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Research Article

Partial Cooperation Based on Dynamic Transmit Antennas for Two-Hop Massive MIMO Systems

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As the ever-increasing attention to green communication, energy efficiency has become an imperative metric in the emerging massive multiple-input multiple-output (MIMO) systems. In order to maximize the energy efficiency, transmit antenna selection has been widely concerned by researchers. In this paper, we investigate the coded cooperation transmission for dynamic transmit antennas aided two-hop massive MIMO systems. Explicitly, we propose a rate-less codes aided cooperation scheme for reducing the implementation complexity in the broadcast phase, compared to the fixed-rate coded cooperation scheme. Furthermore, we develop a partial cooperation scheme in the cooperative phase in order to avoid the low achievable rate caused by the full cooperation, especially when the source-to-relay (S-R) channels are poor. Finally, the number of transmit antennas at the base station (BS) is optimized through theoretical analysis in a metric of maximizing the energy efficiency. Moreover, we also analyze the achievable error performance for different modulations. Our simulation results demonstrate the effectiveness of the proposed scheme.

1. Introduction

Massive multiple-input multiple-output (MIMO) [1] is an emerging technology that exploits hundreds of antennas at the base station (BS) for offering degree of freedom [2], which is capable of meeting the high-data-rate requirement of the fifth-generation (5G) communications [3]. Intuitively, the power consumption is heightening upon increasing the number of antennas, which is caused by adopting a separate radio frequency (RF) chain for each antenna at the BS [4]. Therefore, transmit antenna selection has attracted significant attention both for reducing the RF chain and for improving the energy efficiency [5]. Coded cooperation achieves impressive gains by integrating cooperative signaling with channel coding. Existing coded cooperation schemes are mainly based on conventional fixed-rate channel codes [6], such as Turbo and low density parity check (LDPC). However, when the fixed-rate coded cooperation is applied for the downlink of two-hop massive MIMO system, huge codebooks have to be remembered both at the transmitter and the receiver due to the dynamic transmit antennas pattern. Furthermore, for frequency-division duplexing (FDD) based massive MIMO systems, each terminal estimates its own channel state information (CSI) during the downlink training phase and feeds back the estimation via the reverse uplink channel to the BS. However, acquiring the perfect CSI is a challenging task in time-varying massive MIMO systems [2, 6]. Moreover, the feedback error and feedback overhead may also degrade the achievable system performance. Hence, the fixed-rate coded cooperation is sensitive to the variation of channel statistics, unless it is operated at a very low rate [7]. Therefore, how to design the coded cooperation schemes based on dynamic transmit antennas in the downlink of two-hop massive MIMO systems is considerably challengeable.

Unlike fixed-rate coded cooperation, rate-less codes aided cooperation is capable of adaptively adjusting the code rates depending on the channel quality without explicit CSI at the transmitter [8]. In conventional downlink of two-hop massive MIMO systems, the overall transmission of rate-less codes aided cooperation is divided into the broadcast phase and the cooperative phase [9]. In the broadcast phase, the BS obtains the optimal cooperative antennas by exploiting transmit antenna selection algorithm for maximizing the energy efficiency. Then, the selected antennas, namely, the cooperative systems, keep on transmitting their own coded symbols. When the relay station (RS) successfully decodes at least one of the destinations' information, it independently starts the cooperative phase and sends the reencoded symbols to the destination. Therefore, the cooperative phase cannot start unless the RS has successfully decoded, which is called full cooperation scheme. However, it will lead to a low achievable rate, especially when the source-to-relay (S-R) channels are poor. To overcome this problem, we propose a partial cooperation scheme based on dynamic transmit antennas for two-hop massive MIMO systems.

The novelties of the paper are as follows. Firstly, compared with the fixed-rate coded cooperation scheme, the rate-less codes aided cooperation is adopted in the broadcast phase. When the fixed-rate coded cooperation is applied, huge codebooks have to be memorized both at the transmitter and the receiver caused by the transmit antenna selection to maximize the energy efficiency, while the rate-less codes aided cooperation is capable of adaptively adjusting the cooperative rate as well as reducing the implementation complexity. Secondly, unlike earlier full cooperation scheme, cooperative phase is started regardless of whether the decoded signal received from the source is correct or not in the proposed partial cooperation scheme, which can avoid the low achievable rate caused by the full cooperation, especially when the S-R channels are poor.

