Cooperative Communication with Grouped Relays for Zero-Padding MB-OFDM

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***Abstract*—The emerging technology of cooperative communication has been intensively examined in the recent years. However, few investigate its combination with the Multi-band (MB) OFDM physical layer. In the paper, we propose a cooperative MB-ODFM communication with efficiently grouped relays under multipath channel. Taking advantage of the multiple bands together with the grouped relays, the proposed zero-padding MB-OFDM is proven to collect the full cooperative diversity only with linear equalizer rather than a Maximum-Likelihood (ML) receiver, and without bandwidth efficiency waste that Alamouti-like codes suffer. Furthermore, the QPSK modulation for Rayleigh channel and the dual carrier modulation for an IEEE Ultra-Wide-Band (UWB) channel are both tested to show that the full cooperative diversity can be gained. Finally, the case with multiple carrier frequency offsets (CFOs) is also discussed.**

Keywords-OFDM; Cooperative; Diversity; CFOs; UWB

I. INTRODUCTION

With desirable properties such as high spectral efficiency, inherent resilience to narrowband radio-frequency (RF) interference and spectral flexibility, the orthogonal frequency division multiplexing (OFDM) technology shows attractive features for the dispersive channels. Conventionally, a cyclic-prefix (CP) is used to eliminate inter-symbol interference (ISI) due to multipath through transforming the linear convolution channel into a circular convolution channel. However the CP in the transmitted signal through its correlation introduces more transmitting power and creates discrete spectral ripples into the average power spectral density (PSD), which are not appreciated. Therefore, zero-padding (ZP) is recommended instead of CP in the currently adopted MB-OFDM based UWB system [1]. The differences between ZP-OFDM and CP-OFDM have already been investigated a lot such as [2], [19]. Besides, a new modulation method named dual-carrier-modulation (DCM) is also proposed for high speed communication of MB-OFDM instead of QPSK [1], [3]. From the constellation aspect, DCM is actually a square-16QAM modulation related with two QPSK mapping.

Apart from the multiple-input-multiple-output (MIMO) system, the cooperative communication (COCOM) has attracted increasing attention [4-6], especially when multiple antennas are not preferred. For COCOM, Alamouti time-space codes [7] are normally needed to achieve full space diversity but Alamouti codes reduce data rate. Reference [8] proposed a space-time linear constellation precoding (LCP), further [9] suggested a full-rate coding for OFDM under multipath channel without CFO over a frequency-selective channel. In [10] and references therein, the criterion about how to achieving full diversity with linear receivers was proposed. The condition when the linear equalization can collect the same diversity as ML was discussed in [11]. [12] proposed a distributed linear convolutional coding to achieve a full diversity with linear receivers and multiple CFOs but under a flat channel, and Reference [13] suggested a full-rate full-diversity coding based on interleaving method for CP-OFDM over multipath channel without CFOs. A COCOM with MB-OFDM using different scenario is examined in [14].

In this paper, we propose a ZP-MB-OFDM cooperative communication theme with a novel idea of grouping relays. The rest of this paper is organized as follows. In the section II, we give the system model for our proposed scheme based on multiple bands with grouped relays, and then discuss the most efficient grouping method, and consequently the case with multiple CFOs is discussed. In the section III, we provide the computer simulation results to verify our ideas, where we test both QPSK and DCM modulation schemes, and use Multipath Rayleigh channel first and then the IEEE802.15.3a UWB channel. Finally, we draw some conclusions in Section IV. It should be noted throughout the paper that the independence of the relays and their channels is assumed in order to guarantee the possible full cooperative diversity.

Notations: We use upper (lower) case bold face letters to denote matrices (vectors). Superscripts $(\cdot)^T$, $(\cdot)^H$ represent the transpose and Hermitian transformation respectively. $\|\cdot\|$, $\det(\cdot)$ and $\mathrm{diag}(\cdot)$ denotes respectively the Frobenius norm of a vector or matrix, the determinant and main diagonal entries of a square matrix, and $\lfloor a \rfloor$ denotes the floor integer of a. $\mathbf{I}_N$ as $N\times N$ identity and $\mathbf{0}_{N\times M}$ as $N\times M$ null matrix, $\mathbf{F}_N$ and $\mathbf{F}_N^H$ as N point DFT and IDFT respectively.

