Cooperative communication in OFDM-based systems

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Cooperative communication in OFDM-based systems

This thesis is presented as part of the requirements for the award of the Degree

Master by Research - Engineering

from

UNIVERSITY OF WOLLONGONG

by

Zixuan Lin

School of Electrical, Computer and Telecommunications Engineering

March 2013
I, Zixuan Lin, declare that this thesis, submitted in partial fulfilment of the requirements for the award of Master by Research – Engineering, in the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Zixuan Lin
March 20, 2013
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<td>Amplify-and-Forward</td>
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<td>BER</td>
<td>Bit error rate</td>
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<tr>
<td>BPSK</td>
<td>Binary phase shift keying</td>
</tr>
<tr>
<td>CC</td>
<td>Coded cooperation</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code division multiple access</td>
</tr>
<tr>
<td>DF</td>
<td>Decode-and-forward</td>
</tr>
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<td>MB-OFDM UWB</td>
<td>Multiband orthogonal frequency division multiplexing ultra-wideband</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-input multiple-output</td>
</tr>
<tr>
<td>ML</td>
<td>Maximum likelihood</td>
</tr>
<tr>
<td>MRC</td>
<td>Maximum ratio combining</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal frequency division multiplexing</td>
</tr>
<tr>
<td>OSTBC</td>
<td>Orthogonal space-time block code</td>
</tr>
<tr>
<td>WBAN</td>
<td>Wireless body area network</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless local area network</td>
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<tr>
<td>WPAN</td>
<td>Wireless personal area network</td>
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<tr>
<td>WSN</td>
<td>Wireless sensor network</td>
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<td>QAM</td>
<td>Quadrature amplitude modulation</td>
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<td>QOSTBC</td>
<td>Quasi-orthogonal space-time block code</td>
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<tr>
<td>QPSK</td>
<td>Quadrature phase-shift keying</td>
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<td>RF</td>
<td>Radio frequency</td>
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<td>Rx</td>
<td>Receiver</td>
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<td>SISO</td>
<td>Single-input Single-output</td>
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<td>SNR</td>
<td>Signal to noise ratio</td>
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<td>UWB</td>
<td>Ultra-Wideband</td>
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Abstract

Multiband orthogonal frequency division multiplexing ultra-wideband (MB-OFDM UWB) is an emerging technology proposed for wireless personal area network (WPAN) communication. It provides high data rate transmission with low power consumption. However, it has a disadvantage that the MB-OFDM UWB channels are much more dispersive than the channel in a conventional wireless system. Therefore, the communication range of MB-OFDM UWB systems is relatively short, which is typically up to ten meters.

This thesis targets at finding efficient techniques to increase further the data rate and communication range of MB-OFDM UWB systems without increasing the power consumption. One of the possible solutions is to adapt the concepts of the emerging techniques, namely cooperative communication, multiple-input multiple-output (MIMO) and space-time-frequency codes (STFCs), in order to tailor for their implementations in MB-OFDM UWB systems.

This research area has been almost unexplored with the cooperative communication scheme namely 2-OCCS for a two-source node MB-OFDM UWB system being proposed [4]. This thesis thus extends that idea to propose several cooperative communication schemes for four-source node MB-OFDM UWB systems, namely the 4-OCCS and 4-QOCCS schemes. These proposed schemes have been proved to improve significantly the system error performance in numerous cases, compared to a non-cooperative MB-OFDM UWB system, without any increase of transmission power.

Although cooperative communication with space-time codes (STCs) is beneficial in...
various cases, it is unfortunately not always better than non-cooperative communication due to the erroneous decoding at the source nodes. One important question from the source nodes’ perspective is when they need to cooperate with one another. This research thus continues by analysing the bit error performance of cooperative communication systems in comparison with that of a non-cooperative communication one to find out the threshold conditions where cooperative communication starts to be useful.

In summary, the proposed cooperative communication schemes facilitate a flexible network design of up to four cooperative source nodes in MB-OFDM UWB systems. This thesis also derives for the first time an in-depth mathematical analysis of the usefulness of cooperative communication in both non-OFDM and OFDM-based systems. This analysis allows source nodes to know whether they should be in cooperation. It is believed that the contributions of this research are important pavements to a future, intelligent cooperative communication in wireless personal area networks WPANs, wireless body area networks (WBANs), and wireless sensor networks (WSNs).
Acknowledgement

Eager am I to thank my principle supervisor Dr. Le Chung Tran, who is a respectable, responsible and resourceful scholar, and I would like to take this opportunity to extend my deepest gratitude and respect to his constant encouragement and guidance. Special thanks also go to my co-supervisor Prof. Farzad Safaei for his support, guidance and knowledge. Without their illuminating instructions and continuous supports, this thesis could not have reached its present form.

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Chapter 1

Introduction

Wireless communication is one of the most vibrant areas in the communication field today. It is used to transfer information over a distance without the use of a guided medium. Due to the sharply increasing in demand for wireless connectivity, it has developed extremely fast during the last two decades. However, wireless communication is not as reliable as guided medium communication, due to fading and other propagation effects [1]. Accordingly, the techniques to improve its capacity and reliability become the key objective for current research. Numerous techniques have been proposed to enhance the performance and reduce the interference for wireless communication, such as Multiple-Input Multiple-Output (MIMO), Space-Time Codes (STCs) and Orthogonal Frequency Division Multiplexing (OFDM).

It is widely acknowledged that the combination of MIMO and STCs is able to provide a significant improvement of the capacity and bit error performance of wireless systems. However, there are some existing limitations of MIMO. For instance, transmitters/receivers 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)/receive (Rx) antennas. Thus, cooperative communication technique has been introduced to allow single-antenna devices to cooperate and create a virtual (or distributed) MIMO system in such a way that the STC and MIMO concepts can still be implemented.
OFDM is a technique to against the frequency-selective fading or narrowband interference in wireless communication, thus improving the system reliability. This technique allows data to be transmitted in parallel by modulating the data on a set of orthogonal sub-carriers. It has been widely applied in practice, such as in Ultra-Wideband (UWB) [2] and WLAN (such as IEEE802.11a and IEEE 802.11g). Multiband OFDM (MB-OFDM) is a special OFDM system that uses the 7.5GHz available radio frequency (RF) spectrum from 2.1 to 10.6 GHz. MB-OFDM UWB provides low-complexity receivers to capture sufficiently the multipath energy, and it is easier for the RF (Radio frequency) design. The concept of MB-OFDM is to divide the large UWB band into multiple smaller bands (called subbands) with the bandwidths greater than 500MHz. In the frequency domain, consecutive MB-OFDM symbols are transmitted over different subbands with distinct central carrier frequencies.

Recently, the research interest starts to focus on the combination of these emerging techniques for MB-OFDM UWB systems. An order-2 orthogonal cooperative communication scheme (2-OCCS) for the Space-Time Frequency Coded (STFC) MB-OFDM UWB system using the Alamouti STFC [3] was proposed in [4]. This scheme was proposed for a two-source node MB-OFDM UWB system. The results show that the combination of cooperative communication and STFCs (i.e. MIMO) could significantly improve the performance of the conventional MB-OFDM UWB system. A drawback of the aforementioned 2-OCCS is that it cannot be used for more than two cooperative nodes. A question that could be raised is whether it is possible for more than two source nodes (up to four nodes for instance) to collaborate in the cooperative STFC MB-OFDM UWB system. The up-to-four source node systems are particular of interest, since they might be able to provide a higher diversity order than the two-source node one, while their implementation is not too complicated. Resolution for this question
would be very useful, since it might allow the hybrid cooperation scheme with a flexible selection of two, three, and up to four cooperative nodes. Thus, it is vital to develop a four node cooperative STFC MB-OFDM UWB system.

In addition, the discussion of the usefulness of the cooperative communication in OFDM-based systems, i.e. in which scenario cooperative communication is useful for OFDM-based systems, is still missing in the literature. An analysis which could clearly point out when the application of cooperative communication to OFDM-based systems shall significantly improve the system bit error performance, compared to a SISO system, is highly desired.

1.1 Research objectives

This research project aims to develop a four-source node cooperative STFC MB-OFDM UWB system and examine the usefulness of cooperative communication in OFDM-based systems. The key research questions are as follows:

- Is it possible for four source nodes to collaborate in the cooperative STFC MB-OFDM UWB system?
- If yes, how much could the performance of four-source node cooperative systems be better than that of the 2-OCCS?
- Does cooperative communication provide performance improvement at any Signal-to-Noise Ratio (SNR) for OFDM-based systems?
- If not, in which channel condition does cooperative communication become useful?

The specific objectives of this project are:
• Provide a comprehensive literature review of cooperative communication, MB-OFDM UWB and STFCs.

• Simulate the 2-OCCS scheme that was proposed by Le Chung Tran [4] for a two source node STFC MB-OFDM system using the Alamouti STFC [3].

• Propose a cooperative communication framework for four source nodes to cooperate in STFC MB-OFDM UWB systems. More specifically, the order-4 orthogonal cooperative communication scheme (4-OCCS) and the order-4 quasi-orthogonal cooperative communication scheme (4-QOCCS) will be proposed for MB-OFDM UWB systems, which apply orthogonal space-time-frequency codes (OSTFCs) and quasi-orthogonal space-time-frequency codes (QOSTFCs) respectively.

• Propose new sub-band allocation techniques for the proposed cooperative communication systems.

