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Abstract

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Keywords

era2015, 4, quasi, orthogonal, cooperative, communication, stfc, mb, ofdm, order, uwb

Disciplines

Engineering | Science and Technology Studies

Publication Details

Lin, Z., Tran, L. Chung., Safaei, F. & Wysocki, T. A. (2012). Order-4 Quasi-Orthogonal Cooperative Communication in STFC MB-OFDM UWB. 6th International Conference on Signal Processing and Communication Systems (ICSPCS 2012) (pp. 920-925). Australia: IEEE.

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Abstract—Recently, cooperative communication and Space-Time-Frequency-Codes (STFCs) have been introduced into the Multi-band OFDM Ultra-Wideband (MB-OFDM UWB) to improve the reliability, data rate and system capacity. This paper proposes a cooperative communication scheme for a four source node MB-OFDM UWB system using Quasi-Orthogonal STFCs, which is referred to as order-4 Quasi-Orthogonal Cooperative Communication Scheme (4-QOCCS). Simulation results show that the proposed 4-QOCCS provides significantly better error performance over the conventional MB-OFDM UWB and our order-2 Orthogonal Cooperative Communication Scheme (2-OCCS) using the Alamouti STFCs, and even better than the order-4 Orthogonal Cooperative Communication Scheme (4-OCCS), which we have been recently proposed, in the high spectral efficiency cases.

I. INTRODUCTION

Recently, the combination of the emerging technologies including Multiband Orthogonal Frequency Division Multiplexing Ultra-Wideband (MB-OFDM UWB) [1], Multiple Input Multiple Output (MIMO), and Space-Time Frequency Codes (STFCs), which is referred to as STFC MB-OFDM UWB, has received great attention from researchers. The literature shows that the STFC MB-OFDM UWB system is able to improve significantly the reliability (bit error performance), data rate, system capacity and achievable wireless communication range compared to the conventional MB-OFDM UWB system [2], [3], [4].

The STFC MB-OFDM UWB systems proposed in [2], [3], [5] must have multiple antennas at the transmitter. However, the source nodes (i.e. the transmitters, such as portable devices) may only be equipped with a single antenna due to their tiny physical size, which does not facilitate the space of at least a half wavelength to install two uncorrelated transmit (Tx) antennas. Cooperative communication has been introduced to the source nodes to create a virtual MIMO system, so that the concepts of MIMO and STFCs can still be implemented in the MB-OFDM UWB system in order to achieve large diversity. While cooperative communication has been intensively researched for the conventional wireless network, such as in [6] [7] [8], it is almost unexplored for MB-OFDM UWB. In [9], we proposed an order-2 orthogonal cooperative communication scheme (2-OCCS) for STFC MB-OFDM UWB systems using the Alamouti STFC, which is the modified version of the original Alamouti space-time block code [14], for two source nodes. The framework of STFCs for MB-OFDM UWB systems has been derived for the first time in

our previous publication [2]. Readers may refer to [2] for more detail about how a STFC is constructed from the corresponding Space-Time Block Code (STBC). The results in [9] show that the combination of cooperative communication, STFCs and MB-OFDM UWB is able to gain the benefits of the MIMO system and improve significantly the performance, compared to the conventional MB-OFDM.

The limitation of the 2-OCCS in [9] that is the aforementioned Alamouti STFC cannot be used for more than two source nodes. Thus, in [10], we proposed an order-4 orthogonal cooperative communication scheme (4-OCCS) for four source nodes through the application of an order-4 orthogonal Space-Time-Frequency Code (OSTFC). This higher order STFC is the modified version of the conventional order-4, rate-3/4 STBC proposed in [11]. The order-4 rate-3/4 STBC offers a greater diversity with the cost of having a smaller code rate, compared to the conventional Alamouti STBC [14]. The results in [10] show that the 4-OCCS performs significantly better, compared to the 2-OCCS, at the same data rate and with the same transmission power.

In this paper, we propose another cooperative scheme, namely order-4 quasi-orthogonal cooperative communication scheme (4-QOCCS), for four source nodes by applying an order-4 quasi-orthogonal Space-Time-Frequency Code (QOSTFC), which is the modified version of the conventional order-4, full-rate quasi-orthogonal STBC proposed in [12]. This QOSTFC provides full-rate transmission for four source nodes with the cost of smaller diversity than the order-4, rate-3/4 STFC mentioned in [10]. Additionally, a new subband allocation technique for the 4-QOCCS is also introduced in this paper. We will then show that the performance of the 4-QOCCS is significantly better than that of the 2-OCCS we proposed previously, and even better than the 4-OCCS in some cases.

This paper is organized as follows. Section II briefly reviews our 4-OCCS proposed in [10]. Section III presents the proposed 4-QOCCS. Simulation results are shown in Section IV and Section V concludes the paper.

Notations: The following notations will be used throughout the paper. The superscripts $(\cdot)^*$ and $(\cdot)^T$ denote the complex conjugation and transposition operation, respectively. We denote $\mathbf{a} \bullet \mathbf{b}$ to be the element-wise (or Hadamard) product of the two vectors \mathbf{a} and \mathbf{b} . N_D and N_{fft} are the number of data subcarriers and the FFT/IFFT size, respectively (for MB-OFDM UWB communications [1], $N_D = 100$ and $N_{fft} = 128$).

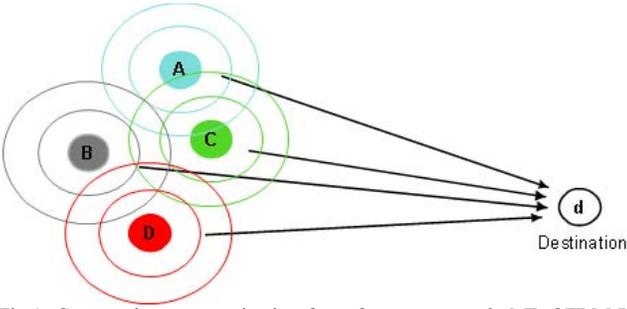


Fig.1. Cooperative communication for a four source node MB-OFDM UWB system

Further, $\bar{a}^{\wedge 2}$ denotes the element-wise power-2 operation of \bar{a} . The complex space C of a symbol s denotes all potential possibilities that the symbol s can take, while the N_D dimensional complex space C^{N_D} of a N_D -length vector \bar{s} denotes all potential possibilities that the vector \bar{s} can take. We define $\bar{1}$ as a column vector of length N_D , whose elements are all ones. We denote $\|\cdot\|_F$ to be the Frobenius norm. Finally, we refer the time required to transmit a MB-OFDM symbol to as a MB-OFDM symbol time slot, which is 312.5 ns, including the FFT/IFFT period of 242.42 ns and the zero padded suffix duration of 70.08 ns [1].

