Recent Advances in Amplify-and-Forward Two-Hop Relaying

Stefan Berger, Marc Kuhn, and Armin Wittneben, ETH Zurich
Timo Unger and Anja Klein, Technische Universität Darmstadt

ABSTRACT

In this article we review an important class of wireless cooperation protocols known as amplify-and-forward relaying. One or more low-complexity relay nodes assist the communication between sources and destinations without having to decode the signal. This makes AF relaying transparent to modulation and coding of the source/destination communication protocol. It is therefore a highly flexible technology that also qualifies for application in heterogeneous networks comprising many nodes of different complexity or even standards. Recently, two-way relaying was introduced, which is readily combined with AF relaying. It is a spectrally efficient protocol that allows for bidirectional communication between sources and destinations. In order to investigate the potential of wireless AF relaying, we introduce three distributed network scenarios that differ in the amount of cooperation between nodes. New challenges arise in those networks, and we discuss approaches to overcome them. For the most general case of a completely distributed system, we present coherent relaying solutions that offer a distributed spatial multiplexing gain even for single-antenna nodes. Based on real-world experiments, we validate the feasibility of all schemes in our laboratory.

INTRODUCTION

Future wireless communication systems will be built for cooperation rather than mere coexistence. Cooperative communication is a hot topic of current research, and many people believe it to be the next big step after multiple-input multiple-output (MIMO) systems. The basic idea is that multiple nodes cooperate in order to increase the link quality, reliability, and data rate of the system. In the future, the density of active nodes competing for a common wireless channel in cellular as well as access or ad hoc networks will increase significantly. Therefore, node cooperation is an efficient means of achieving these gains. An overview of several cooperative diversity protocols for wireless networks can be found, for example, in [1]. Either user nodes or dedicated terminals may assist the communication between sources and destinations. We refer to both types of assisting nodes as relays. In the literature they are classified as either *full-duplex* or *half-duplex*. Full-duplex relays can simultaneously transmit and receive, whereas half-duplex relays cannot. As an example, the nodes in full-duplex frequency-division duplex (FDD) systems transmit and receive signals at the same time but use different frequency channels.

In the following we focus on half-duplex relays. However, the relaying concepts discussed in this article can also be used in full-duplex FDD systems. The typical approach to orthogonalize channel resources in a half-duplex system is to use time-division duplex (TDD) where reception and transmission at the relay are orthogonalized by using two orthogonal time slots:

- Transmission from source to destination and relay
- Transmission from relay to destination

Hence, a bidirectional transmission between two nodes via a relay requires four time slots to exchange only two messages. To increase the spectral efficiency of such bidirectional communication, the authors in [2] proposed a scheme — known as *two-way relaying* — that reduces the number of time slots to two: In the first time slot both nodes transmit their messages simultaneously to the relay. In the second time slot the relay transmits a combined version of the received signals to both nodes. Since each node knows its own transmitted signal, it can subtract the back-propagated *self-interference* prior to decoding. In a full-duplex FDD system, the transmission from the nodes to the relay and from the relay back to the nodes would take place at the same time, but on different frequency channels.

The general relay channel of conventional one-way relaying was first investigated in [3]. One source transmits to one destination while a single relay assists. The capacity of the general relay channel is still not known. Moreover, there is not even a cooperation strategy known that works best for this general case. At least two different basic signal processing strategies are distinguished at the relay. The first strategy, known as decode-and forward (DF) protocol, involves decoding of the source transmission at the relay. The re-encoded and possibly compressed signal is then forwarded to the destination. In terms of sum rate, this protocol is close to optimal when the source-relay channel is excellent, which is practically the case when source and relay are physically close or when dedicated relays are placed intentionally in such a way that a good connection to the source is ensured.

For the second strategy — known as compress-and-forward (CF) or *quantize-and-forward* protocol — the relay does not decode the source signal, but uses its observations in a different way. The received signal is quantized (and possibly compressed) and then forwarded to the destination. This protocol is most efficient in cases where the source-relay and source-destination channels are of comparable quality, and the relay-destination link is good. In this situation the relay may not be able to decode the source signal, but nevertheless has an independent signal observation that can be used to assist the decoding at the destination. Finally, the amplify-and-forward (AF) protocol is a special case of the CF strategy where the signal processing at the relay is only linear. For a multi-antenna relay this means that each transmit antenna may forward a linear combination of the received signals of all receive antennas. In [4] the authors develop capacity scaling laws for such networks and propose protocols that achieve this capacity scaling in the limit for large numbers of relays.

In this article we focus on the use of the AF protocol for applications where the complexity of all involved nodes differs significantly. Based on three scenarios described later, we discuss the achievable gains as well as challenges arising for different signal processing schemes at the relays. Another section also contains results obtained by a real-world demonstrator that show the feasibility of AF relaying in all three scenarios. Finally, we conclude this article by naming open issues and giving an outlook on future research.

