Energy Efficient Cooperative MIMO Systems

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Abstract— **In this paper we propose an energy efficient cooperative MIMO system. Space-time block codes (STBC) and code combining techniques are applied to utilize the inherent spatial diversity in wireless cooperative MIMO systems. We form a group of senders and receivers to provide higher order MIMO diversity and implement our STBC scheme in a distributed manner. In the receiving group, code combining is used with error control coding techniques to utilize receiver diversity. With the distributed implementation of STBC and code combining, MIMO diversity can be obtained in cooperative MIMO systems. We present analysis and simulation results for reliability (BER vs SNR curves) and energy efficiency. Our reliability curves are significantly better than SISO achieving MIMO-like diversity gains. Additionally, we examine energy consumption and show that the data transmission power can be low as 0.7 mW for 4-node send/receive group size in our cooperative MIMO system, compared to a point-to-point SISO system that consumes 30 mW. However, the cooperative MIMO introduces overhead and sacrifices system capacity. With the same number of sending nodes/antennas, the system capacity of 4×4 cooperative MIMO system is less than conventional 4×4 MIMO system due to cooperation overheads [1]. Thus there is tradeoff between energy consumption and system capacity in proposed system. In summary, our proposed system provides reliable and energy-efficient transmission by leveraging MIMO diversity gains through cooperation between nodes.**

I. INTRODUCTION

Diversity techniques have been widely used in wireless networks for suppressing channel variation in wireless channels. Various schemes proposed in previous research show that spatial diversity can be leveraged in the network, link or physical layers to 1) provide reliable transmission with low power, 2) reduce energy consumption, and 3) extend battery life. In link layer and network layer, opportunistic routing, network coding [2] and other designs, such as ExOR [3] and Many-to-Many communication [4] have been proposed. ExOR [3] integrates routing and MAC protocol and opportunistically chooses the next-hop node for multi-hop transmission in wireless networks. Many-to-Many communication [4] divides transmissions in frequency and codes, using successive interference cancelation (SIC) to allow decoding in receivers.

In the physical layer, MIMO systems use multiple transmitting and receiving antennas for signal transmission to achieve spatial diversity. The spatial diversity in the transmitter and receiver recovers the signal detection for poor quality transmission. However, MIMO systems require multiple antennas equipped in each device, which may not be feasible in some wireless communication devices because of the cost and size limitations. Besides, MIMO systems need to estimate all channels between the source and the destination. For example, a 8×8 MIMO system will require 8 antennas per node and real-time estimation of all 64 channels between source and destination. But if nodes near the sender and receiver cooperate to form sending group and receiving group respectively, each receiving node only needs to estimate the channels between 8 sending nodes and itself. Node cooperation decrease the amount of channel estimation at receiver from 64 to 8. Thus the concept of cooperative diversity has been proposed to achieve virtual MIMO systems with single antenna devices [1], [5]–[13]. With cooperative transmission becoming more at a reality, performance evaluations for cooperative networks is also important. The capacity of cooperative networks is considered in [10], [13]. Özgür, Lévêque, and Tse [13] discuss the capacity of cooperative networks and show that linear capacity scaling can be achieved by hierarchical cooperation.

In cooperative networks, the transmitting nodes use idle nearby nodes as relays to provide spatial diversity. But most of previous research considers the transmission between two senders and one receiver [6]–[8], [11], [12] or multiple relays between source and destination [5]. They discuss the system model under symmetric and asymmetric channel [11] or different relay schemes [7]. These schemes provide transmitter diversity from one or multiple relays, but it does not have receiver diversity because the destination is the only receiving node. Thus in this paper we consider to achieve both transmitter and receiver diversity in a distributed manner and propose to use sending group and receiving group to provide MIMO diversity.

The key challenges faced with implementing cooperative MIMO system are 1) node coordination in sending and receiving group, 2) distributive space-time coding in senders, 3) data combining in the destination. After cooperative MIMO transmission, the destination needs to combine multiple receiving signals and makes signal detection. In link layer, code combining techniques have been considered. Hunter and Nosratinia [12] propose coded cooperation for transmission between two sending nodes and one receiving node. In each time slot, only one of the sending nodes transmits a data block that contains N_1 bits from its own coded bits and N_2 bits from its partner. The receiver then combine the received bits from the two senders by code combining. Coded cooperation for cluster-based cooperative network is considered in [14]. In [14] multiple receiving nodes form the receiving cluster and the sending node transmits packets to the receiving cluster. Each cluster member relays its signal copy to the destination. The destination node uses code combining techniques to decode the original information bits. In this paper we use code combining in the receiving group of cooperative MIMO system.

In our previous work [1] we did capacity analysis and proposed an asynchronous cooperative MISO receiver to address the node coordination problem in sending and receiving group. In this paper we propose a concrete scheme that combines STBC and cooperative code combining. The uses of STBC and code combining address the issues of transmitter diversity and receiver diversity in cooperative MIMO system. Once the sending and receiving groups are formed, space-time block codes (STBC) are deployed in the sending group to utilize transmitter diversity. In the receiving group, error control code combining is used in the destination to combine signals from nodes in receiving group to achieve receiver diversity. With space-time block codes (STBC) and code combining, MIMO diversity in the proposed system can be realized. The proposed diversity gain therefore provides reliable and energy efficient transmission. For 4×4 cooperative MIMO system, the BER can be smaller than $10^{-}6$ when SNR is only 4 dB. With the improvement in BER, the cooperative MIMO system provide a more reliable transmission with low power. Our energy consumption analysis shows the data transmission power for $4{\times}4$ cooperative MIMO system can be low as 0.7 mW, while the point-to-point (SISO) transmission usually transmit with 30 mW.

The key contributions of this paper include: 1) use sending group and receiving group, instead of the relay model, to provide spatial diversity, 2) use distributed implementation of STBC in sending group and code combining in receiving group to provide not only spatial diversity but the MIMO diversity, and 3) analyze energy consumption and show that the cooperative MIMO system provide reliable and energy efficient transmission. This paper is organized as below: the new system is proposed in section II followed by the theoretical analysis and simulation result for bit error rate (BER) performance in section III. Energy consumption for the proposed system is shown and compared in section IV. Finally, we conclude the paper in Section V.