II. ORDER-4 ORTHOGONAL COOPERATIVE COMMUNICATION SCHEME (4-OCCS)

This section briefly reviews the 4-OCCS that we proposed in [10]. The proposed system model is illustrated in Fig.1. Due to the limited space, the STFC construction method for MB-OFDM UWB system will not be reviewed in this paper. Interested reader may refer to our previous publication [2, Section III] for more detail. In this scheme, we consider the application of the following rate-3/4 orthogonal STFC, which is a modified version of the rate-3/4 STBC in [11], to enable four single-antenna source nodes to cooperate

$$S = \begin{bmatrix} \bar{s}_{A_i} & \bar{s}_{B_i} & \bar{s}_{C_i} & \mathbf{0} \\ -\bar{s}_{B_i}^* & \bar{s}_{A_i} & \mathbf{0} & \bar{s}_{C_i} \\ -\bar{s}_{C_i}^* & \mathbf{0} & \bar{s}_{A_i} & -\bar{s}_{B_i} \\ \mathbf{0} & -\bar{s}_{C_i}^* & \bar{s}_{B_i} & \bar{s}_{A_i} \end{bmatrix} \quad (1)$$

where the STFC symbols \bar{s}_{A_i} , \bar{s}_{B_i} and \bar{s}_{C_i} are corresponding to the i -th MB-OFDM symbols transmitted from the nodes A , B and C , respectively, in the first time slot. These MB-OFDM symbols are the column vectors that consist of the original transmitted data (i.e. before the *IFFT* operation). It is assumed that the nodes in the proposed system are perfectly synchronized.

The channels between nodes are modeled as independent log-normally distributed random variables (RVs) [13]. Denote $\bar{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, \dots, h_{jkm,L_{jkm}}]^T$ to be the channel vector

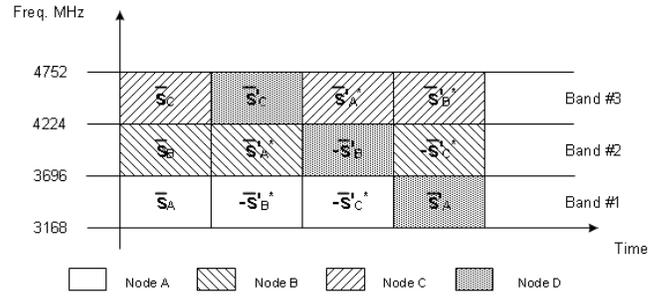


Fig.2. Subband allocation in the 4-OCCS in four time slots

between two nodes j and k , at the m -th antenna of the destination node, where $j \in \{A, B, C, D\}$, $k \in \{A, B, C, D, d\}$, $m \in \{1, 2, \dots, N\}$, and L_{jkm} represents the number of multipath in this link. We assume the channel vectors \bar{h}_{jkm} remain constant during every four MB-OFDM symbol time slots, and are known at the destination node. Each of the source nodes A , B , C and D is equipped with only one antenna for transmitting and receiving signals, while the destination node d might be equipped with N antennas.

One may have a question: Does the four source nodes need to occupy four subbands in the cooperative MB-OFDM UWB system to work properly? From Eq. (1), it is clear that, in the proposed system, one source node always remains idle when three other nodes transmit three MB-OFDM symbols over their three antennas in every time slot. Thus, in the 4-OCCS, we proposed a new subband allocation method that allows the system to work properly by occupying just three subbands in the first band group of MB-OFDM UWB [10]. It is noted that MB-OFDM UWB devices are standardized to support for the first band group (3168 – 4752 MHz) [1, Table 7-1], and that the TFC (Time-Frequency Code) numbers 5, 6 and 7 for the first band group are non-overlapped with each other [1, Table 7-2]. In order for the system to work properly by just taking three subbands, the source nodes A , B and C in the proposed system must be able to transmit data in one certain subband and receive data in other two subbands. In the 4-OCCS, Node A transmits signals using TFC 7 (RF is in the range 4224 - 4752 MHz corresponding to the subband 3) and receives signals using TFC 6 (RF in the range 3696 – 4224 MHz, subband 2) and TFC 5 (3168 – 3696 MHz, subband 1). Node B transmits signals using TFC 6 and receives signals using TFC 5 and TFC 7. Node C transmits signals using TFC 5 and receives via TFC 6 and TFC 7. Node D transmits signals in the subband 1, 2 and 3 sequentially, i.e. this node uses TFC 1 when transmitting, and receives data from all the subbands. The destination node must be able to receive signals from all subbands in the first band group.

As shown in Fig.2, in the first time slot, Nodes A , B and C broadcast the MB-OFDM symbols, \bar{s}_{A_i} , \bar{s}_{B_i} and \bar{s}_{C_i} , to all the nodes in the system in the subbands 3, 2 and 1 respectively, while Node D does not transmit, but just receives the data from these three nodes in three different subbands. After first time slot, every node has received at least two MB-OFDM symbols from their partners. The received data can be

