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***Abstract*— Though cooperative communication has been intensively examined for general wireless systems, such as mobile and ad-hoc networks, it has been almost unexplored in the case of Space-Time-Frequency Coded Multi-band OFDM Ultra-Wideband (STFC MB-OFDM UWB). This paper proposes a framework of cooperative communication in such systems where nodes are equipped with only one antenna. Simulation results show that cooperative communication might, in some cases, provide better error performance than non-cooperative communication without any additional transmission power.**

I. INTRODUCTION

Combination of the emerging technologies Multiband OFDM Ultra-Wideband (MB-OFDM UWB) [1], Multiple Input Multiple Output (MIMO) [2], [3], and Space-Time Codes (STCs) [4], [5], [6] may provide a significant improvement in the form of maximum achievable communication range, bit error performance, system capacity, data rate, or a combined form of those. While the combination of OFDM, MIMO and STCs, which is referred to as Space-Time-Frequency Coded MIMO-OFDM (STFC-MIMO-OFDM), has been well examined in the literature [7], [8], [9], the combination of MB-OFDM UWB, MIMO, and STCs has been sparsely examined with only few published papers, such as [10], [11].

There are two main differences between channel characteristics in conventional OFDM systems and in MB-OFDM UWB ones. First, channels in the latter are much more dispersive than those in the former, with the average number of multipaths in some channel models reaching some thousands [12]. Second, channel coefficients in the former are usually considered to be Rayleigh distributed, while those in the latter are log-normally distributed [12]. Therefore, the systems incorporating MB-OFDM UWB, MIMO, and STCs must be more specifically analyzed, though there exist several similarities between those systems and the conventional STFC-MIMO-OFDM ones. In [13], [14], [15], we proposed the STFC MB-OFDM UWB system for multiple number of transmit/reveive (Tx/Rx) antennas (see Fig. 1).

A question that could be raised is whether the principle of STFCs can be applied to a MB-OFDM UWB network where all transmitters and receivers (referred to as nodes) are equipped with only one antenna. The answer is yes through the implementation of cooperative communication between nodes. The basic idea of cooperative communication is that single-antenna nodes can gain some of the benefits of MIMO systems by sharing their antennas with each other to create a virtual MIMO system. Though cooperative communication has been intensively examined for general wireless networks with various exhaustive works, such as [16], [17], [18], [19], [20], [21], [22], it has been however unexplored for MB-OFDM UWB. Thus, in this paper, we propose the cooperative communication model in STFC MB-OFDM UWB by extending further the discussions in the aforementioned works while taking the MB-OFDM UWB technical specifications [1] into account.

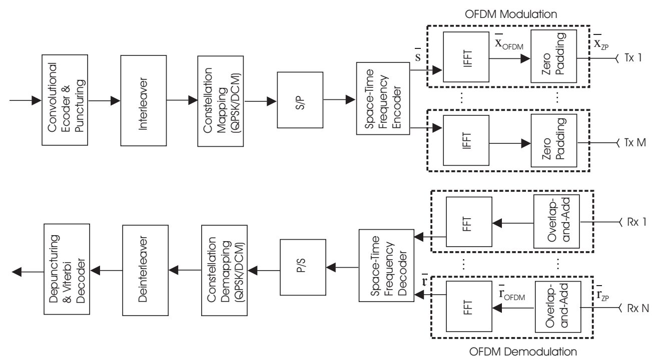

Fig. 1. Structural diagram of the proposed STFC MB-OFDM UWB system.

