A Distributed System for Cooperative MIMO Transmissions

Hsin-Yi Shen *, Haiming Yang*, Biplab Sikdar *, and Shivkumar Kalyanaraman †
* Department of ECSE, Rensselaer Polytechnic Institute, Troy, NY 12180 USA
†IBM India Research Laboratory, Bangalore, India Email: shivkumar-k@in.ibm.com

Abstract— **In this paper we propose a distributed system for facilitating cooperative MIMO transmissions in networks without multiple antenna devices. MIMO diversity is achieved by employing groups of nodes in the vicinity of the source and destination to help with the transmission. The distributed sending nodes are assumed to have different carrier frequency offsets (CFO). Space-time block codes (STBC) and code combining are used to utilize spatial diversity. The estimation of multiple CFO and detector for STBC-coded data under multiple CFO are provided. The BER of the proposed system is shown and discussed. We also consider the energy consumption and compare it with other cooperative designs.**

I. Introduction

Various schemes in previous research have shown that spatial diversity can be leveraged at the network, link or physical layers to provide energy efficient transmissions. At the physical layer, MIMO systems use multiple antennas to achieve spatial diversity. However, MIMO systems require multi-antennas devices, which may not be feasible in some devices due to cost and size limitations. Thus the concept of cooperative diversity has been proposed to provide spatial diversity with single antenna devices. In cooperative networks, the source uses idle nearby nodes to provide spatial diversity. Most of existing research considers the transmission between two senders and one receiver [1]–[4] or multiple relays between source and destination [5]. Also, most of previous schemes can be viewed as an extension of relay models and do not allow arbitrary numbers of cooperating nodes.

The key challenges faced with distributed implementation of cooperative MIMO system are: (1) node coordination in sending and receiving groups, (2) distributed space-time coding and carrier frequency offsets in senders, and (3) data combining in the destination. Compared to the centralized coding scheme in traditional MIMO systems, a distributed coding scheme is expected for cooperative MIMO transmissions. In this paper we propose to use space-time block codes (STBC) and combine it with a distributed MAC protocol to achieve a distributed implementation that allows for flexible number of cooperating nodes. A solution is also proposed to solve the problem of multiple carrier frequency offsets (CFO) arising from the fact that each sending node has its own individual electronic circuits to generate the carrier signal.

To facilitate cooperative MIMO transmissions, this paper proposes a distributed system architecture. The system is based on the source and destination nodes recruiting nearby nodes to cooperate with the transmission. STBC are used at each transmitting nodes and code combining is used at the destination to complete the detection. While the use of multiple nodes provides spatial diversity, the use of STBC and code combining provides MIMO diversity even under imperfect carriers. The proposed system therefore provides a viable alternative for reliable low-power transmissions.

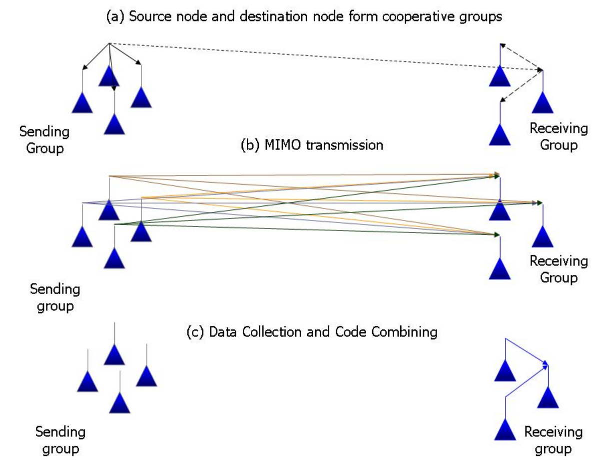

Fig. 1. Proposed cooperative MIMO system: (a) Recruitment, (b) MIMO transmission, (c) Data Collection and Combining

The rest of this paper is organized as follows: the proposed system is described in Section II. The iterative estimation for multiple CFOs and the MMSE detector for received signals are also discussed in section II, followed by the simulation results for BER and energy consumption in Section III. Finally, we conclude the paper in Section IV.

