Cooperative versus Non-cooperative Communications

Abstract

In this paper, we review some of the prominent gains achieved with cooperative communications, a new way of communications, which has found its applications in almost every wireless network, from cellular to sensor networks.

Cooperative communications is a way of transmission, where wireless users not only transmit their own information, but also repeat other users' information during its transmission to a common destination. On the other hand, a non-cooperative communications is the classical multiple access channel, where users send directly to a common destination, without repeating for one another.

We discuss the achievable rates and error rate performance both for cooperative and non-cooperative communications.

Keywords

Cooperative communications, Multiple Access Channel, Achievable rates, Relaying, Decode-and-Forward (DF), Amplify-and-Forward (AF)

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***Abstract*—In this paper, we review some of the prominent gains achieved with cooperative communications, a new way of communications, which has found its applications in almost every wireless network, from cellular to sensor networks. Cooperative communications is a way of transmission, where wireless users not only transmit their own information, but also repeat other users' information during its transmission to a common destination. On the other hand, a non-cooperative communications is the classical multiple access channel, where users send directly to a common destination, without repeating for one another. We discuss the achievable rates and error rate performance both for cooperative and non-cooperative communications.**

I. Introduction

In wireless communications signals travel through a wireless channel that is not physically constraint to restrict the signal travel in a particular direction. Due to the nature of wireless channel, transmitted signal actually broadcasts. This broadcast signal, because of reflection, refraction, diffraction and scattering, follows several different paths to arrive at the final destination. These effects are caused by many different objects present in the way of transmitted signal.

Due to above effects, signal arrives at the destination from many different paths, called multipath, having different path lengths. At the receiver the net effect is that the resultant signal has varying amplitude and phase. This effect of fluctuation in the amplitude of the signal is called fading. For receiver it is very difficult to make any reliable decision about the received bits with this faded signal.

To overcome this problem, one idea, to provide receiver with several independent copies of the same transmitted signal, called diversity gain, has been investigated and used. The benefit of this is that the receiver can combine the received copies with appropriate way like Maximum Ratio Combining (MRC) and can have better resultant signal to decide for the received bits being 0 or 1. For this purpose frequency, time, and space are the resources used. We will here discuss only space diversity.

In space diversity, multiple antennas at the transmit, receive, or at both ends of transmit and receive side are used, for transmission purpose, which results in having multiple copies of the same signal at the receiver. This way of communications is called Multiple Input Multiple Output (MIMO) communications [1].

Furthermore, if multiple antennas are used only at the transmitting or receiving end, then the resultant diversity is termed as transmit or receive diversity, respectively.

To exploit the benefits of transmit diversity, we need multiple antennas at the transmitting side. But in some wireless networks like in mobile communications, due to size of mobile or the devices used in the emerging wireless networks like, Ad hoc networks, having multiple antenna at the user terminal is difficult.

The solution of this problem is the concept of cooperative communications, first introduced by Sendonaris $et\ al.$ [2]. Cooperative communications is a way in which each wireless user transmits not only its own information, but also act as an assisting agent, called relay, for other user. As an example, two user cooperative communications setup, for cellular networks, is depicted in Fig. 1. Here, by using this new strategy of transmission, destination can be provided with several independent copies of the same transmitted signal. The number of copies depends on the number of cooperating users. This result apparently shows that we will have loss in terms of power and rates for cooperating users, because they are transmitting not only for themselves but are transmitting for other users as well. Much work has been done in this direction, results like in [2] and [3], show that because of the diversity achieved, the required transmit powers for users will be reduced. As a result this saved power can be used to enhance the achievable rates.

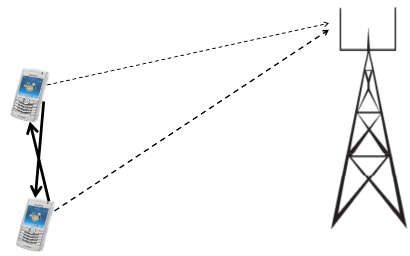

Fig. 1. cooperative communication setup

II. Historical Background

Cooperative communications can be considered as a special case of relay channel, where in simple relay channel there are three nodes, transmitter, receiver and relay. The job of the relay is to receive signal from source and forward it to destination, like repeaters. On the other hand, in cooperative communications, the node acting as a relay, not only forwards other users' information but has its own information to send as well. In the same way source has its own information and acts as a relay for other user.