Notations: The following notations will be used throughout the paper. The superscripts $(.)^*$ and $(.)^T$ denote the complex conjugation and transposition operation, respectively. We denote $\bar{\mathbf{a}} \bullet \bar{\mathbf{b}}$ to be the element-wise (or Hadamard) product of the two vectors $\bar{\mathbf{a}}$ and $\bar{\mathbf{b}}$. Denote N_D and N_{fft} to be the number of data sub-carriers, and the FFT/IFFT size, respectively (for MB-OFDM UWB communications [1], $N_D = 100$ and $N_{fft} = 128$). Further, $\bar{\mathbf{a}}.\hat{}2$ denotes the element-wise power-2 operation of $\bar{\mathbf{a}}$. The complex space $\mathcal{C}$ of a symbol s denotes all potential possibilities that the symbol s can take, while the N_D-dimensional complex space $\mathcal{C}^{N_D}$ of a N_D-length vector $\bar{\mathbf{s}}$ denotes all potential possibilities that the vector $\bar{\mathbf{s}}$ can take. We define $\bar{\mathbf{1}}$ as a column vector of length N_D, whose elements are all 1. Finally, $\| \, . \, \|_F$ denotes the Frobenius norm.

II. COOPERATIVE COMMUNICATION IN MB-OFDM UWB

The proposed model is depicted in Fig. 2. We consider the application of the Alamouti STFC

$$\mathbf{S_2} \quad = \quad \begin{bmatrix} \bar{\mathbf{s}}_1 & \bar{\mathbf{s}}_2 \\ -\bar{\mathbf{s}}_2^* & \bar{\mathbf{s}}_1^* \end{bmatrix}, \tag{1}$$

where the i-th MB-OFDM symbol $\bar{\mathbf{s}}_i$ is a column vector of N_{fft} data corresponding to N_{fft} sub-carriers. It is assumed that nodes are perfectly synchronized. Denote $\bar{\mathbf{h}}_{ij} = \left[h_{ij,1} \; h_{ij,2} \ldots h_{ij,L_{ij}}\right]^T$ to be the channel vector between the two nodes i and j, where $i \in \{A, B\}; j \in \{A, B, D\}$, $(j \neq i)$ (see Fig. 2), while L_{ij} is the number of multipaths in this

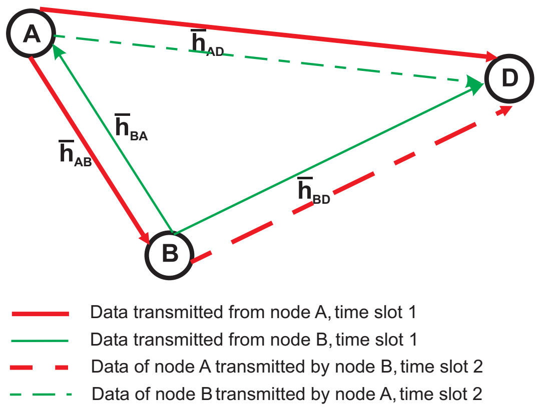

Fig. 2. Cooperative communication in MB-OFDM UWB between the source nodes A, B and the destination node D with the pairing mode.

link. The elements of $\bar{\mathbf{h}}_{ij}$ are modeled as independent log-normally distributed random variables [12]. Channel vectors $\bar{\mathbf{h}}_{ij}$ are assumed to keep constant during every two time slots (MB-OFDM symbol time slots), and change randomly to other values during the next two time slots. The channel coefficients are assumed to be known at the destination node. Each of the source nodes A and B and the destination node D are equipped with only one antenna for transmitting and receiving signals. In cooperative communication, each node transmits its own data as well as performs as a cooperative agent for another node.

In our model, two nodes are paired to cooperate with one another. The issue of how to decide which nodes to be paired with each other is out of scope of this paper. At the first time slot, node A broadcasts its symbol $\bar{\mathbf{s}}_1$ to its partner (node B) and the destination node D. At the same time, node B broadcasts its symbol $\bar{\mathbf{s}}_2$ to its partner (node A) and the destination node D. After receiving their partner's symbol, nodes A and B decode the partner's symbol. We denote the decoded symbols at nodes A and B to be $\bar{\tilde{\mathbf{s}}}_2$ and $\bar{\tilde{\mathbf{s}}}_1$ respectively. Then these two nodes retransmit the symbols to the destination in the form of $-\bar{\tilde{\mathbf{s}}}_2^*$ and $\bar{\tilde{\mathbf{s}}}_1^*$, respectively, during the 2nd time slot. The process continues until all data are transmitted. This proposed scheme is thus referred to as decode-and-forward scheme. This scheme is simpler than some of the existing cooperative communication schemes, such as [17], [21], [22], with the penalty of loosing the flexible cooperation level between two nodes.

