Cooperative Transmission Protocols with High Spectral Efficiency and High Diversity Order Using Multiuser Detection and Network Coding

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***Abstract*— Cooperative transmission is an emerging communication technique that takes advantages of the broadcast nature of wireless channels. However, due to low spectral efficiency and the requirement of orthogonal channels, its potential for use in future wireless networks is limited. In this paper, by making use of multiuser detection (MUD) and network coding, cooperative transmission protocols with high spectral efficiency, diversity order, and coding gain are developed. Compared with the traditional cooperative transmission protocols with single-user detection, in which the diversity gain is only for one source user, the proposed MUD cooperative transmission protocols have the merits that the improvement of one user's link can also benefit the other users. In addition, using MUD at the relay provides an environment in which network coding can be employed. The coding gain and high diversity order can be obtained by fully utilizing the link between the relay and the destination. From the analysis and simulation results, it is seen that the proposed protocols achieve higher diversity gain, better asymptotic efficiency, and lower bit error rate, compared to traditional MUD and to existing cooperative transmission protocols.**

I. Introduction

Cooperative transmission [1], [2] is a new communication technique that takes advantage of the broadcast nature of wireless channels. Recent work has explored cooperative transmission in a variety of scenarios, including cellular networks [3], ad hoc/sensor networks [4], and ultra wide band [5]. One drawback of existing cooperative transmission schemes is a consequent reduction of spectral efficiency. Moreover, most existing techniques require orthogonal channels, which are not available for many wireless networks such as 3G cellular networks.

Multiuser Detection (MUD) [6] deals with the demodulation of mutually interfering digital streams, exploiting the cross-correlations among users to produce better detection performance in the presence of multiple-access interference. MUD implementations for cellular applications have been developed by Datang Telecommunication for TD-SCDMA and by Qualcomm for EVD0. Recently, [7] has considered the joint optimization of Multiple Input Multiple Output (MIMO) systems with MUD. Since a relay in a cooperative communication scheme can be viewed as a virtual antenna for a source node, this work motivates the study of MUD performance in cooperative transmission. However, unlike MIMO MUD where all information from different antennas can be obtained without limitation, in cooperative communication schemes the link between the relay (i.e., the virtual antenna) and the destination is limited.

To overcome this limitation, network coding [8], [9] provides a potential solution. The core notion of network coding is to allow mixing of data at the intermediate network nodes, to improve the overall reliability of transmission across the network. A receiver receives these mixed data packets from various nodes and deduces from them the messages that were originally intended for that data sink. In cooperative transmission, the relay can be viewed as an intermediate network node. If MUD is employed at the relay, the relay can employ network coding by mixing some users' data and transmitting them through the limited link to the destination node. At the destination, the performance of all users destined to that node can be greatly improved by decoding this coded data. This issue is examined in the present paper.

In particular, we propose two cooperative transmission protocols that make use of MUD and network coding. In the first protocol, realizing that improvement in one user's decoding can help the decoding of the other users, we decide which relays to use and whose information the selected relays will retransmit such that the overall system performance can be optimized. In the second protocol, we assume the relays are equipped with MUD. Then the selected users' information is coded by network coding and is relayed to the base station. At the base station, the coding gain is not only realized for the selected users but also for the other users because of the MUD. From both analytical and simulation results, it is seen that the proposed protocols achieve higher diversity and coding gain, better asymptotic efficiency, and lower bit error rate (BER) than existing schemes.

This paper is organized as follows. In Section II, system models are given for multiuser cooperative transmission with MUD in a base station and a set of relays. In Section III, the two above-noted protocols are constructed. In Section IV, the properties of the proposed protocols are studied. Simulation results are shown in Section V, and conclusions are drawn in Section VI.

II. System Model

Consider a wireless network with K synchronized uplink users (i.e., terminals). Among these terminals, N can serve as relays. This system model is illustrated with $N=1$ in Figure 1. At a first transmission stage, all users except the relays send information, and the relays listen (and perform MUD if they have the ability). At a second stage, the other users send their next information signals, while the relays send a certain user's information or key information from the results of MUD applied at the first stage. In the base station, all of the other users' information from the first stage is delayed for one time slot and jointly decoded with the key information sent by the relays at the second stage. Since the users cannot transmit and receive at the same time or at the same frequency, to relay once costs at least two time slots for listening and relaying. So the spectral efficiency is $\frac{K-2N}{K}$, and thus when the number of users is much larger than the number of relays the spectral efficiency approaches 1.