The rest of this paper is organized as follows. The system model is presented in Section 2. The proposed partial cooperation scheme based on dynamic transmit antennas is depicted in Section 3. And the simulation results are discussed in Section 4. Finally, concluding remarks are provided in Section 5.

2. System Model

In this section, we consider the downlink of two-hop massive MIMO system equipped with N_t transmit antennas at the BS, a single receive/transmit antenna at the RS, and N_r receive antennas for each user. Particularly, N_r equals one in this paper.

During the broadcast phase, the signal is encoded and modulated as M-ary quadrature amplitude modulation (M-QAM) at the BS. Assume that the channel is flat fading, and the received signal at the RS is given by

$$\mathbf{y_{sr}} = \sqrt{G_{sr}}\sqrt{P_s}\mathbf{H_{sr}}\mathbf{s_{sr}} + \mathbf{n_{sr}} \tag{1}$$

where G_{sr} is the S-R path loss related power gain, P_s is the transmit power at the BS, $\mathbf{H_{sr}}$ is the channel matrix, and its $1 \times N_t$ entries are independent identical distribution (i.i.d) complex circular symmetric Gaussian random variables with zero mean and unit variance, and $\mathbf{n_{sr}}$ is the additive white Gaussian noise. $\mathbf{s_{sr}}$ is the transmitted signal, while $\mathbf{y_{sr}}$ is the received signal.

During the cooperative phase, the received signal $\mathbf{y_{sr}}$ is demodulated and decoded by the RS. In the full cooperation scheme, the cooperative phase is started only when the RS successfully decodes at least one destination's information. Similarly, the relay-to-destination (R-D) channel is flat fading, and then the received signal at the destination is expressed as

$$\mathbf{y_{rd}} = \sqrt{G_{rd}}\sqrt{P_r}\mathbf{H_{rd}}\mathbf{s_{rd}} + \mathbf{n_{rd}} \tag{2}$$

where G_{rd} is the R-D path loss related power gain, P_r is the transmit power at the RS, $\mathbf{H_{rd}}$ is the i.i.d complex circular symmetric Gaussian random variable with zero mean and unit variance, and $\mathbf{n_{rd}}$ is the additive white Gaussian noise. $\mathbf{s_{rd}}$ is the forwarded signal of the source signal $\mathbf{s_{sr}}$, whilst $\mathbf{y_{rd}}$ is the received signal at the destination. Finally, the received signal $\mathbf{y_{rd}}$ is demodulated and decoded at the destination.

As discussed above, the full cooperation of the rate-less codes aided scheme does not require plenty of codebooks to be stored both at the transmitter and at the receiver. Thus, the implementation complexity is reduced compared to the fixed-rate coded cooperation scheme. However, the cooperative phase is started only when the RS successfully decodes at least one destination's information, which results in a low achievable rate, especially when the S-R channels are poor.

3. Proposed Scheme

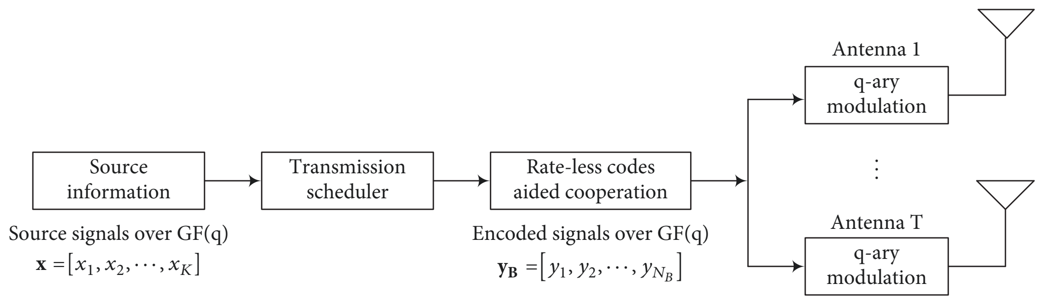
In this section, we will elaborate on the proposed partial cooperation scheme based on dynamic transmit antennas for the downlink of two-hop massive MIMO system. Firstly, in order to reduce the complexity, the rate-less codes aided cooperation is adopted in the broadcast phase, which is capable of adaptively adjusting the cooperative rate according to the dynamic transmit antennas system. Furthermore, the partial cooperation transmission is activated in the cooperative phase for solving the low achievable rate problem suffered by the full cooperation transmission especially.

