Cooperative Communications: A New Trend in the Wireless World

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***Abstract*—This Wireless channel while offering independence of movement also introduces un-reliability in the messages received at the destination. Various strategies have been introduced so far to mitigate the effects of the channel on the message received. In this paper, we give an introductory overview of cooperative communications, a new trend in this field of wireless Communications where the transmitting users help each other to overcome the Effects of wireless channel on the message received at the destination. We compare the new idea of cooperative communications with traditional direct or non-cooperative communications. In particular, we discuss the achievable rates and simulate the system to get the probability of outage performance of cooperative communications and compare it with direct or non-cooperative communications**.

Keywords-Cooperative Communications, Coded Cooperation, Amplify-and-Forward, Decode-and-Forward, Compress-and-Forward, Probability of Outage

I. INTRODUCTION

The even increasing numbers of users demanding service on move have encouraged intensive research in wireless communications. The problem with cooperative communications is the unreliable medium through which the signal has to travel from source to the destination. To mitigate the effects of wireless channel, the idea of diversity has extremely been investigated and, in fact, deployed in many wireless systems [1, 2, 3]. Diversity is a communication technique where the transmitted signal is managed to travel through various independent paths and as a result the probability that all the wireless paths are in fade is made negligible. Frequency diversity, time diversity and space diversity are the basic techniques providing diversity to the communication systems.

Multiple antenna system where the transmitters as well as receivers are equipped with multiple antennas, formally called the Multiple-input multiple-output (MIMO) systems proved to be a breakthrough in wireless communications which offered a new degree of freedom, in spatial domain, to wireless communications. Very soon after its introduction, MIMO became part of many modern wireless communications standards like LTE-Advanced [1], WiMAX [2, 3] and Wireless LAN [4]. However, the use of MIMO in small size nodes, like used in wireless sensor or cellular networks proved to be a challenge. To address this challenge, the idea of cooperative communications came as a solution to implement the idea of MIMO in small size nodes. The idea of cooperative communications is based on the principle that transmitting users share each others' antennas to give a virtual MIMO concept. Though, the idea of cooperative communications was given by Sendonaris *et al.* [5, 6] in 2003, it is still considered a new idea and extensive research is going on to exploit its benefits in the next generation wireless communication systems [7, 8].

In this paper, we give an overview and potential benefits offered by this new trend in wireless communications. We discuss those potential benefits of cooperative communications in terms of the improved rate region and enhanced reliability. In rest of the paper, we proceed as follows. Section 3 gives the historical background of the field. Section 2 is devoted to discuss the system model to be used for evaluating the performance of cooperative communications. In Section 5 we give the performance analysis of the scheme. Explicitly in Section 5.1 we give the achievable rates and in Section 5.2, we simulate a cooperative communications scenario using Matlab and compare its performance with direct or non-cooperative communications. Finally conclusion is made in Section 6.

II. SYSTEM MODEL

For explanation purpose, we consider two transmitting users and a single destination. To make the discussion interesting, we take cellular system as an example, but the idea of cooperative communications presented can be applied to any wireless system such as wireless LAN, Ad hoc or sensor networks. The cellular scenario with two wireless users and a single base station is depicted in Fig. 1. Both of the users are considered to have in-Dependent information represented as *wi*, where $i = 1, 2$. The transmission of the message to the destination is assumed to take place in two phases. First phase is called the broadcast phase, as in this phase, the users broad-cast their information to the destination. Whereas, in the second phase, the users access the destination simultaneously, hence the second phase is known as multiple-access phase of the transmission.

The transmitting users are considered to be in the close proximity of each other and both of the users along with the destination, receive these messages transmitted from each other. In the next phase, both of the co-operating users, decode the message received from each other and forward some refinement information, on behalf of each other, to the destination. By doing this, it is hoped that the information from both of the users has been received twice and from two statistically independent paths. First path is due to user's direct transmission to the destination and the second path is from the partner user, which forward some additional information, based on its receive signal to the destination.

As a result, the decision made on the received message will be more reliable as it would have been with one time reception of the signal.