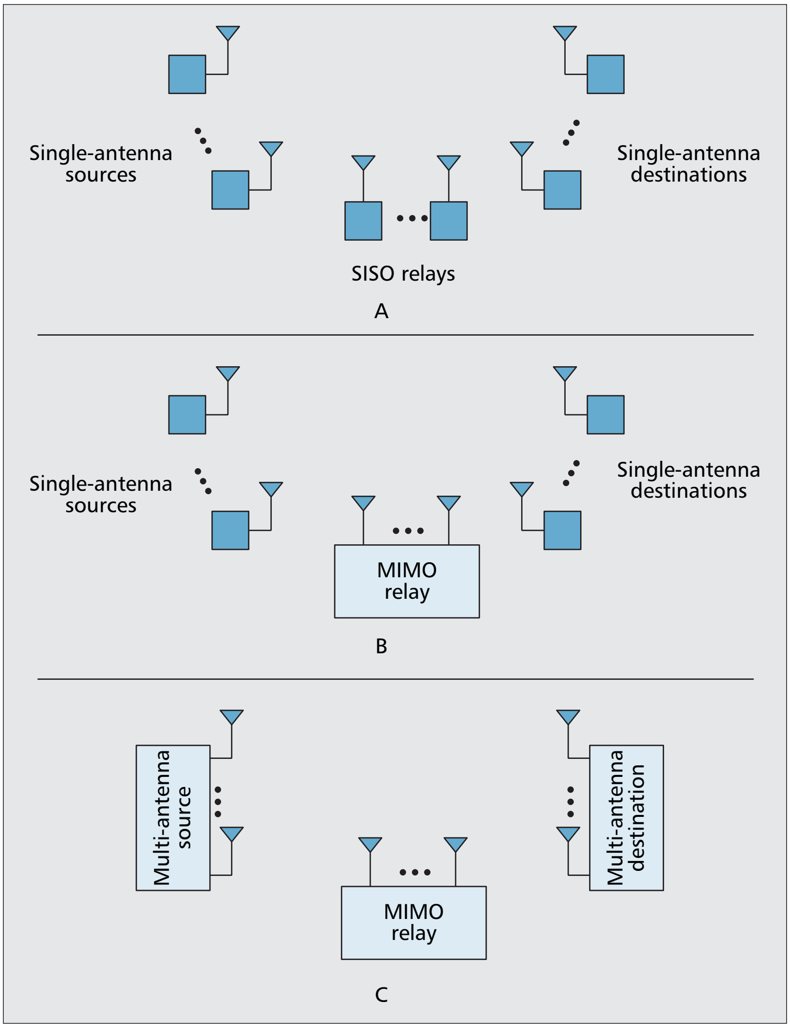

Figure 1. *Amplify-and-forward relaying scenarios with an amount of cooperation that increases from A to C: from distributed nodes and relays in scenario A to multi-antenna nodes and relays in scenario C.*

Scenarios and System Model

We investigate three scenarios, as depicted in Fig. 1, that differ in the complexity of the participating nodes. In scenario A we consider a distributed wireless network with single-antenna nodes and single-antenna AF relays. N sources and N destinations communicate with the help of M relays (multiuser relaying). Each source communicates with a single dedicated destination terminal, together forming a source/destination pair. A distributed spatial multiplexing gain can be achieved if the AF relay gains are chosen appropriately. This essentially allows multiple source/destination pairs to communicate concurrently over the same physical channel. Note that DF relaying is not applicable in this scenario because due to the strong multiuser interference, the single-antenna relays are not able to efficiently decode the data streams of all sources. In scenario B a single multi-antenna relay assists the communication between N single-antenna source/destination pairs. Because all relay antennas can fully cooperate, the number of available degrees of freedom increases compared to scenario A, and efficient precoding schemes can be implemented at the relay. A typical application could be a sensor network with one central node of high complexity. Finally, scenario C comprises one multi-antenna source/destination pair and a multi-antenna relay. This configuration could correspond to a single link in a cellular system with high-data-rate bidirectional communication.

With increasing cooperation between the relay antennas (scenario B) and between the source and destination antennas (scenario C), increasing performance gains are available. In this sense, scenario C constitutes an upper bound on the performance of scenario B. Note that for scenarios A and B, the extension to the case where some of the sources and destinations employ multiple antennas is straightforward.

