AN ADAPTIVE PROTOCOL FOR COOPERATIVE COMMUNICATIONS ACHIEVING ASYMPTOTIC MINIMUM SYMBOL-ERROR-RATE

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ABSTRACT

This paper investigates the protocol design issue for cooperation systems in wireless communications. A tight approximate symbol error rate (SER) for such systems is derived and analyzed. Based on such analysis, an optimum power allocation scheme is proposed by optimizing the derived approximate SER subject to fixed transmission rate and total transmit power constraints. Then, a novel adaptive protocol is proposed for cooperative communications based on minimizing the asymptotic SER (i.e. in an averaging sense under high-enough SNR regimes) of such systems. This proposed adaptive protocol is able to achieve the maximum achievable diversity gain available in such systems without sacrificing any transmission rate or the total transmit power, and optimally adapts the number of cooperation partners under the changing environments. Simulation results show that the proposed adaptive protocol provides a lower SER compared with existing protocols. In addition, the proposed adaptive protocol with optimum power allocation can remarkably enhance the SER performance in comparison with the equal power allocation scheme.

1. INTRODUCTION

In the future wireless communications, high data-rate transmission services with broad coverage areas is highly demanded [1, 2]. It has been well-known that a multiple-input multiple-output (MIMO) system is one of prominent communication schemes making such demands a reality. However, given the current technology, equipping more antennas to the handheld devices is far from practical implementation. Recently, a generalized MIMO system called cooperative communication [1, 2] has been proposed for realizing the advantages of the conventional MIMO system, e.g. the diversity gain. By the cooperation of the active users equipped with a single antenna in the wireless networks, the generalized MIMO system can be established in a distributed fashion. In addition, the coverage range of such communication is also expanded, which results in less power consumption for a particular user who communicates with far-away destinations, and in turn prolongs a battery life.

Recently, various protocols have been proposed for the cooperation system [1]-[3], in which each user acts as a relay to assist other users transmit their information. A relay can either amplify the received signal and forward it, or decode the received signal first and then forward it. In addition, outage probability performance has been analyzed for such cooperation systems. The direct benefit of cooperatively working with more users is the diversity gain that comes at the price of the reduced transmission rate since the cooperation partners need to sacrifice their time slots for transmitting the source information. In the other words, the larger number of cooperation users, the more diversity gain but the less transmission rate. Furthermore, given a fixed transmission rate, the optimal guideline for choosing the best cooperation partners when there are more than 2 active users in the cooperation system are not fully discovered. These are the motivations of this paper. To address these concerns, the main contributions of this paper are as follows,

- We propose an adaptive protocol for the cooperation system, based on minimizing an asymptotic SER, i.e. in an averaging sense under high-enough SNR regimes, of such system. The proposed protocol can achieve the maximum achievable diversity gain available in such system without sacrificing any transmission rate or total transmit power. Furthermore, this proposed adaptive protocol is able to optimally adapt the number of cooperation partners corresponding to the changing environment and users' mobility.
- We present a tight approximate SER analysis and an optimum power allocation scheme for such systems.
- We can show that in low signal-to-noise (SNR) regimes, a noncooperation strategy is preferred, whereas in high SNR regimes, the more number of cooperation partners results in a better error probability performance enhancement.

The rest of this paper is organized as follows. In Section 2, we describe the channel and system models to be considered. In section 3, we analyze the SER for three different cooperation strategies, including a noncooperation strategy with BPSK modulation, a 1-relay cooperation strategy with QPSK modulation, and a 2-relay cooperation strategy with 8-PSK modulation. The optimum power allocation issue is addressed in Section 4. Then, we propose the asymptotic minimum SER adaptive protocol for the cooperation system in Section 5. The simulation results are shown in Section 6, and we conclude this paper in Section 7.

2. CHANNEL AND SYSTEM MODELS

For the sake of exposition, we consider cooperative communications in a wireless network with two phases, three users (i.e. one user acts as a source node and the other users act as relay nodes), and one destination. In Phase I, user 1 transmits a modulated signal to its destination, while user 2 and user 3 also receive this transmitted signal due to a broadcast nature of wireless channels. In Phase II, user 2 and user 3, or either of them relay the received signal to user 1's destination in an amplify-and-forward fashion. Likewise, in the next communication periods, user 2 and user 3 act as the source node, respectively, and the other users act as the relay nodes. In both phases, all users transmit signals through orthogonal channels by using time-division multiplexing (TDMA), frequency-division multiplexing (FDMA), or code-division multiplexing (CDMA) scheme [1]-[5]. Due to the symmetry of the three users, we will analyze only user 1's performance by considering user 1 as the source node, user 2 as relay 1, and user 3 as relay 2. In this study, we employ an M-PSK modulation scheme. In order to maintain a fixed transmission rate, e.g. rate=1, an adaptive modulation scheme is considered. Specifically, for a noncooperation strategy where no relay nodes are employed, BPSK modulation is used. For a 1-relay cooperation strategy where either relay 1 or relay 2 is employed,