After the overlap-and-add operation (OAAO) [1], [13] and FFT have been performed, the signals received at the destination node D during the two time slots can be represented as

$$\begin{aligned} \bar{\mathfrak{r}}_1 &= \bar{\mathfrak{h}}_{AD} \bullet \bar{\mathbf{s}}_1 + \bar{\mathfrak{h}}_{BD} \bullet \bar{\mathbf{s}}_2 + \bar{\mathfrak{n}}_1 \\ \bar{\mathfrak{r}}_2 &= -\bar{\mathfrak{h}}_{AD} \bullet \bar{\tilde{\mathbf{s}}}_2^* + \bar{\mathfrak{h}}_{BD} \bullet \bar{\tilde{\mathbf{s}}}_1^* + \bar{\mathfrak{n}}_2 \end{aligned} \qquad (2)$$

where $\bar{\mathfrak{h}}_{ij} := FFT(\bar{\mathbf{h}}_{ij})$, $\bar{\mathfrak{n}}_t := FFT(\bar{\mathbf{n}}_t)$, while $\bar{\mathbf{n}}_t$ ($t = 1, 2$) denotes the column vector of complex Gaussian noises affecting the receive antenna of the destination node at the t-th time slot. Denote $\bar{\mathfrak{h}}_{ij} = \left[\hbar_{ij,1}\ \hbar_{ij,2} \ldots \hbar_{ij,N_{fft}}\right]^T$ and $\bar{\mathfrak{r}}_t = \left[\mathfrak{r}_{t,1}\ \mathfrak{r}_{t,2} \ldots \mathfrak{r}_{t,N_{fft}}\right]^T$. Once the destination node receives the symbols transmitted during the two time slots, it is able to decode the symbols.

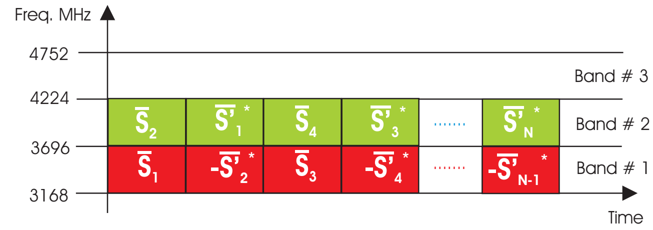

Fig. 3. Node A transmits symbols in the band number 1, while node B transmits symbols in the band number 2, inside the first band group.

If we assume theoretically that the information transmitted from the source nodes is error-freely received at their partner, i.e. $\bar{\tilde{\mathbf{s}}}_1 \equiv \bar{\mathbf{s}}_1$ and $\bar{\tilde{\mathbf{s}}}_2 \equiv \bar{\mathbf{s}}_2$, the detailed maximum likelihood (ML) decoding metrics in the cases of PSK or QAM modulation schemes can be found in Table I (see also Table II in [13]). Clearly, from Table I, each data point among N_D data points ($N_D = 100$ data sub-carriers) within each of the MB-OFDM symbols $\bar{\mathbf{s}}_1$ and $\bar{\mathbf{s}}_2$ can be decoded separately, rather than the whole N_D data in each of these MB-OFDM symbols are decoded simultaneously. Thus the decoding process is completely linear, and relatively simple. In particular, the decoding metrics for data at the n-th sub-carrier, for $n = 1, \ldots, N_D$, in the MB-OFDM symbols $\bar{\mathbf{s}}_1$ and $\bar{\mathbf{s}}_2$ are