III. BACKGROUND

The idea of cooperative communications is based on simple three terminal relay channel idea introduced by Van der Meulen [9, 10]. In his seminal work on relay channel, it was shown that two nodes, the transmitter and receiver, can be aided by a relay node to improve the rate region of the transmitter. Later the concrete idea of cooperative communications was given by Sendonaris [5, 6]. The authors based on two users cooperative communication scenario, prove that cooperative communications improves the achievable rate for both of the users.

This is further extended by Laneman *et al.* [11, 12, 13]. The authors introduced and extended the idea of amplify-and-forward, decode-and-forward, dynamic decode-and-forward. They used outage probability as a performance metric to advocate the idea of cooperative communications.

The concept of coded cooperation was given by Hunter *et al.* [14, 15] which is the integration of cooperative communication and channel coding. The users code their information into blocks composed of two parts. The transmitting user itself transmits the first part of the block and the second part is transmitted by another cooperating user if it successfully receives the first part, otherwise, user itself transmits the second part of the block. In this way, diversity gain is exploited to counter the wireless channel impairments.

In addition, various channel coding schemes have been applied to cooperative communications scenario. LDPC [16] was first applied by Khojastepour *et al.* [17]. Turbo codes et al. [18] were investigated by various researchers [19, 20, 21]. Extensive work has been done by Hunter et al. [14, 15] where they have applied convolution codes to cooperative communications.

IV. BASIC RELAYING PROTOCOLS

In cooperative communications, the transmitting users not only broadcast their own message but they also relay some information, on behalf of each other, to the destination. The way or strategy, by which they relay this information to destination, is known as protocol. Various protocols have been introduced so far. We describe some of the basic relaying protocols here.

A. Amplify-and-Forward

This is the simplest protocol where the information received by a partner user from original transmitter is amplified and then forwarded by it to the ultimate destination. Based on the principle of amplifying repeaters [22], the amplify-and-forward protocol was formally introduced by Laneman *et al.* [23, 24]

B. *Decode-and-Forward*

This is a relaying protocol where the partner users decodes the message received from the original transmitter re-encodes and then forwards it to the destination. Thomas M. Cover and Abbas A. El Gamal are considered as the pioneer of this protocol [25] and later the idea was explored further by many authors with the name of Decode-and-Forward [13, 12,26].

C. *Compress-and-Forward*

To get the diversity benefits, in this relaying protocol, after decoding the message from the transmitter, the partner user forwards a compressed version of it to the destination [25].

V. PERFORMANCE EVALUATION

In this section, we present the performance evaluation of cooperative communications in comparison with the direct or non-cooperative communications. First we present achievable rates in Section 5.1. This follows the outage probability which is a performance measure used in fading channel with certain rate constraints.

A. *Achievable Rates*

To give achievable rates, we denote the channel gain from user u_i to user u_j as *hij* and from user u_i to the destination as hi and γ is defined as

$$\gamma = \frac{P_i}{N_0}.$$

where *Pi* is the transmit power and N_0 is the noise power spectral density. Finally R_1 and R_2 are used to represent the achievable rates for user u_1 and user u_2. The achievable rates for two user cooperative communications are proved to be [13].

The set of achievable rates for decode-and-forward transmission over a memory less Gaussian multiple-access channel with cooperative diversity is given by the set of all (R_1, R_2) satisfying1

$$R_1 < \log(1 + \alpha_1 |h_{1,2}|^2 \gamma) \quad (1)$$

$$R_2 < \log(1 + \alpha_2 |h_{2,1}|^2 \gamma) \quad (2)$$

$$R_1 + R_2 < \log(1 + \gamma_{1,0} + \gamma_{2,0} + 2\sqrt{(1-\alpha_1)(1-\alpha_2)|h_{1,0}|^2\gamma\ |h_{2,0}|^2\gamma_{2,0}}) \quad (3)$$

For some $0 \leq \alpha_i \leq 1,\ i = 0,\ 1,\ and\ |h_{i.j}|^2$ being fixed and known both at the transmitter and receiver.

Fig. 2 depicts the various achievable rates obtained by using (1), (2) and (3). The lined number ① illustrates a rate region curve for cooperative communications setup with error free inter-user channel. This is similar to (Multiple-Input Single-Output) MISO systems where two antennas are mounted at the transmitting end one at the receiving end. This gives us the upper bound on achievable rate region of the scheme. One more curve, the curve No. ④. which happens to be the lower bound on achievable rates is due to non-cooperative communications.