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QPSK modulation is used. Finally, for a 2-relay cooperation strategy where both relay 1 and relay 2 are employed, 8-PSK modulation is used. In general, for an arbitrary transmission rate, the constellation of the adaptive modulation can be adjusted accordingly. We also consider the half-duplex communication system, i.e. a transceiver transmits or receives the signal in separate time slots, with two periods: an acquisition period and a transmission period. During the acquisition period, the source node determines the cooperation partners as well as the optimum power allocation strategy, and then send its cooperation strategy decision to the destination and the corresponding relay nodes via some control channels. During the transmission period, the source and relay nodes cooperatively communicate with the destination. Here since we focus on a fixed transmission rate of 1, and there are 3 users in the cooperation system, the number of data packets in each transmission period with certain cooperation strategy must be in an order multiple of $6i,\ i \in \mathbb{I}$, so that all cooperation strategies' communications will be terminated at the end of the transmission period simultaneously. In addition, the total transmit power P per data packet is fixed for all cooperation strategies.

In Phase I, the source node broadcasts its transmit signal to the destination and the relay nodes. The received signal z_{1B} at the destination, z_{12} at relay 1, and z_{13} at relay 2 can be expressed as follows,

$$z_{1B} = \sqrt{P_1}h_{1B}u + n_{1B}, \tag{1}$$
$$z_{12} = \sqrt{P_1}h_{12}u + n_{12}, \tag{2}$$
$$z_{13} = \sqrt{P_1}h_{13}u + n_{13}, \tag{3}$$

where P_1 is the transmit power of the source node; u is the transmitted symbol; h_{1B}, h_{12}, and h_{13} are the channel coefficients from the source to the destination, relay 1, and relay 2, respectively; and n_{1B}, n_{12}, and n_{13} are the additive noises modelled as zero-mean, complex Gaussian random variables with variance N_0. In Phase II, the relay nodes amplify the received signals and forward them to the destination with the transmit power $\tilde{P}_2$ and $\tilde{P}_3$ for relay 1 and relay 2, respectively. The received signal at the destination in this phase can be written as

$$y_{2B} = \frac{\sqrt{\tilde{P}_2}}{\sqrt{P_1|h_{12}|^2+N_0}}h_{2B}z_{12} + n_{2B}, \tag{4}$$
$$y_{3B} = \frac{\sqrt{\tilde{P}_3}}{\sqrt{P_1|h_{13}|^2+N_0}}h_{3B}z_{13} + n_{3B}, \tag{5}$$
$$\tilde{P}_2 = \begin{cases} 0;\ \text{If relay 1 is not selected} \\ P_2;\ \text{Otherwise.} \end{cases},$$
$$\tilde{P}_3 = \begin{cases} 0;\ \text{If relay 2 is not selected} \\ P_3;\ \text{Otherwise.} \end{cases},$$

where h_{2B} and h_{3B} are the channel coefficients from relay 1 and relay 2 to the destination, respectively; and n_{2B} and n_{3B} are also additive Gaussian noises with zero-mean and variance N_0. In addition, the channel coefficients $h_{1B}, h_{2B}, h_{3B}, h_{12}$, and h_{13} are modelled as zero-mean, complex Gaussian random variables with variances $\delta_{1B}^2, \delta_{2B}^2, \delta_{3B}^2, \delta_{12}^2$ and δ_{13}^2, respectively. These channel coefficients, assumed known to both the source node and the destination, are to be used in determining cooperation partners and optimum power allocation at the source node during the acquisition period, and in performing the maximum-ratio combining (MRC) [6] to combine all received signals y_{1B}, y_{2B}, and y_{3B} together at the destination during the transmission period.