TABLE I

DECODING METRICS FOR THE 4-OCCS IN THE CASE OF PSK
OR QAM MODULATION

Symbol	Decoding Metric
\bar{s}_{A_i}	$\arg \min_{s \in C^{N_D}} \left\ \left\{ \sum_{m=1}^N (\mathbf{h}_{Adm}^* \bullet \bar{\mathbf{r}}_{1m} + \mathbf{h}_{Bdm} \bullet \bar{\mathbf{r}}_{2m}^* + \mathbf{h}_{Cdm} \bullet \bar{\mathbf{r}}_{3m}^* + \mathbf{h}_{Ddm}^* \bullet \bar{\mathbf{r}}_{4m}) - \bar{s} \right\} \right\ ^2 + [-1 + \sum_{m=1}^N (\mathbf{h}_{Adm} \cdot \wedge 2 + \mathbf{h}_{Bdm} \cdot \wedge 2 + \mathbf{h}_{Cdm} \cdot \wedge 2 + \mathbf{h}_{Ddm} \cdot \wedge 2)] \cdot (\bar{s} \cdot \wedge 2) \Big\ _F^2$
\bar{s}_{B_i}	$\arg \min_{s \in C^{N_D}} \left\ \left\{ \sum_{m=1}^N (\mathbf{h}_{Bdm}^* \bullet \bar{\mathbf{r}}_{1m} - \mathbf{h}_{Adm} \bullet \bar{\mathbf{r}}_{2m}^* - \mathbf{h}_{Ddm} \bullet \bar{\mathbf{r}}_{3m}^* + \mathbf{h}_{Cdm}^* \bullet \bar{\mathbf{r}}_{4m}) - \bar{s} \right\} \right\ ^2 + [-1 + \sum_{m=1}^N (\mathbf{h}_{Adm} \cdot \wedge 2 + \mathbf{h}_{Bdm} \cdot \wedge 2 + \mathbf{h}_{Cdm} \cdot \wedge 2 + \mathbf{h}_{Ddm} \cdot \wedge 2)] \cdot (\bar{s} \cdot \wedge 2) \Big\ _F^2$
\bar{s}_{C_i}	$\arg \min_{s \in C^{N_D}} \left\ \left\{ \sum_{m=1}^N (\mathbf{h}_{Adm}^* \bullet \bar{\mathbf{r}}_{1m} + \mathbf{h}_{Bdm} \bullet \bar{\mathbf{r}}_{2m}^* + \mathbf{h}_{Cdm} \bullet \bar{\mathbf{r}}_{3m}^* + \mathbf{h}_{Ddm}^* \bullet \bar{\mathbf{r}}_{4m}) - \bar{s} \right\} \right\ ^2 + [-1 + \sum_{m=1}^N (\mathbf{h}_{Adm} \cdot \wedge 2 + \mathbf{h}_{Bdm} \cdot \wedge 2 + \mathbf{h}_{Cdm} \cdot \wedge 2 + \mathbf{h}_{Ddm} \cdot \wedge 2)] \cdot (\bar{s} \cdot \wedge 2) \Big\ _F^2$

distinguished by different subbands. We denote the decoded symbols at each nodes to be \bar{s}_{A_i} , \bar{s}_{B_i} and \bar{s}_{C_i} . In the second time slot, Nodes A , B and D transmit the decoded MB-OFDM symbol $-\bar{s}_{B_i}^*$, $\bar{s}_{A_i}^*$ and \bar{s}_{C_i} to the destination in the subbands 3, 2 and 1 respectively. Node D occupies the subband 1 because Node C is silent in the second time slot. In the third time slot, Node B keeps silent while Node A , C and D transmit the data $-\bar{s}_{C_i}^*$, $\bar{s}_{A_i}^*$ and $-\bar{s}_{B_i}$ to the destination node d in the subbands 3, 1 and 2 respectively. Node D occupies the subband 2 since Node B is silent. In the fourth time slot, Nodes B , C and D transmit the data $-\bar{s}_{C_i}^*$, $\bar{s}_{B_i}^*$ and \bar{s}_{A_i} to the destination in the subbands 2, 1 and 3 respectively. Node D occupies the subband 3 since Node A is silent. The destination is able to decode the MB-OFDM symbol \bar{s}_{A_i} , \bar{s}_{B_i} and \bar{s}_{C_i} after four time slots. The decoding procedure is presented as follows.

After the overlap-and-add operation (OAAO) [1], [2] and FFT have been performed, the signals received at the m -th receive (Rx) antenna at the destination node during the four time slots can be represented as

$$\begin{aligned} \bar{\mathbf{r}}_{1m} &= \bar{\mathbf{h}}_{Adm} \bullet \bar{s}_{A_i} + \bar{\mathbf{h}}_{Bdm} \bullet \bar{s}_{B_i} + \bar{\mathbf{h}}_{Cdm} \bullet \bar{s}_{C_i} + \bar{\mathbf{n}}_{1m} \\ \bar{\mathbf{r}}_{2m} &= -\bar{\mathbf{h}}_{Adm} \bullet \bar{s}_{B_i}^* + \bar{\mathbf{h}}_{Bdm} \bullet \bar{s}_{A_i}^* + \bar{\mathbf{h}}_{Ddm} \bullet \bar{s}_{C_i} + \bar{\mathbf{n}}_{2m} \\ \bar{\mathbf{r}}_{3m} &= -\bar{\mathbf{h}}_{Adm} \bullet \bar{s}_{C_i}^* + \bar{\mathbf{h}}_{Cdm} \bullet \bar{s}_{A_i}^* - \bar{\mathbf{h}}_{Ddm} \bullet \bar{s}_{B_i} + \bar{\mathbf{n}}_{3m} \\ \bar{\mathbf{r}}_{4m} &= -\bar{\mathbf{h}}_{Bdm} \bullet \bar{s}_{C_i}^* + \bar{\mathbf{h}}_{Cdm} \bullet \bar{s}_{B_i}^* + \bar{\mathbf{h}}_{Ddm} \bullet \bar{s}_{A_i} + \bar{\mathbf{n}}_{4m} \end{aligned} \quad (2)$$

where $\bar{\mathbf{h}}_{jkm} = FFT(\bar{h}_{jkm})$, $\bar{\mathbf{n}}_{tm} = FFT(\bar{n}_{tm})$, while \bar{n}_{tm} ($t=1,2,3,4$) denotes the column vector of complex Gaussian noise affecting the m -th Rx antenna at the destination node during the t -th MB-OFDM symbol time slot. Denote $\bar{\mathbf{h}}_{jkm} = [\bar{h}_{jkm,1}, \bar{h}_{jkm,2}, \dots, \bar{h}_{jkm,N_{ff}}]^T$ and $\bar{\mathbf{r}}_{tm} = [\mathbf{r}_{tm,1}, \mathbf{r}_{tm,2}, \dots, \mathbf{r}_{tm,N_{ff}}]^T$. Assume that the information transmitted from the source nodes can be error-freely decoded by their partners, i.e. $\bar{s}_{A_i} \equiv \bar{s}_{A_i}$, $\bar{s}_{B_i} \equiv \bar{s}_{B_i}$ and $\bar{s}_{C_i} \equiv \bar{s}_{C_i}$. The ML decoding will be applied to decode the symbols. In the proposed system, each of the MB-OFDM symbols \bar{s}_{A_i} , \bar{s}_{B_i} and \bar{s}_{C_i} can be decoded separately, rather than jointly, thanks to the orthogonality of the code matrix (1) as shown in Table I. Moreover, each among N_D data within each MB-OFDM symbol can also be separately decoded, rather than decoding the whole N_D data simultaneously. Thus the decoding complexity is relatively simple. For $n = 1, \dots, N_D$, the decoding metrics for the n -th data subcarrier in MB-OFDM symbols \bar{s}_{A_i} , \bar{s}_{B_i} and \bar{s}_{C_i} are