• Simulate the proposed systems and examine their performance in comparison with the 2-OCCS and a non-cooperative MB-OFDM UWB system.

• Evaluate the usefulness of cooperative communication in both non-OFDM and OFDM-based systems.

1.2 Thesis organisation

The thesis is organised as follows

• **Chapter 1** introduces the project background and objectives. It also highlights the research contributions and publications.

• **Chapter 2** presents a comprehensive literature review for this project. This
Chapter mainly includes the reviews of three topics, namely cooperative communication, Space-Time Codes (STCs), and OFDM-based systems.

• **Chapter 3** illustrates a novel order-4 orthogonal STFC cooperative communication scheme (4-OCCS) using a rate-3/4 orthogonal space-time frequency code (OSTFC). This chapter also presents a new subband allocation technique specifically designed for the 4-OCCS. Additionally, simulation results for the 4-OCCS are presented in comparison with those of the 2-OCCS in the same conditions of data rate and transmission power.

• **Chapter 4** describes another novel order-4 quasi-orthogonal cooperative communication scheme (4-QOCCS) using a full rate quasi-orthogonal space-time frequency code (QOSTFC). In this chapter, a new subband allocation technique tailored for the 4-QOCCS will also be proposed. Simulation results show that the 4-QOCCS is able to improve significantly the system performance, compared to the 2-OCCS, and even compared to the 4-OCCS in some cases.

• **Chapter 5** reveals the usefulness of the cooperative communication in both non-OFDM and OFDM-based systems. It shows the cooperative communication is able to provide better error performance than a non-cooperative system when the SNR in the channel between source nodes is greater than a certain threshold SNR, which is referred to as the ‘cooperative SNR’ value.

• **Chapter 6** summarises all the research contributions and provides some recommendations and directions of my further work.

1.3 Publications
The publications arisen from my Master-by-research course (March 2012 – March 2013) are listed below.


  **Abstract:** The combination of cooperative communication and Space-Time-Frequency-Codes (STFCs) has been recently proposed in the literature for Multiband OFDM Ultra-Wideband (MB-OFDM UWB) to improve the bit error performance, system capacity, data rate and wireless communication range. This paper proposes a cooperative communication design using order-4 orthogonal STFCs in MB-OFDM UWB systems, which is referred to as order-4 orthogonal cooperative communication scheme (4-OCCS). It will be shown that the 4-OCCS improves significantly the diversity and thus error performance of the MB-OFDM UWB system, compared to the conventional MB-OFDM UWB (without STFCs) as well as our order-2 orthogonal cooperative communication scheme using Alamouti STFCs (2-OCCS) proposed previously, with the same data rate and without any increase of transmission power.


  **Abstract:** Recently, cooperative communication and Space-Time-Frequency-Codes (STFCs) have been introduced into the Multiband 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 2-OCCS using the Alamouti STFCs, and even better than the order-4 orthogonal cooperative communication scheme (4-OCCS), which we have recently proposed, in the high spectral efficiency cases.


**Abstract:** Recently, the combination of cooperative communication, Space-Time-Frequency-Codes (STFCs) and Multiband OFDM Ultra-Wideband (MB-OFDM UWB) has been proposed to improve the data rate, system capacity and reliability. This paper provides further performance evaluation for our cooperative communication schemes for MB-OFDM UWB systems proposed previously in a more practical scenario where the signal-to-noise ratio (SNR) at the inter-node links is different from that in the uplinks. Simulation results show that the implementation of cooperative communication starts to be useful when the inter-node SNR reaches a certain threshold, the so-called cooperative SNR value. In addition, the values of cooperative SNR for different uplink conditions have been derived from the simulation results for the two UWB channel models CM1 and CM2. It is shown that cooperative communication for MB-OFDM UWB might be beneficial even when the inter-node links are noisy and/or when the source nodes are located further apart from each other, compared to the...
destination node. Cooperative communication also plays a more important role when the uplink channels become more dispersive.
Chapter 2

Literature Review

The aim of this chapter is to present a comprehensive literature review of the techniques that are involved in this master project, namely

- cooperative communication,
- Space-time block codes (STBC) and space-time-frequency codes (STFC), and
- Orthogonal Frequency Division Multiplexing (OFDM) and multi-band OFDM ultra-wideband (MB-OFDM UWB).

This chapter provides readers with the background of the above techniques and summarises the open problems which will be addressed in this project.

2.1 Cooperative communication

Multiple-input multiple-output (MIMO) is widely utilised to improve the throughput and reliability of wireless communication systems. As depicted in Fig. 2.1, the concept of a MIMO system is to figure and merge the transmitted signals from multiple wireless paths that are created by the use of multiple transmit and receive antennas.
The multiplexing technique used by MIMO increases the bandwidth and communication range. MIMO uses the extra pathways to transmit more information and then recombines the signals at the destination to reduce the overall system bit error rate (BER), thus improving the system reliability. As illustrated in Fig.2.2, the capacity of a MIMO system is apparently increased in comparison with a single-input single-output (SISO) system.

Figure 2.1 The concept of MIMO system.

Figure 2.2 Capacity for Rayleigh fading channel [5].
The channel capacity can be calculated by Shannon’s law [6], i.e. the system capacity is proportional to the numbers of the antennas

\[ C = B \log_2(1 + \frac{S}{N}) \] (2.1)

where \( B \) denotes bandwidth and \( S/N \) is the signal to noise ratio.

However, in practice, a MIMO system could have some disadvantages. One of the main drawbacks is the devices (i.e. the transmitter, 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 multiple uncorrelated Tx antennas.

To overcome this drawback, a category of techniques named cooperative communication is proposed to enable the single antenna mobile devices to share their antennas in a sense to build up a virtual MIMO system and obtain certain benefits of a MIMO system. The basic ideas behind cooperative communication can be traced back to the novel work of Cover and El Gamal [7] on the information theoretic properties of the relay channel. They analysed the capacity of a three-node network which contains one source, one relay and one destination. Many ideas regarding to cooperative communication appearing later were first derived from [7].
Figure 2.3 Cooperation between nodes [8].

Figure 2.3 illustrates one source node and one relay transmitting independent copies of a signal to the base station (destination). A single antenna device cannot generate spatial diversity. Nevertheless, the fading between two agents are statistically independent. If one node is able to hear from the other and forward a modified version of the message in its own way, the spatial diversity can be generated to effectively combat against the detrimental effects of channel fading.

There are three fundamental protocols in cooperative communication. They are Decode-and-Forward (DF), Amplify-and-Forward (AF) and Coded Cooperation. The performance of these protocols are considerably examined in the literature, such as in [9], [10], [11], [12], and [13]. In this master project, the concept of Decode-and-Forward will be mainly utilised, thus DF will be reviewed in more detail as below. Readers may refer to [14] for a comprehensive review of all three concepts.
2.1.1 Decode-and-Forward protocol (DF)

The DF concept was firstly proposed in the literature [11]. As illustrated in Fig. 2.4, the DF protocol allows the relay to decode the received message from its partner, afterwards re-encode and retransmit it to the destination.

DF is more advanced, compared to the AF protocol [15], [16]. The AF protocol just simply amplifies the received signals on the relay and retransmits to the destination. This action also causes the relay to amplify the unnecessary noise in the signals. Hence, the performance of AF degrades significantly when the channel SNR decreases. In the DF protocol, relay decodes the received signals instead of just amplifying them. Thus, DF outperforms AF when the channel SNR is low [17].

The data transmission using the DF protocol could be divided in to three time slots.

- First time slot: Source broadcasting
In this time slot, the source transmits the modulated signals to both relay and destination. The signals received at the relay \((r)\) and destination \((d)\) are shown as follows

\[
\begin{align*}
\text{Source to relay: } y_{s,r} &= \sqrt{P_s} h_{s,r} x_s + n_{s,r} \\
\text{Source to destination: } y_{s,d} &= \sqrt{P_s} h_{s,d} x_s + n_{s,d}
\end{align*}
\] (2.2)

where \(y_{s,m}\) \((m \in s, d)\) denotes the received signals, \(h_{s,m}\) denotes the Rayleigh channel coefficient, \(x_s\) denotes for the modulated signals from source nodes, and \(n_{s,m}\) denotes the Gaussian noise. \(\sqrt{P_s}\) is used to scale down the transmission power for a fair comparison with a non-cooperative system.

Figure 2.5 First time slot in the DF protocol.

- Second time slot: Relay decodes the signal

Once the relay receives a noisy signal from the source, it begins to decode the signal. Afterwards it compares the decoded signal \(x_r\) to the original signal \(x_s\). If they are equivalent, the relay continues to re-encode and forward the signal \(x_r\) to the destination.
After the second phase, the destination will receive the signal from the relay which equals to

\[ y_{r,d} = \sqrt{P_r} h_{r,d} x_r + n_{r,d} \]  

(2.3)

where \( y_{r,d} \) denotes the signal received at the destination in the relay-destination link, \( h_{r,d} \) denotes the Rayleigh channel coefficient between relay and destination, \( x_r \) denotes the transmitted signal from the relay, and \( n_{r,d} \) denotes the Gaussian noise. \( P_r \) is the transmission power.

In the case that \( x_r \) and \( x_s \) are not equivalent, the system simply gives up cooperation and the source will transmit the signal to destination with full power in the same way as in a SISO system.