3. SYMBOL ERROR RATE (SER) ANALYSIS

In this section, we derive a closed-form approximation of the SER for cooperation systems with the M-PSK modulation. The output of the MRC detector at the destination can be expressed as follows [6],

$$y = a_1 z_{1B} + a_2 y_{2B} + a_3 y_{3B}, \tag{6}$$
$$a_1 = \sqrt{P_1}h_{1B}^*/N_0,$$
$$a_2 = \begin{cases} 0;\ \text{If relay 1 is not selected} \\ \frac{\sqrt{\frac{P_1\tilde{P}_2}{P_1|h_{12}|^2+N_0}}h_{12}^*h_{2B}^*}{\left(\frac{\tilde{P}_2|h_{2B}|^2}{P_1|h_{12}|^2+N_0}+1\right)N_0};\ \text{Otherwise.} \end{cases},$$
$$a_3 = \begin{cases} 0;\ \text{If relay 2 is not selected} \\ \frac{\sqrt{\frac{P_1\tilde{P}_3}{P_1|h_{13}|^2+N_0}}h_{13}^*h_{3B}^*}{\left(\frac{\tilde{P}_3|h_{3B}|^2}{P_1|h_{13}|^2+N_0}+1\right)N_0};\ \text{Otherwise.} \end{cases}$$

Assuming that the transmitted symbol u has a unit average energy, then the approximate SNR of the MRC output can be written as follows [6, 5],

$$\gamma \approx \gamma_1 + \gamma_2 + \gamma_3, \tag{7}$$

where $\gamma_1 = P_1|h_{1B}|^2/N_0,\ \gamma_2 = \frac{P_1\tilde{P}_2|h_{12}|^2|h_{2B}|^2}{N_0\left(P_1|h_{12}|^2+\tilde{P}_2|h_{2B}|^2\right)},\ \gamma_3 = \frac{P_1\tilde{P}_3|h_{13}|^2|h_{3B}|^2}{N_0\left(P_1|h_{13}|^2+\tilde{P}_3|h_{3B}|^2\right)}$. It is worth noticing that γ_2 and γ_3 are the harmonic mean of $\frac{P_1|h_{12}|^2}{N_0}$ and $\frac{\tilde{P}_2|h_{2B}|^2}{N_0}$; and $\frac{P_1|h_{13}|^2}{N_0}$ and $\frac{\tilde{P}_3|h_{3B}|^2}{N_0}$, respectively.

The conditional SER with the channel coefficients $h_{1B}, h_{2B}, h_{3B}, h_{12}, h_{13}$ for the cooperation system employing the M-PSK modulation can be expressed as follows [7],

$$P_{PSK}^{h_{1B},h_{2B},h_{3B},h_{12},h_{13}} = \frac{1}{\pi}\int_0^{(M-1)\pi/M} \exp\left(-\frac{g_{PSK}\gamma}{\sin^2(\theta)}\right)d\theta, \tag{8}$$

where $g_{PSK} = \sin^2(\frac{\pi}{M})$.

Averaging this conditional SER over the Rayleigh fading channels and using a tight upper bound on SER derived in [4], we can derive the approximate SER of such system as follows. First, for the noncooperation strategy, we can show that the approximate SER with the BPSK modulation can be written as,

$$P_{BPSK} \approx \frac{N_0}{4P\delta_{1B}^2}. \tag{9}$$

Second, for the 1-relay cooperation strategy where relay 1 is selected, we can show that the approximate SER with the QPSK modulation can be written as,

$$P_{QPSK}^{relay\ 1} \approx 4CN_0^2 \cdot \frac{P_1\delta_{12}^2 + P_2\delta_{2B}^2}{P_1^2P_2\delta_{1B}^2\delta_{2B}^2\delta_{12}^2}, \tag{10}$$

where $C = \left[\frac{9}{32} + \frac{1}{4\pi}\right]$ and $P = P_1 + P_2$. Likewise, for the 1-relay cooperation strategy where the relay 2 is selected, we can show that the approximate SER with the QPSK modulation can be written as follows,

$$P_{QPSK}^{relay\ 2} \approx 4CN_0^2 \cdot \frac{P_1\delta_{13}^2 + P_3\delta_{3B}^2}{P_1^2P_3\delta_{1B}^2\delta_{3B}^2\delta_{13}^2}, \tag{11}$$

where $P = P_1 + P_3$.