II. SYSTEM DESIGN FOR COOPERATIVE MIMO SYSTEM

A. *Design Issues for Cooperative MIMO Systems*

In cooperative MIMO systems, transmit and receive diversity are achieved in a distributed manner by the sending group and receiving group. The sending and receiving groups include multiple sending nodes and receiving nodes, each with a single antenna. Therefore, achieving transmit and receive diversity distributively becomes the major design issue in the cooperative MIMO systems.

In the sending group, transmitted signals from multiple sending nodes are mixed before arriving at the receiver. Thus space-time coding and decoding are required at the sending group and receiving group to separate the received signals and exploit the transmit diversity. Many space-time coding schemes have been proposed in previous research [15]–[17]. Among various space-time coding schemes, STBC is appropriate for distributed implementation. STBC is defined by a $M \times L$ encoding matrix, where M is the number of transmitting antennas and L is the number of time periods to transmit one block of coded symbols. The encoding matrix contains orthogonal rows, each with different permutation of symbols $x_1, x_2, \ldots, x_L$. Since the encoding matrix only changes the permutation of symbols, each antenna will transmit the same data bits with different permutation order. In cooperative MIMO system, the source node can broadcast data and helper node change the permutation of symbols according STBC coding matrix. Thus STBC is suitable for distributed implementation and is used in the proposed system to exploit the transmit diversity.

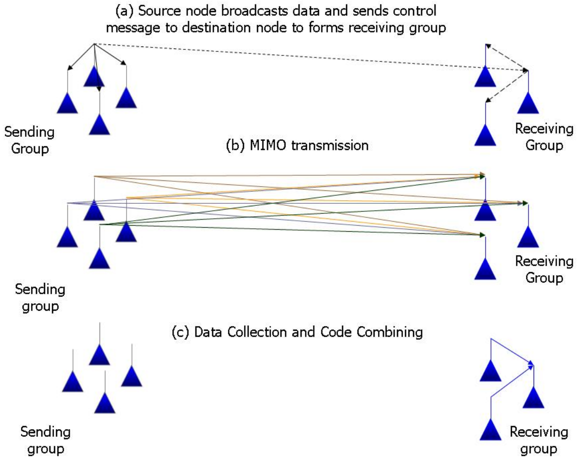

Fig. 1. Proposed cooperative MIMO system: (a)Broadcasting, (b)MIMO transmission, (c)Data Collection and Combining

Although STBC is applied in the sending group and allows maximum-likelihood (ML) decoding algorithm, the ML algorithm cannot be applied in the destination node. The reason is that the ML decoding algorithm for STBC requires channel state information (CSI) for all channels between sending group and receiving group. But the destination node can only observe the channels between sending group and itself. A possible solution is that each receiving node decodes STBC individually by the ML decoding algorithm and send their signals to the destination. The destination node will use combining techniques to combine the signal copies from receiving nodes with its own copy and make signal detection.

Most of existing diversity combining techniques require the SNR in receiving antennas as the threshold, such as selection combining and switched combining, or use SNR as weighting factors, like maximal ratio combining (MRC). But the SNR information in receiving antennas can not be obtained by the destination node because multiple receiving antennas are located distributively. Unlike other combining techniques, code combining uses repeated packets encoded with error control codes and decodes the repeated packets by maximum-likelihood (ML) decoder. The maximum-likelihood (ML) decoder will select the codeword which can maximize the conditional probability of receiving signal given the repetition of selected codeword. Channel state information (CSI) for receiving antennas is not required in code combining. Thus code combining is used in proposed system. The code combining is usually used with convolution code or short block code due to decoding complexity. In this paper we focus our discussion on convolution codes. The details of our system design are described below.

B. *Proposed System Design*

We use a distributed MAC protocol proposed elsewhere [18] to set up the cooperative MIMO transmission. The summary of MAC protocol below is provided for completeness.

The extended discussion of this proposed MAC protocol is in [18]. This paper focusses not on the MAC, but on the STBC and code combining parts.

Before starting data transmission, enough nodes in sending group and receiving group need to be recruited for cooperative MIMO transmission. Otherwise the recruiting process has to be performed again. In order to reduce the interference of the sending group and receiving group, the recruiting power should be less than half of the regular transmission power, so there will be no such nodes that can be recruited by both of source and destination.

At the beginning of each transmission, the source node sends the recruiting RTS (RRTS) message to its neighbors, and the available neighbors will reply with sequential CTS (SCTS) by the purpose of reducing the collision with each other. After recruiting the sending group, the source node sends MIMO RTS control messages (MRTS) to the destination node to establish data transmission link. The destination node also needs to recruit receiving group nodes, which is the same procedure as the source node recruiting sending group. After the destination node get all the SCTS reply, the destination node sends broadcast messages to the selected receiving neighbors to recruit them to help receiving MIMO transmission from the sending group. If the receiving group does not have enough nodes, the MIMO CTS control message (MCTS) will notify the source to retransmit. Otherwise, after receiving the MCTS from the destination node, the source node can start data transmission. The size information of receiving group is included in the MCTS package. In this way, the source node can have the exactly number of nodes both in sending and receiving group. The cooperative MIMO transmission can be described by following steps:

Step 1: Broadcasting-The source node encodes information bits by error control codes. Then the source node broadcasts data and synchronization information with low power to the selected neighbor nodes. The selection can be based on the STBC coding requirement. The number of nodes required by STBC will be selected. The source node also gives order for selected helper nodes so each helper node will choose the corresponding row in space-time block code (STBC) matrix. Because the distance from the helping nodes in the sending group to the source node is quite short, members of the sending group are not required to send acknowledgement back to the source node.

Step 2: STBC MIMO transmission-In this step, the helper nodes in sending group will use the corresponding row in STBC code matrix, which is assigned in *step 1*, to change the permutation of data bits. Then all nodes in the sending group, including the source node, will transmit space-time coded data to the receiving group. Multiple nodes in the sending and receiving group form cooperative MIMO diversity. Because we know the exact number of nodes in the sending group and assigning order to each helper node in *step 1*, we can use STBC properly.

