Cooperative Communication in Wireless Networks

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ABSTRACT

Transmit diversity generally requires more than one antenna at the transmitter. However, many wireless devices are limited by size or hardware complexity to one antenna. Recently, a new class of methods called cooperative communication has been proposed that enables single-antenna mobiles in a multi-user environment to share their antennas and generate a virtual multiple-antenna transmitter that allows them to achieve transmit diversity. This article presents an overview of the developments in this burgeoning field.

INTRODUCTION

The advantages of multiple-input multiple-output (MIMO) systems have been widely acknowledged, to the extent that certain transmit diversity methods (i.e., Alamouti signaling) have been incorporated into wireless standards. Although transmit diversity is clearly advantageous on a cellular base station, it may not be practical for other scenarios. Specifically, due to size, cost, or hardware limitations, a wireless agent may not be able to support multiple transmit antennas. Examples include most handsets (size) or the nodes in a wireless sensor network (size, power).

This article presents a tutorial overview of a class of techniques known as *cooperative communication*, which allow single-antenna mobiles to reap some of the benefits of MIMO systems. The basic idea is that single-antenna mobiles in a multi-user scenario can "share" their antennas in a manner that creates a virtual MIMO system. Several important milestones in this area have been achieved, leading to a flurry of further research activity. It is our hope that this article will serve to illuminate the subject for a wider audience, and thus accelerate the pace of developments in this exciting technology.

The mobile wireless channel suffers from fading, meaning that the signal attenuation can vary significantly over the course of a given transmission. Transmitting independent copies of the signal generates *diversity* and can effectively combat the deleterious effects of fading. In particular, spatial diversity is generated by transmitting signals from different locations, thus allowing independently faded versions of the signal at the receiver. Cooperative communication generates this diversity in a new and interesting way.

For a preliminary explanation of the ideas behind cooperative communication, we refer the reader to Fig. 1. This figure shows two mobile agents communicating with the same destination. Each mobile has one antenna and cannot individually generate spatial diversity. However, it may be possible for one mobile to receive the other, in which case it can forward some version of "overheard" information along with its own data. Because the fading paths from two mobiles are statistically independent, this generates spatial diversity.

In the course of the development of cooperative communication, several complicating issues must be addressed, including the loss of rate to the cooperating mobile, overall interference in the network, cooperation assignment and handoff, fairness of the system, and transmit and receive requirement on the mobiles. Some of these issues are visited in this brief tutorial article. The interested reader is referred to the literature for a more comprehensive treatment.

In the figures we use icons resembling base stations or handsets, but this is only a convenient graphical representation. The idea of cooperation is general, and perhaps even more suitable to ad hoc wireless networks and wireless sensor networks than cellular networks.

COOPERATIVE COMMUNICATION

In cooperative wireless communication, we are concerned with a wireless network, of the cellular or ad hoc variety, where the wireless agents, which we call *users*, may increase their effective quality of service (measured at the physical layer by bit error rates, block error rates, or outage probability) via cooperation.

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In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user (Fig. 2).

Cooperation leads to interesting trade-offs in code rates and transmit power. In the case of power, one may argue on one hand that more power is needed because each user, when in cooperative mode, is transmitting for both users. On the other hand, the baseline transmit power for both users will be reduced because of diversity. In the face of this trade-off, one hopes for a net reduction of transmit power, given everything else being constant.

Similar questions arise for the rate of the system. In cooperative communication each user transmits both his/her own bits as well as some information for his/her partner; one might think this causes loss of rate in the system. However, the spectral efficiency of each user improves because, due to cooperation diversity the channel code rates can be increased. Again a trade-off is observed. The key question, whether cooperation is worth the incurred cost, has been answered positively by several studies, and is demonstrated by plots toward the end of this article.

One may also describe cooperation as a zero-sum game in terms of power and bandwidth of the mobiles in the network. The premise of cooperation is that certain (admittedly unconventional) allocation strategies for the power and bandwidth of mobiles lead to significant gains in system performance. In the cooperative allocation of resources, each mobile transmits for multiple mobiles.