Finally, for the 2-relay cooperation strategy, we can show that the approximate SER with the 8-PSK modulation can be written as,

$$P_{8PSK} \approx \frac{DN_0^3}{E} \cdot \frac{\left(P_1\delta_{12}^2 + P_2\delta_{2B}^2\right)\left(P_1\delta_{13}^2 + P_3\delta_{3B}^2\right)}{P_1^3P_2P_3\delta_{1B}^2\delta_{2B}^2\delta_{3B}^2\delta_{12}^2\delta_{13}^2}, \tag{12}$$

where $D = \left[\frac{-13}{128} + \frac{23}{12\sqrt{2}}\right]$, $E = \frac{1}{2}\left[1 - \frac{1}{\sqrt{2}}\right]$, and $P = P_1 + P_2 + P_3$.

4. OPTIMUM POWER ALLOCATION

In this section, we present the optimum power allocation strategy for the cooperation systems. The optimization objective is to minimize the approximate SER with respect to users' power subject to a fixed total power constraint. For the sake of simplicity, we normalize the total power P to be 1 W. First, for the noncooperation strategy, the entire power is dedicated to the source node only, hence, the optimum power allocation is given by

$$P_1 = 1. \tag{13}$$

Second, for the 1-relay cooperation strategy, say relay 1 is selected, the optimization objective is to minimize (10) with respect to P_1 and P_2, given by

$$\arg\min_{P_1,P_2} \ln\left(\frac{P_1\delta_{12}^2 + P_2\delta_{2B}^2}{P_1^2 P_2}\right) \quad \text{s.t.} \quad P_1 + P_2 = 1. \tag{14}$$

By applying a Lagrange multiplier approach to (14), the optimum power allocation can be obtained as,

$$P_1 = \frac{4\delta_{2B}^2}{(4\delta_{2B}^2 - \delta_{12}^2) + \delta_{12}\sqrt{8\delta_{2B}^2 + \delta_{12}^2}} \text{ and } P_2 = 1 - P_1. \tag{15}$$

Similarly, if relay 2 is selected, then the optimum power allocation can be derived as,

$$P_1 = \frac{4\delta_{3B}^2}{(4\delta_{3B}^2 - \delta_{13}^2) + \delta_{13}\sqrt{8\delta_{3B}^2 + \delta_{13}^2}} \text{ and } P_3 = 1 - P_1. \tag{16}$$

Finally, for the 2-relay cooperation strategy, the optimization objective is to minimize (12) with respect to P_1, P_2, and P_3, represented as

$$\arg\min_{P_1,P_2,P_3} \ln\left(\frac{(P_1\delta_{12}^2 + P_2\delta_{2B}^2)(P_1\delta_{13}^2 + P_3\delta_{3B}^2)}{P_1^3 P_2 P_3}\right)$$
$$\text{s.t.} \quad P_1 + P_2 + P_3 = 1. \tag{17}$$

Likewise, by applying a Lagrange multiplier approach to (17), the optimum power allocation is as follows,

$$\begin{aligned}
&P_1 = \frac{3P_2^2\delta_{2B}^2}{(1-3P_2)\delta_{12}^2},\\
&[C_1^2 A - 3C_1C_2 + 9C_4]P_2^4 + [C_1(-3C_3 + C_2) - 24C_4]P_2^3\\
&+[C_1C_3 + 22C_4]P_2^2 - 8C_4P_2 + C_4 = 0, \text{ where } P_2 \in [0,1],\\
&C_1 = \frac{3\delta_{2B}^2}{\delta_{12}^2}, C_2 = 6\delta_{3B}^2 - 3\delta_{13}^2, C_3 = 2\delta_{13}^2 - 6\delta_{3B}^2,\\
&C_4 = 3\delta_{3B}^2, \text{ and } A = 3(\delta_{3B}^2 - \delta_{13}^2),\\
&P_3 = 1 - P_1 - P_2.
\end{aligned} \tag{18}$$

Since we have to solve for the roots of the 4^{th}-order linear equation to obtain P_2, there may exist many roots satisfying $P_2 \in [0,1]$. Therefore, all possible roots P_2's and the corresponding P_1 and P_3 need to be thoroughly compared for determining the optimum power allocation that yields a minimum value to (17) given such total power constraint. Due to the space limitation, the detail derivations in section 3 and 4 are omitted. The interested readers are encouraged to contact the authors directly.