Step 3: Data Collection and Combining-After receiving data from the sending group, each node in the receiving group uses the channel state information to decode the space-time block coded data. After decoding for STBC, the helper nodes in receiving group relay their copies to the destination node. The destination receives signal copies from the helper nodes and detect them as soft symbols. Then the destination uses code combining and chooses the most possible codeword base on received soft symbols.

If the original data is decoded correctly in step 3, the destination node will send back an ACK message to the source node. In the case of error happens, the source node will timeout, retransmission will begin, and the whole procedure will be repeated.

III. BER IN COOPERATIVE MIMO SYSTEMS

In the proposed scheme for cooperative transmission, the bit error rate is assumed to be 0 in the first step (Broadcasting) since a node can be in the sending group only if it receives the data packet correctly. Thus we consider the BER performance analysis in *step 2* and the BER performance after code combining in *step 3*. Our longer unpublished manuscript [19] provides the full proof of lemmas for BER. In this paper we summarize the BER analysis in proposed system and use the BER to analyze system energy consumption.

A. Performance Analysis

We assume the system transmits BPSK signals through Rayleigh fading channels with AWGN noise. The noise power spectral density is $N_0/2$. Pathloss constant is denoted as α. The sizes of the sending group receiving group are M and N, including the source node and destination node. In the *step 2* (STBC MIMO transmission), each node in sending group transmits with equal transmission power P_T. The helper nodes in the receiving group also transmit with equal transmission power P_{rc} for the transmission between the receiving group and the destination node in *step 3*.

In *step 2*, each node in the receiving group will detect the signals by STBC decoding after STBC-MIMO transmission. The channel gain between receiving node j and sending node i in time t is denoted as $h_{j,i}(t)$. We assume the channel gain is constant over many symbol periods, i.e., $h_{j,i}(t) = h_{j,i}$. Since each receiving node will apply STBC decoding separately, we consider one of the nodes in receiving group, denoted as node j. We assume the STBC coding matrix is a $M \times L$ matrix, which means it requires L time periods to transmit one block of STBC coded symbols. In STBC decoding, node j will choose detected BPSK symbols to minimize the maximum likelihood metric:

$$\min \sum_{t=1}^{L} |r_t^j - \sum_{i=1}^{L} h_{j,\epsilon_t(i)} x_t^{\epsilon_t(i)}|^2$$

where r_t^j is the received signal in node j at time t. ϵ_t denoted the permutation of symbols from $[x_1, x_2, \cdots, x_L]$ to the t^{th} column in STBC encoding matrix. The row position of x_i in the t^{th} column is represented by $\epsilon_t(i)$. $x_t^{\epsilon_t(i)}$ is the symbol transmitted at time t by sending node $\epsilon_t(i)$. $h_{j,i}$ is the channel gain and can be expressed as $h_{j,i} = \frac{\lambda_{j,i}}{d_{j,i}^{\alpha/2}}$, where α is path-loss constant and $\lambda_{j,i}$ is the fading gain. For Rayleigh fading, $\lambda_{j,i}$ is the circular complex Gaussian R.V.

It is assumed that the original STBC-encoded symbols $\mathbf{X}$ is $M \times L$ matrix. The first row of $\mathbf{X}$ is $[x_1, x_2, \cdots, x_L]$. The other rows in $\mathbf{X}$ are different permutation of $[x_1, x_2, \cdots, x_L]$ and are orthogonal to each other. The detected BPSK symbols in node j is $\hat{\mathbf{X}}$, where the rows in $\hat{\mathbf{X}}$ are permutations od $[\hat{x_1}, \hat{x_2}, \cdots, \hat{x_L}]$. Due to space limitation, we present our analysis by following lemmas. The full proof of lemmas is shown in our unpublished manuscript in [19].

Lemma 1: For node j in the receiving group, the pairwise error probability is [19]

$$P_j(\mathbf{X}, \hat{\mathbf{X}}) = \\ \frac{1}{\pi}\int_0^{\pi/2} \det[\mathbf{I_M} + \frac{P_T}{2N_0 \sin^2\theta}\mathbf{\Sigma}(\mathbf{X}-\hat{\mathbf{X}})(\mathbf{X}-\hat{\mathbf{X}})^{\mathbf{H}}]^{-1} d\theta \tag{1}$$

where $\mathbf{I_M}$ is the $M \times M$ identity matrix and the matrix $\mathbf{\Sigma}$ is

$$\mathbf{\Sigma} = E[\mathbf{h_j^H h_j}] = \begin{bmatrix} \frac{1}{d_{j1}^{\alpha}} & 0 & \cdots & 0 \\ 0 & \frac{1}{d_{j2}^{\alpha}} & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & \cdots & 0 & \frac{1}{d_{jM}^{\alpha}} \end{bmatrix}$$

Lemma 1 shows the pairwise error probability between original symbols $\mathbf{X}$ and detected symbols $\hat{\mathbf{X}}$. For the space-time code with code matrix size $M \times L$, each sending node will reorder the symbols $x_1, x_2, \cdots, x_L$ according to the corresponding row in STBC encoding matrix and transmit the data with the new order. Thus, for a specific bit x_k, the bit error rate in receiving node j can be expressed as

$$P_j(x_k \neq \hat{x}_k) = \sum_{\mathbf{X}} \sum_{\hat{\mathbf{X}} \textit{ such that } x_k \neq \hat{x}_k} \frac{1}{2^L} P_j(\mathbf{X}, \hat{\mathbf{X}}) \tag{2}$$

After obtaining the bit error rate performance in the Rayleigh fading channel shown in equation 2, we consider performance for code combining. The bit error rate in equation 2 is denoted as P_e^j for further use in following discussion.

In step 3, the destination node will have N signal copies from the receiving group nodes, including itself. The received signal will be quantized as soft symbols. We denote the N received soft symbol data streams as $\mathbf{r}_1, \cdots, \mathbf{r}_N$. $\mathbf{r}_j$ is the received soft-symbol signal from node j in the receiving group. Thus the received signal set in the destination node will be $\mathbf{r} = \{\mathbf{r}_1, \cdots, \mathbf{r}_N\}$.