Historical Background

The basic ideas behind cooperative communication can be traced back to the groundbreaking work of Cover and El Gamal on the information theoretic properties of the relay channel [1]. This work analyzed the capacity of the three-node network consisting of a source, a destination, and a relay. It was assumed that all nodes operate in the same band, so the system can be decomposed into a broadcast channel from the viewpoint of the source and a multiple access channel from the viewpoint of the destination (Fig. 3). Many ideas that appeared later in the cooperation literature were first exposited in [1].

However, in many respects the cooperative communication we consider is different from the relay channel. First, recent developments are motivated by the concept of diversity in a fading channel, while Cover and El Gamal mostly analyze capacity in an additive white Gaussian noise (AWGN) channel. Second, in the relay channel, the relay's sole purpose is to help the main channel, whereas in cooperation the total system resources are fixed, and users act both as information sources as well as relays. Therefore, although the historical importance of [1] is indisputable, recent work in cooperation has taken a somewhat different emphasis.

We now review several of the main cooperative signaling methods. A simplified demonstration and comparison of these methods appears in Fig. 4.

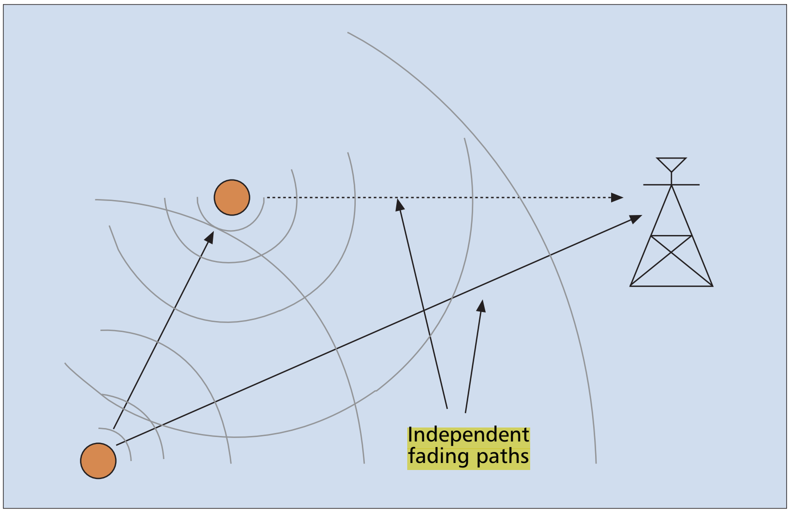

Figure 1. *Cooperative communication.*

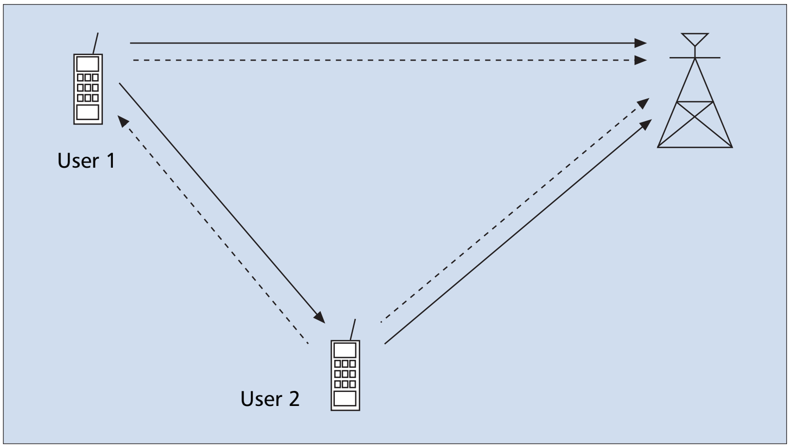

Figure 2. *In cooperative communication each mobile is both a user and a relay.*

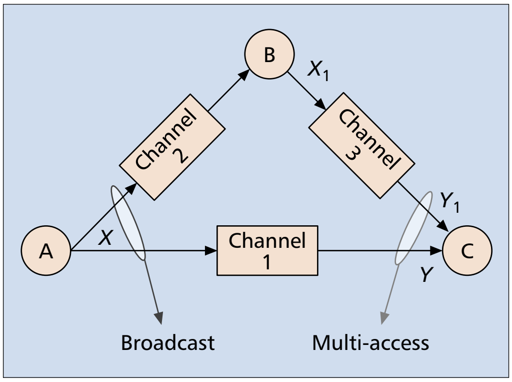

Figure 3. *The relay channel.*

Detect and Forward Methods

This method is perhaps closest to the idea of a traditional relay. In this method a user attempts to detect the partner's bits and then retransmits the detected bits (Fig. 4). The partners may be assigned mutually by the base station, or via some other technique. For the purposes of this tutorial we consider two users partnering with each other, but in reality the only important factor is that each user has a partner that provides a second (diversity) data path. The easiest way to visualize this is via pairs, but it is also possible to achieve the same effect via other partnership topologies that remove the strict constraint of pairing. Partner assignment is a rich topic whose details are beyond the scope of this introductory article.