Relay channel was first introduced by Van der Meulen [4]. Further comprehensive work was done by Cover and El Gamal [5], where they discuss different ways in which relay can assist the source. They also give some capacity results for special cases of relay channel, like degraded relay channel. The way, relay can help the source for its information to be sent reliably to destination, are sometime called relaying protocols [3]. We will stick with this name for the same purpose throughout our paper.

Afterwards many independent researchers worked on different aspects, like capacity [6], diversity [7], and diversity-multiplexing tradeoff [8] of relay channel.

Cooperative communications after first introduction by Sendonaris $et\ al.$ [2], [9] got considerable attention from research community and many results were published to show its capabilities and ways to achieve those capabilities [10], [7], [11], [12].

III. Relaying Protocols

We take cellular system, shown in Fig. 1, as an example to illustrate our cooperative communications setup, but it can be generalized to any wireless network. In cellular networks, when a user transmits, it is received by the destination base station and the other user in its vicinity. In cooperative communications setup, the other users' receiver called its partner, will in some way repeat this information to destination by using some suitable relaying protocol.

Many relaying protocols like, Amplify-and-Forward (AF), Decode-and-Forward (DF) and Compress-and-Forward (CF), have been introduced, but all of them are somehow the variations of simple AF and DF.

A. Amplify-and-Forward

In this relaying protocol, every cooperating user or partner, after receiving the noisy version of the transmitted signal of its partner, amplifies and re-transmits it to common destination, base station in our case.

B. Decode-and-Forward

With DF relaying protocol, every cooperating user, after receiving the noisy version of the transmitted signal of its partner, decodes and then sends to base station, the re-encoded version of the it.

In this paper, we will restrict our attention to only DF protocol and will elaborate its achievable rates and error rate performance.

IV. System Model

For simplicity, to show the benefits of user cooperation with DF, we take two synchronous cooperating users as an example. Both of the users are using orthogonal channels as in [3], orthogonality is achieved by Time Division Multiple Access (TDMA) channel for our simulations, as shown in Fig. 2. Transmitter uses Binary Phase Shift Keying (BPSK)

u_1 Tx and u_2 Rx	u_1 Tx and u_2 Relay	u_2 Tx and u_1 Rx	u_2 Tx and u_1 Relay

Fig. 2. orthogonal cooperative communication

with transmit power constraint of P_i. Furthermore, we consider the inter-user channel as well as user destination channel, h_{ij}, as a Rayleigh block-fading channel and the receiver noise is assumed to be Additive White Gaussian Noise (AWGN) with zero mean and unit variance and power spectral density. Receiver is assumed to have full channel state information available and the transmitter knows the phase of the channel. The signal-to-noise ratio (SNR) is defined as:

$$s_{i,j} = |h_{i,j}|^2 \frac{P_i^2}{N_j} \tag{1}$$

V. Achievable Rates

The set of achievable rates for decode-and-forward transmission over a memoryless Rayleigh multiple access channel with cooperative diversity is given by the set of all (R_1, R_2) *satisfying* [3]

$$R_1 < \mathrm{E}\Big\{ \log(1 + \alpha_1 s_{1,2}) \Big\} \tag{2}$$

$$R_2 < \mathrm{E}\Big\{ \log(1 + \alpha_2 s_{2,1}) \Big\} \tag{3}$$

$$\begin{aligned} R_1 + R_2 < \mathrm{E}\Big\{ & \log(1 + s_{1,0} + s_{2,0} \\ & + 2\sqrt{(1-\alpha_1)(1-\alpha_2) s_{1,0} s_{2,0}}) \Big\} \end{aligned} \tag{4}$$

for some $0 \leq \alpha_i \leq 1$, i = 0, 1.

E shows the expectation with respect to channel gains $h_{i,j}$. R_1 and R_2 are the rates for user 1 and user 2, s_{ij} is the SNR defined in 1 and, all logarithms used are to base-2.