II. SYSTEM MODEL

In this paper, the cooperative communication with grouped relays relies on the decode and forward (DF) protocol [15] shown in Fig.1, where all the relays are grouped into G groups with the index G_j for j=1,…,G, the Phase I stands for the broadcasting from the source to the relays, which is assumed perfect and share only one frequency band, and Action I means certain additional coding by the source on the original data. While Phase II is for the relays and the destination, and Action II means certain additional coding by the relay on the decoded data. In the meantime in Fig.1, the relays may also contact each other occasionally to organize themselves which will be explained later. If any relay fails to decode the information from the source, this relay is considered inactive for this cooperative communication. Otherwise, the relay is active. Assuming the source broadcasts on Band #b, the j-th relay group transmits signals to the destination on Band #b_j.

The transceiver scheme with one ZP-OFDM symbol between the relay and destination is given in Fig.2, where the subcarrier allocation within one OFDM symbol and the ZP length obey the MB-OFDM standard proposed by ECMA-368[1]. The length of ZP here equals to the number Z which tends to eliminate the inter-symbol interference (ISI). If N subcarriers are used in one OFDM symbol, we donate $P=N+Z$. The multipath channels of Phase II are considered to have L as the maximum number of taps. For the MB-OFDM, the carrier frequency of the different OFDM symbols can be varied according to Time-Frequency codes [1], so that multiple frequency bands can be used.

A. Grouping Relays

In this subsection, we give the system model of the COCOM based on grouped relays and the criterion about the size of each group. Suppose M_j active relays are in the j-th group and there are G groups in order that $\sum_{j=1}^{G} M_j = M$ since there are total M active relays. For example in Fig.1, discarding the inactive relays, M_1=4 and M_G=4 respectively in the G_1 and G_G group at this moment.

For the communication between the j-th group and the destination, we modify the Space Time Multipath coding based on a grouped LCP for a CP-OFDM system proposed by [9] to suit our case.

We design an digital phase sweeping coding as a permutation matrix $\mathbf{P}_{i,j}$ in the time domain as the Action II in Fig.2 for the i-th relay for i=1,…,M_j.

$$\mathbf{P}_{i,j} = \begin{bmatrix} \mathbf{0} & \mathbf{I}_{(i-1)L} \\ \mathbf{I}_{P-(i-1)L} & \mathbf{0} \end{bmatrix}$$

where we note that adding $\mathbf{P}_{i,j}$ doesn't change the original data rate.

However unlike [9] we completely delete the LCP which may increase the decoding burden of the relays in the DF protocol if it is applied as Action I in Fig.1, but adopted a P-point DFT followed with a ZP-OFDM-FAST-ZF equalizer from [2] at the destination receiver to process the summed received signal of the relays in the j-th group.

So that the communication between the j-th group and the destination can be described as

$$\mathbf{y}_j = \sum_{i=1}^{M_j} \mathbf{F}_P \mathbf{H}_{i,j} \mathbf{P}_{i,j} \mathbf{T}_{ZP} \mathbf{F}_N^H \mathbf{x} + \mathbf{n}_j = \bar{\mathbf{H}}_j \mathbf{x} + \mathbf{n}_j \tag{1}$$

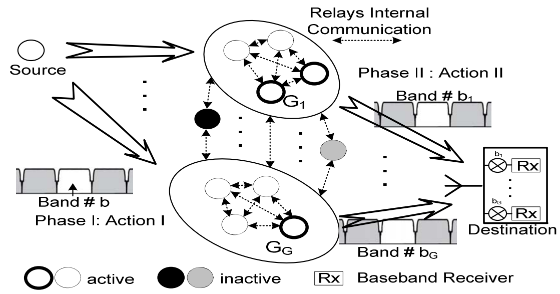

Figure 1. DF based cooperative system model for multiple-band transmission.