$$\begin{aligned} s_{A_i,n} &= \arg \min_{s \in C} \left\{ \left| \sum_{m=1}^N (\bar{h}_{Adm,n}^* \mathbf{r}_{1m,n} + \bar{h}_{Bdm,n} \mathbf{r}_{2m,n}^* + \bar{h}_{Cdm,n} \mathbf{r}_{3m,n}^* + \bar{h}_{Ddm,n}^* \mathbf{r}_{4m,n}) - s \right|^2 + [-1 + \sum_{m=1}^N (|\bar{h}_{Adm,n}|^2 + |\bar{h}_{Bdm,n}|^2 + |\bar{h}_{Cdm,n}|^2 + |\bar{h}_{Ddm,n}|^2)] |s|^2 \right\} \\ s_{B_i,n} &= \arg \min_{s \in C} \left\{ \left| \sum_{m=1}^N (\bar{h}_{Bdm,n}^* \mathbf{r}_{1m,n} - \bar{h}_{Adm,n} \mathbf{r}_{2m,n}^* - \bar{h}_{Ddm,n} \mathbf{r}_{3m,n}^* + \bar{h}_{Cdm,n} \mathbf{r}_{4m,n}) - s \right|^2 + [-1 + \sum_{m=1}^N (|\bar{h}_{Adm,n}|^2 + |\bar{h}_{Bdm,n}|^2 + |\bar{h}_{Cdm,n}|^2 + |\bar{h}_{Ddm,n}|^2)] |s|^2 \right\} \\ s_{C_i,n} &= \arg \min_{s \in C} \left\{ \left| \sum_{m=1}^N (\bar{h}_{Cdm,n}^* \mathbf{r}_{1m,n} - \bar{h}_{Adm,n} \mathbf{r}_{3m,n}^* + \bar{h}_{Ddm,n} \mathbf{r}_{2m,n} - \bar{h}_{Bdm,n} \mathbf{r}_{4m,n}^*) - s \right|^2 + [-1 + \sum_{m=1}^N (|\bar{h}_{Adm,n}|^2 + |\bar{h}_{Bdm,n}|^2 + |\bar{h}_{Cdm,n}|^2 + |\bar{h}_{Ddm,n}|^2)] |s|^2 \right\} \end{aligned} \quad (3)$$

It has been shown that the 4-OCCS in [10] achieves a significantly better performance than the 2-OCCS in [9] that we proposed previously. However, the 4-OCCS provides better diversity to the system with the cost of having a smaller bit rate. The smaller bit rate may cause the performance degradation in the high spectral efficiency cases. Thus, in this paper, we propose a full-rate order-4 quasi-orthogonal cooperative communication STFC scheme, referred to as 4-QOCCS.

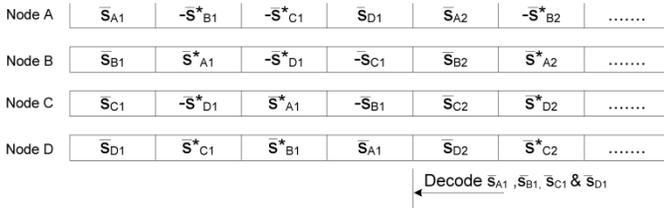


Fig.3. Transmission protocol in the 4-QOCCS

III. ORDER-4 QUASI-ORTHOGONAL COOPERATIVE COMMUNICATION SCHEME (4-QOCCS)

In this scheme, we consider the application of the following full-rate quasi-orthogonal STFC (QOSTFC), which is in turn the STFC version of the full-rate QOSTBC in [12],

$$S = \begin{bmatrix} \bar{S}_{A_i} & \bar{S}_{B_i} & \bar{S}_{C_i} & \bar{S}_{D_i} \\ -\bar{S}_{B_i}^* & \bar{S}_{A_i} & -\bar{S}_{D_i} & \bar{S}_{C_i} \\ -\bar{S}_{C_i} & -\bar{S}_{D_i} & \bar{S}_{A_i} & \bar{S}_{B_i} \\ \bar{S}_{D_i} & -\bar{S}_{C_i} & -\bar{S}_{B_i} & \bar{S}_{A_i} \end{bmatrix} \quad (4)$$

where the STFC symbols \bar{S}_{A_i} , \bar{S}_{B_i} , \bar{S}_{C_i} and \bar{S}_{D_i} are column vectors that consist of the original transmitted data and correspond to the i -th MB-OFDM symbol transmitted by the nodes A , B , C and D respectively in the first time slot. Symbols transmitted in the subsequent time slots are depicted in Fig.3. The four symbols can be decoded after four MB-OFDM symbol time slots. It is well-known that the orthogonality (and thus the diversity) of QOSTBCs is partially released, i.e. not all columns (and rows) are orthogonal with each others, to increase the code rate, and that these rate-improved codes might still provide better error performance than the counterpart STBCs at a certain SNR range [12].

Denote $\bar{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, \dots, h_{jkm,L_{jkm}}]^T$ to be the channel vector between two nodes j and k , at the m -th Rx antenna of the destination node, where $j \in \{A, B, C, D\}$, $k \in \{A, B, C, D, d\}$, $m \in \{1, 2, \dots, N\}$, and L_{jkm} represents the number of multipath in this link. The channels between nodes are modeled as independently log-normally distributed RVs [13] and we assumed the channel vectors \bar{h}_{jkm} remain constant during every four MB-OFDM symbol time slots, and are known at the destination node. Each of the source nodes A , B , C and D is equipped with only one antenna, while the destination node d might be equipped with N antennas. It is also assumed that the nodes in the proposed system are perfectly synchronized.