II. System Design

To facilitate cooperative, virtual MIMO communication in networks without multiple-antenna devices, the source and destination nodes require the help of surrounding nodes to help with the transmissions and receptions. This section describes the design of such a system and is based on a three step process with the source and destination nodes forming clusters to aid in the transmission and reception. An overview of the proposed scheme is shown in Figure 1 and consistes of the following steps: *Step 1: Cluster Formation:* At the beginning of each transmission, the source node sends a recruiting RTS (RRTS) message to its neighbors to solicit help form them for transmitting the data packet. The RRTS message is transmitted at a power level lower than that used for normal transmissions (at least by a factor of two) in order to reduce the interference and power consumption, and also to ensure that only nearby nodes are recruited. Neighboring nodes that are available, reply with a sequential CTS (SCTS) packet in order to eliminate collisions. The sequence is explicitly mentioned in the RRTS packet which lists the order in which the neighbors of the source are expected to reply (neighbor discovery is assumed to have been done). After recruiting the sending group, the source node sends a MIMO RTS control message (MRTS) to the destination node to reserve the channel for the transmission. If the destination node is able to receive the MRTS message, it first recruits receiving group nodes, using the same procedure as the source node (using RRTS and SCTS messages). The destination node then replies with a MIMO CTS (MCTS) message to the source node to confirm the transmission. The size of the receiving group is included in the MCTS packet. If no RCTS is received, the source node times out and follows an exponential backoff mechanism similar to IEEE 802.11.

Step 2: STBC MIMO Transmissions: Once the MCTS message is received, the source node encodes the information bits of the data packet using error correction codes. Then the source node broadcasts the data and synchronization information with low power to the selected neighbor nodes. The source node also specifies to each helper node which row in the STBC matrix it is supposed to use. Since the distance between the source and the helping nodes is quite short, members of the sending group are not required to send an ACK back to the source node. All nodes in the sending cluster then transmit their data to the destination cluster.

Step 3: Data Collection and Combining: After receiving the data from the sending group, each node in the receiving group uses the channel state information and estimated carrier frequency offsets to decode the space-time block coded data. After decoding for STBC, each node in the receiving group relays its copy of the data to the destination node. The destination receives signal copies from the helper nodes and detects them as soft symbols. Then the destination uses code combining and chooses the most probable codeword based on the received soft symbols. If the original data is decoded correctly, the destination node sends an ACK to the source node. Otherwise, no ACK is sent and the source node will timeout and initiate a backoff mechanism before attempting a retransmission (where the whole procedure is repeated).

A. Carrier Frequency Offset Estimation

A key challenge in the design of the system proposed above is that since the cooperative transmissions will be made at different nodes, a frequency offset is expected in their carrier frequencies. This in turn may lead to unacceptably high levels of bit errors at the receiving nodes. In this section we propose a mechanism for enabling each receiver to estimate the multiple carrier frequency offset (CFO) using uncorrelated pilot symbols. Note that existing schemes like [6] either require independent data streams (not possible with STBC) or are not accurate when the number of senders increases [7] in addition to not specifying how to design uncorrelated pilot symbols.

To design pilot symbols for distributed senders, we use pseudo-random noise (PN) sequences because the receiver only needs information on the shift register length and initial state in each sender to obtain pilot symbols. To send pilot symbols, the source node first decides the length of the shift register and assigns the initial state of the shift register for each sending node. PN-sequences use primitive polynomials to generate sequences and each specific value of shift register length L has only one corresponding primitive polynomial. Thus a receiver only needs to know the length L and can find the corresponding primitive polynomial. Besides, the PN sequence only has high autocorrelation $R(t_1 - t_2)$ when $t_1 = t_2$. If the initial state is different (i.e, $t_1 \neq t_2$), the autocorrelation function is almost 0. Thus the sending nodes can use the same length of shift register as PN-sequence generator and choose different initial states to generate uncorrelated pilots. The receiving node only needs to know the length L of the shift register and the initial states of the sending nodes, instead of the whole pilot symbol sequence. This information can be obtained by the receiving nodes through MIMO RTS control messages.