The destination receives two copies of the signal from two independent fading paths. At this point, the destination could decode the signals by applying the Maximum Ratio

Figure 2.6 Second time slot in the DF protocol.
Combining (MRC) technique to maximise the overall SNR of the received signal [18].

The combined signal is illustrates as follows:

\[ y = a_1 y_{s,d} + a_2 y_{r,d}. \]  

(2.4)

where \(a_1\) and \(a_2\) are two weighting coefficients.

\[ a_1 = \frac{\sqrt{P_m h_{s,d}}}{N_0}, \quad a_2 = \frac{\sqrt{P_m h_{r,d}}}{N_0} \]

where \((.)^*\) denotes the complex conjugate and \(N_0\) denotes the noise power.

![Figure 2.7 Third time slot in the DF protocol.](image)

Simulation results for the DF protocol are shown in Fig. 2.8.
From Fig. 2.8, it is clear that the DF protocol provides better bit error performance compared to the direct SISO transmission, especially when the channels have good conditions.

Although the cooperative communication technique has been intensively analysed in the literature, such as in [8],[12],[17],[19],[20] and [21], for non-OFDM based systems, only a few works focus on this technique for OFDM-based systems, especially in the context of MB-OFDM UWB systems. Moreover, the field of Space-Time Codes (STC) cooperative communication is not fully explored yet. For instance, a comprehensive work that could formulate the STC cooperative communication system and point out clearly in which scenario the cooperative communication is useful is still missing in the literature.
2.2 Space-time block codes (STBC)

Space-time block coding (STBC) is aimed to transmit multiple copies of a data stream via multiple Tx antennas, thus improving the data robustness and the reliability of wireless systems. Alamouti STBC [3] is the simplest code proposed for a system with two Tx antennas.

2.2.1 Alamouti STBC

Alamouti STBC is a simple and effective transmit diversity technique that is specifically designed for two transmit antennas and has remarkably low decoding complexity. In the case of a two-Tx and one-Rx system, the use of Alamouti STBC provides the same diversity order as the MRC technique with one Tx and two Rx [18]. The structure of the Alamouti STBC is illustrated as follows

\[
\begin{bmatrix}
 s_1 \\
 -s_2^* \\
 s_2 \\
 s_1^*
\end{bmatrix}
\]  

(2.5)

where \(s_1\) and \(s_2\) are the symbols transmitted through two Tx antennas in first time slot and the superscript \((. )^*\) denotes the complex conjugation. To perform the Alamouti STBC in the MIMO system, following three steps are required:

- Symbols encoding and transmission sequence

As depicted in Fig. 2.9, at a given time phase, two symbols are transmitted from two antennas simultaneously. In the first time phase, symbols \(s_1\) and \(s_2\) are transmitted by the 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) antenna, respectively. In the next time phase, symbol \(-s_2^*\) is transmitted
by the 1st antenna and symbol $s_1^*$ is transmitted by the 2nd antenna. This encoding process results in the signals which have diversity in both space and time. Assume the channel is modelled by a complex multiplicative distortion at time $t$ and the fading remains constant in two consecutive symbol periods. The channel coefficient can be expressed as follows

$$h_1(t) = h_1(t + T) = h_1 = \alpha_1 e^{j\theta_1} \quad (2.6)$$

$$h_2(t) = h_2(t + T) = h_2 = \alpha_2 e^{j\theta_2}$$

where $T$ denotes the symbol duration, $\alpha$ and $\theta$ denote the amplitude and phase of the channel coefficient. The signals received at the destination node during the two time phases could be expressed as

$$r_1 = r(t) = h_1 s_1 + h_2 s_2 + n_1$$

$$r_2 = r(t + T) = -h_1 s_2^* + h_2 s_1^* + n_2 \quad (2.7)$$

where $r_1$ and $r_2$ present the received signals in the two time phases, and $n_1$ and $n_2$
denote the complex random noise variables.

- Signals combining scheme

As shown in Fig. 2.9, the combiner generates two combined signals and sends to the maximum likelihood decoder

\begin{align*}
\tilde{s}_1 &= h_1^* r_1 + h_2^* r_2^* \\
\tilde{s}_2 &= h_2^* r_1 - h_1^* r_2^*
\end{align*}

(2.8)

- Maximum Likelihood (ML) decoding

The symbols $s_1$ and $s_2$ are easily recovered by the following ML decoding equations

\begin{align*}
s_1 &= \text{arg} \min_{s \in \mathbb{C}} \{(h_1^* r_1 + h_2^* r_2^*) - s|^2 + [-1 + (|h_1|^2 + |h_1|^2)]|s|^2\} \\
s_2 &= \text{arg} \min_{s \in \mathbb{C}} \{(h_2^* r_1 - h_1^* r_2^*) - s|^2 + [-1 + (|h_1|^2 + |h_1|^2)]|s|^2\}
\end{align*}

(2.9)

where $\mathcal{C}$ denotes all potential possibilities that the symbol $s$ can take.

Although the Alamouti STBC significantly improves the performance of wireless systems, it still has one drawback that it cannot be used when the MIMO system has more than two Tx antennas. Thus, in [22] and [23], the authors have proposed the orthogonal STBC for multiple antenna systems to provide more diversities and better performance. Since the system of up to 4 Tx antennas is mainly of interest in this thesis, we will focus on reviewing the order-4 orthogonal and quasi-orthogonal STBCs.
2.2.2 Orthogonal space-time block code (OSTBC)

In this master project, we utilised the order-4 OSTBC that was proposed in [22] to enable four antennas to transmit signals simultaneously. This OSTBC offers a greater diversity compared to the Alamouti STBC with the cost of having \(\frac{3}{4}\) bit rate (rather than rate-1), which means it transmits three symbols over four time slots, to maintain the orthogonality of the code (for the simple ML decoding complexity). An example structure of the order 4, rate-3/4 OSTBC is shown as follows

\[
\begin{bmatrix}
s_1 & s_2 & s_3 & 0 \\
-s_2^* & s_1^* & 0 & s_3 \\
-s_3^* & 0 & s_1^* & -s_2^* \\
0 & -s_3^* & s_2^* & s_1
\end{bmatrix}
\] (2.10)

Figure 2.10 Structural diagram of a 4Tx, 1Rx rate-3/4 orthogonal STBC system.

As depicted in Fig. 2.10, in a certain time slot, three symbols are transmitted from three
(out of four) antennas simultaneously. In the first time slot, symbols \( s_1, s_2 \) and \( s_3 \) are transmitted by Tx1, Tx2 and Tx3 respectively, while Tx4 remains idle. In the second time slot, Tx1, Tx2 and Tx4 transmit the symbols \( -s_2^*, s_1^* \) and \( s_3 \) respectively. In the third time slot, Tx2 keeps silent, while Tx1, Tx3 and Tx4 transmit the data \( -s_3^*, s_1^* \) and \( -s_2^* \) to the destination. In the fourth time slot, Tx2, Tx3 and Tx4 transmit the symbols \( -s_3^*, s_2^* \) and \( s_1 \) respectively and Tx1 stays silent. The received signals during these four time slots can be presented as follows

\[
\begin{align*}
    r_1 &= h_1 s_1 + h_2 s_2 + h_3 s_3 + n_1 \\
    r_2 &= -h_1 s_2^* + h_2 s_1^* + h_4 s_3 + n_2 \\
    r_3 &= -h_1 s_3^* + h_3 s_1^* - h_4 s_2^* + n_3 \\
    r_4 &= -h_2 s_3^* + h_3 s_2^* + h_4 s_1 + n_4
\end{align*}
\]

where \( h_t (t = 1,2,3,4) \) is the channel coefficient modelled by a complex multiplicative distortion, which is assumed to be constant in four consecutive symbol periods. \( n_t \) denotes the complex Gaussian noise affecting the destination node at the \( t \) time slot. The destination is able to decode three symbols \( s_1, s_2 \) and \( s_3 \) after four time slots. The symbols can be decoded by the ML decoding concept [24] and the decoding metrics are shown as follows

\[
\begin{align*}
    s_1 &= \arg \min_{s \in C} \left\{ \left( h_1^* r_1 + h_2^* r_2 + h_3^* r_3 + h_4^* r_4 \right) - s \right\}^2 + \left[ -1 + \left( |h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2 \right) \right] |s|^2 \\
    s_2 &= \arg \min_{s \in C} \left\{ \left( h_1^* r_1 - h_2^* r_2 + h_3^* r_3 + h_4^* r_4 \right) - s \right\}^2 + \left[ -1 + \left( |h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2 \right) \right] |s|^2 \\
    s_2 &= \arg \min_{s \in C} \left\{ \left( h_1^* r_1 - h_2^* r_2 + h_3^* r_2 - h_4^* r_4 \right) - s \right\}^2 + \left[ -1 + \left( |h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2 \right) \right] |s|^2
\end{align*}
\]
Although the order-4 OSTBC provides better performance than the Alamouti STBC, it cannot achieve a full transmission rate. Thus, H. Jafarkhani [25] proposed a new space-time block code which can achieve the full rate using a quasi-orthogonal design.