An example of decode-and-forward signaling can be found in the work of Sendonaris *et al.* [2], which has inspired much of the recent activity in this area. This work presents analysis and a simple code-division multiple access (CDMA) implementation of decode-and-forward cooperative signaling. In this scheme, two users are paired to cooperate with each other. Each user has its own spreading code, denoted $c_1(t)$ and $c_2(t)$. The two user's data bits are denoted $b_i^{(n)}$ where $i = 1, 2$ are the user indices and n denotes the time index of information bits. Factors $a_{i,j}$ denote signal amplitudes, and hence represent power allocation to various parts of the signaling. Each signaling period consists of three bit intervals. Denoting the signal of user 1 $X_1(t)$ and the signal of user 2 $X_2(t)$,

$$X_1(t) = [a_{11}b_1^{(1)}c_1(t)\ , a_{12}b_1^{(2)}c_1(t)\ , \\ a_{13}b_1^{(2)}c_1(t) + a_{14}b_2^{(2)}c_2(t)]$$

$$X_2(t) = [a_{21}b_2^{(1)}c_2(t)\ , \\ a_{22}b_2^{(2)}c_2(t)\ a_{23}\hat{b}_1^{(2)}c_1(t) + a_{24}b_2^{(2)}c_2(t)]$$

In other words, in the first and second intervals, each user transmits its own bits. Each user then detects the other user's second bit (each user's estimate of the other's bit is denoted $\hat{b}_i$). In the third interval, both users transmit a *linear combination* of their own second bit and the partner's second bit, each multiplied by the appropriate spreading code. The transmit powers for the first, second, and third intervals are variable, and by optimizing the relative transmit powers according to the conditions of the uplink and interuser channels, this method provides adaptability to channel conditions.

The powers are allocated through the factors $a_{i,j}$ such that an average power constraint is maintained. Roughly speaking, whenever the interuser channel is favorable, more power will be allocated to cooperation, whereas whenever the interuser channel is not favorable, cooperation is reduced.

This signaling has the advantage of simplicity and adaptability to channel conditions. Several notes must be made in reference to this method. First, it is possible that detection by the partner is unsuccessful, in which case cooperation can be detrimental to the eventual detection of the bits at the base station. Also, the base station needs to know the error characteristics of the interuser channel for optimal decoding.

To avoid the problem of error propagation, Laneman *et al.* [3] proposed a hybrid decode-and-forward method where, at times when the fading channel has high instantaneous signal-to-noise ratio (SNR), users detect and forward their partners' data, but when the channel has low SNR, users revert to a noncooperative mode. This is not unlike the adaptability of coefficients $a_{i,j}$ provided by the method of Sendonaris *et al.*, and has been shown to perform very well.