Next, the sending group starts pilot symbol transmission and all receiving nodes use the received mixed signal of pilot symbols to estimate the multiple carrier frequency offset. We assume that there are M sending nodes and N receiving nodes and denote the pilot symbols and carrier frequency offset in sending node i as $\mathbf{p}_i$ and f_i, respectively, and the complex channel gain between sending node i and receiving node r as α_{ir}. The received signal at receiving node r can be denoted by

$$\mathbf{y}_r[n] = \sum_i \alpha_{ir}\mathbf{p}_i[n]e^{j2\pi f_i n}, n = 1, 2, \cdots$$

where n represents the symbol index. The discrete-time Fourier Transform (DTFT) of the received signal is

$$\mathbf{Y}_r(w) = \sum_n \mathbf{y}_r[n]e^{-jwn} = \sum_i \alpha_{ir}\mathbf{P}_i(w - 2\pi f_i)$$

where $\mathbf{P}_i(w)$ is the DTFT of $\mathbf{p}_i$ and $\mathbf{P}_i(w) = \sum_n \mathbf{p_i}[n]e^{-jwn}$. Next, we compute the cross-correlation between $\mathbf{Y}_r(w)$ and the DTFT of the pilot symbol, $\mathbf{P}_i(w) = \Sigma_n \mathbf{p_i}[n]e^{-jwn}$. This cross-correlation is given by [7]

$$\begin{aligned} R_r(w, \theta) &= \int \mathbf{Y}_r(w)\mathbf{P}_i^*(w + \theta)dw \\ &= \alpha_{ir} \int \mathbf{P}_i(w - 2\pi f_i)\mathbf{P}_i^*(w + \theta)dw \quad (1) \end{aligned}$$

since the pilots are uncorrelated and $P_i(w)$ is uncorrelated to $P_k(w)$ for $k \neq w$. From above, $R_r(w, \theta)$ becomes the auto-correlation of $\mathbf{P}_i(w)$. The autocorrelation function will have its maxima at lag 0 and receiving node r can estimate the CFO f_i as [7]:

$$\hat{f}_i = -\frac{1}{2\pi} \max_\theta R_r(w, \theta) \quad (2)$$

However, the channel gain α_{ir} is complex, i.e., $\alpha_{ir} = |\alpha_{ir}|e^{j\phi_{ir}}$. Thus it distorts the signal phase and affects the estimation in Equation (2), which also uses signal phase for the carrier frequency offset estimation. To improve estimation precision, we use iterative updating to update $\hat{f}_i$. The iterative updating algorithm is shown in Algorithm 9. The channel is assumed to be quasi-static fading and the channel state information (CSI) is known at the receivers. The iterative updating can be viewed as a digital phase

Algorithm 1 Iterative CFO estimation.

while $\sum_n |\hat{\mathbf{y}}_r[n] - \mathbf{y}_r[n]| < \epsilon$ or $iteration < 100$ **do**
  for k=1 to M **do**
    $\hat{\mathbf{x}}_{kr}[n] = \mathbf{y}_r[n] - \sum_{i,i\neq k} \alpha_{ir}\mathbf{p}_i[n]e^{j2\pi\hat{f}_i n}$
    $\hat{\mathbf{X}}_{kr}(w) = \sum_n \hat{\mathbf{x}}_{kr}[n]e^{-jwn}$
    $R_{kr}(w,\theta) = \int \mathbf{X}_{kr}(w)\mathbf{P}_k^*(w+\theta)dw$
    $\hat{f}_k = -\frac{1}{2\pi}\max_\theta R_{kr}(w,\theta)$
  end for
  $\hat{\mathbf{y}}_r[n] = \sum_i \alpha_{ir}\mathbf{p}_i[n]e^{j2\pi\hat{f}_i n}$
end while

lock loop (PLL) for multiple carrier drift signals. Through iterative updating, the estimation is more precise and the multiple carrier frequency offsets are locked.

