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Performance of Coded Cooperative Diversity with Interference in Nakagami Fading Environments

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Abstract. Diversity is an effective technique in enhancing the link quality and increasing network capacity. When multiple antennas can not be used in mobile units, user cooperation can be employed to provide transmit diversity. In this paper, we analyze the error performance of coded cooperative diversity with multiple cooperating users over Nakagami fading channels under interference conditions. We derive the end-to-end bit error probability of coded cooperation (averaged over all cooperation scenarios). Results show that allowing more cooperating users improves the performance of the network under low loads, where two cooperating users suffice for highly loaded networks. Furthermore, the gains obtained by increasing the number of cooperating users decreases with increasing the network load.

Keywords: Cooperation, coding diversity, union bound, error probability, Rayleigh, Nakagami, fading, convolutional, interference

JEL codes: D24, L60, 047

1. Introduction

Diversity is an effective technique to mitigate the effect of multipath fading in wireless communication networks. Among diversity techniques, transmit diversity relies on the principle that signals transmitted from geographically separated transmitters experience independent fading. Employing transmit diversity improves the performance compared to systems with no diversity [3, 18, 19]. Since most wireless networks operate in a multiuser mode, user cooperation [15, 16] can be employed to provide diversity. In user cooperation, mobile units share their antennas to achieve uplink transmit diversity as illustrated in Figure 1. Since the signal of each user undergoes an independent fading path to the base station (BS), this approach achieves spatial diversity through the partner antenna. In principle, the idea of user cooperation is based on the relay channel [2, 12] and on the multiple access channel [21]. However, the latest work specifically on user cooperation has appeared in [15, 16].

Conventionally, a cooperating user repeats the received bits from his partner (via either forwarding or hard detection). Recently, a *coded cooperation* was proposed [6–10] to provide cooperation between two users. In coded cooperation, the codeword of each user is partitioned into two subframes; one subframe is transmitted by the user, and the other by the partner. Coded cooperation is capable of providing significant performance gains for a variety of channel conditions. Such performance gains can be achieved by employing different code

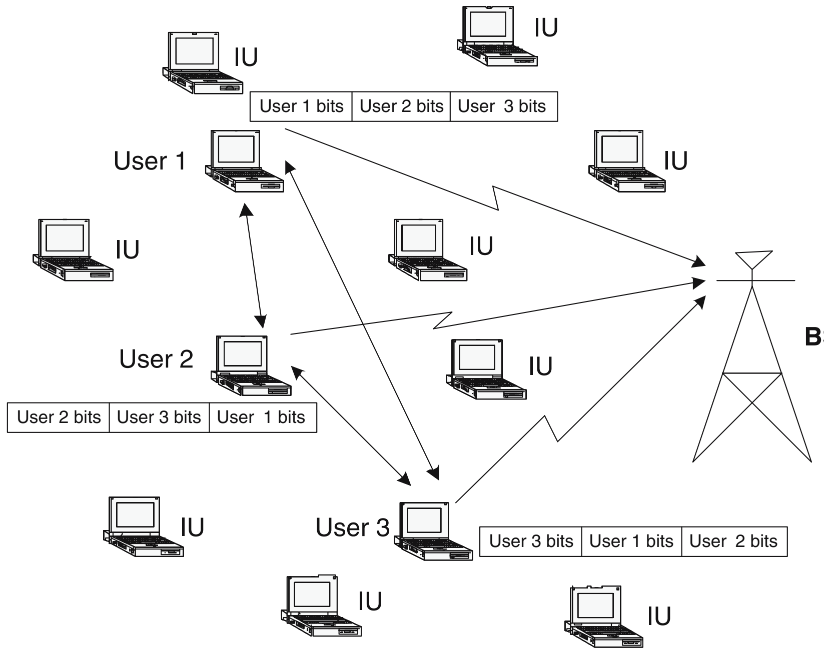

Figure 1. Schematic diagram of a wireless network employing 3-user coded cooperation with N_u interfering users (IU) in the network.

rates through rate compatible codes [5]. The performance of coded cooperation was derived in [7] for two cooperating users and was generalized to multiple cooperating users in [22].