$$\begin{aligned} s_{1,n} &= \arg\min_{s \in \mathcal{C}} \Big\{ \left| \left(\hbar_{AD,n}^* \mathfrak{r}_{1,n} + \hbar_{BD,n} \mathfrak{r}_{2,n}^* \right) - s \right|^2 \\ &\quad + \Big[-1 + \left(|\hbar_{AD,n}|^2 + |\hbar_{BD,n}|^2 \right) \Big] |s|^2 \Big\} \qquad (3) \\ s_{2,n} &= \arg\min_{s \in \mathcal{C}} \Big\{ \left| \left(\hbar_{BD,n}^* \mathfrak{r}_{1,n} - \hbar_{AD,n} \mathfrak{r}_{2,n}^* \right) - s \right|^2 \\ &\quad + \Big[-1 + \left(|\hbar_{AD,n}|^2 + |\hbar_{BD,n}|^2 \right) \Big] |s|^2 \Big\}. \end{aligned}$$

In fact, there exit errors in decoding processes at the partner nodes, i.e. $\bar{\tilde{\mathbf{s}}}_1 \neq \bar{\mathbf{s}}_1$ and $\bar{\tilde{\mathbf{s}}}_2 \neq \bar{\mathbf{s}}_2$, thus decoding errors at the destination node are the accumulative errors of the decoding processes at the partner nodes as well as the decoding process at the destination node. Intuitively, when the errors at the partner nodes become serious, the advantage of higher transmission diversity, which is gained by the cooperation between nodes, over non-cooperative communication can be ruined. As a result, cooperative communication might not be better than non-cooperative communication in this case. This analysis will be confirmed later in this paper by the simulation results.

To solve the problem of transmission and reception at the same time at a node, in the existing works [21], [22], a code division multiple access (CDMA) was proposed. This means that each node is assigned with an unique spreading code, thus the two nodes can work in the same band. Unlike the existing proposed schemes, we take advantage of the important technical specifications of MB-OFDM UWB devices that, support for the first band group (3168 - 4752 MHz, see [1], Table 7-1) is mandatory, and that the Time Frequency Code (TFCs) numbers 5, 6 and 7 for the first band group are non-overlapped with each other (see [1], Table 7-2). Thus, in order for the nodes to be able to transmit their own data and receive

TABLE I

DECODING METRICS IN PSK OR QAM MODULATIONS.

Symbol	Decoding Metric
$\bar{\mathbf{s}}_1$	$\arg\min_{\bar{\mathbf{s}} \in \mathcal{C}^{N_D}} \Vert \Big\{ \big\vert (\bar{\mathfrak{h}}^*_{AD} \bullet \bar{\mathfrak{r}}_1 + \bar{\mathfrak{h}}_{BD} \bullet \bar{\mathfrak{r}}^*_2) - \bar{\mathbf{s}} \big\vert .\hat{}2 + \Big[-\bar{\mathbf{1}} + (\vert\bar{\mathfrak{h}}_{AD}\vert .\hat{}2 + \vert\bar{\mathfrak{h}}_{BD}\vert .\hat{}2) \Big] \bullet (\vert\bar{\mathbf{s}}\vert .\hat{}2) \Big\} \Vert^2_F$
$\bar{\mathbf{s}}_2$	$\arg\min_{\bar{\mathbf{s}} \in \mathcal{C}^{N_D}} \Vert \Big\{ \big\vert (\bar{\mathfrak{h}}^*_{BD} \bullet \bar{\mathfrak{r}}_1 - \bar{\mathfrak{h}}_{AD} \bullet \bar{\mathfrak{r}}^*_2) - \bar{\mathbf{s}} \big\vert .\hat{}2 + \Big[-\bar{\mathbf{1}} + (\vert\bar{\mathfrak{h}}_{AD}\vert .\hat{}2 + \vert\bar{\mathfrak{h}}_{BD}\vert .\hat{}2) \Big] \bullet (\vert\bar{\mathbf{s}}\vert .\hat{}2) \Big\} \Vert^2_F$

the partner's data at the same time via only one antenna, node A may take TFC 5 (i.e. the radio frequency (RF) is in the range 3168 - 3696 MHz corresponding to the band number 1), for instance, while node B may take TFC 6 (i.e. RF in the range 3696 - 4224 MHz, band number 2). This example is shown in Fig. 3. The principle of transmitting information in one frequency band and receiving information in another frequency band has been widely implemented, such as at the transponders in satellite communications.