Two-way relaying can basically be used in all three scenarios. In [5] it has been extended from a single-antenna configuration to the MIMO case for DF relaying, in [6] to MIMO AF relaying. Scenario C allows very efficient implementation of two-way relaying, because there is no interuser interference, and the self-interference can be completely subtracted from the data stream at both nodes. In contrast to that, the relay has to suppress $2N - 1$ interferers in scenarios A and B.

The mutual information is a measure of qual-

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ity for the communication link. For a single channel realization and source/destination pair, it is given by [7]

$$I = \frac{1}{2}\log_2 \det(\mathrm{I} + (\mathbf{R}_1 + \mathbf{R}_\mathrm{N})^{-1}\mathbf{R}_\mathrm{S}), \qquad (1)$$

where $\mathbf{R}_\mathrm{I}$, $\mathbf{R}_\mathrm{N}$, and $\mathbf{R}_\mathrm{S}$ are the covariance matrices of the interference (if present), noise, and signal 1 at the destination, respectively. The pre-log factor 1/2 comes from the fact that a two-hop transmission cycle is assumed to require two time slots of equal length. Averaging the mutual information over many channel realizations delivers the average rate.

Scenario A

In classical wireless multiple access scenarios, the amount of resources available for each individual user reduces with the number of terminals sharing the channel. Coherent multiuser relaying is a promising approach to break this paradigm by allowing multiple users to communicate concurrently on the same physical channel (distributed spatial multiplexing gain). Although we lose spectral efficiency by requiring two time slots for each transmission cycle, large gains are feasible for more than two source/destination pairs. The maximum achievable distributed spatial multiplexing gain, which enters the sum rate expression 1 as pre-log factor, lies in the order of the number of source/destination pairs. If the relay gain factors are chosen properly, this can even be realized with low-complexity single-antenna nodes.

Relay Gain Allocation

In [8, references therein] coherent gain allocation schemes that achieve a distributed spatial multiplexing gain are discussed. One approach to allow multiple users to access the channel simultaneously is to compute the relay gain factors such that the source/destination streams are completely orthogonalized in space (multiuser zero-forcing [MUZF] relaying). The complex baseband signals are scaled and rotated at the relays in such a way that interuser interference is suppressed completely. A necessary but not sufficient condition for this to be possible is $M > N(N - 1)$. Note that if we allow for relays with multiple antennas, significantly fewer relays are required. We refer to the case that $M = N(N - 1) + 1$ as minimum *relay configuration*. The gain vector is then (apart from a complex-valued scaling factor) uniquely determined. If the number of relays is larger than the minimum relay configuration, there is room for further optimization (e.g., to achieve additional diversity gain).

Another coherent gain allocation scheme that achieves a distributed spatial multiplexing gain is based on a minimum mean squared error (MMSE) criterion. This approach achieves even better performance than MUZF but requires additional knowledge of the noise covariance matrices in order to compute the relay gain factors. Furthermore, since a small amount of interuser interference is tolerated, no minimum number of relays is required. Performance instead degrades smoothly for decreasing M, which makes this scheme also suitable for smaller system configurations.

Major Challenges in Distributed Wireless Networks

Compared to classical point-to-point communications links, new challenges (e.g., distributed time synchronization) arise if multiple distributed nodes want to cooperate. However, since AF relaying is transparent to modulation and coding, the relays need only to be synchronized on a time slot — not a sample — basis. This is a great alleviation of a major demand. Furthermore, in order to coherently forward the signals, the relays require channel knowledge. For the gain allocation schemes described above (MUZF and MMSE relaying) they have to know the complete first-hop and second-hop channel matrix. This involves channel estimation and dissemination of the estimates between all relays so that the gain factors can be computed locally at the relays. Although this is a major effort, in low-mobility scenarios the gain largely outweighs the cost. Finally, it was widely believed that all relays require a global phase reference in order to be able to coherently forward the signal. We showed that this is not true if a basic principle is followed when the channels are estimated. Our results have been proven on a real-world demonstrator, where we successfully implemented the MUZF and MMSE gain allocation schemes [9].

Channel Estimation — In order to provide all relay nodes with knowledge of the first-hop and second-hop channels (we speak of "global channel state information"), a *channel estimation* and a *dissemination phase* are required. If the relays are not phase synchronous, it is important to estimate all channels in the same "direction." Consider a point-to-point communication situation where node A wants to transmit data to node B. The propagation channel between the two nodes can be estimated in two directions: either node A transmits a training sequence to node B that estimates the channel ("forward direction"), or B transmits the training sequence and the estimation is done by A ("backward direction"). Although the wireless propagation channel between the two nodes is reciprocal, the equivalent baseband channels are generally not if A and B are not phase-synchronous. This is because the transmission involves shifting the signal to and from passband. The current (random and unknown) local oscillator (LO) phases of the nodes enter the signal as a positive (shifting from baseband to passband) or negative (shifting from passband to baseband) phase rotation. Consequently, in order to obtain knowledge of the forward (backward) channel at node A (B), it has to be estimated at B (A) and fed back to A (B). Likewise, the first-hop and second-hop channel coefficients in the two-hop scenario have to be estimated all in forward direction (from sources to relays and from relays to destinations) or all in backward direction (from destinations to relays and relays to sources). The estimated product channels (i.e. the product of estimated first-hop and second-hop channel matrices) are then independent of the LO phase offsets of the relays. For MUZF and MMSE relaying this means that the computed gain factors are also independent of the LO phases.