The remaining two curves represented as number ② and No. ③, in the middle of the curves give the upper and lower bound on achievable rates of cooperative communications based on decode-and-forward protocol.
In this way, the figure clearly shows that we get double of the rates with cooperative communications as compared to non-cooperative communications. Explicitly, the cure shows that with non-cooperative communications all we can have is data up to 2b/channel use whereas with cooperative communications, we can get as high as 3.4b/channel use.

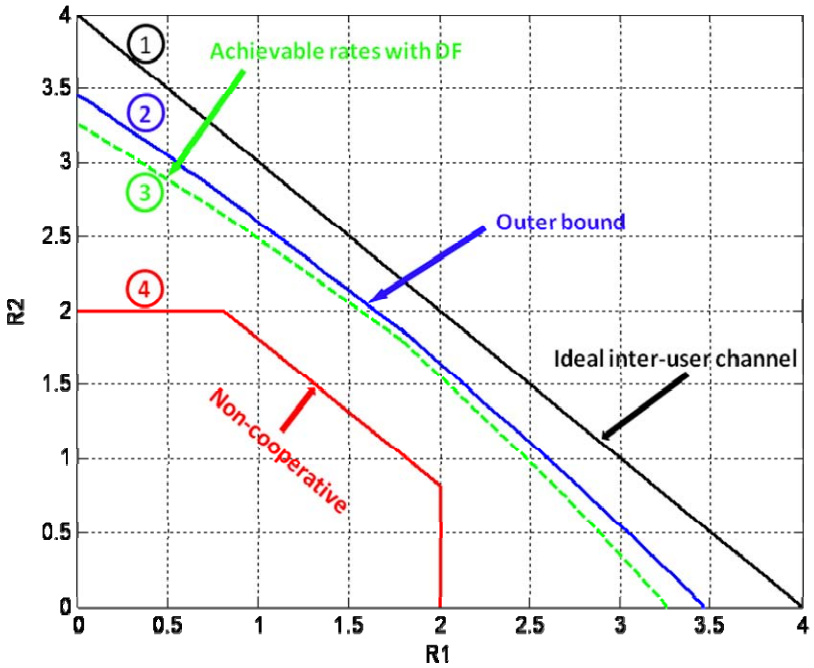

Figure 2: Achievable rate regions obtained with cooperative communications based on decode-and-forward protocol. The rate region for MISO systems as well as non-cooperative transmissions is also shown.

B. Probability of Outage

As we consider non-fading environment where the channel stays constant for some time and changes state. Afterwards, as a result, the achievable rates at the destination vary. Some of the user applications require axed rate to be received at the destination. In this case, the suitable performance metric would the probability of outage. Probability of outage is defined as the Probability where due to channel conditions, the rate requirement *R'*, dictated by some application, is not fulfilled, i.e.,

$$P[\text{outage}] = P[R < R']$$

For this, we can find out the probability of outage using the information theoretic results given by (3), but we would prefer to simulate the cooperative communications scenario and we use Matlab for this purpose. The information theoretic probability of outage using (3) can be found in [27, 11, 12]. Furthermore, to realize the system practically, we only consider the nodes having half duplex constraints, so that the nodes can not transmit or receive at the same time. In detail, the scheme works as follows.

The transmitting users in the network are assigned orthogonal channels and the orthogonality is achieved by assigning deferent time slots to each of the transmitting user. This is illustrated in Fig. 3. Let us suppose that user u_1 transmits first. Its information is broadcast with the intention to be received at the destination. Another user u_2, being in the proximity of the first user, along with the intended destination, also receives this message. In the next time slot, the other user u_2. After decoding that message repeats the same to the destination. In the same way, as happened previously, this time user u_2 broadcasts and the destination receives this message. Next, user u_1 repeats the information repeats the information received from user u_2.