In existing work on coded cooperation, interference between nodes within the network is usually neglected. However, interference exists in cooperative networks due to the use of shared resources. In [13], the performance of coded multiple-access wireless networks was analyzed under interference conditions. In this paper, we derive the error performance of coded cooperative networks with interference over Nakagami fading channels for arbitrary number of users. We derive the end-to-end probability of error averaged over different cooperation scenarios. In addition, the bit error probability is derived for specific cooperation scenarios. Results show that two cooperating users suffice for highly loaded networks, whereas allowing more cooperating users improves the performance under low network traffic.

The paper is organized as follows. In Section 2, the coded cooperative network with multiple cooperating users is described. The end-to-end average error performance of coded cooperation is derived in Section 3. Results are presented and discussed in Section 4. The paper is concluded with main outcomes in Section 5.

2. System Model

In this paper, we consider a multiple-access wireless network of N_u users transmitting to a common BS. Users are assumed to be active with probability p. The corresponding network load is $G = pN_u$. In the network, every J users (partners) cooperate in the transmission to the BS by forming a cluster of size J. For each user in the network, a frame is formed by encoding K bits into $L = K/R$ bits, where R is the code rate. Partners within a J-user cluster cooperate by dividing their L-bit frames into J *subframes* containing $L_1, L_2, \ldots, L_J$ bits, where $L = L_1 + L_2 + \cdots + L_J$. The partitioning of the coded bits in the J subframes may be achieved using a rate-compatible punctured convolutional (RCPC) codes [5] as in [6, 22].

During the first subframe duration, each user transmits his first subframe [7] composed of $L_1 = K/R_1$ coded bits, where R_1 is the code rate of the codeword in the first subframe, obtained by puncturing the L-bit codeword into a L_1-bit punctured codeword. Clearly, $R_1 > R_J = R$. Upon the end of the first subframe, each user decodes the rate-R_1 codewords of his partners. In the remaining $J - 1$ subframes, each user transmits one subframe for each of his $J - 1$ partners in a predetermined pattern. The *cooperation level* is defined as the percentage of the total bits per each source block that each user transmits for his partners, i.e., $\frac{L-L_1}{L}$. The BS receiver combines all the received subframes for a user to produce a codeword of a more powerful code (a lower code rate) [5]. The code rates corresponding to different cooperation levels are $R_1 > R_2 > \cdots > R_J = R$.

After encoding an information block, the coded bits are modulated using BPSK. Coherent detection is employed with perfect channel state information at the receiver. The matched filter output at user k due to user l in the time interval t in the jth subframe is modeled by

$$y_{l,k,j}(t) = \sqrt{E_\mathrm{I}}a_{l,k,j}s_{l,j}(t) + z_{k,j}(t) + \sum_{i=1}^{n} a_{i,k,j}\sqrt{E_\mathrm{I}}, \quad (1)$$

where $s_{l,j}(t)$ is the signal transmitted from user l in time instance t in the jth subframe and $z_{k,j}(t)$ is an AWGN sample at user k with a Gaussian distribution given by $\mathcal{N}(0, \frac{N_0}{2})$. Here, E_I is the average received signal energy through the interuser channel. When $k = 0$, the model in (1) represents the signal from user l received at the BS through the uplink channel in the jth subframe, where the average signal energy E_s replaces E_I in (1). The second term in (1) represent the interference received from some n interfering users within the network. Note that we assume that the number of interferers (i.e., n) is the same for all the users in the cluster.

In (1), the coefficient $a_{l,k,j}$ is the gain of the interuser channel between user l and user k in the jth subframe, modeled as a Nakagami random variable whose envelop squared has a probability density function (pdf) given by

$$f_{a^2}(x) = \left(\frac{m}{\Omega}\right)^m \frac{x^{m-1}}{\Gamma(m)} \exp\left(-\frac{mx}{\Omega}\right), \quad x > 0, \qquad m > 0.5, \quad (2)$$

where $\Gamma(.)$ is the Gamma function, m is the fading parameter that indicates the fading severity and $\Omega = \mathrm{E}[a^2]$. The Nakagami distribution covers a wide range of fading scenarios including Rayleigh fading when $m = 1$ and AWGN when $m \to \infty$. Here, the interuser and uplink channels are assumed to be mutually independent and slow enough such that the fading process stays fixed during the transmission of a subframe. This is a reasonable assumption for slowly moving mobile units that are separated enough in the space [9].