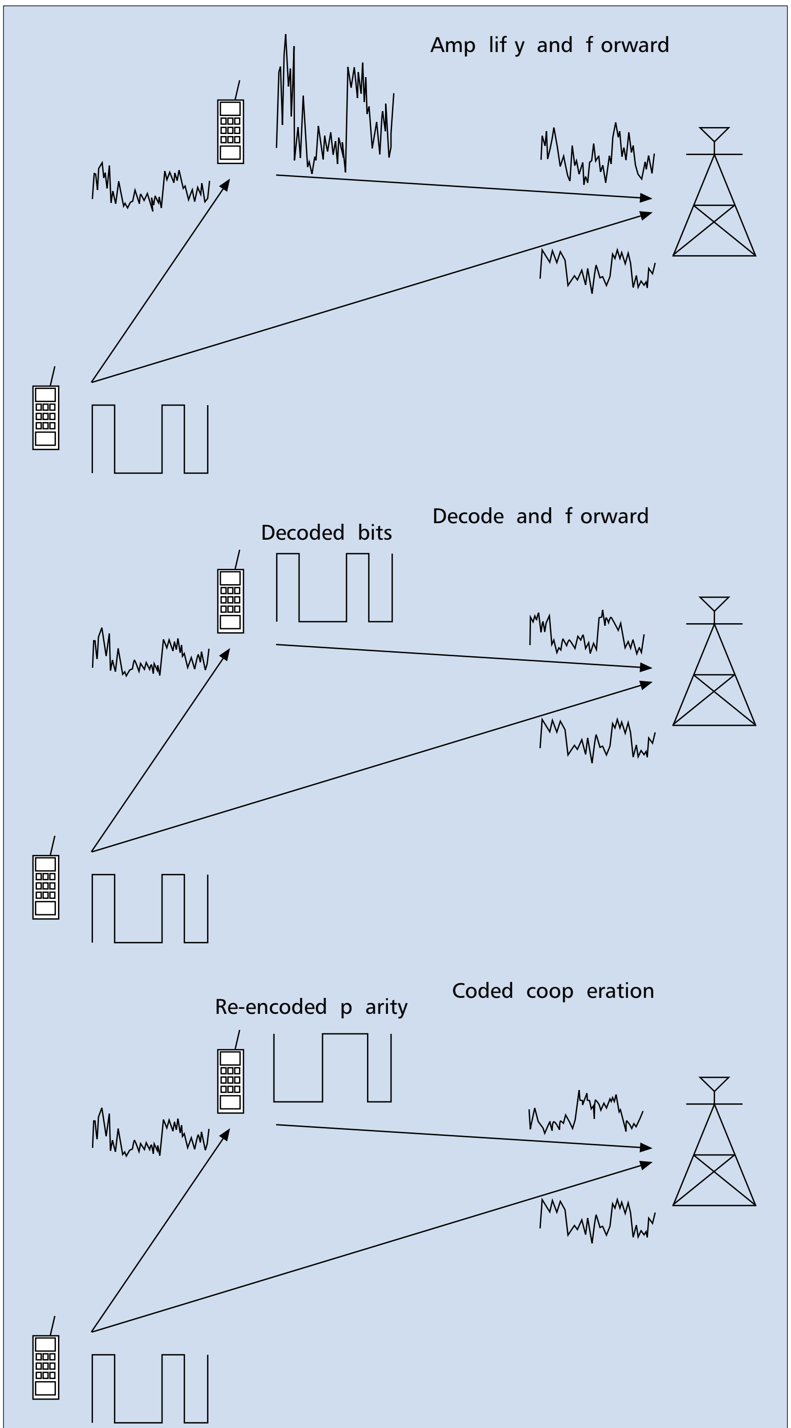

Figure 4. *Comparison of different cooperative methods. For clarity only one user's cooperation is shown via baseband equivalent signals.*

Amplify-and-Forward Methods

Another simple cooperative signaling is the amplify-and-forward method. Each user in this method receives a noisy version of the signal transmitted by its partner. As the name implies, the user then amplifies and retransmits this noisy version. The base station combines the information sent by the user and partner, and makes a final decision on the transmitted bit (Fig. 4). Although noise is amplified by cooperation, the base station receives two independently faded versions of the signal and can make better decisions on the detection of information.

This method was proposed and analyzed by Laneman *et al.* [3]. It has been shown that for the two-user case, this method achieves diversity order of two, which is the best possible outcome at high SNR.

In amplify-and-forward it is assumed that the base station knows the interuser channel coefficients to do optimal decoding, so some mechanism of exchanging or estimating this information must be incorporated into any implementation. Another potential challenge is that sampling, amplifying, and retransmitting analog values is technologically nontrivial. Nevertheless, amplify-and-forward is a simple method that lends itself to analysis, and thus has been very useful in furthering our understanding of cooperative communication systems.