If q quantization levels are used for soft symbol quantization, the transition probability that transmitting information bit $a = \{0, 1\}$ from node j is BPSK modulated mapped to soft symbol $l = \{1, 2, \cdots, q\}$ in the destination node can be denoted as $P_{j,11}, P_{j,1l}, \cdots, P_{j,1q}$ and $P_{j,01}, P_{j,0l}, \cdots, P_{j,0q}$.

If the Viterbi decoder are used for code combining and the channel gain of channels between receiving node and the destination is assumed to be known, the path metric will use the channel gains and the transition probability :

$$\begin{aligned} M(\mathbf{r}|\mathbf{s}) &= \sum_{u=0}^{L+m-1}\sum_{j=1}^{N} \log \frac{P_j(r_j^u = l_{uj}|s_u = a_i)}{P_j(r_j^u|s_u = 0) + P_j(r_j^u|s_u = 1)} \\ &= \sum_{u=1}^{L+m-1}\sum_{j=1}^{N} \log \frac{P_{j,a_i l_{uj}}}{P_{j,0l_{uj}} + P_{j,1l_{uj}}} \end{aligned} \tag{3}$$

where L is the transmitted data length and m is the memory order of convolution code. For the u^{th} transmitted signal, the original information bit is $s_u = \{0, 1\}$ and the received soft symbol is denoted $l_{uj}, j = 1, \cdots, N, u = 1, \cdots, L$.

To achieve the maximum-likelihood decoding, the path metric defined in equation 3 need to be maximized. For a transmitting signal $\mathbf{s}$, the error occurs when a error path $\mathbf{s}'$ has larger metric then it for $\mathbf{s}$, i.e., $M(\mathbf{r}|\mathbf{s}') > M(\mathbf{r}|\mathbf{s})$. The error probability is proved to be following lemma [19].

Lemma 2: The probability of choosing error path $\mathbf{s}'$, instead of $\mathbf{s}$ is [19]

$$P(M(\mathbf{r}|\mathbf{s}') > M(\mathbf{r}|\mathbf{s})) = P(T > 0) \tag{4}$$

where T is a random variable with moment generating function (MGF) defined as following.

$$\begin{aligned} \phi_T(z) &= E[z^{\sum_{u=1}^{L+m-1}\sum_{j=1}^{N} k_u w_{j,l_{uj}}}] \\ &= \prod_{j=1}^{N}\prod_{u=1}^{L+m-1}(1 - p + p z^{w_{j,l_{uj}}}) \qquad (5) \\ &\quad \text{(Note:}p\text{ is defined in equation 7.)} \\ &= \sum_b P_T(b) z^b \qquad (6) \end{aligned}$$

p is the probability of the event $s_u \neq s'_u$:

$$\begin{aligned} p &= P(s_u \neq s'_u) = P(\text{detect 1 from receiving soft symbols}) \\ &= P(\text{receives } l_{u1}, \cdots, l_{uN} \text{ s.t. } \textstyle\sum_{j=1}^{N} \log \frac{P_{j,1l_{uj}}}{P_{j,0l_{uj}}} > 0) \\ &= \sum_{l_u \text{ s.t. } \sum_{j=1}^{N} \log \frac{P_{j,1l_{uj}}}{P_{j,0l_{uj}}} > 0} \prod_{j=1}^{N} P_{0,l_{uj}} \end{aligned} \tag{7}$$

and $w_{j,l_{uj}}$ is the log ratio of transition probability that maps to the same soft symbol l_{uj}:

$$\begin{aligned} w_{j,l_{uj}} = \log \frac{P_{j,1l_{uj}}}{P_{j,0l_{uj}}} \quad &, u = 0, 1, \cdots, L + m - 1 \\ &l_{uj} = \{1, 2 \cdots, q\} \\ &j = \{1, 2, \cdots, N\} \end{aligned} \tag{8}$$

The coefficient $P_T(b)$ is the probability $T = b$. And we assume the number of bit disagreement between path $\mathbf{s}'$ and path $\mathbf{s}$ is d. With received soft symbols $\mathbf{r}$ and d error bits after code combining, the probability of error in the pairwise comparison of $\mathbf{s}$ and $\mathbf{s}'$ is

$$\begin{aligned} P_{\mathbf{r},d} &= P(M(\mathbf{r}|\mathbf{s}') > M(\mathbf{r}|\mathbf{s})) = P(T > 0) \\ &= \sum_{b>0} P_T(b) \end{aligned} \tag{9}$$

For the BER after code combining, we consider all possible received soft symbols, $\mathbf{r}$, and all possible number of error bits in path, d. By union bound, the bit error rate P_b can be bounded as

$$\begin{aligned} P_b &< \sum_{d=d_{free}}^{\infty} B_d \cdot prob(\text{detect with } d \text{ error bits}) \\ &= \sum_{d=d_{free}}^{\infty} B_d (\sum_{\mathbf{r}} P_{\mathbf{r},d}) \end{aligned} \tag{10}$$

where B_d is the number of codewords of Hamming distance d from the all zero codeword.

B. Simulation results

We simulate the cooperative MIMO system to evaluate system performance and compare with different system designs. BPSK modulation is applied to the signal and the channel is assume to be quasi-static Rayleigh fading. The distance between source node and destination node is 125 meters. The locations of sending group nodes are randomly generated and assumed to be around the source node in a circle with radius of 25 meters. The receiving group nodes are also randomly located to be around the destination node in a circle with 25 meters radius. The transmission power between receiving group nodes and the destination node in *step 3* is assumed to be 10 dB less than the transmission power used in the MIMO transmission in *step 2*. The transmission power used in the MIMO transmission in *step 2* is set to achieve equivalent receiving SNR in point-to-point transmission. Thus, the transmission power in step 2 is defined as $SNR \cdot d_{SD}^{\alpha} \cdot N_0/M$, where d_{SD} is the distance between the source node and destination node, α is the path-loss constant, M is the number of nodes in the sending group (includes source node), N_0 is noise power, and SNR varies from 0 dB to 20 dB. We use the equivalent SNR as the X-axis in following figures.