5. THE PROPOSED ASYMPTOTIC MINIMUM SER-BASED ADAPTIVE PROTOCOL

Now let us describe the proposed asymptotic minimum SER-based adaptive protocol in details. For the cooperation system being studied, the transmission rate and the total transmit power are fixed. Hence, the most desirable protocol given these constraints is the protocol that is able to achieve the asymptotic minimum error probability, e.g. SER, in an averaging sense under high-enough SNR regimes, expressed as

$$\arg \min_{\text{number \& index of cooperation partners}} Pr(error)$$
$$\text{s.t. fixed transmission rate and total transmit power constraints.} \tag{19}$$

Therefore, our goal is to design an effective adaptive protocol achieving the asymptotic minimum SER, and it must be able to adaptively choose the number of cooperation partners according to the changing environment and the mobility of users. Our motivation is that if we assume a short term statistics [6] of the channel, i.e. channel variances, within a certain period of time to be known to the source node, then the source node can evaluate the best cooperation partners, i.e. the relay nodes, by choosing the best cooperation strategy yielding the asymptotic minimum SER to the destination. Technically, this adaptive protocol operation is equivalent to finding the best tradeoff between a coding gain, obtained through a variable minimum Euclidean distance of the adaptive modulation constellation chosen, and a diversity gain, obtained through a variable number of cooperation partners in each transmission period, that results in the asymptotic minimum SER. The procedures of the proposed adaptive protocol can be described as follows,

1. The source node acquires a short-term channel variances, i.e. $\delta_{1B}^2, \delta_{2B}^2, \delta_{3B}^2, \delta_{12}^2$, and δ_{13}^2, within the acquisition period. This channel variances will be used as if they were the exact short-term channel variances during the upcoming transmission period given that the channel is slowly varying. In this paper, at the first step, we assume such channel variances to be known in advance before transmitting the signal at the source node. Therefore, this study will serve as a theoretical performance bound for practice protocols. In reality, such channel variances can be obtained through an instantaneous SNR estimation, which is our future work.
2. The source node determines the optimum power allocation derived in Section 4 for the noncooperation strategy, the 1-relay cooperation strategy, and the 2-relay cooperation strategy.
3. The source node calculates the approximate SER derived in Section 3 for such cooperation strategies, and then compares them all. The best cooperation strategy that results in the asymptotic minimum SER will be chosen for the upcoming transmission period.
4. The source node notifies the chosen cooperation partners and the destination about the cooperation strategy decision via some control channels.

Therefore, the proposed adaptive protocol can achieve the asymptotic minimum SER without sacrificing the transmission rate and the total transmit power. This advantage stems from the fact that the proposed adaptive protocol always chooses the best cooperation strategy yielding the minimum SER in each transmission period, hence, in average under high-enough SNR regimes, the asymptotic minimum SER is achieved. Computer simulations are used to illustrate this advantage.

6. SIMULATION RESULTS

In this section, based on simulations, performance evaluation of the proposed adaptive protocol is conducted. Adaptive modulation with BPSK, QPSK, and 8-PSK constellations are employed. The total transmit power is fixed to be P=1 W, and the bandwidth efficiency is 1 bit/s/Hz. In addition, one transmission period consists of 6 data packets so that all cooperation strategies' communications will be terminated at the end of the transmission period simultaneously. In this study, we assume that the variance of the noises is 1, i.e. N_0=1. The variance of the channel links between source node and destination, relay 1 and destination, and relay 2 and destination are $\delta_{1B}^2 = 1, \delta_{2B}^2 = 1$, and $\delta_{3B}^2 = 1$, respectively. The variance of the channel link between source node and the relay 1 is $\delta_{12}^2 = 10$, and between source node and the relay 2 is $\delta_{13}^2 = 5$. For a fair comparison, we illustrate the average SER curves as function of P/N_0.

In Fig.1, we show the simulated average SER versus SNR(dB) for different cooperation strategies, including the noncooperation strategy, the 1-relay cooperation strategy, and the 2-relay cooperation strategy, and the proposed adaptive protocol with both the equal and optimum power allocation schemes. For comparison, the approximate

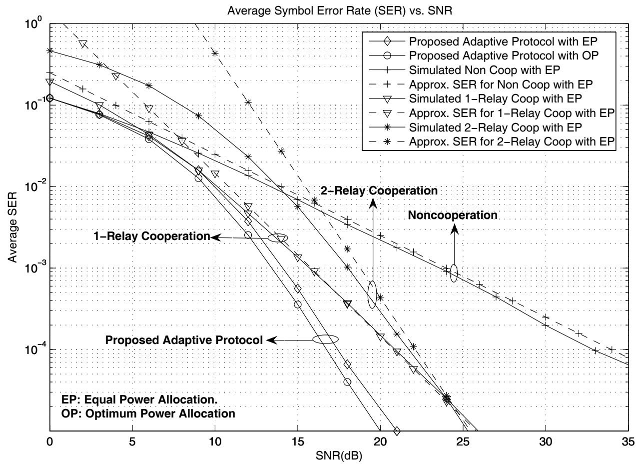

Fig. 1. The curves of the simulated and approximate average SER with different cooperative protocols.