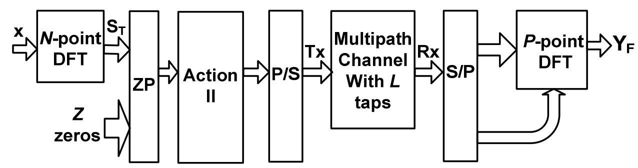

Figure 2. ZP-OFDM baseband signal transceiver between one relay and the destination.

where $\bar{\mathbf{H}}_j = \sum_{i=1}^{M_j} \mathbf{H}_{i,j} \mathbf{P}_{i,j} \mathbf{T}_{ZP}$ denotes the grouped channel matrix for the j-th relay group, $\mathbf{T}_{ZP} = \begin{bmatrix} \mathbf{I}_N \\ \mathbf{0}_{Z\times N} \end{bmatrix}$, and $\mathbf{x}$, $\mathbf{y}_j$ and $\mathbf{n}_j$ as the decoded information data at the relay nodes, the received signal at the destination and the noise respectively corresponding to the j-th group in the frequency domain, and $\mathbf{H}_{i,j}$ is a P×P Toeplitz matrix with its first column vector as $\left[\mathbf{h}_{i,j}^T, 0\cdots, 0\right]^T$ with $\mathbf{h}_{i,j} = \left[h_{1,i,j}, \cdots, h_{L,i,j}\right]^T$ and its first row vector as $\left[h_{1,i,j}, 0\cdots 0\right]$, $h_{k,i,j}$ is the value of the k-th tap for k=1,…,L corresponding to the L taps multipath channel between the i-th relay of the j-th group and the destination, and N is the number of subcarriers of one OFDM symbol.

With multiple groups, we can describe the proposed system with grouped relays as

$$\mathbf{y}_j = \sum_{i=1}^{M_j} \mathbf{F}_P \mathbf{H}_{i,j} \mathbf{P}_{i,j} \mathbf{T}_{ZP} \mathbf{F}_N^H \mathbf{x} + \mathbf{n}_j = \bar{\mathbf{H}}_j \mathbf{x} + \mathbf{n}_j \tag{2}$$

where ⊗ as the Kronecker product, $\mathbf{Y} = [\mathbf{y}_1^T, \cdots \mathbf{y}_G^T]^T$ and, $\mathbf{y}$ and $\mathbf{n}$ are the overall received signal and the noise in the frequency domain. All the $\mathbf{y}_j$ for j=1,…,G from different groups are processed according to the maximal ratio combination. One check that if $LM_j \le Z < N$ for j=1,…,G, each $\bar{\mathbf{H}}_j$ is a P×N tall Toeplitz matrix with its first column vector as $\bar{\mathbf{h}}_j = \left[\mathbf{h}_{1,j}^T, \cdots, \mathbf{h}_{M_j,j}^T, 0, \cdots, 0\right]^T$, and furthermore $\tilde{\mathbf{H}} = \left[\bar{\mathbf{H}}_1^T \ \cdots \ \bar{\mathbf{H}}_G^T\right]^T$ is also a GP×N tall Toeplitz matrix with its first column vector as $\tilde{\mathbf{h}} = \left[\bar{\mathbf{h}}_1^T, \cdots, \bar{\mathbf{h}}_G^T, 0, \cdots, 0\right]^T$.Otherwise $\bar{\mathbf{H}}_j$ will become a circulant structure while $\tilde{\mathbf{H}}$ also lose its linear structure.

From [11], when $\tilde{\mathbf{H}}$ keeps its tall Toeplitz structure, this system can be proven to have the same diversity with a linear equalizer as a ML receiver does, so that only linear receiver like Zero-forcing receiver (ZF) is considered in this paper.

If ignoring the noise, we rewrite (1) as

$$\mathbf{y}_j = \sum_{i=1}^{M_j} \mathbf{F}_P \mathbf{H}_{i,j} \mathbf{P}_{i,j} \mathbf{T}_{ZP} \mathbf{F}_N^H \mathbf{x} + \mathbf{n}_j = \bar{\mathbf{H}}_j \mathbf{x} + \mathbf{n}_j \quad (3)$$

where $\mathbb{H} \triangleq (\mathbf{I}_G \otimes \mathbf{F}_P)\tilde{\mathbf{H}}\mathbf{F}_N^H$ and according to the commutativity of linear convolution $\mathbf{H}\mathbf{F}_N^H \mathbf{x} = \mathbf{X}\tilde{\mathbf{h}}$ where $\mathbf{X}$ is a tall Toeplitz matrix corresponding to $\mathbf{F}_N^H \mathbf{x}$ so that $\mathbb{S} = (\mathbf{I}_G \otimes \mathbf{F}_P)\mathbf{X}$.