2.2.3 Quasi-orthogonal space-time block codes (QOSTBCs)

QOSTBCs were first introduced in [25]. The system model for QOSTBCs is shown in Fig. 2.11. The concept of a quasi-orthogonal design is to divide the transmission matrix columns into groups. While different groups of columns are orthogonal to each other, columns within each group might not be orthogonal to each other. QOSTBCs are able to achieve full rate transmission while sacrificing slightly the diversity. The symbols could be decoded in groups at the destination node. In this master project, we utilised the following order-4 full rate QOSTBC
As revealed in the matrix, in a certain time slot, four symbols are transmitted from four Tx antennas simultaneously. In the first time slot, symbols $s_1$, $s_2$, $s_3$ and $s_4$ are transmitted by Tx1, Tx2, Tx3 and Tx4 respectively. In the second time slot, Tx1, Tx2, Tx3 and Tx4 transmit the symbols $-s_2^*$, $s_1^*$, $-s_4^*$ and $s_3^*$ respectively. In the third time slot, Tx1, Tx2, Tx3 and Tx4 transmit the data $-s_3^*$, $-s_4^*$, $s_1^*$ and $s_2^*$ respectively to the destination. In the fourth time slot, the symbols $s_4^*$, $-s_3$, $s_2$ and $s_1$ are transmitted by Tx1, Tx2, Tx3 and Tx4 respectively to the destination. The received signals during these four time slots can be presented as follows

$$
\begin{align*}
    r_1 &= h_1s_1 + h_2s_2 + h_3s_3 + h_4s_4 + n_1 \\
    r_2 &= -h_1s_2^* + h_2s_1^* + h_3s_4^* + h_4s_3^* + n_2 \\
    r_3 &= -h_1s_3^* - h_2s_4^* + h_3s_1^* + h_4s_2^* + n_3 \\
    r_4 &= h_1s_4^* - h_2s_3^* + h_3s_2^* + h_4s_1^* + n_4
\end{align*}
$$

Unlike the aforementioned Alamouti STBC and the OSTBC, the symbols in the QOSTBC matrix could not be decoded separately due to the quasi-orthogonal design. Instead, the symbols $s_1$ and $s_4$ ($s_2$ and $s_3$) can be decoded in pairs by applying the ML decoding. It is slightly more complex than decoding individual symbols. The decoding
procedure is illustrated as follows

\[
(s_1, s_4) = \arg \min \left\{ \sum_{j=1}^{4} |h_j|^2 \left( |s_1|^2 + |s_4|^2 \right) + 2 \Re \left\{ \left( -h_1^* r_1^* - h_2^* r_2^* - h_3^* r_3^* - h_4^* r_4^* \right) s_1 + \left( -h_4^* r_1^* + h_3^* r_2^* + h_2^* r_3^* - h_1^* r_4^* \right) s_4 + \left( h_1^* h_4^* - h_2^* h_3^* - h_1^* h_2^* \right) s_1 s_4^* \right\} \right\}
\]

\[
(s_2, s_3) = \arg \min \left\{ \sum_{j=1}^{4} |h_j|^2 \left( |s_2|^2 + |s_3|^2 \right) + 2 \Re \left\{ \left( -h_2^* r_1^* + h_3^* r_2^* - h_4^* r_3^* + h_4^* r_4^* \right) s_2 + \left( -h_3^* r_1^* - h_4^* r_2^* + h_1^* r_3^* - h_2^* r_4^* \right) s_3 + \left( h_2^* h_3^* - h_4^* h_4^* - h_1^* h_4^* + h_2^* h_3^* \right) s_2 s_3^* \right\} \right\}
\]

where \( \Re \{a\} \) is the real part of \( a \). As shown in the simulation results in [25], the full rate QOSTBC has more benefits in the low-to-medium SNR region. Meanwhile full diversity orthogonal STBCs offer better bit error performance in the medium-to-high SNR region. The following figure is the simulation results for BER comparison between OSTBC and QOSTBC with the same spectral efficiency of 3bits/s/Hz.
Figure 2.12 Bit-error probability versus SNR for space–time block codes at 3 bits/s/Hz; 1 receive antenna [25].

2.2.4 Space-time frequency code (STFC)

STFCs are widely applied to Orthogonal Frequency Division Multiplexing (OFDM) systems. STFCs fully utilise three main diversities: temporal diversity, spatial diversity and frequency diversity. The structures of STFCs are the same as the structures of conventional STBCs, except that each element in STFCs is not a complex number, but is defined as a column vector $\bar{s}_{t,m} = [\bar{s}_{t,m,1}, \bar{s}_{t,m,2}, ..., \bar{s}_{t,m,N_{fft}}]^T$, where $N_{fft}$ is the FFT (Fast Fourier Transform) size. The vector $\bar{s}_{t,m}$ denotes the original transmitted data before IFFT where the individual symbols $\bar{s}_{t,m,k}$ are drawn from a DCM (Dual Carrier Modulation) or QPSK modulation. An example illustrating the differences between a STFC and a STBC is shown in Fig 2.13.

STFCs also provide a relatively low decoding complexity to OFDM-based systems. While the performance of the ordinary MIMO STFC OFDM is intensively examined in the literature, such as in [26], [27], [28] and [29], the use of STFCs in Multiband OFDM Ultra-Wideband (MB-OFDM UWB) has not been so widely examined with only a few publications, such as [30] and [31].

Figure 2.13 Comparison between the Alamouti STBC and an order-2 STFC.
2.3 Orthogonal Frequency Division Multiplexing (OFDM) based systems

The increasing needs for higher transmission rates and greater bandwidths in wireless communication may cause some serious problems, such as signal distortions in frequency selective channel fading and inter-symbol interference. The concept of OFDM was first proposed in [32], which is aimed to split up a high rate data stream into a set of low rate sub-streams and thus turn the frequency selective fading into flat (or non-frequency selective) fading for each sub-stream. Therefore, the signals transmitted over each sub-stream could be received with a one-tap frequency domain equaliser. Due to the huge advantages brought by OFDM, it has been widely applied in practice, such as in Ultra-Wideband [2], WLAN (such as IEEE802.11a and IEEE 802.11g), and WiMax [33]. The performance of ordinary OFDM systems has been intensively researched in the literature [32], [34], [35], [36], [37] and [38]. The combination of MIMO and STFC concepts with ordinary OFDM systems have been also mentioned in the literature [26], [27] and [39]. However, a few works considered the combination between MIMO, STFC and MB-OFDM UWB. In this thesis, a specific OFDM based system, namely MB-OFDM UWB will be considered. Thus overviews of UWB and MB-OFDM will be mentioned below.

2.3.1 History of ultra-wideband technology

Ultra-wideband technology was first employed by G. Marconi in 1901 to transmit Morse code sequences across the Atlantic Ocean using spark gap radio transmitters.
From the 1960s to the 1990s, the UWB technology only served for the military and Department of Defense (DoD) applications under classified programs [40]. However, as the research interest increased rapidly over the past few years, researchers began to request the FCC (federal communications commission) to approve UWB for commercial use. In February 2002, the FCC Report and Order (R&O) issued to allocate 7,500 MHz of spectrum for unlicensed use of UWB devices in the 3.1 to 10.6 GHz frequency band.

The UWB communication is fundamentally different from all other communication techniques because it employs extremely narrow RF pulses for communication between transmitters and receivers. The spectrum in UWB can be spread widely in the frequency domain. Consequently, the UWB communication can offer several advantages, such as large throughput, robustness to jamming and coexistence with current radio service [40], [41], [42].

There are two main types of UWB systems, which are carrier-less and carrier-based UWB systems [43]. The carrier-less UWB system uses baseband short duration pulses to carry the information. Example for a carrier-less UWB system is impulse-response UWB (IR UWB) system. The carrier-based UWB system has the baseband signal with more than 500MHz bandwidth shifted to the desire frequency band by modulating single or multiple carrier waves. Example of a carrier-based UWB system is Direct-sequence UWB (DS-UWB) and the Orthogonal frequency-division multiplexing UWB (OFDM-UWB).

Multiband OFDM (MB-OFDM) is a carrier-based UWB system that uses the 7.5GHz available RF spectrum in UWB in the way that differs from the impulse, or direct sequence UWB. The carrier-based system provides low complexity of receivers to capture sufficient multipath energy, and is easier for RF design. The concept of the
MB-OFDM UWB is to divide the large UWB band into multiple smaller bands each with the bandwidth greater than 500MHz. In a frequency domain, MB-OFDM UWB is able to transmit data over multiple carriers simultaneously with distinct carrier frequencies [40].

### 2.3.2 MB-OFDM Physical Layer specifications

MB-OFDM UWB PHY (Physical Layer) specifications were proposed by A. Batra et al [44] with the support from the WiMedia Alliance. According to these specifications, MB-OFDM UWB utilises the unlicensed 3.1 - 10.6 GHz UWB frequency band and is able to support various data rates of 53.3, 80, 106.7, 160, 200, 320, 400, and 480 Mb/s by applying different modulation and coding schemes. The whole UWB spectrum is divided into 14 subbands, each of which has a bandwidth of 528 MHz. As depicted in Fig 2.14, 14 bands can be separated into five groups. The first four groups consist of three subbands and the last two subbands are assigned into the fifth group. The number of data sub-carriers used in each subband to transmit information is one-hundred (100) and the support for the first band group is mandatory.

Figure 2.14 Frequency bands in MB-OFDM UWB [2].
The Forward Error Correction (FEC) codes with different code rates are applied to modify the data rates of the system. The coded binary data sequence then goes through a bit interleaver to avoid burst errors. The interleaved data is then mapped into complex constellations. The QPSK constellation may be applied when the data rates is lower than 200Mbps. When the data rates reach more than 200 Mbps, the multi-dimensional constellation like dual carrier modulation (DCM) technique may be used instead [30].