B. STBC decoding under Multiple Carrier Frequency Offset

In the cooperative MIMO transmission described earlier in this section, the receiving nodes decode the space-time block coded data and relay their decoded signal copies to the destination code. With STBC-coded data $\mathbf{x}$, the received signal at receiving node r, $\mathbf{y}_r$, is given by

$$\mathbf{y}_r = \mathbf{H_r}\mathbf{x} + \mathbf{N} \tag{3}$$

where $\mathbf{N}$ is Gaussian noise and $\mathbf{H_r}$ is the matrix of path gains at receiving node r. Let τ_t denote the permutation of symbols from $[x_1, x_2, \cdots, x_c]$ to the t^{th} column in the STBC encoding matrix. The row position of x_i in the t^{th} column is represented by $\tau_t(i)$. The element in position $(t, \tau_t(i))$ of the matrix $\mathbf{H_r}$, $h^r_{t,\tau_t(i)}$, is the path gain for symbol x_i transmitted at time t by sending node $\tau_t(i)$. $h^r_{t,\tau_t(i)}$ can be expressed as $h^r_{t,\tau_t(i)} = \frac{\alpha_{\tau_t(i),r}}{d^{\lambda/2}_{\tau_t(i),r}}$, where λ is the path-loss exponent and $\alpha_{i,r}$ is the fading gain. If the size of the sending group is odd, symbol x_i may not be transmitted at time t and $h^r_{t,\tau_t(i)}$ is 0.

If the coded data bits are transmitted without carrier frequency offsets and we assume quasi-static channels, the matrix $\mathbf{H_r}$ is an orthogonal matrix, i.e, $\mathbf{H_r} = [\mathbf{h_1}\mathbf{h_2}\cdots\mathbf{h_c}]$ and $\mathbf{h_1}, \mathbf{h_2}, \cdots, \mathbf{h_c}$ are orthogonal to each other. Thus the symbols $\mathbf{x}$ can be easily decoded. However, for cooperative MIMO transmissions without perfect carriers, the matrix $\mathbf{H_r}$ is not orthogonal and becomes time-variant. This time varying matrix is denoted by $\mathbf{H_{r,k}}$ and the element at position $(t, \tau_t(i))$ of matrix $\mathbf{H_{r,k}}$ is given by

$$h^{r,k}_{t,\tau_t(i)} = h^r_{t,\tau_t(i)} e^{j2\pi f_{\tau_t(i)} t}, \qquad k = \left\lfloor \frac{t}{c} \right\rfloor \tag{4}$$

where c is the coding length. Thus $h^{r,k}_{t,\tau_t(i)}$ is a function of time t and thus $\mathbf{H_{r,k}}$ is time-variant and nonorthogonal.

Receiving node r can estimate the matrix $\mathbf{H_{r,n}}$ through the channel gain $\alpha_{\tau_t(i),r}$ and the estimated CFOs $\hat{f}_{\tau_t(i)}$. However, the receiving node j still needs to detect the symbols x through the nonorthogonal matrix $\mathbf{H_{r,n}}$. Considering the computation complexity, in this paper we propose to use a linear MMSE detector to detect the STBC-coded data under multiple carrier frequency offsets. We now describe the detector design.

At time kc, the signal received at receiving node r is

$$\mathbf{y}_{r,k} = \mathbf{H_{r,k}}\mathbf{x} + \mathbf{N}, \qquad k = 1, 2, \cdots, \kappa \tag{5}$$

where c is the coding length and is the size of the square matrix $\mathbf{H_{r,k}}$ and κ = (packet length)/c. We assume that symbols $\mathbf{x}$ are transmitted using BPSK and a linear detector $\mathbf{D_i}$ is used. $\mathbf{D_i}$ is a vector with length $c \times 1$. For the linear detector $\mathbf{D_i}$, the BPSK symbol x_i is detected by the phase of the term $(\mathbf{D_i}^T \cdot \mathbf{y})$. If the phase is between $-\pi/2$ and $\pi/2$, x_i is detected as 1. Otherwise it is detected as -1. To simplify the computational complexity in receiving node r, we use $\tilde{\mathbf{y}}$ instead of $\mathbf{y}$ [8]:

$$\tilde{\mathbf{y}} = \mathbf{H_{r,k}}^H \cdot \mathbf{y} = \mathbf{H_{r,k}}^H \mathbf{H_{r,k}}\mathbf{x} + \mathbf{H_{r,k}}^H \cdot \mathbf{N} = \mathbf{R}\mathbf{x} + \tilde{\mathbf{N}} \tag{6}$$

where $\mathbf{R} = \mathbf{H_{r,k}}^H\mathbf{H_{r,k}}$ and $\tilde{\mathbf{N}}$ is Gaussian noise $N(0, \sigma^2\mathbf{R})$ and σ^2 is the noise power. $\mathbf{R}$ is a Hermitian matrix, i.e, $\mathbf{R}^H = \mathbf{R}$. The mean square value of detection error $(x_i - \mathbf{D_i}^H \cdot \tilde{\mathbf{y}})$ is given by

$$\begin{aligned} \text{MSE} &= E[(x_i - \mathbf{D_i}^H \cdot \tilde{\mathbf{y}})^*(x_i - \mathbf{D_i}^H \cdot \tilde{\mathbf{y}})] \\ &= E[(x_i^* - \mathbf{D_i}^T \cdot \tilde{\mathbf{y}}^*)(x_i - \tilde{\mathbf{y}}^T \cdot \mathbf{D_i}^*)] \\ &= E[x_i^* x_i - x_i \cdot (\mathbf{D_i}^T \cdot \tilde{\mathbf{y}}^*) - x_i^* \cdot (\tilde{\mathbf{y}}^T \cdot \mathbf{D_i}^*) \\ &\quad + \mathbf{D_i}^T \cdot \tilde{\mathbf{y}}^* \tilde{\mathbf{y}}^T \cdot \mathbf{D_i}^*] \end{aligned} \tag{7}$$

The linear detector $\mathbf{D_i}$ minimizes the mean square error if the gradient

$$\nabla_{\mathbf{D_i}} = E[-x_i\tilde{\mathbf{y}}^* + \tilde{\mathbf{y}}^*\tilde{\mathbf{y}}^T\mathbf{D_i}^*] = 0 \tag{8}$$

Thus the linear MMSE detector for x_i is

$$\mathbf{D_i} = ((E[\tilde{\mathbf{y}}^*\tilde{\mathbf{y}}^T])^{-1}E[x_i\tilde{\mathbf{y}}^*])^* \tag{9}$$

with $E[\tilde{\mathbf{y}}^*\tilde{\mathbf{y}}^T]$ and $E[x_i\tilde{\mathbf{y}}^*]$ defined as

$$E[\tilde{\mathbf{y}}^*\tilde{\mathbf{y}}^T] = E[(\mathbf{R}^*\mathbf{x}^* + \tilde{\mathbf{N}}^*)(\mathbf{x}^T\mathbf{R}^T + \tilde{\mathbf{N}}^T)] \tag{10}$$
$$= \mathbf{R}^*\mathbf{R}^T + \sigma^2\mathbf{R}^* \tag{11}$$

$$E[x_i\tilde{\mathbf{y}}^*] = E[x_i(\mathbf{R}^*\mathbf{x}^* + \tilde{\mathbf{N}}^*)] \tag{12}$$
$$= \mathbf{R}^* \cdot \mathbf{e_i} \tag{13}$$

where $\mathbf{e_i}$ is a $c \times 1$ vector that only has 1 in the i^{th} element and 0 otherwise. Thus the linear MMSE detector $\mathbf{D_i}$ is

$$\mathbf{D_i} = (\mathbf{R}^*\mathbf{R}^T + \sigma^2\mathbf{R}^*)^{-1}\mathbf{R}^* \cdot \mathbf{e_i}^* \tag{14}$$
$$= (\mathbf{R}^T + \sigma^2\mathbf{I})^{-1} \cdot \mathbf{e_i}^* \tag{15}$$

