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Cooperative Diversity for Mobile Users to Combat Fading

Jyoti Sawant, Leena Govekar and Y. M. Patil

Abstract-- **Mobile users' data rate and quality of service are limited by the fading problem. In fading, within the duration of any given call, mobile users experience severe variations in signal attenuation. Solution to this problem is the use of some type of spatial diversity. Spatial diversity generally requires more than one antenna at the transmitter. However, many wireless devices are limited by size or hardware complexity to one antenna. When mobiles cannot support multiple antennas due to size or other constraints, conventional space-time coding can not be used to provide uplink transmit diversity.**

In this paper, a new concept of cooperation diversity has been introduced; where mobiles achieve transmit diversity by relaying each other's messages. A particularly powerful variation of this principle is coded cooperation. Instead of a simple repetition relay, coded cooperation partitions the codeword of each mobile and transmits portions of each codeword through independent fading channels. Results show that, even though the inter-user channel is noisy, cooperation leads not only to an increase in capacity for both users but also to a more robust system, where users' achievable rates are less susceptible to channel variations.

Index Terms -- **Coded cooperation, Cooperation diversity, fading, inter-user channel, space-time coding.**

I. INTRODUCTION

We know that the transmit diversity improves the effective SNR of a fading wireless channel. In particular, this would require multiple antennas. However, in many cases, mobiles may not be able to support multiple antennas due to size or other constraints. In these cases, conventional space-time codes cannot be used. However, most wireless systems operate in a multi-user mode. Therefore, this paper presents a new idea of user cooperation; where mobiles share their antennas to achieve uplink transmit diversity. Fig. 1 shows the basic idea behind this concept.

Since each of the users sees an independent fading path to the base station, diversity is obtained by transmitting each user's data through both paths. In *coded cooperation* [1]–[3], symbols are not repeated by the partner. Instead, the codeword of each user is partitioned into two sets; one partition is transmitted by the user, and the other by the partner.

Cooperation between pair of wireless communication agents [4]-[5] achieves diversity by a signaling scheme that allows two single-antenna mobiles (users) to send their information using both of their antennas.

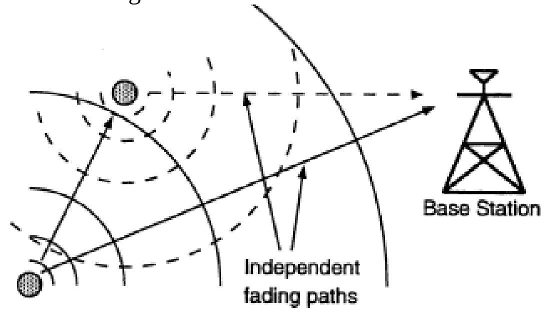

Fig. 1. Cooperation between mobiles

This paper presents a user cooperation methodology called *coded cooperation*, where cooperative signaling is integrated with channel coding [1]. The basic approach to the cooperation has been for a mobile to "listen" to a partner's transmission, and to retransmit it on orthogonal channels (e.g., TDMA, CDMA, or FDMA). Apart from the cellular system, user cooperation diversity has the potential to be successfully used in wireless ad hoc networks also.

II. OVERVIEW OF CODED COOPERATION

Coded cooperation [1],[6] 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 non-cooperative 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. In coded cooperation, each of the users' data is encoded into a codeword that is partitioned into two segments, containing $N1$ bits and $N2$ bits, respectively. Consider that the original codeword has $N1 + N2$ bits; puncturing this codeword down to $N1$ bits, we obtain the first partition, which itself is a valid (weaker) codeword. The remaining $N2$ bits in this example are the puncture bits. Of course, partitioning is also possible via other means.

The data transmission period for each user is divided into two time segments of $N1$ and $N2$ bit intervals,

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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.

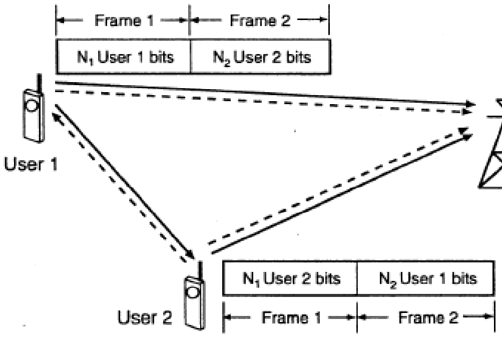

Fig. 2. Coded cooperation transmission scheme.

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 the user transmits for its partner. Figure 2 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[10], 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 in this paper, we employ a simple but very effective rate-compatible punctured convolutional (RCPC) codes [7]. 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.