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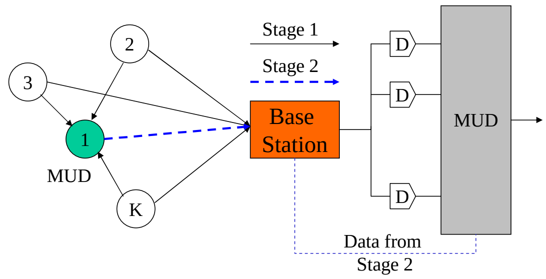

Fig. 1: System Model

We consider an uplink synchronous CDMA system with Gaussian ambient noise. Define $\mathfrak{R}$ as the group of relay terminals, and $\mathfrak{L}$ as the group of terminals listening and preparing for a relay in the next time slot. The received signal at the base station can be expressed as

$$y(t) = \sum_{k\in K\backslash\mathfrak{R}\backslash\mathfrak{L}} A_k b_k s_k(t) + \sum_{k\in\mathfrak{R}} A_k z_k s_k(t) + \sigma n(t), \quad (1)$$

and at user $i \in \mathfrak{L}$, who is listening and preparing for a relay in the next time slot, as

$$y^i(t) = \sum_{k\in K\backslash\mathfrak{R}\backslash\mathfrak{L}} A_k^i b_k s_k(t) + \sum_{k\in\mathfrak{R}} A_k^i z_k s_k(t) + \sigma^i n^i(t), \quad (2)$$

where A_k is the received amplitude of the k^{th} user's signal at the base station, A_k^i is the received amplitude of the k^{th} user's signal at relay i, $b_k \in \{-1, +1\}$ is the data symbol transmitted by the k^{th} user, z_k is the relayed bit, s_k is the unit-energy signature waveform of the k^{th} user, $n(t)$ and $n^i(t)$ are normalized white Gaussian noise processes, and σ^2 and $(\sigma^i)^2$ are background noise power densities. For simplicity, we assume $\sigma = \sigma^i$, although the more general case is straightforward.

The received signal vectors at the base station and at the relay after processing by a matched filter bank can be written as:

$$\mathbf{y} = \mathbf{RAb} + \mathbf{n}, \quad (3)$$

and

$$\mathbf{y}^i = \mathbf{RA}^i\mathbf{b} + \mathbf{n}^i, \quad (4)$$

where $\mathbf{A} = diag\{A_1, \ldots, A_K\}$, $\mathbf{A}^i = diag\{A_1^i, \ldots, A_K^i\}$, $E[\mathbf{nn}^T] = E[\mathbf{n}^i\mathbf{n}^{iT}] = \sigma^2\mathbf{R}$, $\mathbf{R}$ is the cross-correlation matrix, whose $i - j^{\text{th}}$ element can be written as

$$int_0^T s_i(t)s_j(t)dt, \quad (5)$$

where T is the inverse of the data rate, and $\mathbf{b} = [b_1, \ldots, z_i, \ldots, 0, b_K]^T$ consists of symbols of direct-transmission, relay, and listening users.

In this paper, we will investigate the BER performance of MUD under cooperative transmission. Specifically, we will consider the optimal MUD and successive cancellation detector which is one type of decision driven MUD. As pointed out in [6], there is no explicit expression for the error probability of the optimal multiuser detector, and bounds must be used. A tight upper bound is provided by the following proposition from [6].

Proposition 1: The BER of the i^{th} user for optimal MUD is bounded according to

$$P_r^{i,opt} \leq \sum_{\epsilon\in F_i} 2^{-\omega(\epsilon)} Q\left(\frac{\|S(\epsilon)\|}{\sigma}\right) \quad (6)$$

where ϵ is a possible error vector for user k, and $\|S(\epsilon)\|^2 = \epsilon^T\mathbf{H}\epsilon = \epsilon^T\mathbf{ARA}\epsilon$. $\omega(\epsilon)$ is the number of nonzero elements in ϵ, and F_i is the subset of indecomposable vectors. Due to limited space, for details refer to [6, Chapter 4].

For the successive cancellation detector, a recursive approximation is given by the following proposition [6].