Explicitly, the proposed partial cooperation scheme based on dynamic transmit antennas for the downlink of two-hop massive MIMO systems is depicted in Figure 1, where the number of the total users is I.

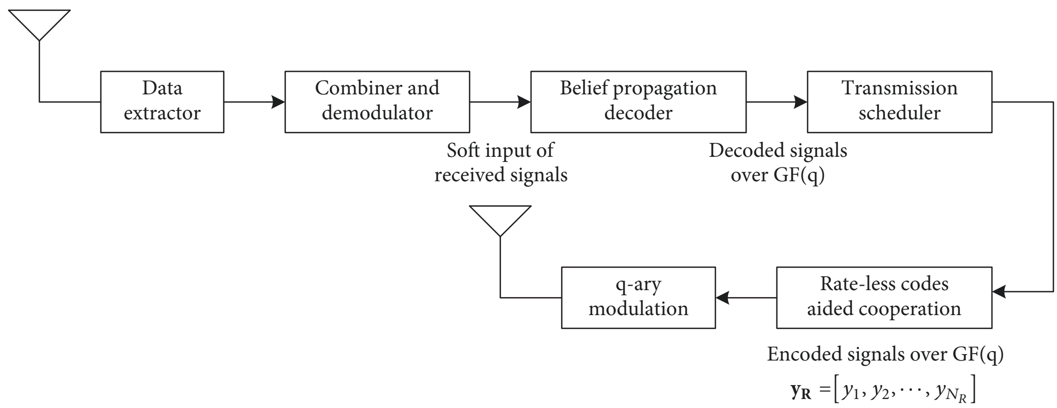
As shown in Figure 1(a), the source information $\mathbf{x} = [x_1, x_2, \cdots, x_K]$ is forwarded to the transmission scheduler. After the transmission scheduler and the rate-less codes aided cooperation, a sequence of K input symbols are encoded to a potentially infinitely long stream of parity-check symbols. Suppose that the maximum number of encoded symbols is N_B in some time-delay communication systems as shown in Figure 1(a). After the M-QAM, the signal $\mathbf{s_{sr}}$ is transmitted to the RS at the broadcast phase. It is worth mentioning that multiuser interference is not considered, which can be implemented by the zero forcing beamforming before transmitting the signal to the users. Thus, the energy efficiency of the broadcast phase of the two-hop system model is given by [10]

$$EE = \frac{C(P_s, L_{sr})}{P_{sr,t}} \tag{3}$$

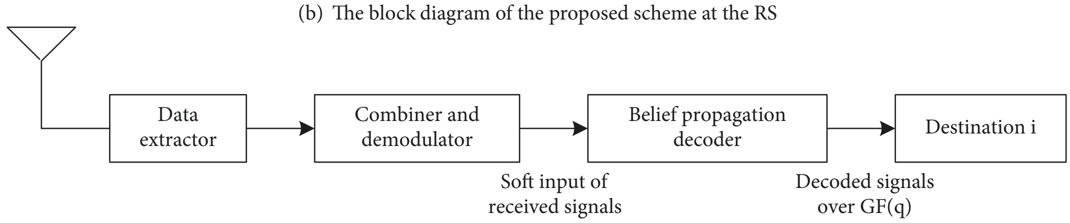
where $C(P_s, L_{sr})$ and $P_{sr,t}$ represent the instantaneous capacity [11] and the total power consumption in