To show that full diversity can be achieved by linear receivers, let's cite the following theorem for certain constellations like Square QAM from [10]. In this paper QPSK and DCM both meet this condition.

Theorem 1: For Square QAM, if the following condition holds:

$$\|\mathbb{H}\| \le \alpha \|\tilde{\mathbf{h}}\| \quad \text{and} \quad \det\left(\mathbb{H}^H \mathbb{H}\right) \ge \beta \|\tilde{\mathbf{h}}\|^{2N}$$

where α and β are positive constants independent of $\tilde{\mathbf{h}}$, then this system can achieve the full diversity using a linear equalization. Here the diversity order equals to ML in our case under the L taps multipath channel.

For our system scheme in this subsection, we can show that

$$\|\mathbb{H}\| \le \|\mathbf{F}_P\| \|\tilde{\mathbf{H}}\| \|\mathbf{F}_N^H\| = \alpha \|\tilde{\mathbf{h}}\| \quad (4)$$

$$\|\mathbb{H}\| \le \|\mathbf{F}_P\| \|\tilde{\mathbf{H}}\| \|\mathbf{F}_N^H\| = \alpha \|\tilde{\mathbf{h}}\| \quad (5)$$

where $\alpha = \sqrt{N} \|\mathbf{F}_P\| \|\mathbf{F}_N^H\|$ is a positive constant independent of $\mathbf{h}$ and β is a positive constant independent of $\tilde{\mathbf{h}}$ [10], N is the length of $\mathbf{x}$.

Eventually, together with a MRC operation, the proposed system can achieve a full diversity using a linear equalizer when $LM_j \le Z < N$ for j=1,…,G.

Note that if CP is applied to OFDM as in [9] or the overlap-add and N-point DFT instead of a P-point DFT is applied to ZP-OFDM, $\bar{\mathbf{H}}_j$ or $\tilde{\mathbf{H}}$ will lose the tall Toeplitz structure unless $\mathbf{x}$ has enough null subcarriers which is not accepted because it will harm the bandwidth efficiency significantly. Then, in *Theorem1*, the condition $\det\left(\mathbb{H}^H \mathbb{H}\right) \ge \beta \|\mathbf{h}\|^{2N}$ can't be satisfied at least. Consequently there is no guarantee that it can collect full diversity with linear equalizers.

B. Efficient regrouping

Given the same total number of active relays, more groups don't contribute to the diversity but cost more frequency resources, which is not efficient. Only when each group contains $M_{\max,j} = \lfloor Z/L \rfloor$ relays for j=1,…,G, there is an efficient utilization of the frequency bands. In other words, when the number of the relays in each group reaches the maximal number $M_{\max,j}$, we can obtain the most efficient grouping approach to exploit the spectrum.

Unfortunately, the full decoding is not available all the time, when some active nodes may become inactive and certain inactive nodes turn active. Therefore, it would be wise for the relays to re-group themselves to achieve the most efficient utilization of the frequency bands, for which relays should be able to contact each other occasionally. One possible way for the internal connection among the relays can be a time division type or even a cognitive way [16], [17]. For example, M_1=2 and M_G=1 respectively in the G_1 and G_G group using bold circle in Fig.1 while one separate new active relay in grey in Fig.1 exists right now. After grouping, the grey relay and also the only active relay in G_G in Fig.1 will be grouped into G_1, consequently G_G will disappear and the band #b_G will be released too.

With the regrouping, the number of relays in each group approaches the maximal number $M_{\max,j}$ in order to most efficiently utilize the frequency resources.