Once the channel coefficients are estimated, they have to be disseminated to the relays. The number of required channel uses is $2NM$. In order to broadcast a channel coefficient, the respective node has to transmit the signal at a rate that all relays are able to decode. A short-range secondary system (e.g., Bluetooth or ultra-wideband (UWB)) could provide a very efficient means of exchanging the required channel state information (CSI).

LO Imperfections and Phase Noise — Another crucial issue that arises in distributed networks with multiple relays is LO accuracy. In contrast to point-to-point communication systems or single-relay networks (e.g., scenarios B and C), the unknown and random LO phases at the relay terminals pose a potential problem for networks where multiple relays want to coherently forward the signal at the same time. The individual relays' LO phase enters the signal in the mixer, where the received passband signal is shifted to baseband. Fortunately, this phase error is compensated if the signal is mixed to passband again *given that the LO phase has not changed in the meantime*. Thus, phase stability is a crucial point. In practical systems, LO phase noise introduces a random change of the LO phases during the time between reception and retransmission, thus destroying coherency between the relays. In general, the phase uncertainty increases with time (e.g., Wiener phase noise model, which is widely used in orthogonal frequency-division multiplexing [OFDM] literature). Therefore, the larger the time difference between reception and retransmission, the larger the potential phase error.

In practical systems the LO of each node also exhibits a frequency offset. Fortunately, the error introduced by a carrier frequency offset when mixing the signal to baseband at a relay is compensated for when mixing it to passband again.

Performance Evaluation and Demonstration

In this section we assess the performance gain of two-hop multiuser relaying in scenario A over a classic single-hop (point-to-point) reference scenario, where N single-antenna source/destination pairs communicate in a time-division duplexing (TDD) manner. In both cases the total transmit power for each transmission cycle (i.e., two time slots for the relaying case and N time slots for the point-to-point reference case) is the same. In the two-hop case, the sum transmit power of all sources is equal to the sum transmit power of all relays. For the Matlab simulation results, all channels are frequency-flat and subject to i.i.d. Rayleigh block fading of unit variance.

In the simulation results, the same transmit power is used for both the relaying and reference scenarios. The resulting average sum rates are then plotted vs. the receive signal-to-noise ratio (SNR) of the reference case (simply denoted SNR in Fig. 2). First, we show results of Monte Carlo simulations in MATLAB, where the simulation environment is perfectly defined. Then we prove that our findings regarding phase noise and channel estimation hold in practical systems by providing performance results of the real-world demonstrator.

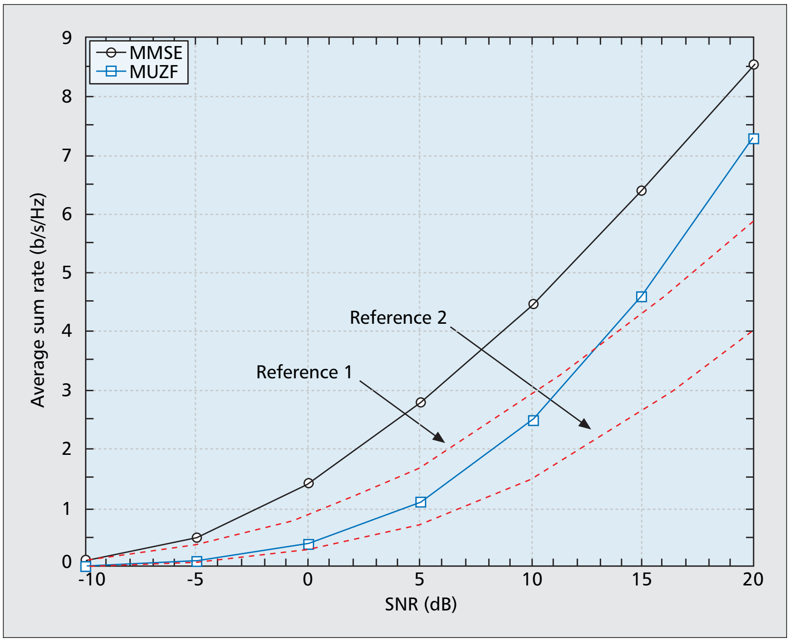


Figure 2. *Average sum rate versus SNR for 4 single-antenna source/destination pairs and 13 relays.*