(a) The block diagram of the proposed scheme at the BS



(b) The block diagram of the proposed scheme at the RS



(c) The block diagram of the proposed scheme at the i-th user

FIGURE 1

S-R channels [12], respectively, which can be described as

$$C(P_s, L_{sr}) = \log_2\left(1 + \left(1 + \ln\frac{N_t}{L_{sr}}\right) \cdot P_s \cdot L_{sr}\right) \quad (4)$$

$$P_{sr,t} = \frac{1}{\eta_{sr}} P_s + L_{sr} \cdot P_{sr,ct} + P_{sr,cr} + P_{sr,c0} \quad (5)$$

where η_{sr} is the efficiency of the power amplifier, P_s is the transmit power at the BS, L_{sr} is the number of active transmit antennas at the BS, and $P_{sr,ct}$ and $P_{sr,cr}$ stand for the power consumed by each transmitter and receiver RF chain, respectively. $P_{sr,c0}$ is the total power of frequency synthesizers and other units of circuits.

It is worth noting that L_{sr} is variable for different user according to the CSI to maximize the energy efficiency EE. Moreover, there exists an optimal value of L_{sr} for maximizing the energy efficiency by invoking Lemma 1.

Lemma 1. *As the number of active transmit antennas L_{sr} increases, the energy efficiency EE increases initially and decreases afterwards. Therefore, there exists an optimal value of the number of transmit antennas that is capable of maximizing the energy efficiency EE.*

Proof. According to (3), the energy efficiency EE is a function of the active transmit antennas L_{sr}, which can be expressed as

$$f(L_{sr}) = \frac{\log_2\left[1 + (1 + \ln(N_t/L_{sr})) \cdot P_s \cdot L_{sr}\right]}{1/\eta_{sr} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_{sr,cr} + P_{sr,c0}} \quad (6)$$

Assume that $P_2 = P_{sr,cr} + P_{sr,c0}$, and then the first-order derivative of the function $f(L_{sr})$ is shown as

$$f'(L_{sr}) = \frac{\ln(N_t/L_{sr}) \cdot P_s (1/\eta_{sr} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_2) - P_{sr,ct} \cdot \left[1 + (1 + \ln(N_t/L_{sr})) \cdot P_s \cdot L_{sr}\right] \cdot \ln\left[1 + (1 + \ln(N_t/L_{sr})) \cdot P_s \cdot L_{sr}\right]}{\ln 2 \cdot \left[1 + (1 + \ln(N_t/L_{sr})) \cdot P_s \cdot L_{sr}\right] (P_s/\eta_{sr} + L_{sr} \cdot P_{sr,ct} + P_2)^2} \quad (7)$$

Observing from (7) that the denominator of the function $f'(L_{sr})$ is greater than zero, then the numerator can be rewritten as

$$y(L_{sr}) = \ln\frac{N_t}{L_{sr}} \cdot P_s\left(\frac{1}{\eta_{sr}} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_2\right) - P_{sr,ct} \cdot \left[1 + \left(1 + \ln\frac{N_t}{L_{sr}}\right) \cdot P_s \cdot L_{sr}\right] \cdot \ln\left[1 + \left(1 + \ln\frac{N_t}{L_{sr}}\right) \cdot P_s \cdot L_{sr}\right] \quad (8)$$

Furthermore, the first-order derivative of the function $y(L_{sr})$ can be described as

$$y'(L_{sr}) = -\frac{P_s(1/\eta_{sr} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_2)}{L_{sr}} - P_{sr,ct} \cdot P_s \cdot \ln\frac{N_t}{L_{sr}} \cdot \ln\left[1 + \left(1 + \ln\frac{N_t}{L_{sr}}\right) \cdot P_s \cdot L_{sr}\right] \quad (9)$$

Observing from (9), $y'(L_{sr})$ also can be expressed as

$$y'(L_{sr}) = -\left\{\frac{P_s(1/\eta_{sr} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_2)}{L_{sr}} + P_{sr,ct} \cdot P_s \cdot \ln\frac{N_t}{L_{sr}} \cdot \ln\left[1 + \left(1 + \ln\frac{N_t}{L_{sr}}\right) \cdot P_s \cdot L_{sr}\right]\right\} \quad (10)$$

