sufficient to consider it alone. Therefore, future research must exhaustively investigate the effect of adjusting parameters which are specific for cooperative diversity systems. In the following section we will closer examine the topics of future work.

V. Conclusion and future work

In the previous sections we have introduced user cooperative diversity as a promising approach to increase transmission performance in wireless multi-user scenarios. We have provided a survey of cooperative diversity schemes which allow users to act as a multiple antenna system by sharing their antennas and time slots. The gain achieved by cooperative diversity depends on the appropriate selection of the scheme and its parameters according to the scenario factors. This selection can be optimized to increase the performance of the system. However, it is neither useful nor possible to consider all scenario factors and system parameters for optimization. Only scenario factors which are available at the corresponding node/layer and which can be observed at sufficient precision in given time are useful for optimization. For example, without GPS accurate node locations may not be available or the time required to characterize a channel's fading behavior by measurements may be not acceptable. In this case, a subset of scenario factors which is easier to obtain may be used for optimization, e.g. the number of neighbors or the mean SNR. We call this subset *observables*. A classification of the

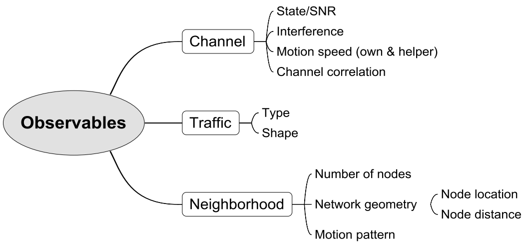


Fig. 19. Relevant observables which may be considered for optimizing cooperative diversity systems.

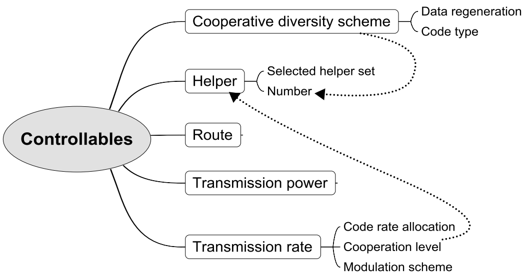


Fig. 20. Controllable parameters of cooperative diversity systems which may be optimized according to observables and optimization objective.

observables discussed in this paper is given in Figure 19. In this figure, only those observables that are relevant for cooperative diversity systems are shown, e.g. the number of neighboring nodes or the channel correlation. However, in some scenarios further factors such as battery state may also be considered. It is important to note that these observables can be correlated. For example, in dense networks the amount of neighbors *and* the interference may both be high.

Not all system parameters may be adjusted by the optimization scheme. For example, in many wireless sensor or cellular networks only one modulation scheme is available. The controllable subset of system parameters is called *controllables*. Figure 20 lists controllables which are specific for cooperative diversity systems, e.g. the selected partner or cooperation level. As illustrated by the arrows, adjusting one parameter may depend on or influence other parameters. For example, a number of helpers can only be selected if the cooperation scheme supports it. A further example was discussed in Section III, where the cooperation level defines which and how many helpers are available at a given SNR.

An optimization scheme uses the observables to select optimal values for the controllables (Figure 21) according to a given optimization objective and function. For example, the measured SNR to all neighbors can be used to select the cooperation partner in order to maximize the throughput for a single node transmitting a packet to the destination, or, under a different optimization objective, to minimize the latency for this transmission. Which objective is selected basically depends on the traffic flows, user scenario, and further factors, e.g. service-level agreements. The optimization function f_{Opt} may either be a generic or scenario-specific algorithm which provides optimal or, due to time constraints, approximative results. Hence, a complete optimization scheme consists of

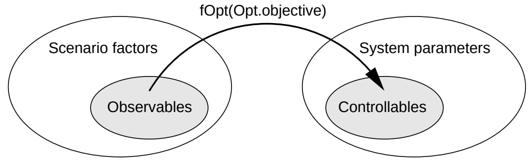


Fig. 21. The optimization function f_{Opt} maps observable scenario factors to controllable system parameters in order to reach a given optimization objective.

the functions *measure observables*, *solve optimization problem (f_{Opt})*, and *adjust system parameters*. All functions have to be performed within one optimization cycle.

To integrate cooperative diversity schemes into practical systems and to enable *cooperation-aware optimization* of transmission performance in user cooperative networks we point out the following future work:

- *Factor and parameter studies:* Further studies on the effect of scenario factors and system parameters specific to user cooperative systems are required. These studies should focus on observables and controllables which are available in practical scenarios/systems. Furthermore, the effects of time-scale, measurement accuracy, and correlation have to be evaluated in detail. Finally, these studies should provide suggestions for feasible observables, controllables, and the required accuracy and time-scale in practical scenarios.
  While for this evaluation abstract scenarios and metrics, as used in this paper, provide a good starting point, further results for practical scenarios and metrics are required, e.g. the mean decrease of the webpage 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 cooperative diversity schemes under real-world constraints.
- *Optimization schemes and allocation:* In addition to the plain integration of cooperative 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 adjust controllables in partner selection, rate, and cooperation level adaptation schemes. This requires functions for measuring observables, defining optimization objectives (e.g. by monitoring the traffic type), solving the optimization problem, and controlling system parameters. Depending on the scenario, all these functions may have to be solved under strict timing constraints. Further aspects, such as fairness and traffic-aware prioritization, have to be considered.
- *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. For efficiency it is not sufficient to remove redundancy from the transferred data. 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 on the node, which needs to be carefully synchronized. Finally, the optimization result is used for selecting the partner and cooperation parameters. Transferring this selection to the partner and synchronizing the cooperation timing requires further signaling which needs to be efficiently performed by protocols.

- *Standard integration:* In order to provide transparent usage of user cooperation schemes the above protocols have to be integrated into future mesh, WLAN, or cellular network standards. These standards or amendments should focus on the parameters of the PHY and the cooperation scheme, and on MAC/Data Link Control layer (DLC) protocols rather than defining details of solving optimization or cooperation problems. This ensures internode compatibility, while enabling the freedom for device manufacturers to choose the integrated optimization and cooperation algorithms.
- *Fairness and security:* How can we make sure that a user does not intentionally deteriorate other users' channel conditions, e.g. by causing interference, and offering them cooperation in order to accumulate rewards? How can users make observations about such malicious/selfish users and share the knowledge? "Reputation systems" [47–49] is another research area to tackle this problem in ad hoc networks and again, it becomes more crucial in user cooperative networks. Sharing channels by cooperation may enable "attacks" and malicious use of the network. Just like the security flaws discovered in early versions of IEEE 802.11 and the consequent enhancements of the protocol, implementations of user cooperation may show some design flaws. The earlier we can predict them, the faster and more reliable deployment will be.

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

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