The matrix $(\mathbf{R}^T + \sigma^2\mathbf{I})^{-1}$ does not have a high computational complexity since the matrix $\mathbf{R}$ is a Hermitian matrix and $\mathbf{I}$ is the identify matrix. The inverse is thus easy to compute. Also, $\mathbf{D_i}$ is the i^{th} column in the matrix $(\mathbf{R}^T + \sigma^2\mathbf{I})^{-1}$. Thus the linear MMSE detector $\mathbf{D_i}$ is applied to the received signal $\tilde{y}$

$$\mathbf{D_i}^H\tilde{\mathbf{y}} = ((\mathbf{R}^T + \sigma^2\mathbf{I})^{-1} \cdot \mathbf{e_i})^T\tilde{\mathbf{y}} \tag{16}$$
$$= [((\mathbf{R}^T + \sigma^2\mathbf{I})^{-1})^T\tilde{\mathbf{y}}]_i \tag{17}$$

and the i^{th} element in the output vector above is detected as x_i.

III. SIMULATION RESULT

This section presents simulation results to evaluate the performance of the proposed cooperative MIMO system with multiple CFO and compare it against other system designs. BPSK modulation is applied to the signal and the channel is assumed to be quasi-static Rayleigh fading. The distance between source and destination nodes is 125 meters. The locations of the sending and receiving group nodes are randomly generated and assumed to be within a circle of radius 25 meters around the source and destination nodes, respectively. The length of the shift registers is set as 5 and the length of pilot symbol sequences is 32 bits. The total transmission power used in *step 1* and *step 3* of the proposed scheme is assumed to the 10dB lower than the total transmission power used in the MIMO transmission in *step 2*. Also, the total transmission power is divided equally among all transmission nodes. The transmission power used in the MIMO transmission in *step 2* is set to achieve equivalent receiving SNR in a point-to-point transmission. Thus, the transmission power in *step 2* is defined as $SNR{\cdot}d_{SD}^{\lambda}{\cdot}N_0/M$, where d_{SD} is the distance between the source node and destination node, λ is the path-loss exponent, M is the number of nodes in the sending group (including source node), and N_0 is the noise power.

To evaluate the proposed cooperative STBC system, we compare it with two other schemes: (i) cooperative code combining without STBC and (ii) cooperative MIMO systems without code combining. The performance of the three systems in terms of the BER for sending and receiving group sizes of 3×3 is shown in Figure 2. The figure also show the performance of a traditional point-to-point transmission with the same total power consumption as the cooperative schemes. The system with STBC but no code combining has the worst performance among the three schemes because the destination node only detects symbols based on the majority in multiple receiving signal copies. The performance of the system with code combining but no STBC and the proposed system with both STBC and code combing are close since the path gain matrix $\mathbf{H}_{\mathbf{r},\mathbf{k}}$ is not orthogonal due to multiple carrier frequency offsets and no full transmitter diversity is guaranteed. However, the performance of proposed system is a little better than that of the system with only code combining. Although no full transmitter diversity is guaranteed due to multiple CFO and nonorthogonal $\mathbf{H}_{\mathbf{r},\mathbf{k}}$, space-time block coding and the proposed linear MMSE detector still improves BER performance.

In Figure 3 we evaluate the proposed system (with code combining and STBC) under different carrier estimation methods and discuss the effect of inaccurate CFO estimation. The figure corresponds to group sizes of 3×3. We evaluate the system in three scenarios: (1) no CFO estimation schemes are used, (2) CFO estimation without the proposed iterative technique, and (3) CFO estimation with the proposed iterative estimation technique. The BER of the system without any CFO estimation is around 0.4-0.5 and does not decrease as the SNR increases. For BPSK signals, the performance is near the performance of random guessing for binary data bits. For systems without the iterative estimation

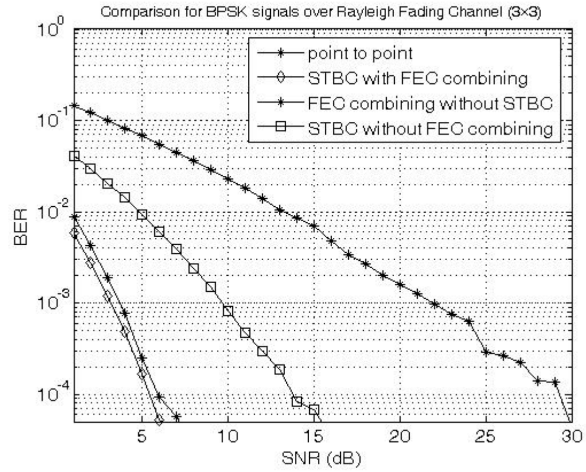

Fig. 2. Comparison of Bit error rate (BER) in different systems when the size of sending/receiving group is 3.