C. Transmission with CFOs

Here we assume that each group has a maximal number of active relays, and still G independent groups currently. To keep the linear structure of the channel matrix is crucial for a linear receiver to collect full cooperative diversity in this paper. Unfortunately when variant CFOs between each relay and the destination exist, the channel matrix $\bar{\mathbf{H}}_j$ or $\tilde{\mathbf{H}}$ in (2) will lose the linear structure since $\mathbf{H}_{i,j} \to \mathbf{D}_{i,j}\mathbf{H}_{i,j}$ for $\mathbf{D}_{i,j} = \text{diag}\left(1, \alpha_{i,j}, \cdots, \alpha_{i,j}^{P-1}\right)$, $\alpha_{i,j} = \exp\left(j2\pi\Delta q_{i,j}/N\right)$, and $\Delta q_{i,j} = \Delta f_{i,j}/f_S$ as the normalized carrier frequency offset of i-th relay in the j-th group, $\Delta f_{i,j}$ is the frequency offset and f_S is the sampling frequency for the baseband signal.

However, if within one frequency band, the CFOs can be appropriately mitigated [18], and then there can be only one single CFO between one relay group and the destination. But the CFOs keep different for different, so that $\tilde{\mathbf{H}}' = \left[\bar{\mathbf{H}}_1'^T, \cdots, \bar{\mathbf{H}}_G'^T\right]^T$, $\bar{\mathbf{H}}_j' = \mathbf{D}_j \bar{\mathbf{H}}_j$; $\mathbf{D}_j = \text{diag}\left(1, \alpha_j, \cdots, \alpha_j^{P-1}\right)$ is called Multiple Grouped CFOs.

We can also prove that the system achieve full cooperative diversity as following

$$\mathbf{Y} = (\mathbf{I}_G \otimes \mathbf{F}_P)\tilde{\mathbf{H}}'\mathbf{F}_N^H \mathbf{x}_F = \mathbf{F}'\tilde{\mathbf{H}}\mathbf{F}_N^H \mathbf{x}_F = \tilde{\mathbb{H}}'\mathbf{x}_F = \mathbb{S}'\tilde{\mathbf{h}} \quad (6)$$

where $\mathbf{F}' = \begin{bmatrix} \mathbf{F}_P\mathbf{D}_1 & & 0 \\ & \ddots & \\ 0 & & \mathbf{F}_P\mathbf{D}_G \end{bmatrix}$ and $\mathbb{S}' = \mathbf{F}'\mathbf{X}$, $\tilde{\mathbb{H}}' = \mathbf{F}'\tilde{\mathbf{H}}\mathbf{F}_N^H$ with $\mathbf{X}$, $\tilde{\mathbf{H}}$ and $\tilde{\mathbf{h}}$ as same as those in (3).

It should be noted that $\mathbf{F}'$ is actually a unitary matrix since $\mathbf{F}'^H\mathbf{F}' = \mathbf{I}_{GP}$, then

$$\|\tilde{\mathbb{H}}'\| \le \|\mathbf{F}'\| \|\tilde{\mathbf{H}}\| \|\mathbf{F}_N^H\| = \alpha' \|\tilde{\mathbf{h}}\|$$

$$\det\left(\tilde{\mathbb{H}}'^H \tilde{\mathbb{H}}'\right) = \det\left(\mathbf{F}_N \tilde{\mathbf{H}}^H \tilde{\mathbf{H}} \mathbf{F}_N^H\right) = \det\left(\tilde{\mathbf{H}}^H \tilde{\mathbf{H}}\right) \ge \beta' \|\tilde{\mathbf{h}}\|^{2N}$$

where $\alpha' \geq \sqrt{N}\|\mathbf{F}'\|\|\mathbf{F}_N^H\|$ is a positive constant independent of $\tilde{\mathbf{h}}$ and another positive constant β' independent of $\tilde{\mathbf{h}}$ can also be found as before. Therefore, the proposed ZP-MB-OFDM COCOM with multiple grouped CFOs can also achieve full cooperative diversity.

III. SIMULATION RESULTS

In this section we describe the computer simulation results to illustrate the performance of ZP-MB-OFDM COCOM with grouped relays proposed in this paper, with the simulation parameters shown in Table I.