Proposition 2: The BER of the i^{th} user for successive cancellation MUD is given approximately by

$$P_r^{i,sc} \approx Q\left(\frac{A_i}{\sqrt{\sigma^2 + \frac{1}{M}\sum_{j=1}^{i-1} A_j^2 + \frac{4}{M}\sum_{j=i+1}^{K} A_j^2 P_j^{sc}}}\right), \quad (7)$$

where M is the spreading gain.

Notice that the BER is a function of the received amplitudes of the users, which in turn are functions of the user locations and the network topology. As will be shown later, we have degrees of freedom to select which users will serve as relays and which users' information to relay, so as to achieve optimal performance in terms of BER at the base station.

III. Two Cooperative Transmission Protocols

The first protocol seeks to exploit the fact that MUD can improve all signals to be decoded better because of the mitigation of interference from the strongest signals. Suppose terminal i is selected as the relay and it forwards user m's information. At the base station, after a matched filter bank, maximal ratio combining (MRC) is used to combine the signals from these two terminals. The resulting SINR is given by:

$$\Gamma_m = \Gamma_m^0 + \Gamma_i^0, \quad (8)$$

where Γ_m^0 and Γ_i^0 are the SINRs to the base station from user m and user i, respectively. Since the optimal and decision driven MUD algorithms are nonlinear, a closed form expression for (8) is not available. Moreover, the noise terms corrupting different users after MUD are correlated so that (8) can serve only to provide a performance upper bound. In this paper, we assume that some method such as a threshold test [2] is employed so that the potential relays and the base station can know whether the detected signals are correct. Also, rather than using MRC before the decoding, the final decision is based on the decoded signals in both stages. An error occurs only if the decisions in both stages are wrong. So the probability of error can be written as

$$P_r^m = P_r^{m0}(1 - (1 - P_r^{mi})(1 - P_r^{i0})). \quad (9)$$

Here user i is selected as the relay. The error probabilities for user m to the base station, user i to the base station, and for user m to user i are denoted as P_r^{m0}, P_r^{i0}, and P_r^{mi}, respectively. Notice that there is no need for MUD at the relays for the first protocol.

The second protocol seeks to exploit the fact that MUD in the base station and the relay provides a possible data-flow structure

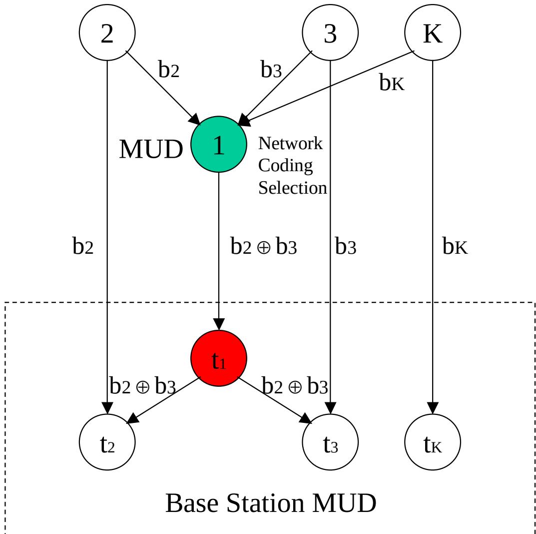

Fig. 2: Joint MUD and Network Coding Example

for jointly optimizing MUD and network coding. In Figure 2, we illustrate an example where there are K users and user 1 is assigned as the relay. At a first stage, users 2 through K send their own information, while the base station and user 1 listen. At a second stage, user 1 sends the coded information (here $b_2 \bigoplus b_3$). Then the base station can improve the decoding of user 2 and user 3.

In general, we can formulate joint MUD and network coding as follows: As a relay, user i selects a set of users $\mathfrak{M}_i$, and then transmits $b_m \bigoplus \cdots \bigoplus b_n$, where $m, \ldots, n \in \mathfrak{M}_i$. Notice that $\mathfrak{M}_i$ is a subset of all users that are successfully decoded at the first stage by user i. At the base station, the user's error probability is given by:

$$P_r^m = P_r^{m0}\{1 - (1 - P_r^{mi})(1 - P_r^{i0}) \prod_{n \in \mathfrak{M}_i / m} [(1 - P_r^{ni})(1 - P_r^n)]\}, \tag{10}$$

and

$$P_r^j \leq P_r^{j0}, \ \forall j \neq \mathfrak{M}_i. \tag{11}$$

The first term in (10) represents the direct transmission error probability. The term in brackets in (10) represents the error probability from the relay using networking coding. The successful transmission from the relay happens only if all users in $\mathfrak{M}_i$ are decoded correctly by user i, the transmission from user i to the base station is correct, and all other users are correctly decoded at the base station. Notice that compared with (9), the error probability for a specific user might be worse. However, since in (10), multiple users' BERs can be improved, the overall BER of the system can be further improved under careful optimization. The inequality in (11) holds since the cancellation of some successfully decoded users' information can improve the other users' decoding.