In (10), $P_s(1/\eta_{sr} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_2)/L_{sr} + P_{sr,ct} \cdot P_s \cdot \ln(N_t/L_{sr}) \cdot \ln[1 + (1 + \ln(N_t/L_{sr})) \cdot P_s \cdot L_{sr}]$ is always greater than 0, because L_{sr} is smaller or equal to N_t. Then, $y'(L_{sr})$ is always lower than 0. So, $y(L_{sr})$ decreases as the number of active transmit antennas L_{sr} increases, which means $y(N_t) \leq y(L_{sr}) \leq y(1)$.

$$y(N_t) = -P_{sr,ct} \cdot (1 + P_s N_t) \cdot \ln(1 + P_s N_t) < 0 \quad (11)$$

Explicitly, $y(1)$ can be expressed as

$$y(1) = \ln N_t \cdot P_s \cdot \left(\frac{1}{\eta_{sr}} \cdot P_s + L_{sr} \cdot P_{sr,ct} + P_2\right) - P_{sr,ct} \cdot [1 + (1 + \ln N_t) \cdot P_s] \cdot \ln[1 + (1 + \ln N_t) \cdot P_s] \quad (12)$$

The second-order derivative of the function $y(1)$ is given by

$$y_1''(P_s) > \left[\frac{2\ln N_t}{\eta_{sr}} - P_{sr,ct}(1 + \ln N_t)^2\right] \quad (13)$$

In fact, $P_{sr,ct}$ is smaller than one [13]. Even if the number of the total transmit antennas at the BS N_t is large, for example, $N_t = 10000$ in massive MIMO systems, $y_1''(P_s)$ is smaller than zero. Then, we have $y_1'(P_s) \geq y_1'(0) > 0$.

$$\lim_{P_s \longrightarrow 0} y(1) = \lim_{P_s \longrightarrow 0} \left\{\ln N_t \cdot P_s\left(\frac{1}{\eta_{sr}} \cdot P_s + L \cdot P_{sr,ct} + P_2\right) - P_{sr,ct}[1 + (1 + \ln N_t) \cdot P_s] \cdot \ln[1 + (1 + \ln N_t) \cdot P_s]\right\} = 0 \quad (14)$$

Thus, we have $y(1) > 0$.

From (8), (11), and (14), we can arrive at that $f'(L_{sr})$ is positive initially and then it becomes negative afterwards as the number of active transmit antennas L_{sr} increases. Thus, there exists an optimal activated number of antennas for maximizing the energy efficiency EE.

According to Lemma 1, classical massive MIMO cannot achieve the optimal energy efficiency if we activate all the antennas, when the energy consumption of all signal processing blocks in RF chains is taken into account. Let us denote Ω as the subset of active transmit antennas for maximizing the energy efficiency and its cardinality $|\Omega|$ is T at the BS. □

It is worth noting that each destination suffers from different propagations. In order to maximize the energy efficiency, the number of the optimal transmit antennas may be different according to (3). Thus, the active antennas of the cooperative transmit antennas system is dynamically changing for each destination. When the fixed-rate coded cooperation is applied, plenty of codebooks have to be stored both at the transmitter and at the receiver. However, the proposed rate-less codes aided cooperation scheme is capable of adaptively adjusting the cooperative rate depending on the dynamic cooperative system, as shown in Figure 1(a).

When the signal $\mathbf{y_{sr}}$ is received at the RS in definite time-delay system, it is first demodulated and decoded, as shown in Figure 1(b). In the proposed partial cooperation scheme, cooperative phase is started regardless of whether $\mathbf{s_{rd}}$ is correct or not. The reason is that the correct decoded information may not be able to be acquired in real system with meeting the requirement of time-delay. Even if the decoded signal $\mathbf{s_{rd}}$ is not absolutely correct, we should forward the signal $\mathbf{s_{rd}}$ in some situation. For example, in unequal error protection transmission, part of the correct signals may be significant.

When the retransmitted signal $\mathbf{y_{rd}}$ arrives at the i-th destination, the demodulated and decoded are carried out as shown in Figure 1(c).

The procedure of the proposed partial cooperation scheme based on dynamic transmit antennas is summarized as follows.