In coded cooperation, each user always transmits a total of N bits per source block over the two frames, and the users only transmit in their own multiple access channels. We define the level of cooperation as N2/N, which is the percentage of the total bits per each source block that the user transmits for his partner. Fig. 3 illustrates the operation of the scheme. In addition, half-duplex operation for mobiles is usually necessary, which is possible by assigning orthogonal channels to users [8].

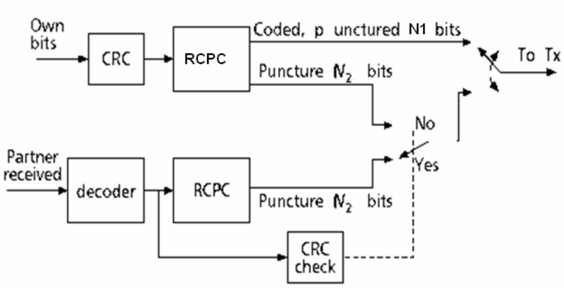

Fig.3. Coded cooperation.

III. PROBLEM SETUP

Our system model consists of two users both transmitting to a single destination. The channels between users (inter-user channels) and from each user to the destination (uplink channels) are mutually independent and subject to flat Rayleigh fading. The receivers have channel state information, but the transmitters do not. The basic premise in this paper is that both users have information of their own to send, denoted by for W_i for i = 1,2 and would like to cooperate in order to send this information to the receiver at the highest rate possible. To distinguish this main/final receiver from the receiving units of the mobiles, we will refer to it as the BS. The channel model we use is depicted in Fig. 4.

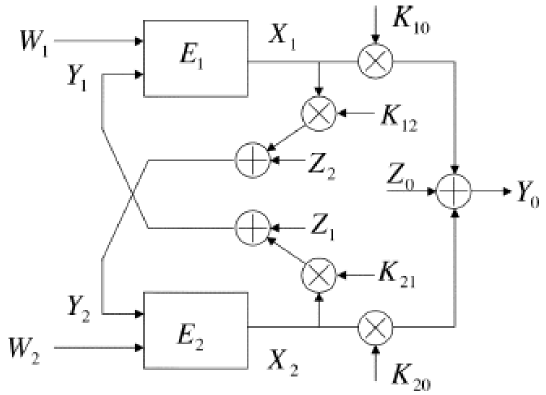

Fig. 4. Channel model.

Each mobile receives an attenuated and noisy version of the partner’s transmitted signal and uses that, in conjunction with its own data, to construct the transmit signal. The BS receives a noisy version of the sum of the attenuated signals of both users. The mathematical formulation of our model in discrete time is –

$$Y_0 = K_{10}X_1 + K_{20}X_2 + Z_0 \quad \text{...(1)}$$

$$Y_1 = K_{21}X_2 + Z_1 \quad \text{...(2)}$$

$$Y_2 = K_{12}X_1 + Z_2 \quad \text{...(3)}$$

Here Y_0,Y_1,Y_2 are the baseband models of the received signals at the BS, user 1, and user 2, respectively, during one symbol period. Also, Xi is the signal transmitted by user, for i = 1, 2, and Zi are the additive channel noise terms at the BS, user 1, and user 2, for i = 0, 1, 2, respectively.

The fading coefficients, Kij remain constant over at least one symbol period.

Our model assumes that transmitted and received signals are isolated. Here to isolate the transmitted signal from the received one, it may be necessary to use two separate channels, two colocated antennas, or some other means. For example, the CDMA implementations of this paper make use of spreading codes to create two separate channels.

Our model further assumes the following: the transmitted signals Xi have an average power of Pi for i =1,2, the noise terms Zi are white zero-mean complex Gaussian random processes with spectral height Ni/2 for i = 0, 1, 2; and the fading coefficients Kij are zero-mean complex Gaussian random variables. We also assume that the BS can track the variations in K_{10} and K_{20}, user 1 can track K_{21}, and user 2 can track K_{12}. All the decoding is done with the knowledge of the fading parameters [9]. Due to the reciprocity of the channel, we assume that $K_{21}$and K_{12} is equal.

Given the above model, the problem lies in finding the best strategy for both users to construct their transmit signals, given their own data and the received signal from their partner, and for the BS to employ the optimal reception scheme so that both users are able to maximize their data rates toward the BS.