Coded Cooperation

Coded cooperation [4, 5] is a method that integrates cooperation into channel coding. Coded cooperation works by sending different portions of each user's code word via two independent fading paths. The basic idea is that each user tries to transmit incremental redundancy to its partner. Whenever that is not possible, the users automatically revert to a noncooperative mode. The key to the efficiency of coded cooperation is that all this is managed automatically through code design, with no feedback between the users.

The users divide their source data into blocks that are augmented with cyclic redundancy check (CRC) code.[1] In coded cooperation, each of the users' data is encoded into a codeword that is partitioned into two segments, containing N_1 bits and N_2 bits, respectively. It is easier to envision the process by a specific example: consider that the original codeword has $N_1 + N_2$ bits; puncturing this codeword down to N_1 bits, we obtain the first partition, which itself is a valid (weaker) codeword. The remaining N_2 bits in this example are the puncture bits. Of course, partitioning is also possible via other means, but this example serves to give an idea of the intuition behind coded cooperation.

Likewise, the data transmission period for each user is divided into two time segments of N_1 and N_2 bit intervals, respectively. We call these time intervals *frames*. For the first frame, each user transmits a code word consisting of the N_1-bit code partition. Each user also attempts to decode the transmission of its partner. If this attempt is successful (determined by checking the CRC code), in the second frame the user calculates and transmits the second code partition *of its partner*, containing N_2 code bits. Otherwise, the user transmits its own second partition, again containing N_2 bits. Thus, each user always transmits a total of $N = N_1 + N_2$ bits per source block over the two frames. We define the level of cooperation as N_2/N, the percentage of the total bits for each source block

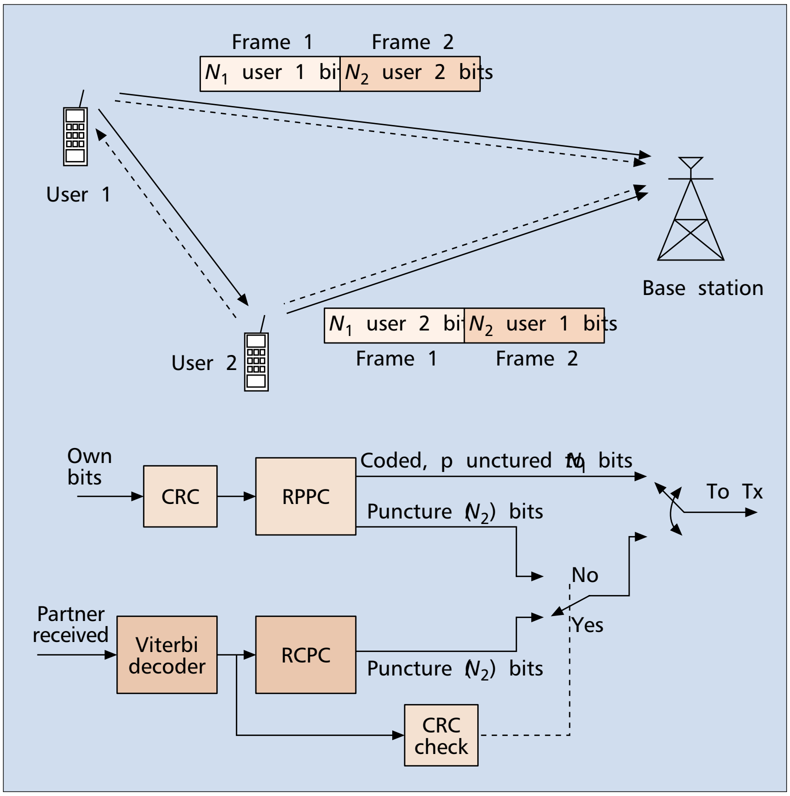

Figure 5. *Coded cooperation.*

the user transmits for its partner. Figure 5 illustrates the coded cooperation framework.