Since the inherent design of MB-OFDM UWB devices might have already allowed them to work with different TFCs (i.e. different bands) in the first band group, the only further tasks are to make source nodes to be able to transmit signals in one band, and receive signals in another band simultaneously, while making the destination node to be able to receive signals from two different bands at the same time. These are not hassling tasks thanks to the implementation of precise filters. As a result, the design of transmitter/receiver at nodes can be created by modifying their current design without additional heavy complexity.

III. COMPARISON WITH THE EXISTING SCHEMES

In this section, we compare the proposed scheme with several existing schemes. For ease of comparison, we only consider the case of *full* cooperation between nodes in all schemes. Simplified graphs of Hunter et. al.'s coded scheme [16, Fig. 1], Laneman et. al.'s TDMA (Time Division Multiple Access) scheme [17, Fig. 2c], Sendonaris et. al.'s CDMA scheme [21, p.1933], and Laneman et. al.'s distributed space-time coded scheme [23, Fig. 4] are depicted in Fig. 4.

In the first two TDMA approaches where nodes can work on the same band by sharing the network resources, i.e. only one frequency band is needed, only a part of the network resources (or the degree of freedoms) is allocated to a node at a certain time. A smaller part of the network resources is allocated for the cooperation between two nodes. Thus the diversity of transmitted information has to be sacrificed. Furthermore, the coded scheme also endures error performance degradation due to the reduction of diversity of the transmitted information as a result of a weaker codeword being sent instead of the original codeword [16].

The CDMA approach [21] also needs only one frequency band, but it requires two spreading sequences for two nodes. Each transmission period includes three time slots and more diversity is only provided for the information transmitted in the second time slots, instead of the whole transmitted signal in each transmission period. As a result, diversity and thus error performance have to be sacrificed.

The distributed space-time coded scheme [23] is the mixed TDMA and FDMA approach, thus still requiring two frequency bands (one for node A and its set of potential relays, and the other for node B and its set of potential relays). Also, the system resources cannot be fully allocated to nodes and their sets of relays since the transmission and reception in TDMA cannot be concurrent. More importantly, if there is only one potential relay for each node A and B, the distributed space-time coded scheme reduces to the repetition-based scheme. Consequently, the advantage of space-time codes over the repetition-based scheme (higher diversity order for larger spectral efficiencies [23, Section V]) vanishes in this case. This is because node A (or B) itself does not involve in the space-time code, but only its relays do. In this reduced case, the distributed space-time coded scheme not only achieves the similar benefit as in the repetition-based scheme, but also is more complicated for implementation than the latter.

The proposed scheme is perhaps the simpler cooperation one for application than the aforementioned schemes, which is necessary for low cost systems such as MB-OFDM UWB ones. The transmission and reception at nodes are concurrent thanks to the FDMA approach, thus full system resources are allocated for cooperation between nodes. In addition, more diversity is not provided for only a part of transmitted information, but for the whole transmitted information. These two advantages have never been achieved in the previous schemes. The advantages of space-time codes (over the repetition-based scheme) in the proposed scheme are still retained even in the case of one existing relay for each node, that is not the case for the distributed space-time coded scheme in [23], since the source nodes themselves involve in the generation of space-time codes.

It would be more specific if simulation comparisons are carried out to compare all schemes. However, since the existing schemes were proposed for general wireless systems and were proposed with different multiple access schemes, it is our difficulty to make a *fair* comparison (with the same data rate and power constraints) between the proposed scheme and the existing schemes via simulations. Therefore, the above analysis serves as the intuitive comparison between these schemes.

IV. SIMULATION RESULTS

To examine the performance advantage of cooperative communication, we ran several Monte-Carlo simulations for both non-cooperative communication and cooperative communication. Each run of simulations was carried out with 1200 MB-OFDM symbols. One hundred channel realizations of each channel model (CM 1 to CM 4) were considered for the transmission of each MB-OFDM symbol. In simulations, SNR is defined to be the signal-to-noise ratio (dB) per sample in a MB-OFDM symbol (consisting of 165 samples), at each Rx antenna (i.e. the subtraction between the total power (dB) of the received signal corresponding to the sample of interest and the power of noise (dB) at that Rx antenna). To fairly compare the error performance of non-cooperative and cooperative communication, we stick to the following constraints

Data rate constraint: Simulations for both systems are run with the same bit rate of 320 Mbps.