A. Subband Allocation

The transmission protocol in the proposed 4-QOCCS is presented in Fig. 3. From Eq. (4), it is clear that, in the proposed system, all the nodes are transmitting signals over four time slots. Thus, in the 4-QOCCS, we have to use at least four subbands to allow all the source nodes to receive and transmit the signals simultaneously. In this paper, we propose a new

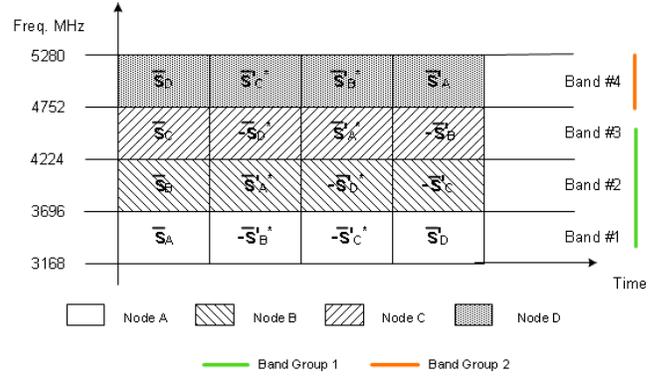


Fig 4. Subband allocation in the 4-QOCCS in four time slots

subband allocation method for the 4-QOCCS that allows every source node in the system to work with minimum number of subbands in each time slot to reduce the complexity of the system. The MB-OFDM UWB devices in the 4-QOCCS must support the three subbands in the first band group (3168 – 4752 MHz) and the first subband in the second band group (4752- 5280 MHz) [1, Table 7-1]. In order for the system to work properly, the source nodes A , B , C and D in the proposed system must be able to transmit data in one certain subband and receive data from two other subbands. The destination node d must be able to receive the data using these four subbands.

The subband allocation for the 4-QOCCS is shown in Fig.4. Node A transmits signals using TFC 5 in band group 1 (RF is in the range 3168 – 3696 MHz corresponding to the subband 1) and receives signals using TFC 6 in band group 1 (RF in the range 3696 – 4224 MHz, subband 2) and TFC 5 in second band group (4752 – 5280 MHz, subband 4). Node B transmits signals using TFC 6 in band group 1 and receives signals using TFC 5 and TFC 7 (RF in the range 4224 – 4752 MHz, subband 3) in band group 1. Node C transmits signals using TFC 7 and receives via TFC 5 in band group 1 and TFC 5 in band group 2. Node D transmits signals using TFC 5 in band group 2 and receives signals using TFC 7 and TFC5 in first band group.

Detail of how the nodes transmit signals in the proposed 4-QOCCS system is explained as follows. Four nodes cooperate in sending the quasi-orthogonal matrix in (4) to the destination. The issue of how this node quadruple is selected among the nodes in the network is out of the scope of this paper. Instead, this paper addresses the full-duplex cooperative communications scheme for this quadruple and the decoding method.

As shown in Fig.4 and Fig.5, each source node in the proposed system transmits signals in one subband and receives signals from one partner in other subband in every time slot. In the first time slot, Nodes A , B , C and D broadcast the MB-OFDM symbols, \bar{S}_{A_i} , \bar{S}_{B_i} , \bar{S}_{C_i} and \bar{S}_{D_i} , to all the nodes in the system in the subbands 1, 2 and 3 in band group 1 and subband 4 in the band group 2 respectively. Node A receives \bar{S}_{B_i} from Node B in subband 2. Node B receives \bar{S}_{A_i} from Node A in subband 1. Similarly, Node C receives the data \bar{S}_{D_i} from Node D in subband 4 and Node D receives the symbol \bar{S}_{C_i} from

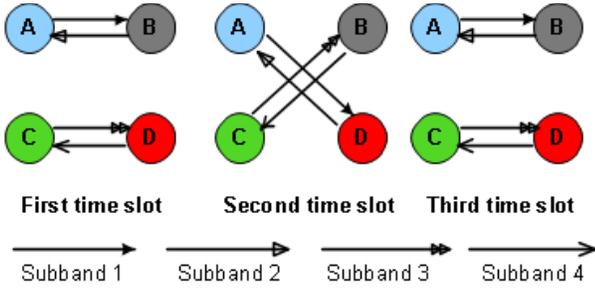


Fig.5. Subband allocation at different time slots in the 4-QOCCS

Node C in subband 3. At this point, every source nodes has the information to construct the transmission for the second time slot of the QOSTFC in (4).

We denote the decoded symbols at each nodes to be $\bar{s}_{A_i}, \bar{s}_{B_i}, \bar{s}_{C_i}$ and \bar{s}_{D_i} . In the second time slot, Nodes A, B, C and D transmit the decoded symbol $-\bar{s}_{B_i}^*, \bar{s}_{A_i}^*, -\bar{s}_{D_i}^*$ and $\bar{s}_{C_i}^*$ to the destination in the subbands 1, 2, 3 and 4 respectively. In this time slot, Node A receives the signal $\bar{s}_{C_i}^*$ from Node D and Node B receives $-\bar{s}_{D_i}^*$ from Node C . Node C receives $\bar{s}_{A_i}^*$ from Node B and Node D receives $-\bar{s}_{B_i}^*$ from Node A .

In the third time slot, Nodes A, B, C and D transmit the signal $-\bar{s}_{C_i}^*, -\bar{s}_{D_i}^*, \bar{s}_{A_i}^*$ and $\bar{s}_{B_i}^*$ to the destination node d in the subband 1 to 4 respectively. In this time slot, Node A and Node B exchange the signals, thus Node A receives $-\bar{s}_{D_i}^*$ from Node B and Node B receives $-\bar{s}_{C_i}^*$ from Node A . Node C and Node D exchange the signals, thus Node C receives $\bar{s}_{B_i}^*$ from Node D and Node D receives $\bar{s}_{A_i}^*$ from Node C .

In the fourth time slot, Nodes A, B, C and D transmit the symbol $\bar{s}_{D_i}, -\bar{s}_{C_i}, -\bar{s}_{B_i}$ and \bar{s}_{A_i} to the destination in the subband 1 to 4 respectively. The destination is able to decode the MB-OFDM symbol $\bar{s}_{A_i}, \bar{s}_{B_i}, \bar{s}_{C_i}$ and \bar{s}_{D_i} after four time slots (cf. Fig.3). The decoding procedure for 4-QOCCS is presented as follows.