The modulated data is attached with 12 pilots, 10 guard sub-carriers and 6 nulls. The total number of sub-carriers becomes 128 (the FFT/IFFT size). The resulting data is transformed via the IFFT to form an OFDM symbol. The resulting OFDM symbol is then appended with the Zero-Padded Suffix (ZPS), which contains 37 zeros. The ZPS is used to against the multi-path fading effects. It also provides a time interval for the transmitter and receiver to allow them to switch between different frequencies. The timing parameters associated with MB-OFDM PHY are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{SD}$: Number of data subcarriers</td>
<td>100</td>
</tr>
<tr>
<td>$N_{SDP}$: Number of defined pilot carriers</td>
<td>12</td>
</tr>
<tr>
<td>$N_{SG}$: Number of guard carriers</td>
<td>10</td>
</tr>
<tr>
<td>$N_{ST}$: Number of total subcarriers used</td>
<td>$122 (= N_{SD} + N_{SDP} + N_{SG})$</td>
</tr>
<tr>
<td>$\Delta_f$: Subcarrier frequency spacing</td>
<td>4.125 MHz ($= 528$ MHz/128)</td>
</tr>
<tr>
<td>$T_{FFT}$: IFFT/FFT period</td>
<td>242.42 ns ($1/\Delta F$)</td>
</tr>
<tr>
<td>$T_{ZP}$: Zero pad duration</td>
<td>70.08 ns ($= 37/528$ MHz)</td>
</tr>
<tr>
<td>$T_{SYM}$: Symbol interval</td>
<td>312.5 ns ($T_{ZP} + T_{FFT} + T_{GI}$)</td>
</tr>
</tbody>
</table>
From Table 2.1, TSYM is the Symbol interval, where TGI is the guard time interval. There are two types of Time-Frequency Codes (TFC) which are mandatorily supported in MB-OFDM UWB to achieve further time and frequency diversities. They are Time-Frequency Interleaving (TFI) and Fixed Frequency Interleaving (FFI). TFI is used when the coded information is interleaved over three subbands, while FFI used where coded information is transmitted on a single subband. The following figure gives an example about how the time-frequency coding works in the first three bands.

Figure 2.15  The transmitted RF pattern using the first three bands.

2.3.3 Structure of MB-OFDM UWB

The basic structure of MB-OFDM UWB system can be presented as follows
• **Series-to-parallel (S/P) and Parallel-to-series converter**

The S/P converter is used to split up a serial bit stream into a group of parallel bit streams. On the contrary, the P/S converter is to combine the parallel bit streams into a serial bit stream.

• **Convolutional encoder and Viterbi decoder**

The convolutional encoder [45] is used to encode the parallel bit streams to create robust signals and provides better bit error performance when the channel SNR is low. The Viterbi decoder [45] is paired with the convolutional encoder. It is used to decode the convoluted signal.

• **Interleaver**

The coded signal is interleaved prior to constellation mapping to avoid the burst errors during the wireless transmission.

• **Constellation mapping**

Various modulation techniques can be applied in the constellation mapping block, such as QPSK and DCM depending on different requirements of the data rate in the
• **Inverse Fast Fourier Transform (IFFT)**

The modulated data is inserted with 10 guard, 12 pilot sub-carriers and 6 nulls, then the signals are processed by the IFFT block [46] and are converted from frequency domain to time domain to form an OFDM symbol.

• **Zero-padding suffix**

Conventional OFDM systems use a Cyclic Prefix (CP) to against the multipath effect. However, it may cause ripples in the average Power Spectral Density (PSD). In the case of MB-OFDM UWB, it could be as large as 1.5dB [47]. In MB-OFDM UWB systems, Zero-Padded Suffix (ZPS) is used instead of the conventional CP to reduce the ripples in the PSD, which essentially reduces the power-backoff problem at the transmitter, and thus the system is able to achieve the maximum possible transmission range.

After this guard insertion, the MB-OFDM symbols will be transmitted through the UWB channel, which is specified in the next section. The received signals can be recovered by applying an inverse process of all the techniques mentioned above.

### 2.3.4 IEEE 802.15.3a MB-OFDM UWB channel models

The IEEE 802.15.3a channel models for MB-OFDM UWB were proposed by the IEEE 802.15.3a Task Group [48]. The channel models have been developed by a slight modification of the Saleh-Valenzuela (SV) model [49]. Instead of the Rayleigh multipath propagate model, the multipath gain magnitudes in the UWB channel models are defined as independent log-normally distributed random variables (RVs). As pointed out in [48], the lognormal distribution seems to better fit the measurement data.
Independent fading is assumed for each cluster as well as each ray within the cluster.

The discrete time impulse response multipath model can be presented as follow

$$h_i(t) = X_i \sum_{l=0}^{L_i} \sum_{k=0}^{K} \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i)$$  \hspace{1cm} (2.16)

where $\alpha_{k,l}^i$ are the multipath gain coefficients, $T_l^i$ is the delay (the arrival time) of the $l$-th cluster, $\tau_{k,l}^i$ is the delay of the $k$-th multipath component relative to the $l$-th cluster arrival time $T_l^i$, $X_i$ represents the log-normal shadowing, and $i$ refers to the $i$-th realization and $\delta$ is the Dirac delta function.

The multipath gain coefficients are defined as follow

$$\alpha_{k,l} = p_{k,l} \xi_l \beta_{k,l}$$  \hspace{1cm} (2.17)

where $p_{k,l}$ is equiprobable $\pm 1$ depends on signal inversion due to reflection. $\xi_l$ is the fading relating to the $l$-th cluster, and $\beta_{k,l}$ stands for the fading relating to the $k$-th ray within the $l$-th cluster.

The IEEE 802.15.3a Task Group also proposed four main MB-OFDM UWB channels models [48].

- CM1: 0 to 4 meters with Line-Of-Sight (LOS)
- CM2: 0 to 4 meters with Non Line-Of-Sight (NLOS)
- CM3: 4 to 10 meters with Non Line-Of-Sight (NLOS)
- CM4: proposed to fit the channel with the rms delay spread of 25 ns representing an extreme NLOS multipath channel
The following table presents the typical values of the parameters in the IEEE 802.15.3a UWB channel models.

<table>
<thead>
<tr>
<th></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{p10dB}$</td>
<td>12.5</td>
<td>15.3</td>
<td>24.9</td>
<td>41.2</td>
</tr>
<tr>
<td>$N_{p85%}$</td>
<td>20.8</td>
<td>33.9</td>
<td>64.7</td>
<td>123.3</td>
</tr>
<tr>
<td>$N_p$</td>
<td>287.9</td>
<td>739.5</td>
<td>1463.7</td>
<td>3905.5</td>
</tr>
</tbody>
</table>

$N_{p10dB}$ is the number of multipaths arriving within 10dB of the peak, $N_{p85\%}$ represents the number of multipath capturing 85% channel energy, and $N_p$ is the average number of multipaths calculated over 100 channel realizations.

From Table 2.2, we can see that the UWB channels are much more dispersive compared to the conventional Rayleigh channel models. The number of multipaths can reach some thousands in the UWB channel models.

2.3.5 MIMO STFC MB-OFDM UWB

As the MB-OFDM UWB has been widely examined [40], [43] and [50], the combination of MIMO, STFC and MB-OFDM UWB also attracts a great attention. Recently, some works have been done to evaluate the performance STFC MB-OFDM UWB system. From the results in [30], [31] and [51], it is clear that the STFC MB-OFDM UWB system is able to improve significantly the reliability (BER performance),
data rate, system capacity and achievable wireless communication range, compared to the conventional MB-OFDM UWB system.

Figure 2.17 Structural diagram of the proposed STFC MB-OFDM UWB system in [30].

The STFC MB-OFDM UWB systems proposed in [30] and [51] must be supported by multiple antennas at the transmitter. However, the source nodes (such as portable devices) may not able to equipped with multiple antennas due to their tiny physical size, which does not facilitate the space of at least a half wavelength to install two uncorrelated transmit antennas. Thus, cooperative communication has been introduced into the STFC MB-OFDM UWB system to create a virtual MIMO system, so the concepts of MIMO and STFCs can still be implemented and achieve large diversity.

2.4 Research questions

The aim of this section is to present the research questions for this thesis. After the techniques namely cooperative communication, STBC and MB-OFDM UWB have
been studied, it is believed that the combination of these emerging techniques could bring significant benefits to wireless communication systems.

Although cooperative communication techniques have been intensively examined for general wireless networks in the literature, such as [8], [12], [17], [19], [20] and [21]. However, it has been almost unexplored in the context of MB-OFDM UWB. In [4], L. C. Tran proposed an order-2 orthogonal cooperative communication scheme (2-OCCS) for the STFC MB-OFDM UWB system using Alamouti STFC. It has been shown that the 2-OCCS design is able to improve significantly the system bit error performance. However, a drawback of the aforementioned Alamouti STFC in [4] is that it cannot be used for more than two cooperative nodes. Thus, the research questions could be summarised as follows:

- Is it possible for more than two source nodes (up to four nodes for instance) to collaborate in the cooperative STFC MB-OFDM UWB system? Resolution for this question would be very useful, since it might allow the hybrid cooperation scheme with a flexible selection of two, three and up to four cooperative nodes.
- The discussion of the usefulness of the cooperative communication in the OFDM based system (i.e. Does a cooperative communication system always provide greater performance than a non-cooperative one? If not, in what channel conditions should cooperative communication be used?)