In general, various channel coding methods can be used within this coded cooperation framework. For example, the overall code may be a block or convolutional code, or a combination of both. The code bits for the two frames may be selected through puncturing, product codes, or other forms of concatenation. To obtain the performance results given in this article, we employ a simple but very effective implementation using rate-compatible punctured convolutional (RCPC) codes [6]. In this implementation the code word for the first frame is obtained by puncturing a code word of length N bits to obtain N_1 code bits. The additional code bits transmitted in the second frame are those punctured to form the first frame code word.

The users act independently in the second frame, with no knowledge of whether their own first frame was correctly decoded. As a result, there are four possible cooperative cases for the transmission of the second frame: both users cooperate, neither user cooperates, user 1 cooperates and user 2 does not, and vice versa. Analysis of the effects of these four cases is beyond the scope of this article, and we refer the reader to the literature for more comprehensive treatment. We only note that the performance curves shown in this article include all the effects of the interuser channel.

Performance

Figure 6 gives some examples of the performance of cooperative communication using the three classes of signaling described in the previ-

[1] We emphasize that since most current and future wireless systems already employ CRC codes, this does not represent additional overhead required by coded cooperation.

ous section. The hybrid version of detect-and-forward is superior to the simple version, so it is used in this comparative study. In these experiments binary phase shift keying (BPSK) modulation is used with coherent detection at the receiver.

For comparisons one must take note that, unlike amplify-and-forward and detect-and-forward methods, coded cooperation is inherently integrated into channel coding. In order to present equitable comparisons, we consider a coded baseline system with the same overall rate of 1/4 for all cases: noncooperative, amplify-and-forward, detect-and-forward, and coded cooperation.

For both hybrid decode-and-forward and amplify-and-forward, the users initially transmit a RCPC code word punctured to rate 1/2. This code word is subsequently repeated by the relay, resulting in an overall rate of 1/4 (rate 1/2 code, repeated).

For coded cooperation, a cooperation level of 25 percent is used. The two users transmit a code word punctured to rate 1/3 in the first frame. In the second frame, the relay transmits the bits punctured from the first frame such that the total bits received for each user form a rate 1/4 code word.