The problems to be considered here are: which relays to select among the potential users; and whose data to retransmit. We need to select the relay i from set $\mathfrak{R}$ of size N, and the set $\mathfrak{M}_i$ which represents whose information should be relayed by user i. The problem formulation to minimize the overall BER can be written as:

$$\min_{\mathfrak{R}, \mathfrak{M}_i} \sum_{j \in \{K \backslash \mathfrak{R}\}} P_r^j. \tag{12}$$

TABLE I: Cooperative Transmission Protocols

1. At stage one, the relays decode using MUD.
2. At stage one, the base station decide which users are most important.
3. Using feedback from the base station, at stage two, the relays forward the selected users' information or encode using network coding so as to optimize the decoding goal.
4. At stage 2, MUD decoding is used at the base station.

To optimize (12), we propose an algorithm shown in Table I. The basic idea is that the base station can know at stage 1 which users' links need to be improved so as to maximize the network performance. So at stage 2, the relay with the best location will send the corresponding information to the base station. At the base station, the information sent at the first stage is delayed and combined with the relay's information at the second stage. Consequently, the performance of all users can be improved.

IV. Performance Analysis

In this section, we first examine the diversity order and coding gain of the proposed protocols. Then, a performance upper bound is given using MIMO-MUD. Finally, we study a special case for how the relay changes the MUD asymptotic efficiency.

At stage one, we order the received signals at the base station according to the signal strength, where user K has the highest SINR (i.e. the lowest BER). For Protocol One, we assume all relays select user K's information to retransmit if the relay decodes it correctly. The diversity order for user K can be easily shown to be $N+1$. Since only user K's copy of the information at stage 1 is retransmitted, the diversity order of the other user is still 1. However, the remaining users have better performance since the strongest interference (user K's signal) can be more successfully cancelled. Define the coding gain ρ_i as the SINR improvement ratio for the remaining users. For successive cancellation MUD, we have

$$\rho_{K-1} = \frac{\sigma^2 + \frac{1}{M}\sum_{j=1}^{K-2} A_j^2 + \frac{4}{M} A_K^2 P_r^K}{\sigma^2 + \frac{1}{M}\sum_{j=1}^{K-2} A_j^2 + \frac{4}{M} A_K^2 \hat{P}_r^K}, \tag{13}$$

where $\hat{P}_r^K$ is user K's new BER and $\hat{P}_r^K \approx (P_r^K)^{N+1}$. If $\frac{1}{M}A_K^2 >> \sigma^2 + \frac{1}{M}\sum_{j=1}^{K-2} A_j^2$, the coding gain can be quite large. For the coding gains of other users, we can calculate $P_r^{K-1}, \ldots, P_r^1$ recursively. For optimal MUD, the performance is lower bounded by that of successive cancellation MUD.

For Protocol Two, if at the second stage, the relays retransmit the following information

$$z_i = \bigoplus b_j, j \in \mathfrak{M}_i. \tag{14}$$

We consider any user i's information. When the SINRs are sufficiently large, the channels between the senders and relays are approaching ideal links. If the other direct links are also sufficiently good, at the second stage after network decoding, the only signals remaining are user i's information from the N relays, and these signals will be combined with the direct transmission sent at the first stage. So the diversity order is $N+1$.

Next, the proposed cooperative transmission protocol with MUD has a performance upper bound given by that of MIMO MUD [7] in which there is infinite bandwidths between the relays and the base station. Here we assume that the combination is performed after decoding. Decoding error happens when all the $N+1$ links fail, i.e.

$$P_r^k = P_r^{k0} \prod_{i=1}^{N} P_r^{ki}, \tag{15}$$

where P_r^{k0} is the BER for direct transmission and P_r^{ki} is the BER for transmission from user k to relay i. For MIMO MUD, the diversity order is $N+1$.