Similarly, the coefficient $a_{i,k,j}$ is the gain of the interuser channel between an interfering user i and user k in the jth subframe, modeled as a Nakagami random variable whose pdf is gievn by (2). Given that n users are interfering with the signal of user l at user k, the signal-to-interference-and-noise ratio (SINR) at user k in the jth subframe is written as

$$\beta_{l,k,j} = \frac{a_{l,k,j}^2 \gamma_\mathrm{I}}{1/2 + \gamma_\mathrm{I} \sum_{i=1}^{n} a_{i,k,j}^2}, \quad (3)$$

where $\gamma_{\mathrm{I}} = \frac{E_{\mathrm{I}}}{N_0}$ is the average signal-to-noise ratio (SNR) for the interuser channels. In (3), we assumed that the desired and interfering signals have the same average received energy. Setting $k = 0$ and replacing E_{I} and γ_{I} with E_{s} and $\gamma_{\mathrm{s}} = \frac{E_{\mathrm{s}}}{N_0}$, respectively, (3) becomes the SINR at the BS due to the reception of the jth subframe of user l. In the rest of the paper, the users' subscripts; namely, l and k will be removed from the SINR expression to simplify notation.

3. Performance Analysis

In this section, we derive the end-to-end average bit error probability for users in a coded cooperative network. Moreover, the bit error probability of a specific cooperation scenario is derived. Throughout the paper, the subscripts c, u, and b are used to denote conditional, unconditional and bit error probabilities, respectively.

3.1. Average Error Probability

In a cluster of J cooperating users, each user acts independently from his partners, not knowing whether his partners have decoded successfully his first subframe. In a cluster of size J, there are J^2 possible cooperation scenarios. The end-to-end error probability of a user is obtained by averaging the probability of error over two random variables. The first random variable, denoted by U, indicates the number of partners who were able to decode the first subframe of the user. The second variable, denoted by V, represents the number of partners whose first subframes were decoded successfully by the user. For example, if a user was able to decode the first subframes of v users, then he would use the remaining $J - 1 - v$ subframes to send his parity subframes that were not sent by his partners. This makes his code stronger since more parity bits are received at the BS. Furthermore, if u partners were able to decode the first subframe of a user, then the codeword of this user would consist of $(u + 1)$ subframes, each suffering from an independent fading realization. In order to simplify analysis, we assume that the effect of duplicate reception of subframes (from the user and one of his partners) is negligible, i.e., subframes are transmitted once through the cluster.

The end-to-end bit error probability averaged over all cooperation scenarios [22] is given by

$$P_{\mathrm{b}} = \sum_{v=0}^{J-1} \sum_{u=0}^{J-1} \binom{J-1}{v} \binom{J-1}{u} p_{v,u} P_{\mathrm{b}}(v, u), \tag{4}$$

where $P_{\mathrm{b}}(v, u)$ is the conditional bit error probability of a user given that $U = u$ and $V = v$, and $p_{v,u}$ is the probability of such cooperation scenario given by

$$p_{v,u} = E_\beta \left\{ [1 - P_B(\beta)]^{v+u} P_B(\beta)^{2J-2-v-u} \right\}, \tag{5}$$

where β is the SINR of the interuser channel and $P_B(\beta)$ is the frame error probability of the first subframe, which is upper bounded [11] as

$$P_B(\beta) \leq 1 - [1 - P_E(\beta)]^B, \tag{6}$$

where B is the number of trellis branches in the rate-R_1 codeword of the first subframe. In (6), $P_E(\beta)$ is the error event probability that is evaluated using the *limiting-before-averaging* approach [14] as

$$P_E(\beta) \leq \min\left\{1, \sum_{d=d_{\min}}^{L_1} a_d P_c(d|\beta)\right\}, \tag{7}$$

where a_d is the number of error events with a Hamming distance d from the all-zero codeword and $P_c(d|\beta) = Q(\sqrt{2d\beta})$ is the conditional pairwise error probability of a weight-d codeword over the interuser channel.