TABLE I. TABLE TYPE STYLES

Parameters	**Value**
DFT size	*P=160*
IDFT size	*N=128*
Number of Zero-Padding	*Z=32*
Modulation	*QPSK or DCM*
Source convolutional encoder	*No*
Source Viterbi decoder	*No*
Monte-Calo Loop	*10000*
OFDM symbol number for one loop	*10*
Number of Channel realization	*Best 100 of 1000*
Multipaths of Rayleigh channel	*L=8*
IEEE UWB channel type	*CM1, CM2,CM3*
Receiver	*ZF*

First we test the transmission under Rayleigh multipath channel with L=8 taps without CFOs when the QPSK modulation is used for the information sequence. In Fig.3, "Rk" stands for k active relays totally, and "$\eta \times \mu$" means η groups with μ active relays in each group. According to different slopes of the BER vs. SNR curves with different numbers of relays, the cooperative diversity increases as more independent relays are used according to the grouping criterion proposed in this paper. When $\mu > \lceil Z/L \rceil = 4$ relays in the same group, the full diversity will not be gained as mentioned before. For example according to the similar slope of their curves, 1×8 relays in Fig.3 almost collect a diversity as 1×4 relays, although a slightly better BER is reached for 1×8 case mainly due to more received signal power using more relays. However, with a correct grouping, the cooperative diversity keeps increasing as shown in Fig.3. However, it should be noted that with a total k=8 relays, the "2×4" grouping method is proposed in this paper, because each group has an allowed maximal number of relays, i.e., 32/8=4, while other grouping can be seen as non-efficient. It can be seen in Fig.3that different groupings of k=8 relays actually collect the same cooperative diversity according to their same slope of their curves, but the "2×4" grouping is the most efficient one. In other words, when each group meets the grouping criterion, more groups do not contribute to the diversity but cost more frequency resources. Furthermore, we should note that the slight differences of the BER between these grouping methods are reasonable since with more frequency bands allocated to more groups, the MRC operation may attain a higher effective SNR with more combination branches during the simulation.

Consequently, we denote $|\Delta q_j|$ as |CFOj| for the j-th group. It is no surprise that when the |CFOj| is larger, BER of the system deteriorates significantly if there is no multiple CFOs compensation at the destination. As seen in Fig.4, whether with multiple grouped CFOs or not, the cooperative diversity can be gained.

Finally, we replace Rayleigh channel with the IEEE standard UWB channel based on Saleh-Valenzuela model, with types of CM1, CM2 and CM3, where from CM1 to CM3 the channel gets worse and we assume L=16 for the multipath length. Besides, the DCM modulation is adopted instead of QPSK. Fig.5 repeats a similar simulation as Fig.3 but under CM1 and CM3 UWB channel, while Fig.6 iterates a similar simulation as Fig.4 but under CM2 UWB channel. As witnessed in these two figures, whether there are multiple grouped CFOs or not, the proposed system with grouped relays can also collect full cooperative diversity under UWB channel with DCM modulation. This clearly illustrates that this scheme suits the MB-OFDM UWB system.

IV. CONCLUSIONS

A zero-padding MB-OFDM cooperative communication scheme with efficiently grouped relays is proposed. With a bandwidth efficient coding and taking advantage of multiple bands, this system can gain the full cooperative diversity using linear equalizers even when multiple grouped CFOs exist. This system was tested both for QPSK and DCM modulation, and under Rayleigh multipath channel as well as the standard UWB channel. Simulation results verify the effectiveness of the proposed grouping in gaining full diversity of MB-OFDM cooperative communication system. This scheme can also be utilized in the dynamic environments by adaptive grouping.

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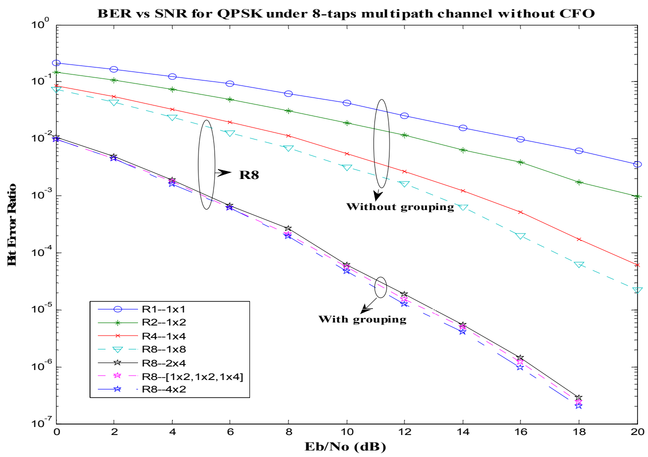

Figure 3. Non-Grouped vs. Grouped Relays Cooperative communication under 8-taps Rayleigh channel for QPSK constellation without CFOs. "Rk" stands for k active relays totally, and "$\eta \times \mu$" means η groups with μ active relays in each group.