Power constraint: The average power of the signal constellation points is always scaled down by a factor of 2 in the case

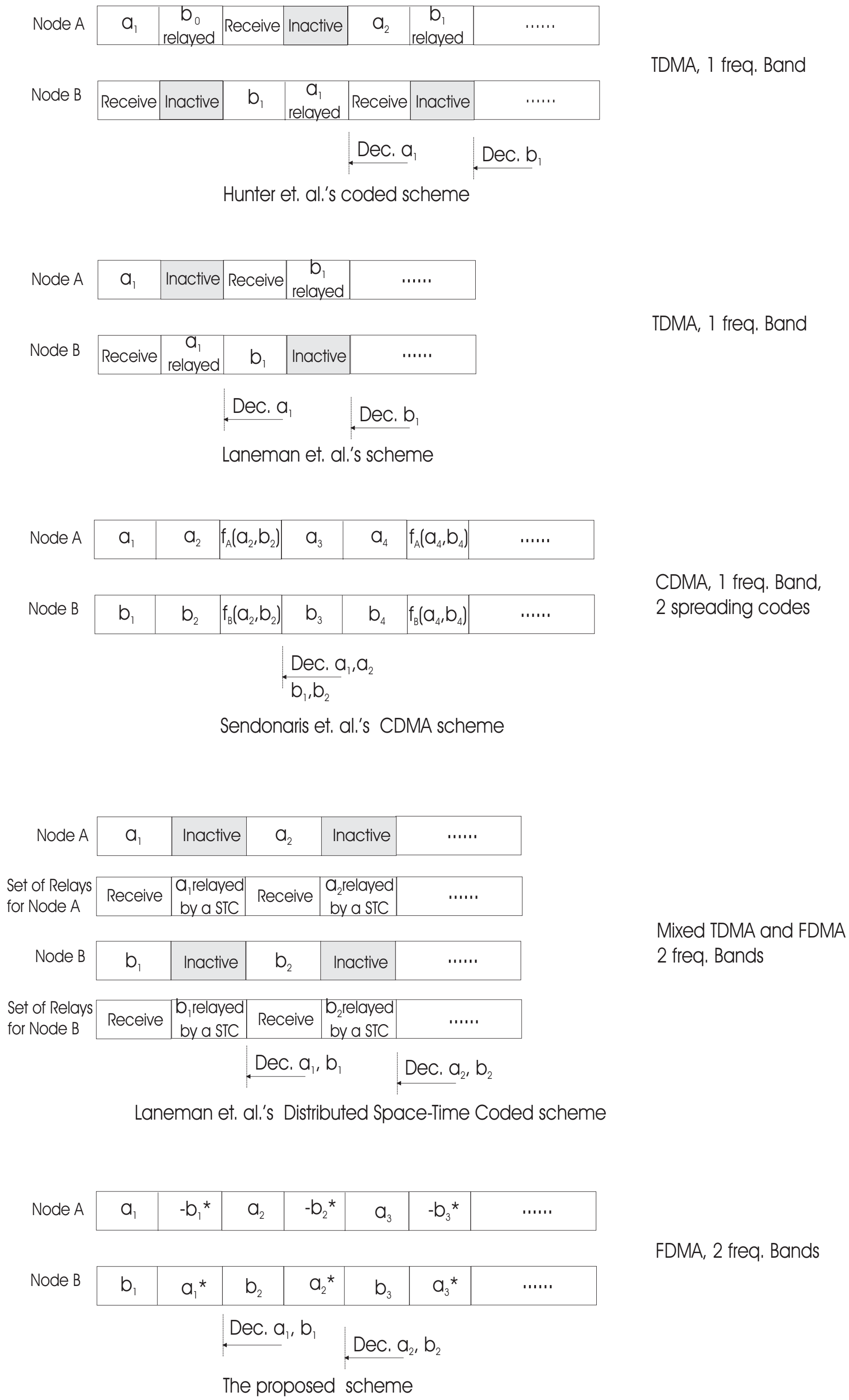

Fig. 4. Comparison of the proposed scheme with Hunter et. al.'s coded scheme [16], Laneman et. al.'s TDMA scheme [17], Sendonaris et. al.'s CDMA scheme [21], and Laneman et. al.'s distributed space-time coded scheme [23].

of cooperative communication. Thereby, the total transmission power from the source nodes to the destination node at a certain time is the same for the two cases.

Decoding processes at nodes are ML decoding. The complete set of simulation parameters is presented in Table II.

Fig. 5 shows that cooperative communication may provide better error performances than non-cooperative communication for the SNR being greater than certain values SNR_{min}, which are 7, 8, and 10 dB, respectively, in the channel models CM 1, CM 2 and CM 3. For instance, cooperative communication brings about the gain of approximate 1.5 dB at $BER = 10^{-3}$, and approximate 3 dB at $BER = 4 \times 10^{-4}$,

TABLE II
SIMULATION PARAMETERS.

Parameter	Value
FFT and IFFT size	$N_{fft} = 128$
Data rate	320 Mbps
Convolutional encoder's rate	1/2
Convolutional encoder's constraint length	$K = 7$
Convolutional decoder	Viterbi
Decoding mode	Hard
STFC decoding at nodes	ML decoding
Number of transmitted MB-OFDM symbols	1200
Modulation	QPSK
IEEE Channel model	CM1, 2, 3 & 4
Number of data subcarriers	$N_D = 100$
Number of pilot subcarriers	$N_P = 12$
Number of guard subcarriers	$N_G = 10$
Total number of subcarriers used	$N_T = 122$