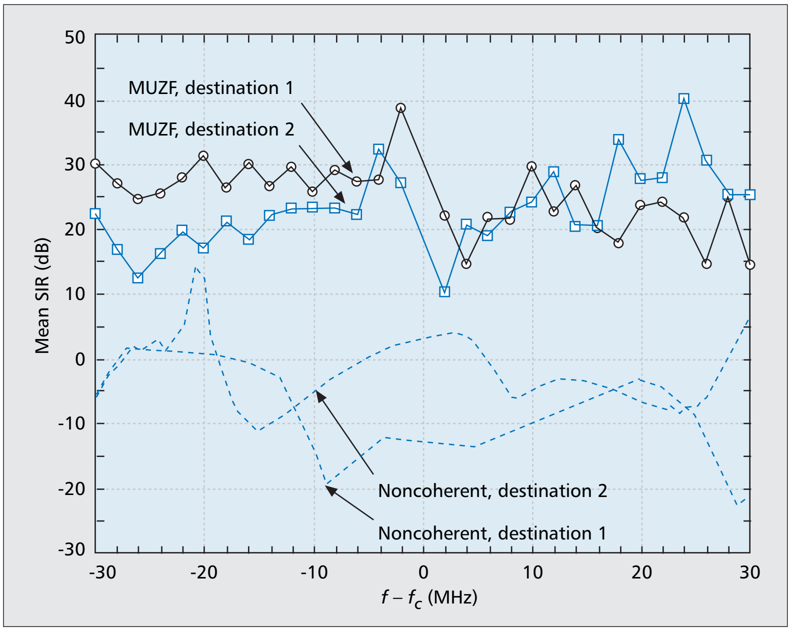
Simulation Results — We performed Monte Carlo simulations in Matlab, where all channel estimates are perfect and there is no phase noise. Two cases for the reference scenario are considered:

- All channel coefficients exhibit unit variance (denoted reference 1).
- The variance of the channel coefficients in the reference scenario is 1/4, while it is one for the first-hop and second-hop channel coefficients in the relaying case (reference 2). In an environment where the path loss is similar to free-space propagation, this corresponds to a situation where the relays are halfway between sources and destinations.

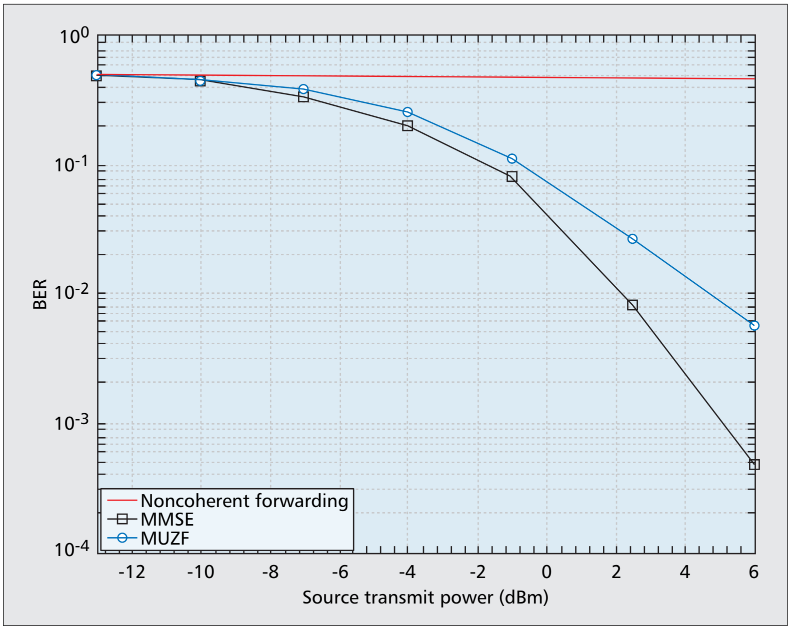
Figure 2 shows the average sum rate for MUZF and MMSE relaying as well as the two reference cases. Obviously, the relaying schemes are able to offer performance gains over the reference cases. MUZF and MMSE relaying will converge for high SNR and offer a distributed spatial multiplexing gain in the order of the number of source/destination pairs.

Measurement Results — A custom-built radio testbed called Radio Access with Cooperating Nodes (RACooN), which can be used to demonstrate multiuser relaying scenarios, is available at the Communications Technology Laboratory at ETH. Ten identical single-antenna nodes can each act as either source, relay, or destination node in a wireless network.