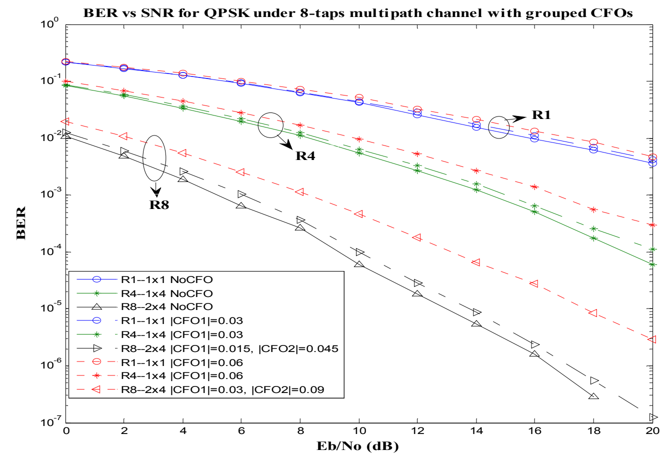

Figure 4. Grouped Relays Cooperative communication under 8-taps Rayleigh channel for QPSK constellation with multiple grouped CFOs. |CFOj| stands for the CFO between the j-th group and the destination.

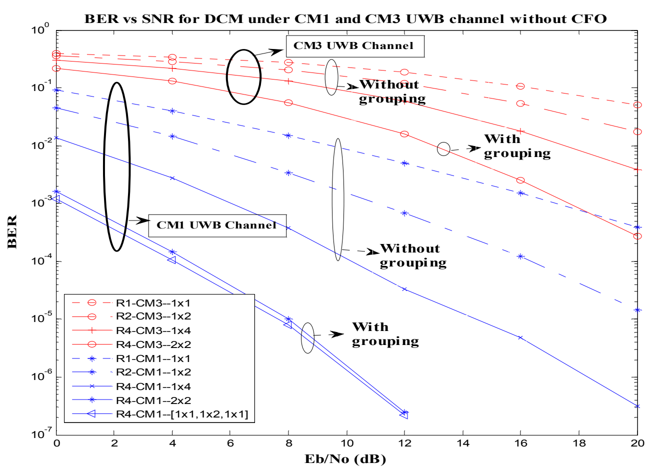

Figure 5. Non-Grouped vs. Grouped Relays Cooperative communication under CM1/CM3 UWB channel for DCM constellation without CFOs

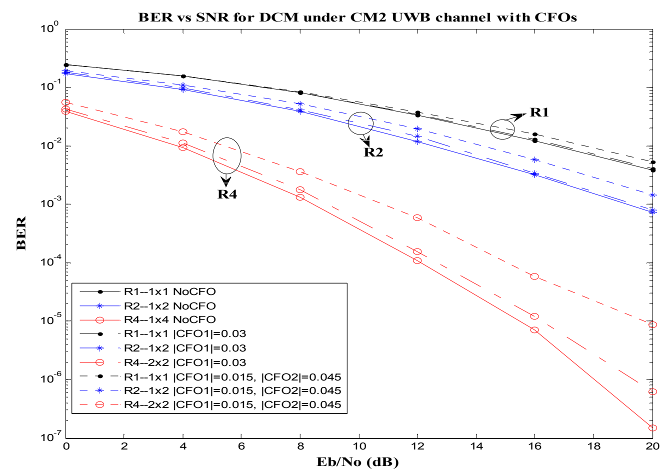

Figure 6. Grouped Relays Cooperative communication under CM2 UWB channel for DCM constellation with multiple grouped CFOs

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