Step 1. According to Lemma 1, the number of optimal transmit antennas is supposed to be T at the BS for the $i - th$ destination in maximizing the energy efficiency EE.

Table 1: Simulation parameters.

Parameter	Value
Number of transmit antennas at BS N_t	200
S-R/R-D path loss related power gain G_{sr}/G_{rd}	1
Efficiency of the power amplifier η_{sr}	0.38
Power consumed by each transmitter $P_{sr,ct}$	47.8mW
Sum of power consumption $P_{sr,cr}$ and $P_{sr,c0}$	63.5mW
Number of the source information K	500
Number of the encoded signals $N_B = N_R$	1000
Encoding degree for the $j-th$ encoded signal d_j	3
Transmit power at the RS P_r	1

Step 2. In the broadcast phase, the source information $\mathbf{x}$ is encoded and modulated before broadcasted to the RS, as shown in Figure 1(a). Note that the transmitted signal is $\mathbf{s}_{\mathbf{sr}}$, and the maximum number of the encoded signals is N_B. In real system, different user has different number of optimal transmit antennas based on Step 1.

Step 3. In the cooperative phase, the received signal $\mathbf{y}_{\mathbf{sr}}$ is demodulated and decoded, as shown in Figure 1(b). Regardless of whether the retransmitted signal $\mathbf{s}_{\mathbf{rd}}$ is correct or not, reencoding and remodulation are adopted in the proposed partial cooperation scheme. Note that if S-R channels are satisfied, the number of the rate-less codes aided cooperation signals transmitted from the BS may be less than N_B in the broadcast phase, when the retransmitted signal $\mathbf{s}_{\mathbf{rd}}$ is correct.

Step 4. Finally, when the signal $\mathbf{y}_{\mathbf{rd}}$ is received at the destination, the demodulation and decoding are implemented, as shown in Figure 1(c).

In summary, the proposed scheme is capable of reducing the complexity as well as improving the achievable rate compared to the fixed-rate coded cooperation scheme and the full cooperation, respectively.

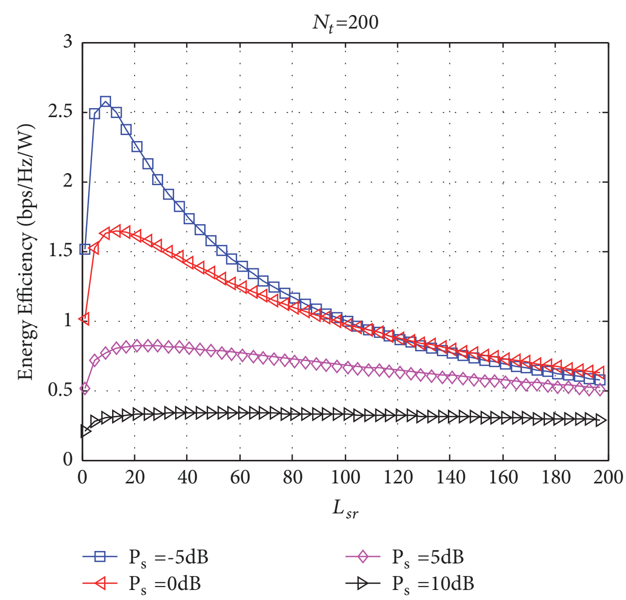


Figure 2: Energy efficiency versus number of active transmit antennas with the different transmit power at the BS.

4. Simulation Results

In this section, we investigate the achievable performance of the proposed scheme through simulations. Then, the error performances of the proposed partial cooperation scheme based on dynamic transmit antennas for two-hop massive MIMO systems are studied. The simulation parameters are presented in Table 1 [14].

In Figure 2, the number of the total transmit antennas N_t is set to be 200. We can observe from Figure 2 that the energy efficiency increases as the number of active transmit antennas L_{sr} increases when L_{sr} is small; however, it turns to degrade as L_{sr} is larger than 10. Therefore, in the following simulation, the number of optimal transmit antennas at the BS is supposed to be defined.