We set up a network comprising two source/destination pairs and three relays operating at a carrier frequency of f_c =5.5 GHz. This is the minimum relay configuration for MUZF. The propagation environment is a typical laboratory room of about 8 m × 4 m containing cupboards and tables with electronic equipment. In Fig. 3 we plot the average signal-to-interference ratio (SIR) at destination 1 for MUZF relaying and noncoherent forwarding (mere amplitude scaling at the relays). Compared to noncoherent forwarding, the ZF gain allocation is able to suppress the interference on average by about 20 dB in this system configuration. Correlation of the source-relay-destination channels has a large impact on the performance. The less correlated the channels, the better the gain allocation is able to suppress interference. The results prove that coherent multiuser relaying indeed works in the real world even if there is no LO phase reference at the relays.



■ **Figure 3.** *Measured mean SIR for MUZF relaying and noncoherent forwarding.*



■ **Figure 4.** *Bit error rate at destination 1 versus the transmit power of each source.*

Finally, we use OFDM to obtain frequency-flat subchannels and compute the gain factors for each of them. Bit error curves are then generated for a single subcarrier. In Fig. 4 we show the results at destination 1 for MUZF relaying, MMSE relaying, and noncoherent forwarding as reference. We see that with the coherent gain allocation schemes, communication between both source/destination pairs indeed becomes possible. Note that these experiments not only validate the feasibility of scenario A, but also of scenarios B and C because increasing the amount of cooperation among the nodes actually reduces the challenges.

SCENARIO B

Compared to scenario A, in scenario B it is much easier to provide the relay with global CSI because the antennas are collocated and the dissemination phase is thus not required. Furthermore, since a single LO reference is used for all relay antennas, phase noise does not destroy coherence. Finally, each relay transmit antenna may forward a linear combination of the received signals of all receive antennas. In the following we discuss how these simplifications can be exploited in one-way and two-way relaying.

In one-way relaying N sources share the physical channel, which means that $N - 1$ interferers are received at each destination. The gain allocation at the relay is required to suppress this interference because it cannot be canceled by the destinations themselves. However, there are additional degrees of freedom available for the gain allocation compared to scenario A because the relay antennas can cooperate. The number of required antennas is thus reduced significantly. In general, $M = N$ relay antennas are sufficient in order to separate the data streams of all N sources. The separation can be achieved by multiuser beamforming approaches at the relay (e.g., according to the ZF or MMSE criterion). This beamforming is a combination of receive beamforming in the first-hop multiple access channel and transmit beamforming in the second-hop broadcast channel.

In two-way relaying, $2N$ sources access the channel simultaneously. Since each destination can eliminate the self-interference coming from its own transmitted data stream, $2(N - 1)$ effective interferers are present. This essentially means that the gain allocation at the relay has to suppress about double the amount of interfering data streams as in one-way relaying. If the relay has at least $2N$ antennas, it can also suppress the self-interference at all destinations, allowing to sources and destinations of low complexity to be implemented. In this case multiuser beamforming approaches similar to the one-way relaying case can be applied [6].

SCENARIO C

With respect to channel estimation/dissemination and the impact of relay phase noise, scenario C behaves as scenario B. Since all source and destination antennas are also collocated, joint processing of their transmit and receive signals now becomes possible.

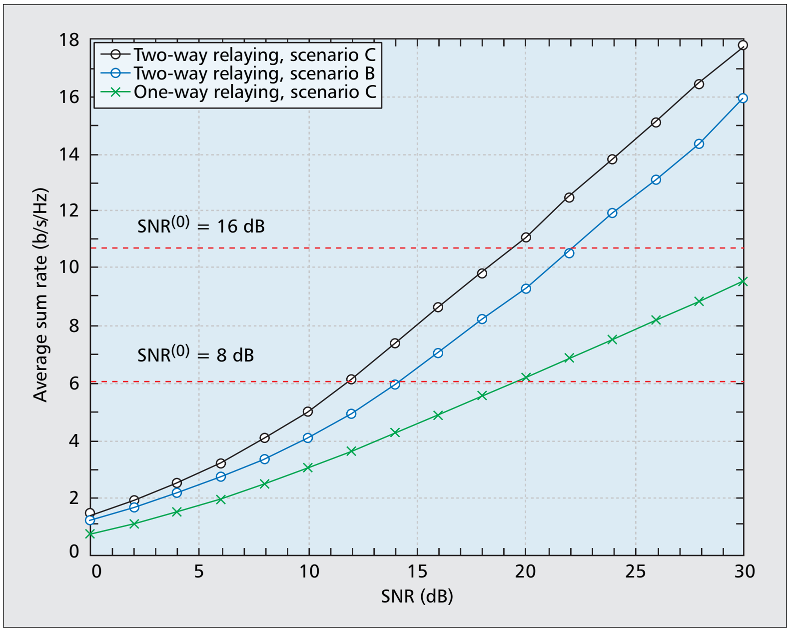
For one-way relaying, N data streams can be transmitted simultaneously if $M \geq N$. Since the destination node can apply joint decoding, there is no interference in scenario C. The relay antennas can then be used exclusively to maximize the desired figure of merit (e.g., sum rate). Note that for $M < N$ the rank of the equivalent two-hop channel collapses. In [10] the authors show how to maximize the instantaneous sum rate for one-way relaying in scenario C by beamforming at the relay. The spatial substreams can be separated by beamforming matched to the eigenmodes of the first-hop and second-hop channels. By appropriate pairing of the first- and second-hop subchannels, and using water filling to weight the subchannels, the instantaneous sum rate can be maximized.