B. Decoding Metrics

After the overlap-and-add operation (OAAO) [4], [6] and FFT have been performed in the destination node, the signals received at the m -th Rx antenna at the destination node during the four time slots can be represented as

$$\begin{aligned}
 \bar{\mathbf{r}}_{1m} &= \bar{h}_{Adm} \cdot \bar{s}_{A_i} + \bar{h}_{Bdm} \cdot \bar{s}_{B_i} + \bar{h}_{Cdm} \cdot \bar{s}_{C_i} + \bar{h}_{Ddm} \cdot \bar{s}_{D_i} + \bar{\mathbf{n}}_{1m} \\
 \bar{\mathbf{r}}_{2m} &= -\bar{h}_{Adm} \cdot \bar{s}_{B_i} + \bar{h}_{Bdm} \cdot \bar{s}_{A_i} - \bar{h}_{Cdm} \cdot \bar{s}_{D_i} + \bar{h}_{Ddm} \cdot \bar{s}_{C_i} + \bar{\mathbf{n}}_{2m} \\
 \bar{\mathbf{r}}_{3m} &= -\bar{h}_{Adm} \cdot \bar{s}_{C_i} - \bar{h}_{Bdm} \cdot \bar{s}_{D_i} + \bar{h}_{Cdm} \cdot \bar{s}_{A_i} + \bar{h}_{Ddm} \cdot \bar{s}_{B_i} + \bar{\mathbf{n}}_{3m} \\
 \bar{\mathbf{r}}_{4m} &= \bar{h}_{Adm} \cdot \bar{s}_{D_i} - \bar{h}_{Bdm} \cdot \bar{s}_{C_i} - \bar{h}_{Cdm} \cdot \bar{s}_{B_i} + \bar{h}_{Ddm} \cdot \bar{s}_{A_i} + \bar{\mathbf{n}}_{4m}
 \end{aligned} \quad (5)$$

where $\bar{h}_{jkm} = FFT(\bar{h}_{jkm})$, $\bar{\mathbf{n}}_m = FFT(\bar{\mathbf{n}}_m)$, while $\bar{\mathbf{n}}_{tm}$ ($t=1,2,3,4$) denotes the column vector of complex Gaussian noise affecting the m -th Rx antenna of the destination node at the t -th MB-OFDM symbol time slot. Denote $\bar{\mathbf{h}}_{jkm} = [\bar{h}_{jkm,1}, \bar{h}_{jkm,2}, \dots, \bar{h}_{jkm, N_{ff}}]^T$

TABLE II

DECODING METRICS FOR THE 4-QOCCS WITH PSK OR QAM MODULATION

Symbols	Decoding Metric
$\begin{pmatrix} \bar{s}_A \\ \bar{s}_D \end{pmatrix}$	$ \begin{aligned} & \arg \min_{s_A, s_D \in C^{ND}} \left\ \sum_{m=1}^N \left(\left(\sum_{j=A}^D h_{jdm} \cdot \cdot \right)^2 \right) \cdot (\bar{s}_A \cdot \cdot^2 + \bar{s}_D \cdot \cdot^2) \right. \\ & + 2 \operatorname{Re} \left\{ (-\bar{h}_{Adm}^* \cdot \bar{\mathbf{r}}_{1m} - \bar{h}_{Bdm} \cdot \bar{\mathbf{r}}_{2m} - \bar{h}_{Cdm} \cdot \bar{\mathbf{r}}_{3m} \right. \\ & - \bar{h}_{Ddm}^* \cdot \bar{\mathbf{r}}_{4m}) \cdot \bar{s}_A + (-\bar{h}_{Ddm} \cdot \bar{\mathbf{r}}_{1m} + \bar{h}_{Cdm} \cdot \bar{\mathbf{r}}_{2m} \\ & + \bar{h}_{Bdm} \cdot \bar{\mathbf{r}}_{3m} - \bar{h}_{Adm} \cdot \bar{\mathbf{r}}_{4m}) \cdot \bar{s}_D + (\bar{h}_{Adm} \cdot \bar{\mathbf{r}}_{1m} \\ & \left. \left. - \bar{h}_{Bdm} \cdot \bar{\mathbf{r}}_{2m} - \bar{h}_{Cdm} \cdot \bar{\mathbf{r}}_{3m} + \bar{h}_{Ddm} \cdot \bar{\mathbf{r}}_{4m}) \cdot \bar{s}_A \cdot \bar{s}_D^* \right\} \right\ _F^2 \end{aligned} $
$\begin{pmatrix} \bar{s}_B \\ \bar{s}_C \end{pmatrix}$	$ \begin{aligned} & \arg \min_{s_B, s_C \in C^{ND}} \left\ \sum_{m=1}^N \left(\left(\sum_{j=A}^D h_{jdm} \cdot \cdot \right)^2 \right) \cdot (\bar{s}_B \cdot \cdot^2 + \bar{s}_C \cdot \cdot^2) \right. \\ & + 2 \operatorname{Re} \left\{ (-\bar{h}_{Bdm} \cdot \bar{\mathbf{r}}_{1m} + \bar{h}_{Adm} \cdot \bar{\mathbf{r}}_{2m} - \bar{h}_{Ddm} \cdot \bar{\mathbf{r}}_{3m} \right. \\ & - \bar{h}_{Ddm} \cdot \bar{\mathbf{r}}_{4m}) \cdot \bar{s}_B + (-\bar{h}_{Cdm} \cdot \bar{\mathbf{r}}_{1m} - \bar{h}_{Ddm} \cdot \bar{\mathbf{r}}_{2m} \\ & + \bar{h}_{Adm} \cdot \bar{\mathbf{r}}_{3m} + \bar{h}_{Bdm} \cdot \bar{\mathbf{r}}_{4m}) \cdot \bar{s}_C + (\bar{h}_{Bdm} \cdot \bar{\mathbf{r}}_{1m} \\ & \left. \left. - \bar{h}_{Adm} \cdot \bar{\mathbf{r}}_{2m} - \bar{h}_{Cdm} \cdot \bar{\mathbf{r}}_{3m} + \bar{h}_{Ddm} \cdot \bar{\mathbf{r}}_{4m}) \cdot \bar{s}_B \cdot \bar{s}_C^* \right\} \right\ _F^2 \end{aligned} $