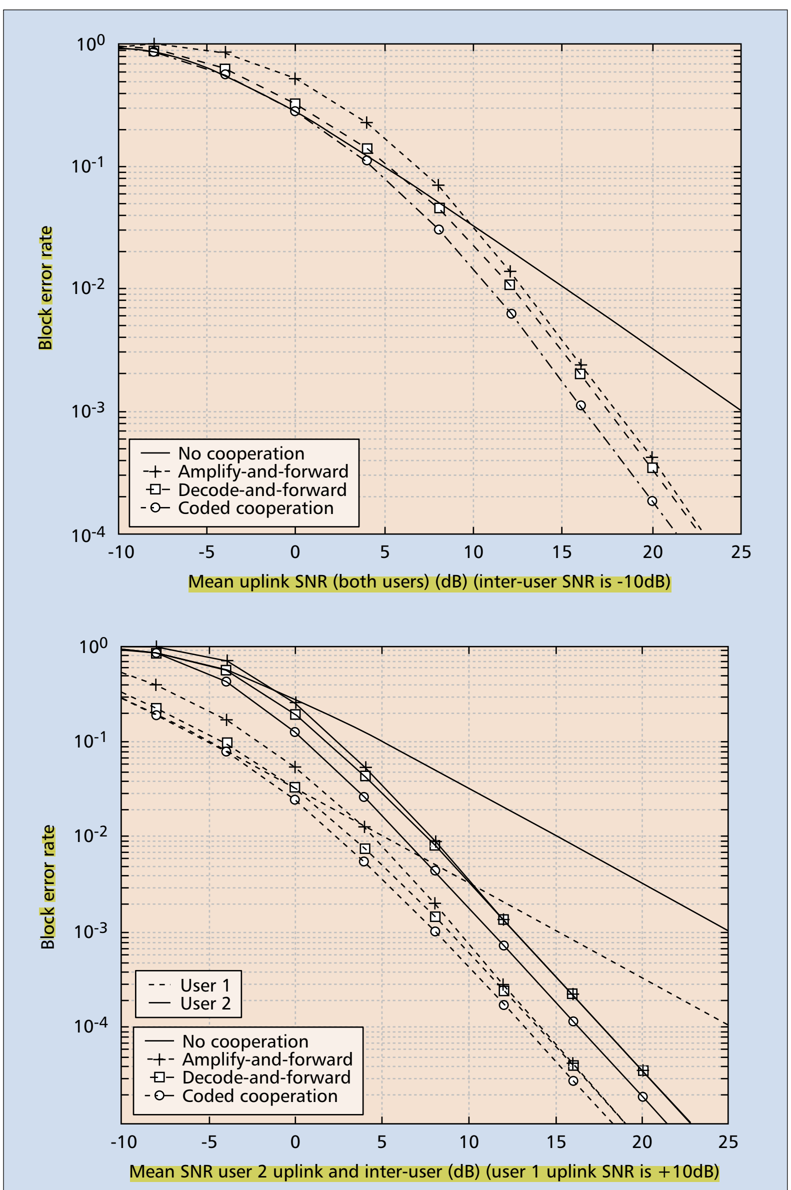

Figure 6. *Performance of various cooperative signaling methods.*

The first plot in Fig. 6 illustrates a case in which the user channels to the base station (uplink channels) have the same mean SNR, while the mean SNR of the interuser channel is 10 dB below that of the uplink channels, showing that diversity improves markedly over a comparable noncooperative system. The diversity, indicated by the slope of the block error rate vs. SNR curves at high SNR, is two for cooperation, which is equivalent to the diversity provided by standard two-antenna transmit or receive diversity schemes. This experiment also demonstrates the robustness of cooperative communication to the conditions of the interuser channel: cooperation provides substantial improvement in error rate performance even when the interuser channel quality is poorer than that of the uplink channels.

The second plot illustrates a case in which the mean uplink SNR for user 1 is 10 dB higher than that of user 2, while the interuser mean SNR is equal to that of the uplink channel for user 2. Two significant results of cooperation can be noted. First, user 2, as one might expect, improves significantly by cooperating with a user that has a better quality uplink channel. More interestingly, however, user 1 also improves significantly, despite cooperating with a user having a poorer quality uplink channel. This result illustrates that even a user with a good uplink channel has strong motivation to cooperate. Second, we note that the difference in performance between users 1 and 2 is significantly reduced by the cooperation methods. This shows that cooperation inherently reallocates the system resources in a more effective manner.

In comparing the three cooperative transmission schemes, we see that both amplify-and-forward and hybrid decode-and-forward are not very effective at low SNR. This is due to the fact that their signaling is equivalent to repetition coding, which is relatively inefficient at low SNR. Coded cooperation, however, has graceful degradation and performs better than or as well as a comparative noncooperative system at all SNRs. In addition, coded cooperation generally performs better than other cooperative methods for moderate to high SNR.

Multiple Access and Other Practical Issues

Cooperative communication, as described previously, assumes that the base station can separately receive the original and relayed transmissions. This is accomplished by transmitting the two parts orthogonally so that they can be separated. The most straightforward method is separation in time, that is, the user's data and relayed data are transmitted in nonoverlapping time intervals. In the example of Sendonaris *et al.* [2], orthogonality was achieved via spreading codes. In principle, it is also possible to achieve separation in frequency.

Separation of signals is closely related to the issue of hardware requirements on the mobiles. In cellular systems, even time-division multiple access (TDMA) ones, the uplink and downlink transmissions are performed on separate frequency bands. Ordinary mobiles receive only in the downlink band, but cooperative mobiles need to also receive in the uplink band, thus requiring additional input filters and frequency conversion. In ad hoc wireless networks where users may transmit and receive on the same frequency band, this is less of an issue.

Another technological issue is transmit and receive requirements on the mobiles. In TDMA systems this is generally not a problem, since the uplink transmissions by definition are nonoverlapping in time. However, in other multiple access systems, such as CDMA, the mobiles may be required to transmit and receive at the same time. Transmit signals can be up to 100 dB above the level of receive signals, which is beyond the isolation achievable by existing directional couplers. Two preliminary solutions to this problem come to mind. First, cooperating users may agree to "timeshare" their transmission, so between the two they will create a mini-TDMA scenario where each transmits for 50 percent of the time at twice the power. A second solution is arrived at by realizing that most CDMA systems are actually hybrid, with more than one frequency band allocated to the uplink channel. Then the base station may require that cooperating mobiles reside on separate bands.