Number of samples in ZPS	$N_{ZPS} = 37$
Total number of samples/symbol	$N_{SYM} = 165$
Number of channel realizations	100

over the non-cooperative communication in the channel model CM 1. Note that this advance is achieved when all nodes (including the destination node) are installed with only one antenna and without any increase of total transmission power. The error performance advantage is gained due to the fact that the diversity of the transmitted signals has been increased by the cooperation between nodes. Fig. 5 also presents that the use of cooperative communication might not be useful for the very dispersive channel model CM 4. The reason behind this observation is that the advance achieved by the increase of the transmission diversity is drowned by the error accumulation through the erroneous decoding processes at nodes A and B as well as at the destination node. In this case, the conventional (non-cooperative) communication would be the better choice.

V. CONCLUSIONS

This paper has presented the framework for cooperative communication in STFC MB-OFDM UWB systems. Various other tasks must be done to fully examine the topic. Therefore, our further studies would be the consideration of the imperfect synchronization between nodes, the node-pairing mechanism, and the transmission algorithm in the case of one or more links between nodes being corrupted.

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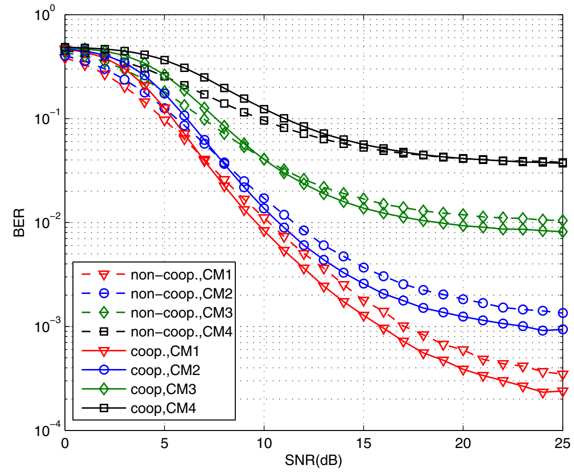

Fig. 5. Cooperative communication vs. non-cooperative communication in MB-OFDM UWB.

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