As Figure 1 described, the rate-less codes aided cooperation is implemented over the finite field GF(q) with q-ary modulation in the proposed scheme. Then, the symbol conversion from binary to nonbinary at the transmitter and nonbinary to binary for belief propagation (BP) decoding at the receiver are avoided. Generally, rate-less codes aided cooperation can be constructed both from the generator matrix and the parity-check matrix. The example of the former is fountain codes and that of the latter is extended irregular repeat-accumulate (eIRA) codes. It is shown that the eIRA codes have capacity-achieving performance over wireless fading channels with low encoding and decoding complexity [15], which is utilized in this paper. When the source information $\mathbf{x} = [x_1, x_2, \cdots, x_K]$, the j-th encoded signal $y_j (1 \le j \le N, N = N_B or N_R)$ can be shown as

$$y_j = \begin{cases} x_1, & j = 1 \\ y_{j-1} + x_j, & 1 < j \le K \\ y_{j-1} + c_{j,1}x_{j,1} + c_{j,2}x_{j,2} + \cdots c_{j,d}x_{j,d_j} & j > K \end{cases} \quad (15)$$

where d_j is the encoding degree which can be a random integer picked from any given probability distribution,

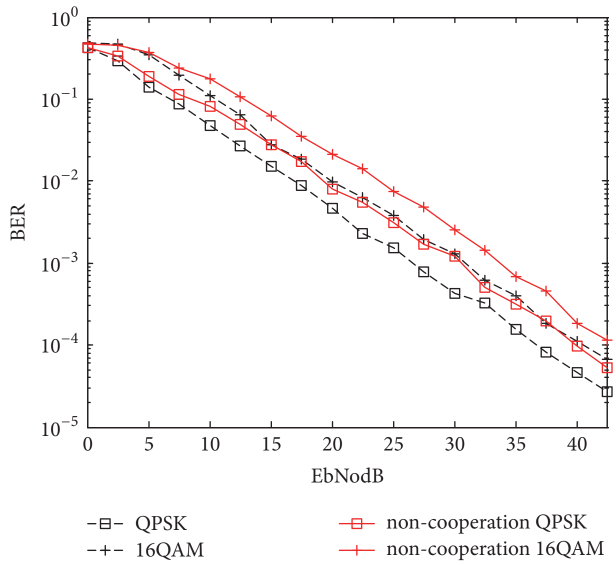


Figure 3: BER versus EbN0dB for the different modulations with dynamic transmit antennas.

$c_{j,1}, c_{j,2}, \cdots, c_{j,d_j}$ is the weight of the transmitted information, and $x_{j,1}, x_{j,2}, \cdots, x_{j,d_j}$ is the selected transmitted information. The BP is implemented at the receiver, and the iteration is defined as 100. Note that the number of optimal transmit antennas is ten at the BS for maximizing the energy efficiency according to Figure 2. The bit error rate (BER) performance of the proposed partial cooperation scheme with different modulations for two-hop massive MIMO systems is shown in Figure 3.

As shown in Figure 3, the proposed partial cooperation scheme achieves preferable performance gain for different modulations, compared with that of noncooperation scheme. For example, for 16-ary QAM (16QAM), the achieved gain is about 3dB at the BER level of 10^{-3}. A better performance is achieved when quadrature phase shift keying (QPSK) is utilized, compared with that of 16QAM, whereas the spectrum effectiveness is higher for 16QAM, in contrast to that of QPSK.

5. Conclusions

In this paper, we investigate the error performance of the proposed partial cooperation scheme based on dynamic transmit antennas in two-hop massive MIMO systems, where different modulations have been investigated. Compared with the fixed-rate cooperation, the rate-less codes aided cooperation is adopted in the broadcast phase for the dynamic transmit antennas to reduce the complexity. Moreover, we propose a partial cooperation scheme in the cooperative phase for avoiding the low achievable rate caused by the full cooperation, especially when the S-R channels are poor. Furthermore, we have theoretically analyzed that there exists an optimal activated number of antennas for maximizing the energy efficiency. The proposed scheme is capable of achieving significant BER gain with different modulations. Specifically, when the number of optimal transmit antennas at the BS is ten, the proposed scheme using 16QAM achieves about 3dB performance gain at the BER of 10^{-3}.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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