In two-way relaying $2N$ data streams can be transmitted simultaneously if $M \geq 2N$. Since the self-interference can be completely suppressed at the destinations, the beamforming at the relay can be used exclusively to maximize the instantaneous sum rate as in one-way relaying. The relay cannot adapt simultaneously to the eigenmodes of both first-hop channels and both second-hop channels. However, it can adapt to the eigenmodes of the joint first-hop channel and joint second-hop channel, where the joint channels are concatenations of the two matrix channels between the nodes and the relay. With this adaptation, the number of optimization variables for the beamforming at the relay is always given by $(2N)^2$ even for the case $M > 2N$. Up to now, the beamformers at the relay are determined by numerical methods; analytical solutions achieving the maximum sum rate are subject to future research.

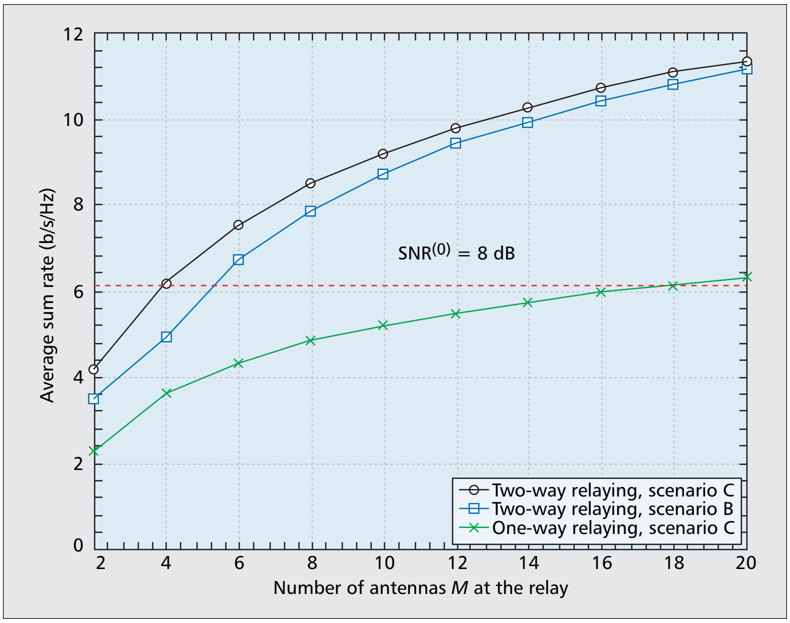
In this article a comparison of the sum rates of one-way and two-way relaying in scenarios B and C is presented. Figure 5 shows a comparison of the sum rates in one-way and two-way relaying for $M = 4$ and $N = 2$. The SNR is given by the ratio between the transmit power of each transmitter and the noise variance at the respective receiver. It is assumed that the SNR for the transmission from each source to the relay is the same as the SNR from the relay to each destination. Obviously, the two-way relaying scheme significantly outperforms the one-way relaying scheme due to the more efficient utilization of the available channel resources.

As a reference, the average sum rate of a point-to-point one-hop MIMO system with $N = 2$ antennas is depicted for $\mathrm{SNR}^{(0)} = 8$ dB and $\mathrm{SNR}^{(0)} = 16$ dB, where $\mathrm{SNR}^{(0)}$ is the SNR of the point-to-point link between source and destination. The plot shows that two-way relaying outperforms the reference case if the relay is placed such that the source/relay and relay/destination links exhibit an SNR of at least 12 dB and 19 dB, respectively.

Figure 6 finally shows the average sum rate vs. M for SNR = 12 dB and $N = 2$. Obviously, for $M = 4$ the spatial multiplexing gain is already fully exploited in two-way relaying. By increasing M, the array gain as well as the spatial diversity increase. The relative increase in average sum rate is the same for one-way and two-way relaying. For large M, the average sum rate of two-way relaying in scenario B converges to the sum rate of two-way relaying in scenario C because the interference in scenario B can be suppressed more efficiently by the relay if M increases.