It is also important to consider the knowledge required by the base station to handle cooperative communication. The amount of additional information varies for the various schemes introduced previously. In the simple detect-and-forward method, the base station needs to know the error probability of the interuser channel for optimal detection. In amplify-and-forward this is not required, since conventional channel estimation methods can be used to extract the necessary information from the direct and relayed signals. For coded cooperation, as well as the hybrid detect-and-forward scheme, no knowledge of the interuser channel is needed in the base station. However, since cooperation is conditional, the base station needs to know whether the users have cooperated or not. More precisely, the base station needs to know whose bits each user is transmitting in the second frame. A simple solution is that the base station simply decodes according to each of the possibilities in succession (based on their relative likelihood) until successful decoding results. This strategy maintains the overall system performance and rate at the cost of some added complexity at the base station.

One may ask what the tangible benefits of cooperation are at the network level. To answer this, we point to the multi-antenna technologies that motivated cooperation in the first place. Studies have shown that the diversity provided by MIMO space-time codes can improve performance at the medium access control (MAC), network, and transport layers. Since the net effect of cooperation in a microscattering environment, in terms of bit and packet error rates, is similar to that of space-time codes (both provide spatial diversity), one can use the same studies to conclude that cooperation can provide the same advantages as MIMO space-time codes in the higher layers. Cooperation also provides other advantages over and above space-time codes (e.g., resistance to large scale shadowing), but a discussion of such effects is beyond the scope of this introductory article.

Extensions and Continuing Work

While many key results for cooperative communication have already been obtained, there are many more issues that remain to be addressed.

An important question is how partners are assigned and managed in multi-user networks. In other words, how is it determined which users cooperate with each other, and how often are partners reassigned? Systems such as cellular, in which the users communicate with a central base station, offer the possibility of a centralized mechanism. Assuming that the base station has some knowledge of the all the channels between users, partners could be assigned to optimize a given performance criterion, such as the average block error rate for all users in the network. In contrast, systems such as ad hoc networks and sensor networks typically do not have any centralized control. Such systems therefore require a distributed cooperative protocol, in which users are able to independently decide with whom to cooperate at any given time. A related issue is the extension of the proposed cooperative methods to allow a user to have multiple partners. The challenge here is to develop a scheme that treats all users fairly, does not require significant additional system resources, and can be implemented feasibly in conjunction with the system's multiple access protocol. Laneman and Wornell [7] have done some initial work related to distributed partner assignment and multiple partners, and additional work by others is ongoing.

Another important issue is the development of power control mechanisms for cooperative transmission. Work thus far generally assumes that the users transmit with equal power. It may be possible to improve performance even further by varying transmit power for each user based on the instantaneous uplink and interuser channel conditions. Furthermore, power control is critical in CDMA-based systems to manage the near-far effect and minimize interference. Therefore, power control schemes that work effectively in the context of cooperative communications have great practical importance.

For the coded cooperation method, a natural issue is the possibility of designing a better coding scheme. In this tutorial article as well as [5], examples are given using RCPC codes, while in [8], turbo codes are applied to the coded cooperation framework. Both of these coding schemes were originally developed for noncooperative

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systems. An interesting open problem is the development of design criteria specifically for codes that optimize the performance of coded cooperation.

Among other interesting contributions to cooperative communication are space-time cooperative signaling [8, 9], as well as new work on the relay channel, including interesting adaptive scenarios [10]. There are also many other interesting developments; unfortunately, the scope and size of this article does not allow for a comprehensive survey of the rapidly expanding literature on cooperation.

In this tutorial article we focus on cooperation at the physical layer. There is work under the name *cooperation* in other layers [11], but the approach and methodologies are often different from the concepts presented here.

Conclusions

This tutorial describes wireless cooperative communication, a technique that allows single-antenna mobiles to share their antennas and thus enjoy some of the benefits of multiple-antenna systems. Several signaling schemes for cooperative communication are presented. Practical implications and requirements on system design are discussed, as well as extensions to the basic idea. Results to date are indicative of a promising future for cooperative communication.

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