Among the different cooperation scenarios, it was found that the two extreme scenarios of *no cooperation* and *full cooperation* have the dominant probabilities, denoted as $p_{0,0}$ and $p_{J-1,J-1}$, respectively. Thus the performance of coded cooperation is dominated by the performance of these two cooperation scenarios. The probabilities $p_{0,0}$ and $p_{J-1,J-1}$ are listed in Table 1 for different cluster sizes with interference-limited and noise-limited interuser channels and different SNR values. We observe that for a fixed interuser channel quality, the probability of no cooperation increases as the cluster size increases, which causes the performance of large-size clusters to be worse than that of small-size clusters. As the uplink quality improves for a fixed interuser quality, small-size clusters are expected to outperform large-size clusters. This is because small-size clusters have a smaller probability of no cooperation which has a clear effect on the performance especially at high-uplink SNR as will be shown through the results in Section 4.

3.2. Conditional Error Probability

Conditioning on $U = u$ and $V = v$ has two consequences on the error performance of a user. First, the received codeword at the BS has a rate R_ξ, where $\xi = \max(J - v, u + 1)$, i.e., the rate of the received codeword is either R_{J-v} or R_{u+1}. This is due to the negligible effect of duplicate transmission of subframes because of the dominant performance of the no and full cooperation scenarios as discussed above. In this case, $\{c_d\}$ used in (8) are for the rate-R_ξ code. Second, given that $U = u$, each codeword is transmitted over $u + 1$ subframes, whose lengths are $\{L_j\}_{j=1}^{u+1}$ bits. Recall that each subframe is transmitted over an independent fading

Table 1. The probabilities of *no cooperation* and *full cooperation* scenarios for a J-user cluster over Rayleigh interuser channels with a network load of $G = 0.2$ and an interuser SNR of γ_I

Interuser channel	γ_I (dB)	$p_{v,u}$	$J = 2$	$J = 3$	$J = 4$
	10	$p_{0,0}$	0.0912	0.1281	0.1951
Noise-limited		$p_{J-1,J-1}$	0.8964	0.8355	0.7440
	∞	$p_{0,0}$	0	0	0
		$p_{J-1,J-1}$	1	1	1
	10	$p_{0,0}$	0.1859	0.2238	0.2951
Interference-limited		$p_{J-1,J-1}$	0.7964	0.7412	0.6425
	∞	$p_{0,0}$	0.1402	0.1515	0.1613
		$p_{J-1,J-1}$	0.8545	0.8434	0.8298

channel via one of the partners in a cluster. Thus, the pairwise error probability $P_u(v, u; d)$ is a function of the distribution of the d error bits over the $u+1$ subframes transmitted by the $u+1$ partners. Since the coded bits of each subframes may not be consecutive bits due to the puncturing used, this distribution is quantified assuming uniform distribution of the coded bits over the subframes [23] and is derived as follows.

Given $U = u$ and $V = v$ for a user in a cluster, the bit error probability of the corresponding convolutional code is upper bounded [20] as

$$P_{\mathrm{b}}(v, u) \leq \sum_{d=d_{\min}}^{L(v,u)} c_d P_u(v, u; d), \tag{8}$$

where $d_{\min}$ is the minimum distance of the code, c_d is the number of information bit errors in a codeword of weight d. In (8), $L(v, u)$ is the codeword length when $U = u$ and $V = v$ and $P_u(v, u; d)$ is the corresponding pairwise error probability for a weight-d codeword given by

$$P_u(v, u; d) = \sum_{\mathbf{w}} \frac{1}{\binom{L(v,u)}{d}} \prod_{j=1}^{u+1} \binom{L_j}{w_j} P_u(v, u; d|\mathbf{w}), \tag{9}$$

where $\mathbf{w} = \{w_j\}_{j=1}^{u+1}$ and w_j is the weight of the jth subframe, and $P_{\mathrm{c}}(v, u; d|\mathbf{w})$ is the conditional pairwise error probability for BPSK with coherent detection. It is given by

$$P_{\mathrm{c}}(v, u; d|\mathbf{w}) = Q\left(\sqrt{2\gamma_{\mathrm{s}} \sum_{j=1}^{u+1} w_j \beta_j}\right). \tag{10}$$