In this master thesis, these questions are answered with the following contributions:

- The order-4 orthogonal cooperative communication scheme (4-OCCS) is proposed to prove that it is possible to apply four source nodes in cooperative MB-OFDM UWB systems and gain better performance, compared to the 2-OCCS.
• The order-4 quasi-orthogonal cooperative communication scheme (4-QOCCS) is proposed to show that the full rate transmission is able to achieve in four source nodes cooperative MB-OFDM UWB system. It is also illustrated that the performance of the 4-QOCCS could be even better than that of the 4-OCCS when high density modulation is applied.

• We formulate the cooperative communication system in non-OFDM based systems and provide the threshold SNR values of the inter-node links, corresponding to different uplink conditions. It is shown that when the SNR of the inter-node links are better than the threshold SNR, the cooperative communication shall provide better performance than the SISO system.

• We further extend the above performance analysis to the context of MB-OFDM UWB system. The threshold SNR values have also been calculated for the cooperative MB-OFDM UWB system.

2.5 Chapter summary

This chapter provides readers with a state-of-the-art literature review of the main techniques which involve this thesis, namely cooperative communication, STBCs and STFCs, OFDM-based systems and MB-OFDM UWB systems. It also outlines the open research problems which are the main motivations for this project and my contributions in proposing solutions to those research problems. The next chapter starts to mention one of my contributions, namely the 4-OCCS scheme.
Chapter 3

Order-4 Orthogonal Cooperative Communication Scheme

In this chapter, the proposed 4-OCCS will be presented.

3.1 Order-2 orthogonal cooperative communication scheme (2-OCCS)

This section reviews the cooperative communication scheme, referred to as the order-2 orthogonal cooperative communication scheme (2-OCCS) that was proposed for the STFC MB-OFDM UWB system by L. C. Tran in [4].

3.1.1 System model

We consider a cooperative communication system with only two source nodes and one destination node as illustrated in Fig 3.1.
In [4], the authors considered the application of the Alamouti STFC [3], [30]

\[
S = \begin{bmatrix}
    \tilde{s}_{A_i} & \tilde{s}_{B_i} \\
    -\tilde{s}_{B_i} & \tilde{s}_{A_i}
\end{bmatrix}
\]

(3.1)

The STFC symbols $\tilde{s}_{A_i}$ and $\tilde{s}_{B_i}$ are the column vectors that consist of the original modulated data (i.e. before the IFFT operation) and correspond to the $i$-th MB-OFDM symbol transmitted by the nodes $A$ and $B$, respectively. It is assumed that nodes in the system are perfectly synchronised. Denote $\tilde{h}_{jk} = [h_{jk,1}, h_{jk,2}, ..., h_{jk,L_{jk}}]^T$ to be the channel vector between the two nodes $j$ and $k$, where $j \in \{A, B\}$, $k \in \{A, B, d\}$ (see Fig.3.1), and $L_{jk}$ is the number of multipaths in this channel. The channels between nodes are modelled as independent log-normally distributed random variables (RVs) [48] and the channel vectors $\tilde{h}_{jk}$ are assumed to be constant during every two MB-OFDM
symbol 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 the cooperative communication, each source node transmits its own data as well as performs as a cooperative agent for other nodes.

3.1.2 Signals transmission procedure in 2-OCCS

In the 2-OCCS, two nodes are paired to cooperate with one another. The transmission procedure can be divided into two time slots.

- First time slot

Node $A$ broadcasts its symbol $\tilde{s}_{Ai}$ to the destination node $d$ as well as its partner (Node $B$). Simultaneously, Node $B$ also broadcasts its symbol $\tilde{s}_{Bi}$ to its partner node $A$ and the destination node $d$. We denote the decoded symbols at Nodes $A$ and $B$ to be $\tilde{s}_{Bi}$ and $\tilde{s}_{Ai}$.

- Second time slot

These two source nodes retransmit the decoded symbols to the destination in the form of $-\tilde{s}_{Bi}^*$ and $\tilde{s}_{Ai}^*$, respectively. The process continues until all data are transmitted. This proposed scheme is thus referred to as a decode-and-forward scheme [9]. This scheme is simpler than some of the existing cooperative communication schemes, such as [10], [11] with the penalty of losing the flexible cooperation level between two nodes.

3.1.3 Decoding in destination node
The received signals in the destination node will be processed by the overlap-and-add operation (OAAO) and the FFT operation. The OAAO defined in [30] and [52] indicates that the $N_{ZPS}$ samples of a received MB-OFDM symbol $r_n$, from $(N_{fft} + 1)$ to $(N_{fft} + N_{ZPS})$, are added to the beginning of that received symbol. Then the first $N_{fft}$ samples of the resulting symbol will be used to decode the transmitted symbol. These $N_{fft}$ samples are exactly equivalent to the circular convolution of the transmitted MB-OFDM symbol before ZPS at the transmitter. If a ZPS of a length $N_{ZPS}$ is used, the greatest multipath tolerance of the system is $(N_{ZPS} + 1)$. Thus, the number of multipaths (the length of vectors $\bar{h}_{jk}$) must not exceed $(N_{ZPS} + 1)$ to avoid the distortion. FFT is the inverse of IFFT. It converts the signal from the time domain to the frequency domain. After these operations, the signals received at the destination node $d$ during the two time slots can be represented as

$$\begin{align*}
\bar{r}_1 &= \bar{h}_{Ad} \cdot \bar{s}_A + \bar{h}_{Bd} \cdot \bar{s}_B + \bar{n}_1 \\
\bar{r}_2 &= -\bar{h}_{Ad} \cdot \bar{s}_A^* + \bar{h}_{Bd} \cdot \bar{s}_B^* + \bar{n}_2
\end{align*}$$

(3.2)

where $\bar{h}_{jk} = FFT(\bar{h}_{jk})$, $\bar{n}_t = FFT(\bar{n}_t)$, while $\bar{n}_t$ ($t=1,2$) denotes the column vector of complex Gaussian noise affecting the destination node at the $t$-th MB-OFDM symbol time slot. Denote $\bar{h}_{jk} = [h_{jk,1}, h_{jk,2}, ..., h_{jk,N_t}]^T$ and $\bar{r}_t = [r_{t,1}, r_{t,2}, ..., r_{t,N_t}]^T$. Once the destination node receives the symbols transmitted during the two time slots, it is able to decode the symbols.

If we assume theoretically that the transmission between the source nodes can be error-freely decoded by their partners, i.e. $\bar{s}_{A_i} \equiv \bar{s}_{A_i}$ and $\bar{s}_{B_i} \equiv \bar{s}_{B_i}$, the symbols can be
decoded by the ML decoding in [30]. In the 2-OCCS, each of the two MB-OFDM symbols $\tilde{s}_{A_i}$ and $\tilde{s}_{B_i}$ can be decoded separately, rather than jointly. Furthermore, each individual modulated symbol (among $N_D$ symbols) within symbol $\tilde{s}_{A_i}$ (or $\tilde{s}_{B_i}$) can be decoded separately, rather than the whole $N_D$ data are decoded simultaneously. Thus the decoding process is completely linear, and relatively simple. In particular, the decoding metrics for data at the $n$-th subcarrier, for $n = 1, \ldots, N_D$, in the MB-OFDM symbols $\tilde{s}_{A_i}$ and $\tilde{s}_{B_i}$ are

$$s_{A_i,n} = \arg \min_{s \in \mathcal{C}} \left\{ \left( |h_{Ad,n}^* r_{1,n} + h_{Bd,n}^* r_{2,n}|^2 - s^2 \right)^2 + \left[ -1 + \left( |h_{Ad,n}|^2 + |h_{Bd,n}|^2 \right) \right] |s|^2 \right\}$$

$$s_{B_i,n} = \arg \min_{s \in \mathcal{C}} \left\{ \left( |h_{Bd,n}^* r_{1,n} - h_{Ad,n}^* r_{2,n}|^2 - s^2 \right)^2 + \left[ -1 + \left( |h_{Ad,n}|^2 + |h_{Bd,n}|^2 \right) \right] |s|^2 \right\}$$

### 3.1.4 Subband allocation for 2-OCCS

The authors in [4] also introduced the concept of a subband allocation technique in the cooperative MB-OFDM UWB system. In order to achieve the full duplex capability of the cooperative nodes (i.e. transmit and receive the message at the same time), a code division multiple access (CDMA) was proposed in [10] and [11]. This technique assigned a unique spreading code to each node, thus two nodes can work in the same band. However, in the 2-OCCS, the authors took advantage of the important technical specification of MB-OFDM UWB devices that, support for the first band group (3168 – 4752 MHz, see [44], 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 [44] Table 7-2). Thus, in order for the nodes to be able to transmit their own data and receive
the partner’s data at the same time via only one antenna, Node $A$ may, for instance, transmit signals by using TFC 5 (i.e. RF is in the range of 3168 - 3696 MHz corresponding to the subband 1). Similarly, Node $B$ may transmit signals by using TFC 6. The destination node must be able to work with all the subbands 1 and 2. This example is shown in Fig.3.2. 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. A node informs other nodes about its TFC by broadcasting its TFC in the 3-bit TX TFC field (bits T1 –T3) within the PHY (Physical Layer) header [44, p.28].

Figure 3.2 Subband allocation in the 2-OCCS.