and $\bar{\mathbf{r}}_m = [\mathbf{r}_{m,1}, \mathbf{r}_{m,2}, \dots, \mathbf{r}_{m, N_{ff}}]^T$. We also assume that the information transmitted from the source nodes can be error-free decoded by their partners as mentioned in Section II. The ML decoding will be applied to decode the symbols. Unlike the 4-QOCCS, in the 4-QOCCS, the MB-OFDM symbols cannot be decoded separately owing to the partial (rather than complete) orthogonality characteristics of the QOSTFC in (4), in the similar manner of the QOSTBC in [12]. Specifically, the MB-OFDM symbols \bar{s}_{A_i} and \bar{s}_{D_i} , \bar{s}_{B_i} and \bar{s}_{C_i} can be decoded in pair, rather than jointly, as mentioned in Table II. More importantly, each among N_D data within each MB-OFDM symbol can also be decoded in pair, rather than decoding the whole $2N_D$ data simultaneously. For $n = 1, \dots, N_D$, the decoding metrics for the n -th data subcarrier in MB-OFDM symbols $\bar{s}_{A_i}, \bar{s}_{B_i}, \bar{s}_{C_i}$ and \bar{s}_{D_i} are as follows (the subscript i is omitted for simplicity)

$$\begin{aligned}
 (s_A, s_D) &= \arg \min_{s_A, s_D \in C} \sum_{m=1}^N \left(\left(\sum_{j=A}^D |h_{jdm,n}| \right)^2 \right) (|s_A|^2 + |s_D|^2) \\
 & + 2 \operatorname{Re} \left\{ (-\bar{h}_{Adm,n}^* \mathbf{r}_{1m,n} - \bar{h}_{Bdm,n} \mathbf{r}_{2m,n} - \bar{h}_{Cdm,n} \mathbf{r}_{3m,n} \right. \\
 & - \bar{h}_{Ddm,n}^* \mathbf{r}_{4m,n}) s_A + (-\bar{h}_{Ddm,n} \mathbf{r}_{1m,n} + \bar{h}_{Cdm,n} \mathbf{r}_{2m,n} \\
 & + \bar{h}_{Bdm,n} \mathbf{r}_{3m,n} - \bar{h}_{Adm,n} \mathbf{r}_{4m,n}) s_D + (\bar{h}_{Adm,n} \mathbf{r}_{1m,n} \\
 & \left. \left. - \bar{h}_{Bdm,n} \mathbf{r}_{2m,n} - \bar{h}_{Cdm,n} \mathbf{r}_{3m,n} + \bar{h}_{Ddm,n} \mathbf{r}_{4m,n}) \cdot s_A \cdot s_D^* \right\}
 \end{aligned}$$

$$\begin{aligned}
(s_B, s_C) = \arg \min_{s_B, s_C \in C} & \sum_{m=1}^N \left(\sum_{j=A}^D |\tilde{h}_{jdm,n}|^2 \right) (|s_B|^2 + |s_C|^2) \\
& + 2 \operatorname{Re} \left\{ (-\tilde{h}_{Bdm,n} \mathbf{r}_{1m,n}^* + \tilde{h}_{Adm,n} \mathbf{r}_{2m,n} - \tilde{h}_{Ddm,n} \mathbf{r}_{3m,n} \right. \\
& - \tilde{h}_{Ddm,n} \mathbf{r}_{4m,n}^*) s_B + (-\tilde{h}_{Cdm,n} \mathbf{r}_{1m,n}^* - \tilde{h}_{Ddm,n} \mathbf{r}_{2m,n}^* \\
& + \tilde{h}_{Adm,n} \mathbf{r}_{3m,n} + \tilde{h}_{Bdm,n} \mathbf{r}_{4m,n}^*) s_C + (\tilde{h}_{Bdm,n} \tilde{h}_{Cdm,n} \\
& - \tilde{h}_{Adm,n} \tilde{h}_{Ddm,n} - \tilde{h}_{Adm,n} \tilde{h}_{Ddm,n} + \tilde{h}_{Bdm,n} \tilde{h}_{Cdm,n}) \\
& \left. s_B s_C^* \right\} \quad (6)
\end{aligned}$$

C. Comments on Transceiver Design Complexity and Power Consumption

The inherent design of MB-OFDM UWB devices provides an important feature that it might have already allowed the devices to work with different TFCs (i.e. different subbands) in different band groups. As a result, in order to implement the proposed cooperative system, we only need to make all the source nodes to be able to transmit signals in one subband, and receive signals in two other subbands (one subband at a time), while the destination node to be able to receive signals from all four subbands in the first and second band groups at the same time. These are not very difficult tasks thanks to the implementation of precise filters. Therefore, design of the transceivers at nodes can be created by modifying their current design without heavy additional complexity.

As mentioned in detail in Section IV, the total transmitted power from the four source nodes, which is the main portion of the consumed power at these nodes, is kept to be the same when comparing to our previous 2-OCCS and 4-OCCS schemes, for the fair comparison. With this power constraint, the proposed 4-QOCCS can still provide significantly better error performance, compared to the 2-OCCS, and even the 4-OCCS (in high spectral efficiency cases).

IV. SIMULATION RESULTS

To examine the performance advantage of cooperative communication, we ran several Monte-Carlo simulations for the 2-OCCS, 4-OCCS, and 4-QOCCS. Each run of simulations was carried out with 1200 MB-OFDM symbols. One hundred channel realizations of each channel model (CM1 to CM4) 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 at each Rx antenna.

In order to fairly compare the error performance of non-cooperative and our two previous cooperative communication schemes, namely 2-OCCS and 4-OCCS, the following constraint is applied to all simulations.