An exact expression of the pairwise error probability can be found by using the integral expression of the Q-function, $Q(x) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} e^{(-x^2/2\sin^2\theta)} d\theta$ [17] as

$$\begin{aligned} P_u(v, u; d|\mathbf{w}) &= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \mathrm{E}_{\{\beta\}}\left[\exp\left(-\alpha_\theta \sum_{j=1}^{u+1} w_j \beta_j\right)\right] d\theta \\ &= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \prod_{j=1}^{u+1} \Phi_\beta\left(w_j \alpha_\theta\right) d\theta, \end{aligned} \tag{11}$$

where $\alpha_\theta = \gamma_{\mathrm{s}}/\sin^2\theta$ and

$$\Phi_\beta(s) = \mathrm{E}_\beta\left[e^{-s\beta}\right], \tag{12}$$

is the moment generating function (MGF) of the random variable β and the product in (11) results from the independence of the fading processes affecting different subframes.

In order to find the MGF of β, we need to derive its pdf, which depends on the number of interfering users. The conditional pdf of the SINR given the number of interfering users is n

for integer values of the Nakagami parameter m [1] is found to be

$$f_{\beta|n}(\beta) = \frac{m^{m(1+n)}\beta^{m-1}e^{-m\beta}}{\Gamma(m)\Gamma(nm)} \sum_{h=0}^{m} \binom{m}{h} \frac{\Gamma(nm+h)}{(m\beta+m)^{nm+h}}, \quad \beta > 0. \tag{13}$$

Since the users are assumed to be active with probability p, the number of interfering users is a Binomial random variable with parameters p and N_u. Hence, the pdf of the SINR is found by averaging (13) over the statistics of the number of interfering users as follows

$$f_{\beta}(\beta) = \sum_{n=0}^{N_u} \binom{N_u}{n} p^n (1-p)^{N_u-n} f_{\beta|n}(\beta). \tag{14}$$

Therefore, the MGF of the SINR, β is given by

$$\Phi_{\beta}(s) = \sum_{n=0}^{N_u} \binom{N_u}{n} p^n (1-p)^{N_u-n} \Phi_{\beta|n}(s), \tag{15}$$

where $\Phi_{\beta|n}(s)$ is the conditional MGF of the SINR, β. For integer values of the Nakagami parameter m, $\Phi_{\beta|n}(s)$ [1] is given by

$$\begin{aligned}\Phi_{\beta|n}(s) =& \frac{m^m}{\Gamma(nm)} \sum_{h=0}^{m} \binom{m}{h} \frac{\Gamma(nm+h)}{m^h} \\ & \times U\left(m; m(1-n)-h+1; 1+\frac{m}{s}\right),\end{aligned} \tag{16}$$

where $U(.;.;.)$ is the confluent hypergeometric function of the second kind defined in [4]. The MGF required to evaluate (11) is found by substituting (16) in (15) and expressing $U(.;.;.)$ as

$$\begin{aligned}U(a;b;x) =& \frac{\pi}{\sin(\pi b)} \left[\frac{{}_1F_1(a,b;x)}{\Gamma(a-b+1)\Gamma(b)} \right. \\ & \left. - \frac{x^{1-b}}{\Gamma(a)\Gamma(2-b)} {}_1F_1(a-b+1, 2-b; x) \right],\end{aligned} \tag{17}$$

where ${}_1F_1(.,.;.)$ is the confluent hypergeometric function that is available in any numerical package such as MATLAB. Once the MGF is evaluated, the pairwise error probability is evaluated by substituting (15) in (11). The end-to-end bit error probability is then found by substituting (11) in (9) and then in (8) and (4). Note that due to the summation in (9), the union bound in (8) becomes complicated when d is large. Thus an approximation to the bit error probability is obtained by truncating (8) to a distance $d_{\max}$.

4. Numerical Results

In this section, we present numerical results generated using the analysis presented in Section 3. We consider coded cooperation with network loads of $G = 0.2$ and $G = 1$. The network load of $G = 0.2$ corresponds to $N_u = 20$ and $p = 0.01$, whereas the network load of $G = 1$ corresponds to $N_u = 40$ and $p = 0.025$. Within the network, coded cooperation with cluster sizes $J = 1, 2, 3, 4$ was considered. Each user employs a RCPC code from [5] with a memory order $M = 4$, puncturing period $P = 8$ and a mother code rate $R_J = \frac{1}{4}$. In all cases, the source block is $K = 128$ information bits. All the analytical results were obtained by truncating (8) to a distance $d_{\max} = 20$.