To evaluate the proposed system, we compare the proposed cooperative STBC system with two different schemes. One is the cooperative code combining without space-time block coding (STBC) and the other one is cooperative MIMO systems without code combining.

For the cooperative MIMO system without space-time block codes (STBC), only cooperative code combining is applied in receiving group to utilize receiver diversity and no STBC in the sending group. In this scheme, the sending nodes will receive signal from the source node and then simply forward it to the receiving group. In the receiving group, receiving nodes will detect the mixed signal from multiple sending nodes and then relay detect signal copy to the destination node. The destination node then uses code combining technique to combine the multiple signal copies from receiving group.

In the cooperative MIMO systems without code combining, the sending group uses space-time block codes (STBC) to utilize the transmitter diversity. But in the receiving group the destination node does not use code combining technique to utilize the receiver diversity. Instead of code combining, the destination node will compare the multiple signal copies

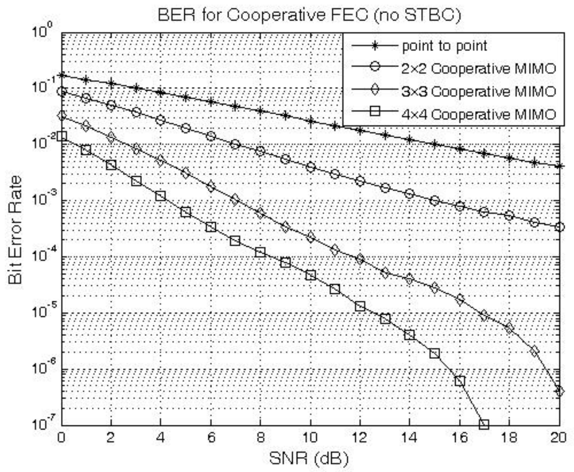

Fig. 2. Bit error rate (BER) in Cooperative MIMO system with code combining (Note: no space-time codes applied)

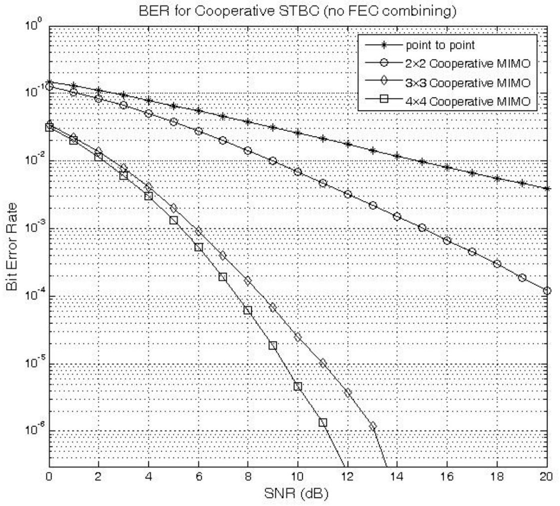

Fig. 3. Bit error rate (BER) in Cooperative MIMO system with space-time block codes (Note: no code combining in receiving group)

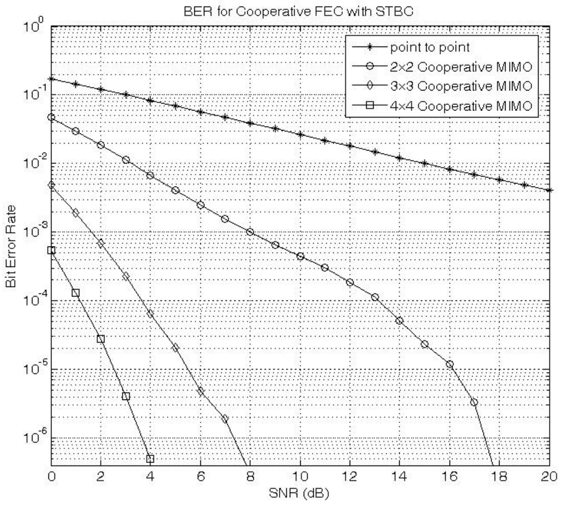

Fig. 4. The proposed cooperative MIMO system has best performance in Bit error rate (BER) among the three systems

from the receiving group and detect signal simply based on the majority in the multiple receiving signal copies.

We compare performance of the three systems under different sending/receiving group sizes. The number of sending/receiving groups range from 1 to 4. The simulation results are shown in Figure 2, Figure 3, and Figure 4.

From Figure 2, 3 and 4, the performance improves as the size of sending/receiving group increases in all three systems. But the reason for performance improvement is different in each scheme. In Figure 2, the transmitter diversity is not fully utilized since no space-time coding is applied in the sending group. Although the system has transmitter diversity (multiple sending nodes), the receiving nodes receives the mixed signal from different sending nodes and cannot extract the transmitted signal from each sending node. But the receiver diversity is used in code combining technique. The destination node will receive multiple signal copies from receiving nodes and combine the signal copies by code combining. Thus, in Figure 2 the performance improvement is due to the receiver diversity.

In Figure 3, it uses space-time block code (STBC) to achieve transmitter diversity. But in the receiver, the destination node does not fully utilize the receiver diversity. It is shown in Figure 3 that the BER performance of 3×3 and 4×4 cooperative MIMO system is quite close. The BER performance of 1×1 and 2×2 cooperative MIMO system is also very close at low SNR. This is because of the detection method used in the destination node. The destination node detects based on the majority in the receiving signal copies and randomly chooses when there is a tie. Thus, the 4×4 cooperative MIMO system provides more receiving diversity, but the simple detection method in the destination node does not utilize the receiving diversity well.

Figure 4 shows the simulation result for proposed system. The proposed system has the best performance among the three systems because it utilized the transmitter diversity and receiver diversity in the sending group and receiving group. The bit error rate decreases much faster as the size of sending/receiving group increases. When the size of sending/receiving group is 4, the BER is smaller than 10^{-6} when SNR is 4 dB.