Finally, we study a special case of two users and one relay to investigate the performance improvement of MUD. Here we make the approximations that the relay can always decode correctly and the base station can use maximal ratio combining of the direct and relay transmissions. In this ideal case, the multiuser efficiency of optimal MUD can been expressed as

$$\begin{aligned}\eta_1 \approx \min\Big\{ & 1, 1 + \frac{(A_2+A_r)^2}{A_1^2} - 2|\rho|\frac{A_2+A_r}{A_1}, \\ & 1 + \frac{A_2^2}{(A_1+A_r)^2} - 2|\rho|\frac{A_2}{A_1+A_r} \Big\},\end{aligned} \tag{16}$$

where ρ is the cross-correlation between the two users' waveforms, and A_1, A_2, and A_r are the channel gains to the base station for user 1, user 2 and the relay, respectively.

In Figure 3, we show the MUD efficiency with A_1=1 and $\rho = 0.8$. With cooperative transmission, the difference between the two users' SINRs can be increased so that the multiuser efficiency can be increased. We can see that when the relay is close to the base station (i.e. A_r is large), the multiuser efficiency can be almost 1. We notice that this comparison is unfair, since the bandwidth is increased with the presence of the relay. However, when the number of users is sufficiently larger than the number of the relays, this increase is negligible.

V. Simulation Results

The following setting is used in the simulation. We consider a one-dimensional model where a base station, a relay, and users are located along a line. The base station is located at 0, the two users are located at 4 and 6, and the relay can move from 0.5 to 3.5. The power received from a given transmitter is proportional to P_t/d^3, where d is the distance between the transmitter and the receiver, and P_t is the transmitted power. In the simulation, we assume that all users and the relay use the same transmitted power, i.e., there is no power control. We also assume the receivers have the same additive noise level.

In the simulations, we choose a simplified model for the relay. The relay can receive and transmit at the same time. This can be achieved by using time sharing, different frequency bands, or simply two relay users. We choose this model to simplify the scenario. In each time slot, the relay transmits a bit generated according to the protocols developed in Section III. The relay and the users transmit their signals using CDMA, and they all use different spreading codes. The relay and the base station perform successive-cancellation multiuser detection on the received signals.

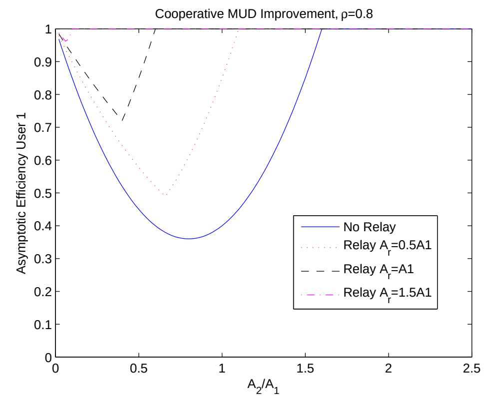

Fig. 3: MUD Asymptotic Efficiency Improvement

Figure 4 shows the average BER as a function of the relay location. There are two users, and both users and the relay use high transmitted power. The curves correspond to the cases without the relay, with the relay re-transmitting user 1's (located at 4) symbol, with the relay re-transmitting user 2's (located at 6) symbol, and with the relay re-transmitting the XOR of both users' symbols (network coding). The first observation is that the location of the relay plays a vital role in the system performance. The relay helps the system performance only when its distance from the base station is below 2.5. The relay will harm the performance if it is close to the user group. This is because for successive cancellation MUD, the performance is better if the received power of the users is different from each other. A relay that is close to the user group is acting more as an interference source than as a relay. The second observation is that there is a "sweet spot" for the location of the relay around 1.6. This is because the relay's decoding performance drops if it is located too far away from the sources. The third observation is that the network coding protocol with the relay re-transmitting the XOR of both users' symbols always performs better than that when the relay just re-transmits one user's symbol. Figure 5 is similar to Figure 4 except that the transmitted power is low here. We observe performance behavior similar to the high transmitted power case.

Figure 6 shows the average BER as a function of the transmitted power of the users and the relay. The relay's location is fixed at 1.6. We can clearly see the higher diversity order of BER vs. power for the proposed protocols. When the transmitted power is sufficiently high, the limiting factor of the performance is the interference. And that is why the curve flattens when the transmitted power grows. We notice the large difference in performance between the case with the relay and the case without. Another interesting observation is that, in a certain transmitted power range, relaying the first user's symbol is better, while in other transmitted power range, relaying the second user's symbol is better. Relaying the XOR of both users' symbols is always the best protocol, but this requires the use of MUD at the relays. We also show the performance of MIMO-MUD, which serves as a performance bound.