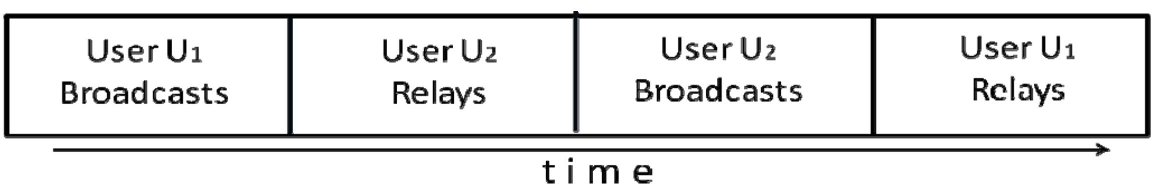

Figure 3: Orthogonal channel assignment for cooperative communications.

In addition, all of the transmitting nodes satisfy a power constraint of Pi = 8 dB. The transmitting users use Binary Phase Shift Keying (BPSK) and the channel between the transmitters and the destination is taken to follow Rayleigh distribution with zero mean unit variance. At the receiver, we simply employ maximum ratio combining.

Furthermore, as observed in our previous discussion, we use repetition coding based decode-and-forward protocol at the cooperating users. With these setting, Fig. 4 shows us the outage probability curve obtained using Matlab for cooperative communications in comparison with direct or non-cooperative commutations. Here the rate requirement is represented by R' and is allowed to vary from 0.2 to 0.8 bits/channel use. From the curve we can see that if we fix the rate requirement at R' 0.35 bits/channel use, there is 92% decrease in outage when we use cooperative communications instead of classical non-cooperative communications. In other way, if we fix probability of outage, for example, at 10^{-3}, we can increase the rate received at the destination from 0.25 to 0.35, which happens to be 29% increase in the achievable rate at the destination.

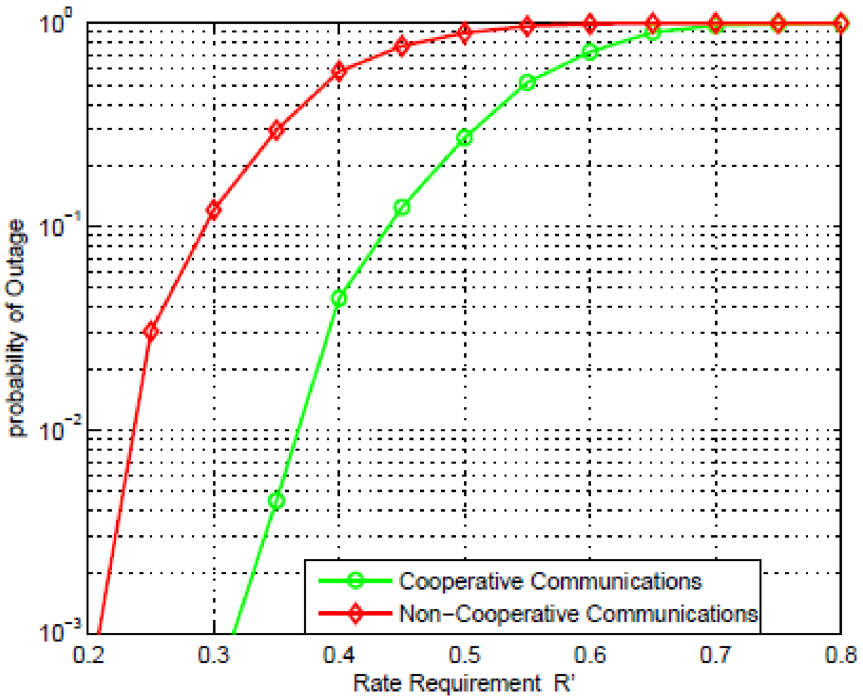

Figure 4: Probability of outage for cooperative communications versus non-cooperative communications

VI. Concluding Remarks

In this paper we give an overview of cooperative communications and compare its performance with classical direct or non-cooperative communications. We discuss some of the basic relaying protocols used by the cooperating nodes to forward their partners' information to the destination. We elaborate on the achievable rates both for cooperative and non-cooperative communications. The information theoretic results show that in terms of Achievable rates, we get almost double times better performance than offered by non-cooperative communications. Moreover, the simulated results on probability of outage indicate that we get 92% reduction in outage with this new trend of communications. As a future trend, this technique can be envisioned to be the leading communications strategy to be used in cellular, Ad hoc as well as sensor networks.

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