IV. ENERGY CONSUMPTION ANALYSIS

With the analysis and simulation result of bit error rate (BER), we consider the energy consumption for one-hop transmission. Although cooperative MIMO system provides a reliable transmission with low power, it requires more control messages due to node cooperation. In the recruiting process to form sending group and receiving group, the source and destination send recruiting RTS (RRTS) message to their neighbors and neighbors reply with sequential CTS (SCTS). Compared to the regular CSMA/CA protocol, which performs transmission with RTS/CTS and ACK messages, the proposed cooperative MIMO system consumes more power in control messages because of recruiting RTS (RRTS) and sequential CTS (SCTS). The proposed cooperative MIMO system also consumes more power for data transmission due to the data broadcasting in sending group and data collection in the receiving group. However, the cooperative MIMO system requires less retransmission due to lower packet error probability and reduces the power consumption for one-hop transmission. Therefore, in this section we consider the total power consumption for one-hop transmission in proposed cooperative MIMO system.

For the point-to-point transmission, the regular CSMA/CA protocol is used. The energy consumed for an unsuccessful transmission attempt is

$$Eu = E_{rts} + E_{cts} + E_{data}$$

and that for a successful attempt is

$$Es = E_{rts} + E_{cts} + E_{data} + E_{ack}$$

and the total energy for one-hop transmission is

$$\begin{aligned} E &= (1-P_e)Es + P_e(1-P_e)(Es+Eu) \\ &+ P_e^2(1-P_e)(Es+2Eu) + \dots \\ &= \frac{P_e}{1-P_e}Eu + Es \end{aligned} \tag{11}$$

where P_e is the packet error probability for point-to-point transmission. E_{rts}, E_{cts}, E_{ack} and E_{data} are the energy consumption of sending RTS, CTS, ACK and point to point data,

In our proposed cooperative MIMO system, the total energy for one-hop transmission can also be expressed as equation 11, but with different Eu, Es and packet error probability P_e. The packet error probability P_e for cooperative MIMO system can be obtained from the bit error rate (BER) analysis and simulation results in previous section. The energy consumed for an unsuccessful transmission attempt and for a successful transmission is also changed because the MAC protocol has changed to form sending and receiving group and make the distributed implementation of space-time block codes (STBC) possible.

We assume the cooperative MIMO transmission is with M sending nodes and N receiving nodes, including source node and destination node respectively. The energy consumed for an unsuccessful transmission attempt is

$$\begin{aligned} Eu_{coop} &= E_{mrts} + E_{mcts} + 2E_{rrts} \\ &+ (M-1)E_{scts} + (N-1)E_{scts} \\ &+ E_{br} + E_{data} + (N-1)E_{col} \end{aligned} \tag{12}$$

and that for a successful attempt is

$$\begin{aligned} Es_{coop} &= E_{mrts} + E_{mcts} + 2E_{rrts} \\ &+ (M-1)E_{scts} + (N-1)E_{scts} \\ &+ E_{br} + E_{data} + (N-1)E_{col} + E_{ack} \end{aligned} \tag{13}$$

The energy E_{mrts}, E_{mcts}, E_{ack} are the energy consumption of sending MIMO RTS, MIMO CTS and ACK. The MIMO RTS (MRTS) and CTS (MCTS) messages are control messages between source and destination and require higher transmission power for such long distance transmission. E_{rrts} and E_{scts} are the energy consumption of sending recruiting RTS (RRTS) and sequential CTS (SCTS) to form sending group and receiving group, respectively. The recruiting RTS (RRTS) and sequential CTS (SCTS) are control messages between source/destination and their neighbors. Compared to the MIMO RTS and CTS, the recruiting RTS (RRTS) and sequential CTS (SCTS) can be transmitted with less power due to short-distance transmission. E_{col} is the energy consumed by data collection in the third phase. In the receiving group, each helping node will transmit its signal back to the destination with energy E_{col}. And there are $N-1$ helping nodes in the receiving group, excluding the destination node. E_{br} is the energy consumption of broadcasting data to helping nodes in sending group. E_{data} is the energy consumption for data transmission between sending group and receiving group. To make the comparison reasonable, we assume there are the same amount of information bits and the same energy consumption E_{data} in point-to-point transmission and cooperative MIMO transmission. In other words, if the source node transmits data with power P_T, the nodes in sending group will transmit data with power P_T/M in cooperative MIMO system.

We assume the control message is with length L_c and the size of data packet is L. The data rate is R and a convolution code with rate R_c is applied on the data packet to enable code combining technique in the receiving group. Thus, the energy of transmitting data is $E_{data} = P_t L/R/R_c$ and that of transmitting control message is $E_{mrts} = P_{mrts} L_c/R$.

Thus, equation 14 and 15 can be rewritten as follows:

$$\begin{aligned} Eu_{coop} &= \frac{L_c}{R}(P_{mrts} + P_{mcts} + 2P_{rrts} \\ &+ (M-1)P_{scts} + (N-1)P_{scts}) \\ &+ \frac{L}{RR_c}(P_{br} + P_{tx} + (N-1)P_{col}) \end{aligned} \qquad (14)$$

and that for a successful attempt is

$$\begin{aligned} Es_{coop} &= \frac{L_c}{R}(P_{mrts} + P_{mcts} + 2P_{rrts} \\ &+ (M-1)P_{scts} + (N-1)P_{scts} + P_{ack}) \\ &+ \frac{L}{RR_c}(P_{br} + P_{tx} + (N-1)P_{col}) \end{aligned} \qquad (15)$$

Similarly, the total energy for one-hop transmission in cooperative MIMO system is

$$E = \frac{P_e}{1-P_e} Eu_{coop} + Es_{coop} \qquad (16)$$

where P_e is the packet error probability for cooperative MIMO transmission, which can be derived from the bit error rate results in previous section.

The values of system parameters are as follows. The data rate R is assumed to be 2 Mbps. The rate R_c of convolution code is $1/2$. The length of control messages, L_c is assumed to be 64 bytes and The length of data packet, L, is 512 bytes. The control messages between source and destination, such as MRTS, MCTS and ACK, are transmitted with 15 dBm. The transmitting power of control messages inside sending/receving group, such as RRTS and SCTS, is assumed to be $1/4$ of the transmitting power for MIMO RTS and CTS. The transmitting power for MIMO transmission in *step 2*, P_{tx}, varies and is shown as the X-axis in figures. And the transmitting power for data collection in *step 3*, P_{col}, is assumed to be 10 dB less than P_{tx}.