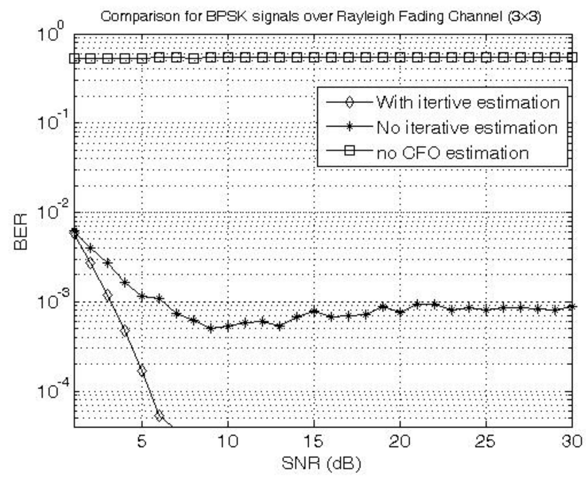

Fig. 3. Comparison of Bit error rate (BER) with different CFO estimation method while the size of sending/receiving group is 3.

method, the performance degrades as the size of the sending group increases and the BER is almost constant when the SNR is greater than 10dB. The performance of the proposed iterative scheme is significantly better.

Next, we consider the energy consumption of the proposed system. We only consider the energy spent during a transmission and compare the proposed scheme with (1) cooperative relay systems and (2) cooperative FEC system, which both have one sending node (i.e. the source node) and the receiving group including the destination node. The source nodes transmits information bits to the receiving group and the receiving nodes relay the received signal to the destination node. In cooperative FEC system the destination node uses code combining to combine the signal copies. In the cooperative relay system, the destination node detects the information bits only based on the majority.

For the calculation of energy consumption, we consider the possibility of retransmissions and the power consumption in control messages. We assume that the MAC protocols for cooperative FEC and cooperative relay systems are the same as the proposed system, except that the recruiting control messages (RRTS and SCTS) are only required in the receiving group. In the proposed system, the energy consumption for an unsuccessful transmission attempt is

$$\begin{aligned} Eu_{coopmimo} &= E_{mrts} + E_{mcts} + 2E_{rrts} \\ &\quad +(M-1)E_{scts} + (N-1)E_{scts} \\ &\quad +E_{br} + E_{data} + (N-1)E_{col} \end{aligned} \tag{18}$$

and that for a successful attempt is

$$\begin{aligned} Es_{coopmimo} &= E_{mrts} + E_{mcts} + 2E_{rrts} \\ &\quad +(M-1)E_{scts} + (N-1)E_{scts} \\ &\quad +E_{br} + E_{data} + (N-1)E_{col} + E_{ack} \end{aligned} \tag{19}$$

where E_{mrts}, E_{mcts}, E_{ack}, E_{rrts} and E_{scts} are the energy spent on sending MRTS, MCTS, ACK, RRTS and SCTS packets. E_{col} is the energy spent by each receiving node during the data collection in the third phase. M and N are the number of nodes in the source and destination clusters, respectively (including the source and destination nodes). E_{br} is the energy spent on broadcasting data to the helping nodes in the sending group. E_{data} is the energy spent on the data transmission between the sending and receiving groups.