3.1.5 Discussion for simulation results

The simulation results in [4] show that the 2-OCCS could provide better bit error performance compared to the conventional MB-OFDM UWB system without any increase of total transmission power in the channel model CM1 to CM3. These results also give the evidences that the combination of cooperative communication and STFCs
could benefit the MB-OFDM UWB system.

3.2 Order-4 orthogonal cooperative communication scheme (4-OCCS)

As mentioned in Section 3.1, it has been proved that it is possible to apply cooperative communication to the STFC MB-OFDM system in order to improve its bit error performance. The drawback of the 2-OCCS scheme is the Alamouti STFC can only be applied to a two-source node system. This motivates us to consider the applications of higher order STFCs to the cooperative MB-OFDM UWB system, which allow more than two source nodes to cooperate. This section presents the details about how to construct the 4-OCCS [53] and provides the performance comparison between the 4-OCCS and 2-OCCS in the condition of the same transmission power and data rate.

3.2.1 System model

We consider a cooperative communication system with four source nodes and one destination node as illustrated in Fig. 3.3. Each source node in the system is equipped with a single antenna, while the destination node may be equipped with multiple antennas.
Figure 3.3 Cooperative communication for a four source node MB-OFDM UWB system.

In order to achieve a higher diversity order, we consider the application of the following rate-3/4 orthogonal STFC, which is in turns the STFC version of the rate-3/4 orthogonal STBC in [22], to enable four single-antenna source nodes to cooperate

\[
S = \begin{bmatrix}
-\bar{s}_A & -\bar{s}_B & -\bar{s}_C & 0 \\
\bar{s}_B & -\bar{s}_A & 0 & -\bar{s}_C \\
-\bar{s}_C & 0 & -\bar{s}_A & -\bar{s}_B \\
0 & -\bar{s}_C & -\bar{s}_B & -\bar{s}_A
\end{bmatrix}
\]  

(3.4)

where the STFC symbols \( \bar{s}_{Ai}, \bar{s}_{Bi} \) and \( \bar{s}_{Ci} \) are considered as the column vectors that consist of the original transmitted data corresponding to the \( i \)-th MB-OFDM symbol by the source nodes \( A, B \) and \( C \) respectively in the first time slot. It is also assumed that the nodes in the proposed system are perfectly synchronised.

Denote \( \bar{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, ..., h_{jkm,L_{jkm}}]^{T} \) to be the channel vector between two nodes \( j \) and \( k \), at the \( m \)-th antenna of the destination node, where \( j \in \{A,B,C,D\} \), \( k \in \{A,B,C,D,d\} \), \( m \in \{1,2,...,N\} \) and \( L_{jkm} \) represents the number of multipaths in this
link. The channels between nodes are modeled as independent log-normally distributed RVs [48]. We assume that the channel vectors $\vec{h}_{jkm}$ remain constant during every four MB-OFDM symbol time slots, and are known at the destination node.

**3.2.2 Subband allocation for 4-OCCS**

The transmission protocol in the proposed 4-OCCS is presented in Fig.3.4. Concept of the subband allocation technique to allow the source nodes working on a full-duplex mode has been mentioned in [4]. One may have a question: Does the four source nodes need to occupy four subbands in the cooperative MB-OFDM UWB system in order to work properly? From Eq. (3.4), it is clear that, in the proposed system, three nodes transmit three MB-OFDM symbols over their three antennas and there is always one source node remaining idle in every time slot. Thus in the 4-OCCS, we propose 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. Again, it is noted that MB-OFDM UWB devices must support for the first band group (3168 – 4752 MHz) [44, Table 7-1], and that the TFC numbers 5, 6 and 7 for the first band group are non-overlapped with each other [44, 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. The source node $D$ must be able to transmit and receive the data using all subbands in the first band group.
The new subband allocation technique proposed for the four cooperative nodes is presented in Fig. 3.5. 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 three subbands. The destination node must be able to receive signals from all three subbands in the first band group.

Figure 3.5 Subband allocation in the 4-OCCS in four time slots.
3.2.3 Signal transmission procedure in the 4-OCCS

Detail of how the nodes transmit signals in the proposed system is explained in this section. In the 4-OCCS, four nodes cooperate to send the orthogonal matrix (3.4) comprising MB-OFDM symbols to the destination. The procedure of how to construct the MB-OFDM symbols is described in Section 2.3. Each of the MB-OFDM symbols contains 100 data subcarriers \( N_D = 100 \), 12 pilot subcarriers \( N_p = 12 \), 10 guard subcarriers \( N_G = 10 \) and 37 samples in ZPS \( N_{ZPS} = 37 \). Thus the total number of samples in one MB-OFDM symbol is 165 \( N_{SYM} = 165 \). The issue of how this node quadruple is selected among the nodes in the network is out of the scope of this thesis. Instead, this thesis addresses the full-duplex cooperative communication scheme for this quadruple and the decoding method.

As shown in Fig.3.4 and Fig.3.5, the signal transmission procedure in the 4-OCCS can be divided to four time slots.

- First time slot

Nodes \( A, B \) and \( C \) broadcast the MB-OFDM symbols, \( \tilde{s}_{A_1}, \tilde{s}_{B_1} \) and \( \tilde{s}_{C_1} \) 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 the first time slot, every node will receive at least two MB-OFDM symbols from their partners. The received data can be distinguished by different subbands. We denote the decoded symbols at each nodes to be \( \tilde{\tilde{s}}_{A_1}, \tilde{\tilde{s}}_{B_1} \) and \( \tilde{\tilde{s}}_{C_1} \).
### Table 3.1 Signal transmission between nodes during four time slots

<table>
<thead>
<tr>
<th>Time slot</th>
<th>Node A</th>
<th>Node B</th>
<th>Node C</th>
<th>Node D</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
<td>$s_{C_1}$</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
<td>$s_{C_1}$</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
<td>$s_{C_1}$</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
<td>$s_{C_1}$</td>
<td>$s_{A_1}$</td>
<td>$s_{B_1}$</td>
</tr>
</tbody>
</table>

- Second time slot

Nodes $A$, $B$ and $D$ transmit the decoded MB-OFDM symbol $-\tilde{s}_{B_1}$, $-\tilde{s}_{A_1}$ and $-\tilde{s}_{C_1}$ 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.

- Third time slot

Node $B$ keeps silent while Nodes $A$, $C$ and $D$ transmit the data $-\tilde{s}_{C_1}$, $-\tilde{s}_{A_1}$ and $-\tilde{s}_{B_1}$ to the destination node $d$ in the subbands 3, 1 and 2 respectively. Node $D$ occupies the subband 2 since Node $B$ is silent.

- Fourth time slot

Nodes $B$, $C$ and $D$ transmit the data $-\tilde{s}_{C_1}$, $-\tilde{s}_{B_1}$ and $-\tilde{s}_{A_1}$ 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 $\tilde{s}_{A_1}$, $\tilde{s}_{B_1}$ and $\tilde{s}_{C_1}$ after four time slots.

The decoding procedure is presented in the next section.
3.2.4 Decoding in destination node

After the OAAO [30], [52] and FFT operation, the signals received at the \( m \)-th Rx antenna at the destination node during the four time slots can be represented as
\[
\begin{align*}
\tilde{r}_{1m} &= \tilde{h}_{Adm} \ast \tilde{s}_{A_1} + \tilde{h}_{Bdm} \ast \tilde{s}_{B_1} + \tilde{h}_{Cdm} \ast \tilde{s}_{C_1} + \tilde{n}_{1m} \\
\tilde{r}_{2m} &= -\tilde{h}_{Adm} \ast \tilde{s}_{B_2} + \tilde{h}_{Bdm} \ast \tilde{s}_{A_2} + \tilde{h}_{Ddm} \ast \tilde{s}_{C_2} + \tilde{n}_{2m} \\
\tilde{r}_{3m} &= -\tilde{h}_{Adm} \ast \tilde{s}_{C_3} + \tilde{h}_{Cdm} \ast \tilde{s}_{A_3} - \tilde{h}_{Ddm} \ast \tilde{s}_{B_3} + \tilde{n}_{3m} \\
\tilde{r}_{4m} &= -\tilde{h}_{Bdm} \ast \tilde{s}_{C_4} + \tilde{h}_{Cdm} \ast \tilde{s}_{B_4} + \tilde{h}_{Ddm} \ast \tilde{s}_{A_4} + \tilde{n}_{4m}
\end{align*}
\] (3.5)