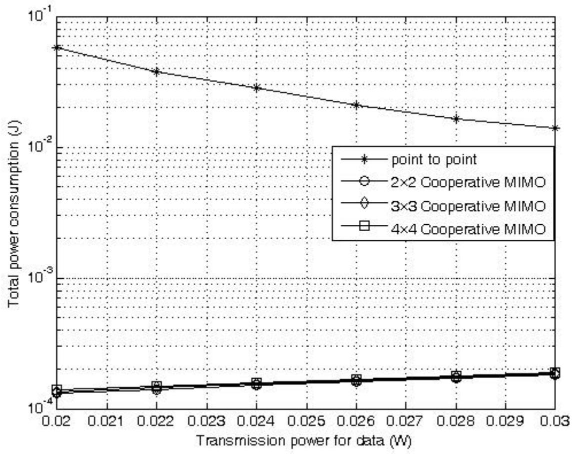

Fig. 5. Energy consumption in cooperative MIMO system is much less than it in point-to-point (SISO) transmission

We first compare energy consumption of proposed system and point-to-point transmission with regular CSMA/CA protocol. The result is shown in Figure 5. In Figure 5, the total energy consumption is much lower for cooperative MIMO system than it for point-to-point transmission. Although cooperative MIMO system requires more control messages and spend power on data broadcasting and collection, the saving on power for data transmission P_{tx} and small packet error probability, P_e, lead to low energy consumption.

Although the cooperative MIMO system can use less power for data transmission, the data transmission power is limited by the packet error probability, which is obtained from the BER. If the transmission power for data is too low, the total energy consumption will approach infinity because the packet error probability is close to 1 and the number of retransmission is close to infinity. If the transmission power for data is too high, it wastes energy even though no retransmission is required. Thus, to achieve energy-efficient cooperative MIMO system, the transmission power for data needs to be optimum.

Figure 6, Figure 7, and Figure 8 shows the optimum value of transmission power P_{tx}, which can achieve lowest energy consumption, for 2×2, 3×3, and 4×4 cooperative MIMO system, respectively. The optimum value of P_{tx} decreases as the size of sending/receiving group increases. This is because the packet error probability decreases as the size of sending/receiving group increases, as shown in previous section. With the same data transmission power P_{tx}, the cooperative MIMO system with larger sending/receiving group has smaller packet error probability and requires less retransmission. Thus it can achieve optimum data transmission power P_{tx} at smaller value and have loweer value for total energy consumption. At 4×4 cooperative MIMO system, the optimum data transmission power P_{tx} is only 0.7 mW when the total energy consumption is only 0.044 mJ.

In spite of the size of sending/receiving group, the proposed cooperative MIMO system is also compared to cooperative MIMO system with STBC (no code combining) and the cooperative code combining system (no STBC). The results

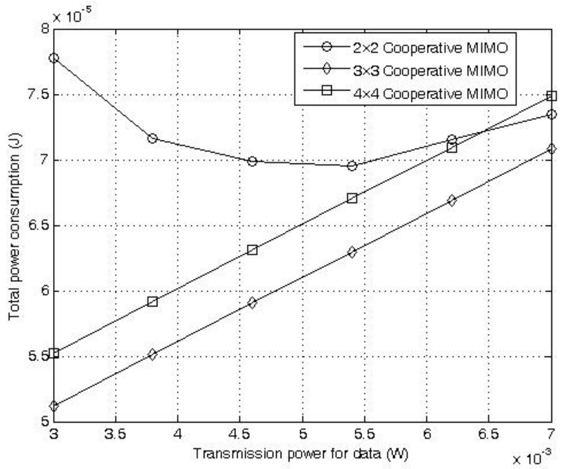

Fig. 6. The optimum value of data transmission power P_{tx} can be low as 5.5 mW in 2×2 Cooperative MIMO systems.

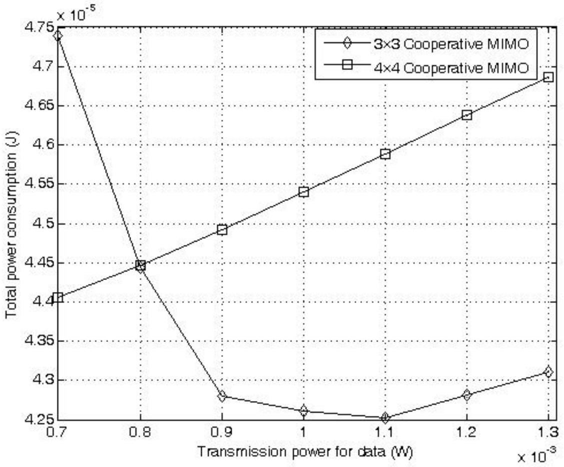

Fig. 7. The optimum value of data transmission power P_{tx} decrease as the sending/receiving group size increases. The optimum P_{tx} is 1.1 mW in 3×3 Cooperative MIMO systems.

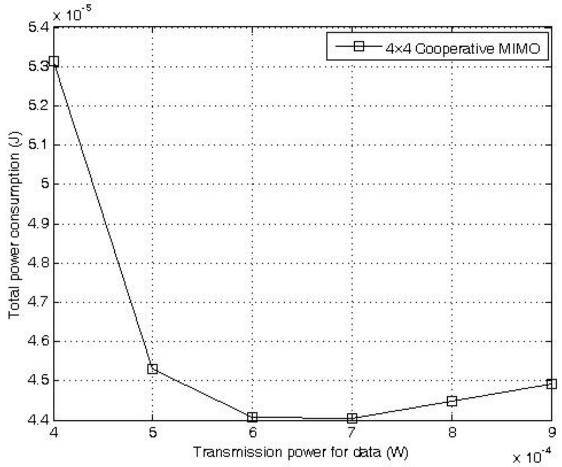

Fig. 8. When the sending/receiving group increase as 4, the optimum value P_{tx} is lower than 1mW. The optimum data transmission power P_{tx} is about 0.7 mW in 4×4 Cooperative MIMO systems.