■ **Figure 5.** *Average sum rate for one-way and two-way relaying,* M = *4 antennas at the relay,* N = *2 antennas at S1 and S2.*



■ **Figure 6.** *Average sum rate for one-way and two-way relaying, SNR = 12 dB,* N = *2 antennas at S1 and S2 average sum rate (b/s/Hz).*

Open Issues and Future Research

A lot of research is currently being done on the topic of wireless multiuser communications. AF relaying is a promising candidate technology for future wireless cooperative systems. Although some interesting and very promising results have been obtained, there are still many issues that have not received much attention yet. These are, *Efficient protocols for the dissemination of system coordination data or CSI using for example a secondary communication system like Bluetooth or UWB will be key issues for future cooperative communication systems.*

for example, two-way relaying schemes in the presence of multiple distributed relays or gain allocation schemes for broadband systems, the assignment of sources, relays, and destinations among a set of nodes, efficient strategies to cope with mobile nodes entering or leaving the system, or robust signal processing schemes taking system imperfections like noisy or outdated CSI, timing errors, phase noise, or hardware imperfections into account. Furthermore, efficient protocols for the dissemination of system coordination data or CSI, using, for example, a secondary communication system like Bluetooth or UWB, will be key issues for future cooperative communication systems. And finally, fundamental performance bounds of distributed communication protocols remain to be found.

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Biographies

STEFAN BERGER [M] (berger@nari.ee.ethz.ch) received his Dipl.-Ing. degree in electrical engineering from Munich University of Technology, Germany, in 2003. Since 2003 he has been working toward his Ph.D. degree in electrical engineering at the Communication Technology Laboratory (CTL), ETH Zurich, Switzerland. His research interests are in the field of distributed wireless ad hoc and sensor networks with special focus on cooperative wireless relaying.

MARC KUHN [M] (kuhn@nari.ee.ethz.ch) received his Diploma degree in electrical engineering and Dr.-Ing. degree frm Saarland University, Saarbrücken, Germany, in 1998 and 2002, respectively. Since 2002 he has been with CTL at ETH Zurich. His main research interests are in wireless communications, including space-time coding, MIMO communication, cooperative wireless communications, wireless relaying, and heterogeneous wireless access networks.

ARMIN WITTNEBEN [M] (wittneben@nari.ee.ethz.ch) received his M.S. and Ph.D. degrees in electrical engineering from the Technical University of Darmstadt, Germany, in 1983 and 1989, respectively. In 1989 he joined the central research unit, ASCOM Tech, of ASCOM Lt., Switzerland, as a postdoctoral researcher. In 1992 he became head of the Wireless Technology and Security Department. In 1996 he also served as co-director of ASCOM Tech. In 1997 he received the Venia Legendi (Habilitation) in communication technology from the Technical University of Darmstadt. in 1998 he accepted a position as full professor of telecommunication at Saarland University. Since 2002 he has been a full professor of wireless technology at ETH Zurich and is serving as head of CTL. His research interests include all aspects of wireless communication with special emphasis on communication theory, signal processing, cooperative wireless signaling and protocols, distributed MIMO systems, and ultra-wideband/ultra-low-power communication.

TIMO UNGER [S] (t.unger@nt.tu-darmstadt.de) received his Dipl.-Ing. degree in electrical engineering from the Technical University of Darmstadt in 2005. He is currently working toward his Ph.D. degree in elecrical engineering in the Communications Engineering Laboratory of the same university. His research interests include future mobile radio systems with focus on two-hop relaying and multiple antenna communications.

ANJA KLEIN [M] (a.klein@nt.tu-darmstadt.de) received her diploma and Dr.-Ing. degrees in electrical engineering from the University of Kaiserslautern, Germany, in 1991 and 1996, respectively. From 1991 to 1996 she was a member of staff with the Research Group for RF Communications at the university. In 1996 she joined Siemens AG, Mobile Networks Division, Munich and Berlin. She was active in the standardization of third-generation mobile radio in ETSI and 3GPP, for instance, leading the TDD group in RAN1 of 3GPP. She was a vice president, headinig a development department and a systems engineering department. In May 200 she joined Darmstadt University of Technology as a full professor, heading he Communications Engineering Laboratory. Her main research interests are in mobile radio, including multiple access, single- and multicarrier transmission schemes, multi-antenna systems, radio resource management, network planning and dimensioning, relaying, and cooperative communication. She has published over 150 refereed papers and has contributed to five books. She is an inventor and a co-inventor of more than 45 patents in he field of mobile radio. In 1999 she was inventor of the year at Siemens AG. She is a member of Verband Deutscher Electrotechniker-Inforationstechnische Gesellschaft (VDE-ITG).