Figure 7 shows the average BER as a function of the number of users. Here we explore the cases with two to six users. In

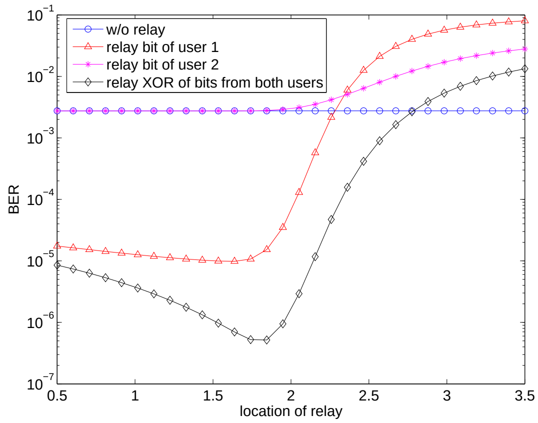

Fig. 4: The average BER as a function of the location of the relay. This is a high average SINR case.

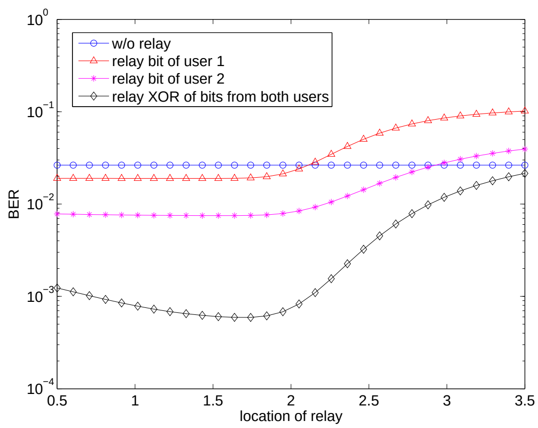

Fig. 5: The average BER as a function of the location of the relay. This is a low average SINR case.

each case, the users are uniformly distributed in the range $[4, 8]$. The relay is located at 1.6, and it transmits the XOR of the nearest two users' symbols. As expected, the performance is best when there are only two users. The performance for the case with more users can be improved by introducing more relays or having the relay transmitting the XOR of more users' symbols.

VI. Conclusions

We have proposed two new cooperative transmission protocols considering MUD as well as network coding. The enhancement of some users' transmissions by cooperative transmission can improve the other users' performance in MUD. Moreover, network coding can provide additional coding gain. From the analysis and simulation results, the proposed protocols achieve much lower average BER, higher diversity order and coding gain, and better asymptotic efficiency, compared to cooperative transmission for single user detection and traditional MUD.

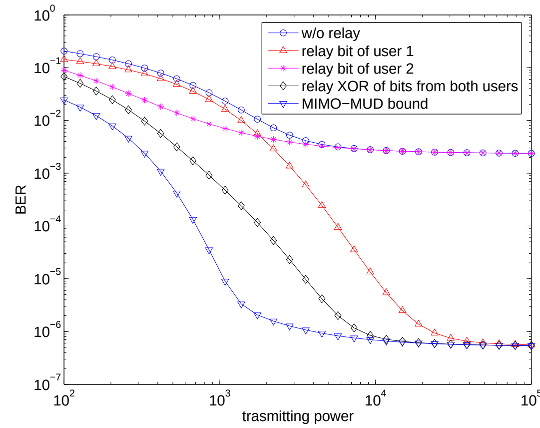

Fig. 6: The average BER as a function of the transmitted power.

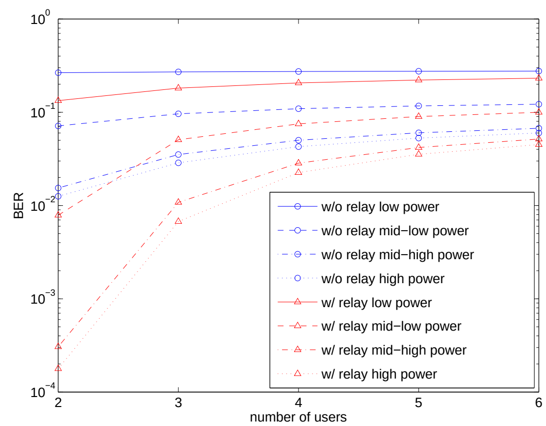

Fig. 7: The average BER as a function of the number of users.

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