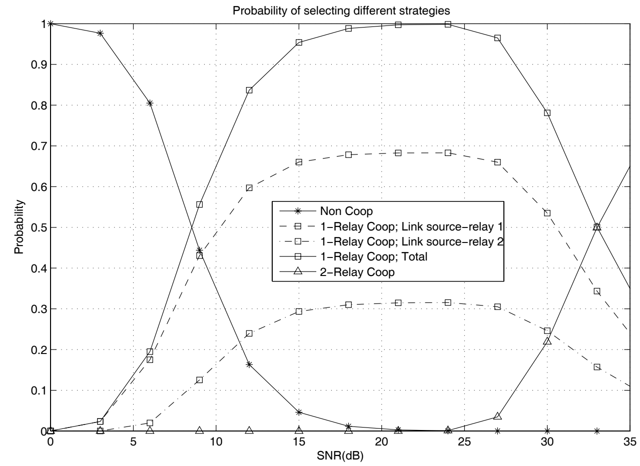

Fig. 2. The curves of the probability of selecting different cooperation strategies.

SER curves derived in Section 3 are also shown. It is worth noticing that the proposed adaptive protocol employing the equal power allocation achieves the maximum diversity of 3 available in the simulated cooperation system, and yields a lower SER. For instance, the SNR differences of 15 dB, 4 dB, and 5 dB at SER of 10^{-4} are observed when compared with the noncooperation strategy, the 1-relay cooperation strategy, and the 2-relay cooperation strategy, respectively. It is also worth noticing that the proposed adaptive protocol with the optimum power allocation can further remarkably improve the SER performance, where a SNR difference of 1 dB at SER of 10^{-4} compared with the proposed protocol with the equal power allocation is observed. Note that the approximate SERs are tight to the corresponding simulated SERs in high-enough SNR regimes; as a result, the proposed adaptive protocol yields the minimum SER in an asymptotic sense. Although it is suboptimal in low SNR regimes, but it still performs well. This result comes from the fact that the approximate SER curves are ordered in the descending order fashion, ranging from the 2-relay cooperation strategy down to the noncooperation strategy; as a result, the noncooperation strategy is always chosen in low SNR regimes as we expected. This is also consistent with our intuition since, in low SNR regimes, more cooperation partners could harm the error probability of the cooperation system, please see the simulated SER curves, because the diversity gain cannot outweigh the loss in the coding gain due to a smaller Euclidean distance of the adaptive modulation constellation chosen.

In Fig.2, we illustrate the probability of selecting different cooperation strategies. It is clear that in low SNR regimes, the noncooperation strategy is dominant. However, in high-enough SNR regimes, the 1-relay cooperation strategy is dominant instead. In extremely high SNR regimes, the 2-relay cooperation strategy is dominant. These results claim that the coding gain outweighs the diversity gain in low SNR regimes, whereas the diversity gain outweighs the coding gain in high-enough SNR regimes.

7. CONCLUSION

In this paper, we have proposed an asymptotic minimum SER-based adaptive protocol for the cooperation system. The proposed adaptive protocol is able to achieve the maximum achievable diversity gain available in such system without sacrificing any transmission rate or total transmit power. The optimum power allocation strategy and the approximate SER have also been investigated. Experimental results indicated that the proposed adaptive protocol provides the lowest SER compared with existing protocols, where the SNR differences of 15 dB, 4 dB, and 5 dB at the SER of 10^{-4} compared with the noncooperation strategy, the 1-relay cooperation strategy, and the 2-relay cooperation strategy, respectively, are observed. It has also been shown that in low SNR regimes, the noncooperation strategy is preferred since the diversity gain cannot outweigh the loss of the coding gain due to a smaller Euclidean distance of the adaptive modulation constellation chosen, whereas in high SNR regimes, more cooperation partners result in a better SER performance due to the diversity gain. In addition, the proposed adaptive protocol with optimum power allocation strategy could remarkably improve the SER performance when compared with the equal power allocation scheme, where the SNR difference of 1 dB at the SER of 10^{-4} was observed.

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