Figures 2–4 show the performance of coded cooperation over Rayleigh fading channels with different number of cooperating users for network loads of $G = 0.2$ and $G = 1$. In the figures, the bit error probability is shown against the uplink SNR in dB. Simulation results are shown in Figure 3 to verify the tightness of the proposed bound to simulation results. We observe that the gains obtained by increasing the number of cooperating users decrease as the network load increases. This is expected since diversity becomes less important to the performance as the interference level increases.

At high-uplink SNR the bit error probability suffers from an error floor due to interference, and the error floor decreases as the number of cooperating users increases. This applies especially for the case of perfect interuser channels as shown in Figure 2, i.e., no interference or noise in the interuser channels. Note that the assumption of perfect interuser channels yields the best performance resulting from coded cooperation. Figures 3 and 4 show the results for the cases of interference-limited and noise-limited interuser channels, respectively. We observe that when interuser channels suffer from noise or interference, the performance of large clusters degrades as the uplink SNR increases. This is because at high SNR the performance becomes limited by the performance of the no cooperation scenario, whose probability increases with the cluster size as shown in Table 1. From the figures, as the uplink SNR exceeds 5 dB, four cooperating users start to perform worse than three cooperating users, whereas they become worse than two cooperating users as uplink SNR exceeds 15 dB.

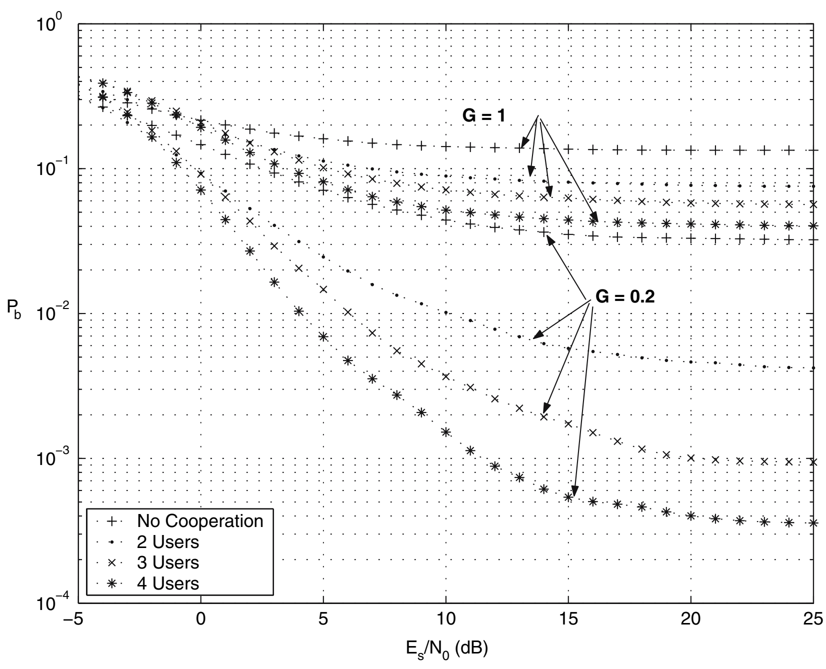

Figure 2. Analytical bit error probability of coded cooperation in Nakagami fading with $m = 1$ (Rayleigh fading) with network loads of $G = 0.2$, 1 and perfect interuser channels.