Power constraint: The total received power at each Rx antenna at the destination during each time slot need to be the same in all systems. Therefore, the signal constellation points in the 2-OCCS are scaled down by a factor of $1/\sqrt{2}$. The signal constellation points in the 4-OCCS (cf. Eq.(1)) are scaled down by a factor of $1/\sqrt{3}$, while the factor is $1/2$ for the case of 4-QOCCS (cf. Eq.(4))

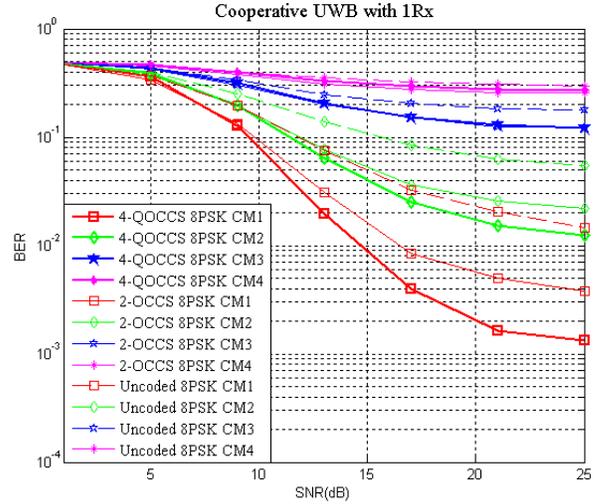


Fig.6. 4-QOCCS vs. 2-OCCS and conventional MB-OFDM UWB with 3bits/s/Hz spectral efficiency

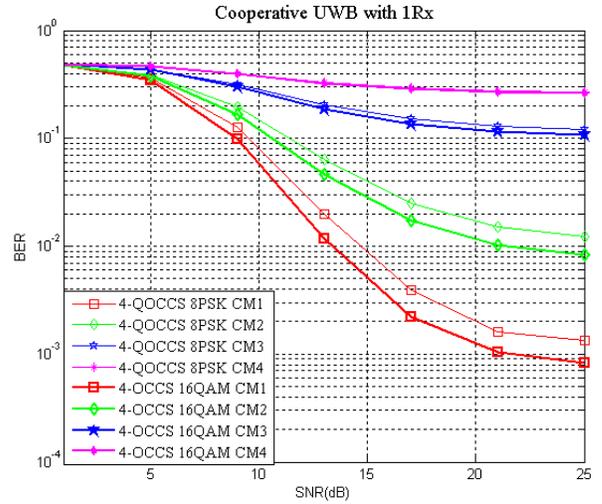


Fig.7. 4-QOCCS vs. 4-OCCS with 3bits/s/Hz spectral efficiency and one-antenna destination node

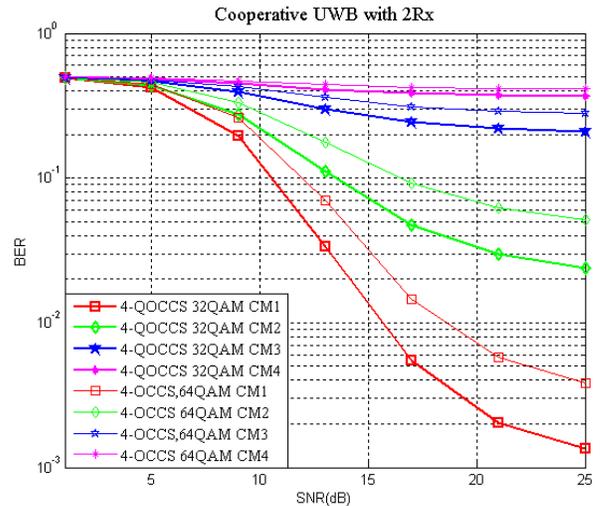


Fig.8. 4-QOCCS vs. 4-OCCS with 5bits/s/Hz and 4.5bits/s/Hz spectral efficiency, respectively, and two-antenna destination node

Fig.6 compares the error performances of the three systems, namely conventional MB-OFDM, 2-OCCS and 4-QOCCS, in the case where all nodes are equipped with one antenna. From Fig.6, it is clear that the 4-QOCCS provides significantly better error performance than the conventional system and the 2-OCCS scheme in the channel models CM1 and CM2. The performances of the two cooperative systems become closer in CM3 and CM4 due to the fact the channels are extremely dispersive, causing a serious inter-symbol interference problem that neutralizes the diversity advantage of the order-4 cooperative communication.

Fig.7 presents the error performances of the 4-OCCS and 4-QOCCS in the case where all nodes are equipped with one antenna. In this simulation, the rate-3/4 4-OCCS uses 16-QAM while the full rate 4-QOCCS uses 8PSK, thus they all have 3bits/s/Hz spectral efficiency. Fig. 7 shows that the 4-OCCS scheme provides better error performance than the 4-QOCCS scheme. The reason is the order-4 orthogonal STFC provides more diversity than the order-4 quasi-orthogonal STFC (as mentioned previously in Section III, QOSTFCs possess partial, rather than full, diversity since not all columns (and rows) are orthogonal). In this case, although the 4-OCCS uses higher density modulation to have the same spectral efficiency as the 4-QOCCS, having higher diversity thanks to the orthogonal STFC still allows the 4-OCCS to have better error performance than the 4-QOCCS.

Fig.8 demonstrates the error performance of the two order-4 systems in the case where the destination node is equipped with 2 Rx antennas. In this simulation, the rate-3/4 4-OCCS uses 64-QAM to achieve 4.5bits/s/Hz spectral efficiency. The full rate 4-QOCCS uses 32-QAM and it has 5bits/s/Hz spectral efficiency, which is even greater than that in the 4-OCCS. From Fig.8, one can observe that the 4-QOCCS is significantly better than the 4-OCCS. The reason is the 4-OCCS only has the code rate of $\frac{3}{4}$, unlike the 4-QOCCS which has the code rate of one. To achieve the 4.5bits/s/Hz spectral efficiency, a higher density modulation scheme has to be used in the 4-OCCS. The high density modulation neutralizes the benefit of the higher diversity possessed by the orthogonal STFC. In other words, the 4-QOCCS has full-rate transmission and it has more advantages when the systems are compared at high spectral efficiency values.

V. CONCLUSIONS

This paper has proposed an order-4 quasi-orthogonal STFC cooperative communication scheme (4-QOCCS) for MB-OFDM UWB communication. A novel subband allocation scheme has also been proposed for this QOCCS in the paper. In addition, the paper has compared the performance of the proposed 4-QOCCS with the 4-OCCS, which we have proposed previously, at different spectral efficiency values. From the simulation results, an important observation can be drawn that,

at lower spectral efficiency, the performance of the 4-OCCS is better than the 4-QOCCS, i.e. the full diversity brings more benefit than the full rate. However, at higher spectral efficiency, the 4-QOCCS can achieve better performance than the 4-OCCS, i.e. the full rate might be more preferred in this case. Our future work would be the examination of the proposed schemes in the scenario where nodes might be erroneously decoded by their partners. Together with our existing analyses, this work shall provide a more comprehensive evaluation of the proposed cooperative communication schemes.

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