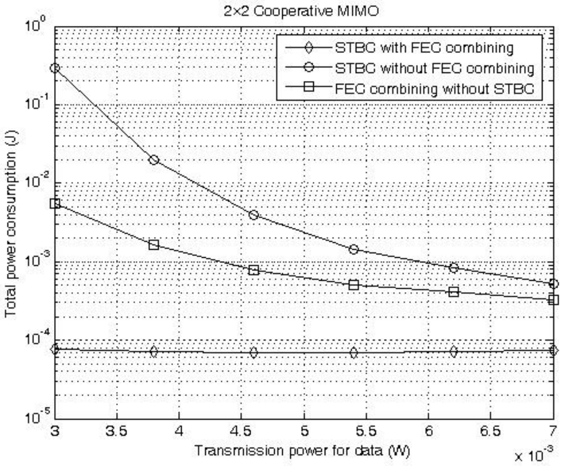

Fig. 9. Energy consumption in 2×2 cooperative system: the proposed cooperative MIMO system has best performance due to transmitter diversity and receiver diversity.

for different size of sending/receiving group are shown in Figure 9, Figure 10, and Figure 11.

From Figure 9, Figure 10, and Figure 11, we can find the proposed cooperative MIMO system has best performance in total energy consumption. This is consistent with our conclusion for BER in previous section. The proposed system has the lowest BER because it utilizes the transmitter diversity by STBC and the receiver diversity by code combining. Lower BER in proposed system implies lower packet error probability and less retransmission. Thus, with the same data transmission power P_{tx}, the proposed cooperative MIMO system has lowest energy consumption among the three systems because of lowest packet error probability and less transmission.

In Figure 9, Figure 10, and Figure 11 it is also shown that the cooperative code combining system (no STBC) has better performance in energy consumption than the cooperative MIMO system with STBC (no code combining) when the size of sending/receiving group is 2 and 4. But the cooperative MIMO system with STBC (no code combining) has better performance when the size of sending/receiving group is 3. This is because in cooperative MIMO system with STBC (no code combining) the destination node detects signals based on the majority in the receiving signal copies and randomly chooses when there is a tie. Thus the BER performance of cooperative MIMO system with STBC (no code combining) degrades when the size of receiving group is even number. This leads to higher total energy consumption since more retransmission is required.

When the size of receiving group is odd number, however, the cooperative MIMO system with STBC (no code combining) has better performance in energy consumption, as shown in Figure 10. This is because it uses STBC to utilized the transmitter diversity. This compensates the performance degradation due to the absence of code combining and receiver diversity. In Figure 10 the SNR is quite low in the range of data transmission power P_{tx}. In low SNR, cooperative MIMO system with STBC utilizes transmitter diversity and the BER at receiving nodes can be lower because of the

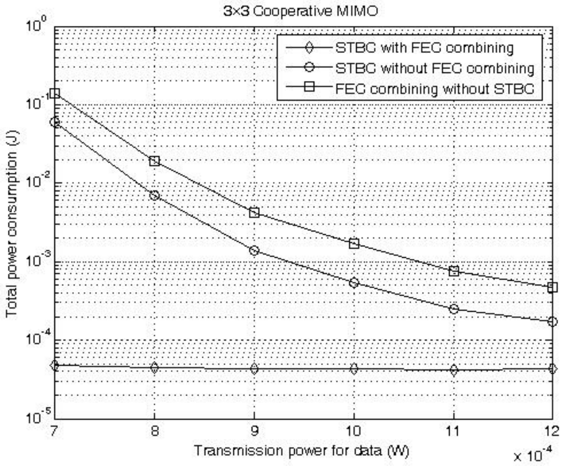

Fig. 10. In 3×3 Cooperative systems the cooperative STBC system (no code combining) has better performance than cooperative code combining system (no STBC).

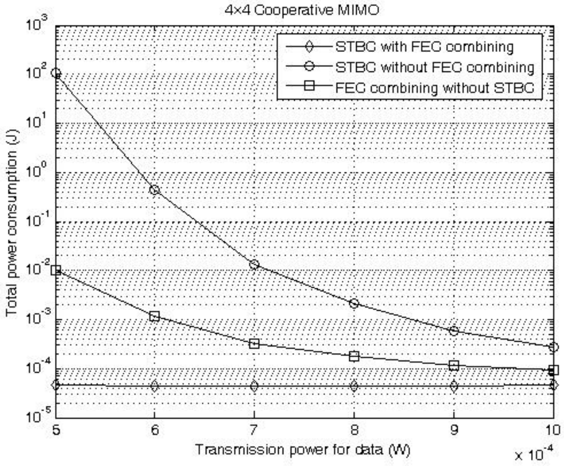

Fig. 11. The total energy consumption decrease very little in proposed system as the sending/receiving group size increases from 3 to 4.

diversity gain. Although the destination node only detects signals based on majority, the BER at destination node is improved since the receiving nodes already detect correctly. On the other hand, cooperative code combining does not utilize the transmitter diversity. The receiving nodes cannot detect the signals correctly due to low SNR and no diversity gain. Although the destination node uses code combining to help recover the original information bits, too much error in receiving signals makes code combining useless. Thus cooperative MIMO system with STBC (no code combining) has better performance than cooperative code combining system (no STBC) when the size of receiving group is odd and SNR is low.

V. CONCLUSION

In this paper, we proposed a energy efficient cooperative MIMO system. STBC and code combining are deployed in the sending group and receiving group, respectively. The bit error rate (BER) performance is analyzed and the empirical results generated by simulation is given. With the analysis and simulation result for BER, the energy consumption for proposed protocol is discussed. The total energy consumption for proposed system is shown and compared to the total energy consumption for different system designs.

According to simulation results and theoretical analysis, the proposed system design utilizes the inherent MIMO diversity in cooperative MIMO system to achieve better performance in bit error rate. Although the cooperative MIMO systems required more control messages, the energy consumption analysis shows the total energy consumption is much lower due to reliable transmission. Thus proposed cooperative MIMO system provide an energy efficient and reliable transmission.

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