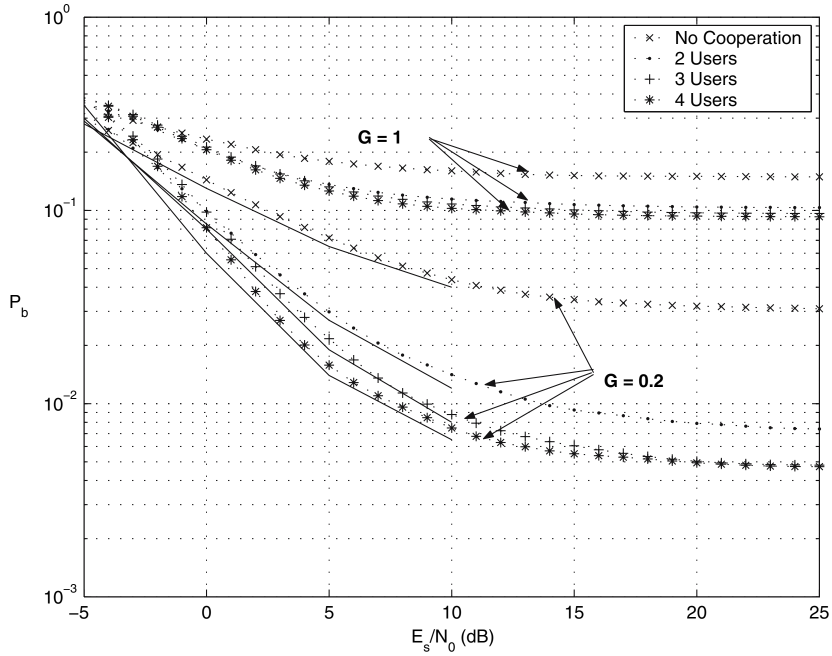

Figure 3. Bit error probability of coded cooperation in Nakagami fading with $m = 1$ (Rayleigh fading) with network loads of $G = 0.2$, 1 and interference-limited interuser channels. (dashed: approximation, solid: simulation.)

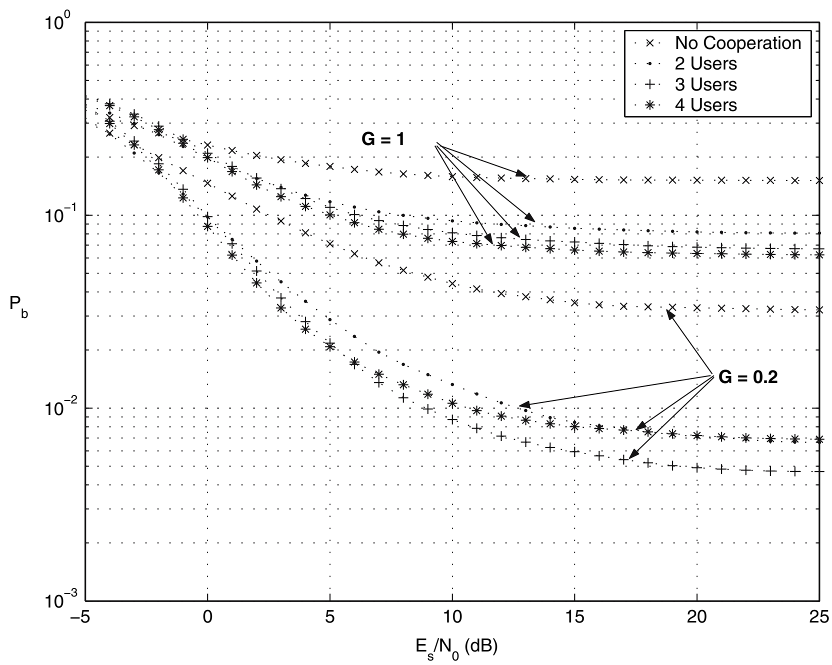

Figure 4. Analytical bit error probability of coded cooperation in Nakagami fading with $m = 1$ (Rayleigh fading) with network loads of $G = 0.2$, 1 and noise-limited interuser channels with $\gamma_I = 10\,\text{dB}$.