We assume that the length of all control messages is L_c and the size of a data packet is L. The data rate is R and a convolutional code with rate R_c is applied on the data packet to enable code combining in the receiving group. Thus, the energy spent on transmitting data is $E_{data} = P_t L/R/R_c$ and that on transmitting control messages is $E_{mrts} = P_{mrts} L_c/R$ where P_t is the power level for transmissions in *step 2* and P_{mrts} is the power level for transmissions in *step 1* and *step 3*. Thus, Equations (18) and (19) can be rewritten as

$$\begin{aligned} Eu_{coopmimo} &= \frac{L_c}{R}(P_{mrts} + P_{mcts} + 2P_{rrts} \\ &+ (M-1)P_{scts} + (N-1)P_{scts}) \\ &+ \frac{L}{RR_c}(P_{br} + P_{tx} + (N-1)P_{col}) \end{aligned} \tag{20}$$

$$\begin{aligned} Es_{coopmimo} &= \frac{L_c}{R}(P_{mrts} + P_{mcts} + 2P_{rrts} \\ &+ (M-1)P_{scts} + (N-1)P_{scts} + P_{ack}) \\ &+ \frac{L}{RR_c}(P_{br} + P_{tx} + (N-1)P_{col}) \end{aligned} \tag{21}$$

Combining the two terms above, the total energy for a transmission in the cooperative MIMO system is

$$E = \frac{P_e}{1-P_e} Eu_{coopmimo} + Es_{coopmimo} \tag{22}$$

where P_e is the packet error probability. The energy consumption of the cooperative relay and cooperative FEC systems is similar to Equation (22), except that there is only one RRTS and $N-1$ SCTS control messages in the systems and $P_{br} = 0$.

In Figure 4 we compare the energy consumption of the three systems when 3 nodes are used in the receiving group or for relaying. The following parameters were used for these figures: $R = 2$ Mbps, $R_c = 1/2$, $L_c = 64$ bytes, and $L = 256$ bytes. The control messages between the source and destination nodes (MRTS, MCTS and ACK)

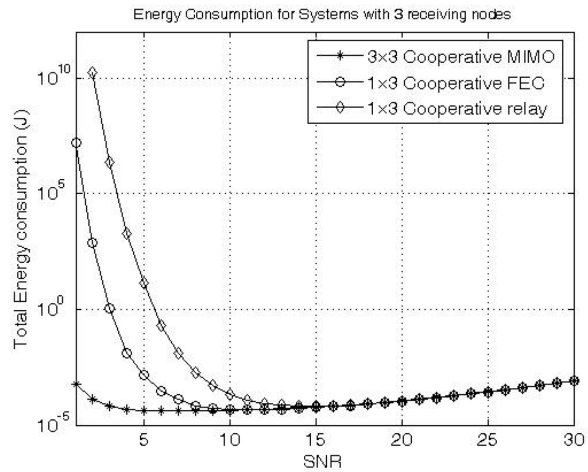

Fig. 4. Energy Consumption for 3×3 cooperative system

are transmitted at 15 dBm while control messages inside each group (RRTS and SCTS), are transmitted at $1/4$ of the transmission power of MRTS and MCTS packets. To make the comparison reasonable, we assume the total power consumption for a transmission attempt is the same in all three systems. However, the power consumed per successful transmission is different in each case, because of the different BERs in each system. Among the three schemes, the energy consumption in the proposed system is the smallest. This is because the proposed system provides transmitter diversity by forming the sending group. Also, the energy consumption of cooperative FEC is smaller than that of cooperative relay systems because code combining improves the decoding. For all schemes, the BER increases at low SNR, which in turn results in multiple retransmissions, thereby resulting in high power consumption. As SNR increases, reduction in the BER decreases the power consumption. However, this decrease does not continue unboundedly since higher power is required for transmitting at high SNRs.

IV. Conclusion

This paper proposed a distributed system for cooperative MIMO transmissions that utilizes space-time block coding and code combining in the sending and receiving groups, respectively. A PN sequence based uncorrelated pilot symbol generation with iterative updates is proposed to estimate the multiple carrier frequency offsets from received mixed pilot signals. For the data transmission, we proposed a MMSE detector for receiving STBC-coded data under multiple CFO. Simulation results are used to demonstrate the performance improvements resulting from the proposed system.

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