We assume mobile 1 divides its information W_1 into two parts: W_{10}, to be sent directly to the BS, and, W_{12} to be sent to the BS via mobile 2. Mobile 1 then structures it's transmit signal so that it is able to send the above information as well as some additional cooperative information to the BS. This is shown in equation 4 –

$$X_1 = X_{10} + X_{12} + U_1 \quad \text{...(4)}$$

and divides its total power accordingly as shown in equation 5 -

$$P_1 = P_{10} + P_{12} + P_{U1} \quad \text{...(5)}$$

Here U_1 refers to the part of the signal that carries cooperative information. Thus X_{10}, is allocated power P_{10} and is used for sending W_{10} at rate R_{10} directly to the BS. X_{12} is allocated power P_{12} and is used for sending W_{12} to user 2 at rate R_{12}. U_1 is allocated power P_{U1} and is used for sending cooperative information to the BS. The transmission rate of W_{12}, i.e., R_{12}, and the power P_{12} should be such that W_{12} can be perfectly decoded by mobile 2. This perfect reconstruction at the partner forms the basis for cooperation. Similarly mobile 2 structures it's transmit signal X_2 and divides its total power P_2 in a similar fashion.

An achievable rate region for the system given in equation (11)–(14) is the closure of the convex hull of all rate pairs (R_1, R2) such that $R_1 = R_{10} + R_{12}$ and $R_2 = R_{20} + R_{21}$ with some power assignment satisfying $P_1 = P_{10} + P_{12} + P_{U1}$ and $P_2 = P_{20} + P_{21} + P_{U2}$.

IV. CDMA IMPLEMENTATION

We now turn our attention to some possible implementations of the user cooperation concept, under some practical wireless system framework such as CDMA. Other frameworks, such as frequency-division multiple access (FDMA) and time-division multiple access (TDMA), may be equally suitable; each of course, with its own unique advantages and challenges.

We know that throughput is defined as the number of successfully received bits/symbol after error correction and is a decreasing function of the probability of error. The functional relationship between throughput and probability of error depends on the modulation and error-correction scheme employed.

Consider a CDMA system in which each user has one spreading code, and modulates one bit onto it. Let L = 3 are the symbol period. Assume that the users' codes are orthogonal; all the fading parameters remain approximately unchanged for L periods.

In absence of cooperation, the users would transmit signals shown in equation 6 –

$$\begin{aligned} X_1(t) &= a_1 b_1^{(1)} c_1(t),\ a_1 b_1^{(2)} c_1(t),\ a_1 b_1^{(3)} c_1(t) \\ X_2(t) &= a_2 b_2^{(1)} c_2(t),\ a_2 b_2^{(2)} c_2(t),\ a_2 b_2^{(3)} c_2(t) \end{aligned} \quad \text{...(6)}$$

where b^i_j is user j's ith bit, C_j is user j's code, and aj = (Pj/T)1/2 where Pj is user j's power, and Ts is the symbol period. Now, assume that the two partners decide to cooperate. How will they do so? To satisfy cooperative strategy the total number of codes used by the two users as well as the modulation type should remain the same. Also, the strategy should not be overly complex. Given the above conditions, the two partners should use a cooperative strategy that maximizes throughput.

When users cooperate, the users would transmit following signals shown in equations 7

$$\begin{aligned} X_1(t) &= a_{11} b_1^{(1)} c_1(t),\ a_{12} b_1^{(2)} c_1(t),\ a_{13} b_1^{(2)} c_1(t) + a_{14} b_2^{(2)} c_2(t) \\ X_2(t) &= \underbrace{a_{21} b_2^{(1)} c_2(t)}_{\text{Period 1}},\ \underbrace{a_{22} b_2^{(2)} c_2(t)}_{\text{Period 2}},\ \underbrace{a_{23} b_1^{(2)} c_1(t) + a_{24} b_2^{(2)} c_2(t)}_{\text{Period 3}} \end{aligned} \quad \text{...(7)}$$

Period 1 is used to send data to the BS only. On the other hand, period 2 is used to send data not only to the BS, but also to each user's partner. After this data is estimated by each user's partner, it is used to construct a cooperative signal that is sent to the BS during period 3. This is accomplished by each user utilizing both users' codes (C_1 and C_2). Period 3 is used to resend, in some sense, the information originally sent during period 2. This implies that the users only send *two* new bits per three symbol periods, whereas they would be sending three new bits per three symbol periods if they were not cooperating [Equation (6)]. This may seem counterproductive, but, under certain channel conditions, "wasting" a few symbol periods for cooperation may be justified. It may be better to receive 1 very high SNR bit per symbol period, than to receive, say, 5 very low SNR bits per symbol period. This is because the performance criterion is the throughput, the number of successfully received bits/transmission, rather than the number of transmitted bits/symbol.

In our proposed cooperative scheme we can control power allocated using the parameters $\{a_{ij}\}$. It is possible to allocate no power to the cooperative signal, that is, transmit no power during period 3 [Equation (7)]. In general, allocating no power to the cooperative signal is equivalent to having a transmitter that voluntarily decides not to transmit during some of its allotted L symbol periods. Since the transmitter has an average power constraint, not transmitting during some of the symbol periods allows it to boost its power during the remaining periods.