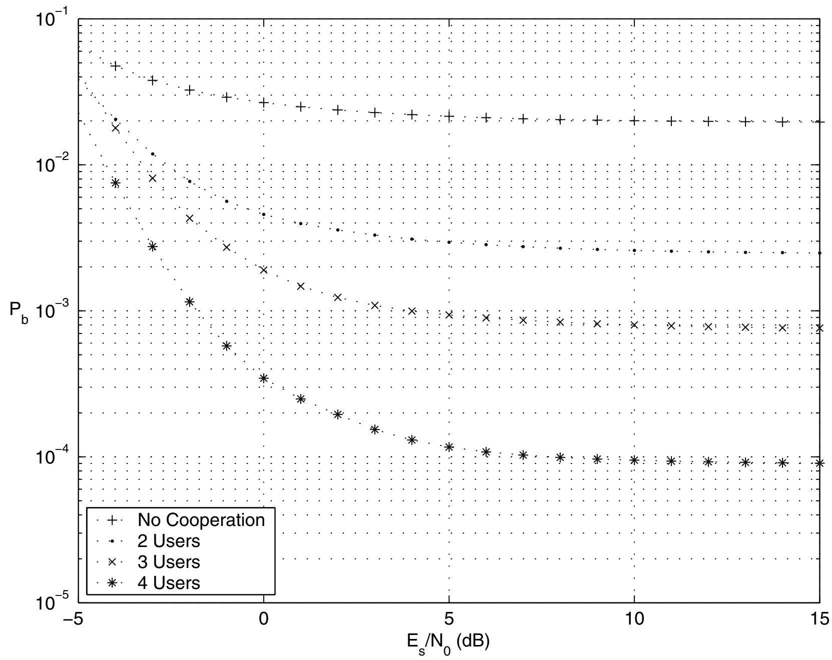

Figure 5. Analytical bit error probability of coded cooperation in Nakagami fading with $m = 5$ and a network load of $G = 0.2$ and perfect interuser channels.

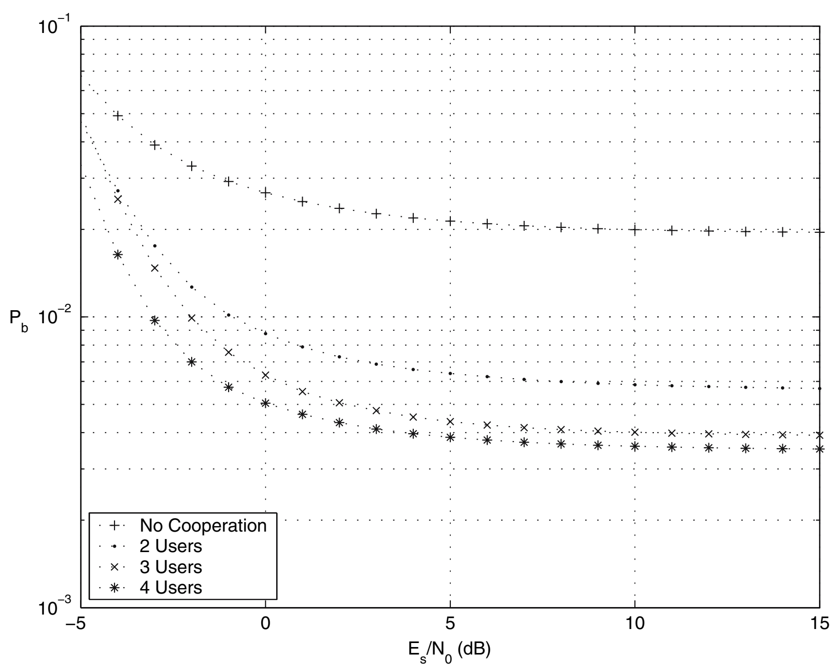

Figure 6. Bit error probability of coded cooperation in Nakagami fading with $m = 5$ and a network load of $G = 0.2$ and interference-limited interuser channels.

Figures 5 and 6 show the results for coded cooperation in Nakagami fading with $m = 5$ and a network load of $G = 0.2$. As discussed above, the performance gain of large clusters decreases as the interuser channels become more noisy. However, counter to the above observation, small clusters do not tend to outperform large clusters as the uplink SNR increases. This is mainly because the interuser channels are distributed according to Nakagami fading with a large Nakagami parameter, $m = 5$, which makes the probability of correct decoding of the first subframe large compared to the case of Rayleigh fading. Therefore, large clusters start to outperform small clusters as the interuser channels become less faded, i.e., Nakagami with a large value of m.

5. Conclusions

The performance of coded cooperation networks was analyzed in Nakagami fading under interference conditions. Results show that gains obtained by increasing the number of cooperating users decrease with increasing the network load. Furthermore, two cooperating users provide the best performance when the interuser channels are bad. On the other hand, the performance of large number of cooperating users improves as the Nakagami parameter increases.

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