Fig. 3 shows various achievable rates for cooperative communications with respect to non-cooperative one [3], where users are not acting as a relay for each other but are sending directly to base station. In Fig. 3 looking from upper-right to down-left, the first curve shows the upper-bound on achievable rates, when users have perfect channel between them, and the system operate as Multiple Input Single Output (MISO) channel. The second curve shows the outer bound when user are acting as relay for each other. Third curve shows the achievable rates with DF protocol and the final, fourth curve, with pentagon shape, shows non-cooperative achievable rates. We have given formula only for achievable rates with DF, (2)-(4). Complete formulation is available in [3]

The clear gap between pentagon shaped region and region under third curve, with dashed line, shows the gain achieved

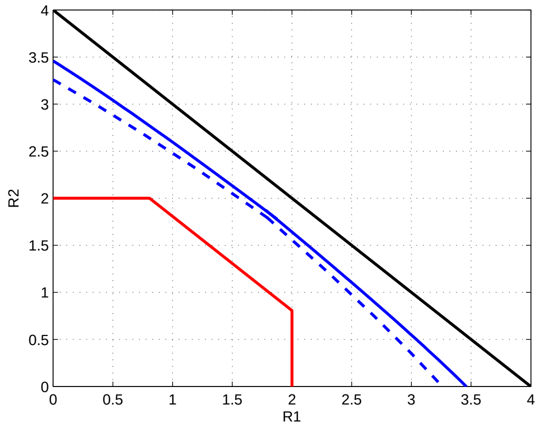

Fig. 3. Rates comparison for different schemes

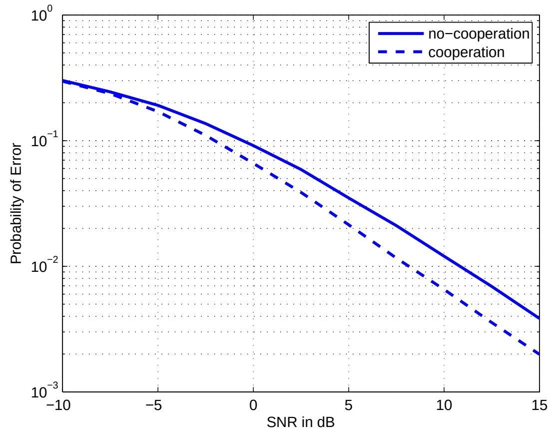

Fig. 4. Error rates comparison

with cooperative communications. We see that, with cooperative communications with DF, it is possible to achieve as high as double of the achievable rates with non-cooperative communications. For example, in Fig. 3, the maximum rates R_1 and R_2 achieved with non-cooperative communications is 2 bits per channel use and for cooperative communications this reaches at 3.4 bits per channel use.

VI. Bit Error Rate Performance

To show the bit error rate performance of both cooperative and non-cooperative communications, we take a simple setup as shown in Fig. 1. We assume that both of the users and base station are at equal distance from each other. Each user is transmitting and relaying other users' information by using their time slots as shown in Fig. 2.

Every partner user decodes and re-encodes the other users information symbol by symbol basis and sends it to the destination, without any error correction code.

At the destination, BS uses MRC, where message received directly from the user and relayed version of it are weighted equally and summed together. For example, during first slot as in Fig. 2 base station receives from user1

$$y_{sd} = x_1 h_{sd} + n_{sd} \tag{5}$$

where y_{sd} is the signal received at destination from source, x_1 is the transmitted signal, h_{sd} is the channel gain and n_{sd} is the AWGN noise. In the next time slot, it receives the relayed version of the same information from its partner, user 2 as

$$y_{rd} = x_{1rd} h_{rd} + n_{rd} \tag{6}$$

Here y_{rd} is the signal received at destination from relay or cooperating user, x_{1rd} is the transmitted signal of user 1, relayed be its partner, h_{rd} is the channel gain, and n_{rd} is the AWGN noise. These two copies of the same signal received at BS are combined and used by the receiver for decision making or decoding purpose. The error rate performance both for cooperative and non-cooperative communications are shown in Fig. 4. It can be seen from Fig. 4 that with cooperation, even without using any error correction code, considerable gain of 3 dB in SNR is achieved at high value of SNR.

VII. Conclusion

In this paper we have compared some of the most prominent aspects of cooperative communications, namely, achievable rates and error rate performance. We showed that achievable rates with cooperative communications can reach the double of the rates for non-cooperative communications. With error rate performance measure, we proved that even with simple decode and forward, without using any error correction coding, a gain of 3 dB in SNR is achievable.

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