As we begin to allocate power to the cooperative signal, the power allocated to the remaining symbol periods is reduced, thus potentially reducing their throughput. At the same time, though, the cooperative signal is now able to enhance the overall throughput due to diversity gains.

Equation (7) refers to cooperation for the special case of L = 3. In each L symbol periods, each of the two partners uses 2Lc of the periods for cooperation and the remaining L – 2Lc periods for sending non-cooperative information, where Lc is some integer between 0 and L/2. When , Lc = 0 the two users are not cooperating at all. When Lc = L/2 , the two users are fully cooperating, that is, cooperating during all symbol periods. For example L = 3 and Lc = 1 for equation (7), whereas L = 3 and Lc = 0 for equation (6). In general, the valu of Lc may not remain constant all the time.

A graphical illustration of cooperation scheme is shown in figure 5. Here we are considering L = 6 and Lc = 2.

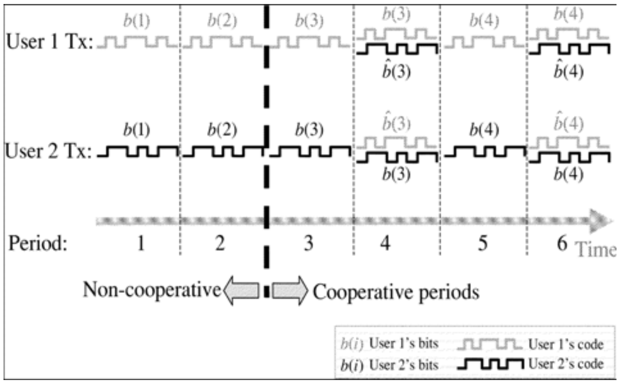

Fig. 5. How cooperation is implemented.

V. RESULTS OF CAPACITY REGIONS

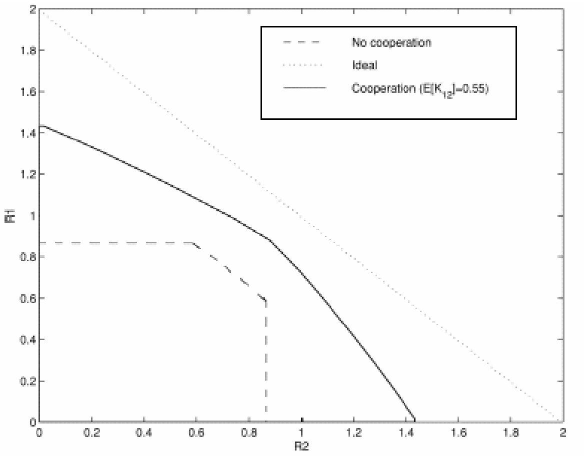

Fig. 6. Capacity region when the two users face statistically equivalent channels toward the BS.

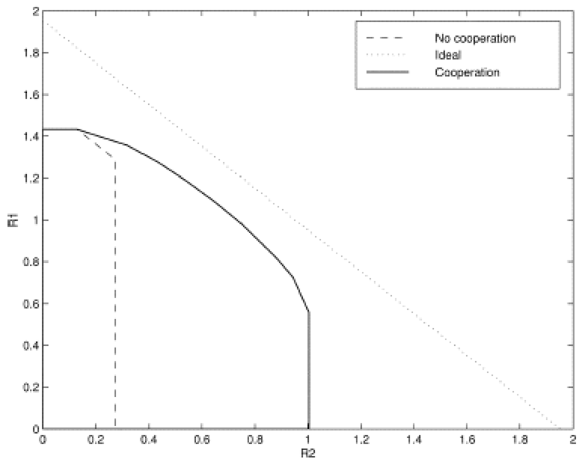

Fig. 7. Capacity region when the two users face statistically dissimilar channels toward the BS.

VI. CONCLUSIONS AND DISCUSSION

We have presented a new method of transmit diversity for mobile users: user cooperation. The type of cooperation we focused on is the cooperation of active users, that is, users who have information of their own to send, and thus, do not want to simply be another user's relay. Results to date indicate that user cooperation is beneficial and can result in substantial gains over a non-cooperative strategy. These gains would result in higher data rate and a decreased sensitivity to channel variations in presence of fading. The increased data rate with cooperation can also be translated into reduced power for the users. With cooperation, the users would use less total power to achieve a certain rate pair than with no cooperation. The partner scheme can thus be used to extend the battery life of the mobiles. Alternatively, the cooperation gains may be used to increase cell coverage in a cellular system.

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VIII. BIOGRAPHIES

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