where \( \tilde{h}_{jkm} = \text{FFT}(h_{jkm}) \), \( \tilde{n}_{tm} = \text{FFT}(n_{tm}) \), while \( \tilde{n}_{tm} \) (\( t = 1, 2, 3, 4 \)) denotes the column vector of complex Gaussian noise affecting the \( m \)-th antenna of the destination node at \( t \)-th MB-OFDM symbol time slot. Denote \( \tilde{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, \ldots, h_{jkm,N_D}]^T \) and \( \tilde{n}_{tm} = [n_{tm,1}, n_{tm,2}, \ldots, n_{tm,N_D}]^T \). We also assume that the information transmitted from the source nodes can be error-free decoded by their partners as mentioned in Section II, i.e. \( \tilde{s}_{A_1} \equiv \tilde{s}_{A_1}, \tilde{s}_{B_1} \equiv \tilde{s}_{B_1} \) and \( \tilde{s}_{C_1} \equiv \tilde{s}_{C_1} \). The ML decoding will be applied to decode the symbols. In the proposed system, each of the MB-OFDM symbols \( \tilde{s}_{A_1}, \tilde{s}_{B_1} \) and \( \tilde{s}_{C_1} \) can be decoded separately, rather than jointly, thanks to the orthogonality of the code matrix Eq. (3.4). More importantly, each among \( N_D \) data within each MB-OFDM symbol can also be separately decoded, rather than the whole \( N_D \) data being decoded simultaneously. For \( n = 1, \ldots, N_D \), the decoding process for the \( n \)-th subcarrier in MB-OFDM symbols \( \tilde{s}_{A_1}, \tilde{s}_{B_1} \) and \( \tilde{s}_{C_1} \) is
\[
S_{A,n} = \underset{\mathcal{C}}{\arg\min}\left\{ \sum_{m=1}^{N} (h_{Adm,n}^{*}v_{1,n} + h_{Bdm,n}^{*}r_{2,n}) - s \right\}^{2} + \left[ -1 + \sum_{m=1}^{N} \left( |h_{Adm,n}|^2 + |h_{Bdm,n}|^2 + |h_{Cdm,n}|^2 + |h_{Ddm,n}|^2 \right) |s|^2 \right\}
\]

\[
S_{B,n} = \underset{\mathcal{C}}{\arg\min}\left\{ \sum_{m=1}^{N} (h_{Bdm,n}^{*}v_{1,n} + h_{Cdm,n}^{*}r_{4,n}) - s \right\}^{2} + \left[ -1 + \sum_{m=1}^{N} \left( |h_{Adm,n}|^2 + |h_{Bdm,n}|^2 + |h_{Cdm,n}|^2 + |h_{Ddm,n}|^2 \right) |s|^2 \right\}
\]

\[
S_{C,n} = \underset{\mathcal{C}}{\arg\min}\left\{ \sum_{m=1}^{N} (h_{Ddm,n}^{*}r_{2,n} - h_{Adm,n}^{*}r_{3,n}) - s \right\}^{2} + \left[ -1 + \sum_{m=1}^{N} \left( |h_{Adm,n}|^2 + |h_{Bdm,n}|^2 + |h_{Cdm,n}|^2 + |h_{Ddm,n}|^2 \right) |s|^2 \right\}
\]

In fact, the nodes may have errors when they decode the received signals from their partners, i.e. \( \tilde{s}_{A_{i}} \neq \tilde{s}_{A_{i}} \) and \( \tilde{s}_{C_{i}} \neq \tilde{s}_{C_{i}} \). Thus performance of the proposed system will be affected by not only the decoding process at the destination node, but also the decoding process at the source nodes. Intuitively, when the decoding errors in the source nodes become serious, they may ruin the advantage of higher transmission diversity that is brought by the cooperative communication.

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 the first band group. Consequently, in order to implement the proposed system, we only need to make the source nodes \( A, B \) and \( C \) be able to transmit signals in
one subband, and receive signals in two other subbands simultaneously, while making the source node $D$ and the destination node be able to receive signals from all three subbands in the first band group at the same time. These are not very 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.

Table 3.2 Decoding metrics for the 4-OCCS with PSK or QAM modulation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Decoding Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{s}_A$</td>
<td>$\arg\min_{s_A \in \mathcal{N}} | {</td>
</tr>
<tr>
<td>$\tilde{s}_B$</td>
<td>$\arg\min_{s_B \in \mathcal{N}} | {</td>
</tr>
<tr>
<td>$\tilde{s}_C$</td>
<td>$\arg\min_{s_C \in \mathcal{N}} | {</td>
</tr>
</tbody>
</table>

3.2.5 Simulation results

To examine the performance advantage of cooperative communication, we ran
several Monte-Carlo simulations for non-cooperative communication, the 2-OCCS, and the 4-OCCS. 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 (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).

In order to fairly compare the error performance of non-cooperative and those of the two cooperative communication schemes, the following constraints are applied to all simulations.

- **Data rate constraint**: Different signal constellation mapping (QPSK/QAM) schemes are applied to guarantee that the simulations for all three systems are run with the same bit rate. In particular, the conventional MB-OFDM UWB and 2-OCCS uses 8-PSK while the rate-3/4 4-OCCS uses 16QAM.

- **Power constraint**: The total received power at each Rx antenna at the destination during each time slot needs to be the same in all three systems. Therefore, the signal constellation points in the 2-OCCS (cf. Eq.(1)) are scaled down by a factor of $1/\sqrt{2}$, while the factor is $1/\sqrt{3}$ for the case of the 4-OCCS (cf. Eq.(4)).
Table 3.3 Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT and IFFT size</td>
<td>$N_m = 128$</td>
</tr>
<tr>
<td>Data rate</td>
<td>320 Mbps</td>
</tr>
<tr>
<td>Convolutional encoder’s rate</td>
<td>$1/2$</td>
</tr>
<tr>
<td>Convolutional encoder’s constraint length</td>
<td>$K = 7$</td>
</tr>
<tr>
<td>Convolutional decoder</td>
<td>Viterbi</td>
</tr>
<tr>
<td>Decoding mode</td>
<td>Hard</td>
</tr>
<tr>
<td>STFC decoding at nodes</td>
<td>ML decoding</td>
</tr>
<tr>
<td>Transmitted MB-OFDM symbols</td>
<td>1200</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK/8PSK/16QAM</td>
</tr>
<tr>
<td>IEEE Channel model</td>
<td>CM1, 2, 3 &amp; 4</td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>$N_d = 100$</td>
</tr>
<tr>
<td>Number of pilot subcarriers</td>
<td>$N_p = 12$</td>
</tr>
<tr>
<td>Number of guard subcarriers</td>
<td>$N_g = 10$</td>
</tr>
<tr>
<td>Total number of subcarriers used</td>
<td>$N_T = 122$</td>
</tr>
<tr>
<td>Number of samples in ZPS</td>
<td>$N_{ZPS} = 37$</td>
</tr>
<tr>
<td>Total number of samples/symbol</td>
<td>$N_{SYM} = 165$</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
</tbody>
</table>

Fig. 3.7 compares the error performances of the conventional MB-OFDM (non-cooperative), 2-OCCS and 4-OCCS in the case where all nodes are equipped with one antenna. The horizontal axis represents the uplink channel SNR (dB) and the vertical axis is the system bit error rate (BER). The BER of the 4-OCCS, 2-OCCS and the conventional MB-OFDM UWB systems is simulated for the channel model CM1 to CM4. It is clear that the 4-OCCS scheme provides significantly better error performance than the 2-OCCS scheme and the conventional system in the channel models CM1, CM2 and CM3 with same data rate and transmission power. The performances of 2-OCCS and 4-OCCS are relatively close to each other in the channel model CM4 due to...
the fact that the channel is extremely dispersive with the number of multipaths reaching some thousands. This channel model causes a serious inter-symbol interference problem that neutralizes the diversity advantage of the order-4 cooperative communication, compared to the order-2 one.

Figure 3.7 4-OCCS vs. 2-OCCS and conventional MB-OFDM UWB with a one-antenna destination node.

Fig.3.8 demonstrates the error performances of the three systems in the case the destination node is equipped with 2 Rx antennas. From Fig.3.8, the overall error performance of the proposed system is significantly improved owing to the higher diversity produced by the multiple antennas at the receiver. As a result, the 4-OCCS provides much better error performance than the 2-OCCS in the channel models CM1, 2 and 3. The performances of these two cooperative schemes are still close for the
dispersive channel model CM4. However, due to large diversities achieved by multiple antennas at the receiver, they have better BER performance compared to the conventional MB-OFDM UWB system.

Figure 3.8 4-OCCS vs. 2-CCS and conventional MB-OFDM UWB with a two-antenna destination node.

3.3 Chapter summary

This chapter has presented the proposed order-4 orthogonal STFCs cooperative communication scheme for MB-OFDM UWB, referred to as the 4-OCCS. Additionally, a new subband allocation technique specifically designed for the 4-OCCS is also derived. This technique takes the advantage of the MB-OFDM UWB specification and allows the
source nodes in the system to work in a full-duplex mode by occupying only three subbands. From the simulation results, we might have the following conclusion:

- The error performance of the 4-OCCS is significantly better, compared to the conventional MB-OFDM UWB in all channel models with the same transmission power and data rate.
- The 4-OCCS might be significantly better than the 2-OCCS in the channel model CM 1, 2 or 3 without significant additional decoding complexity.
- The system error performance could be significantly improved when the destination node is equipped with multiple antennas.

Although the 4-OCCS achieves better bit error performance and higher diversity compared to the other two systems, it cannot reach the full transmission rate due to the orthogonal design of the STFC applied in the 4-OCCS. Thus, we aim to propose another novel STFC cooperative scheme in MB-OFDM UWB providing full rate transmission. This scheme is referred to as the 4-QOCCS scheme which will be discussed in the next chapter.
Chapter 4

Order-4 Quasi-Orthogonal Cooperative Communication Scheme

It has been shown in Chapter 2 that the 4-OCCS achieves a significantly better performance than the 2-OCCS and the conventional MB-OFDM UWB system at the same data rate and with the same transmission power. 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 project, a full-rate order-4 quasi-orthogonal cooperative communication STFC scheme, referred to as the 4-QOCCS [54], has also been proposed.

4.1 System model

The system structure for the proposed 4-QOCCS is similar to that of the 4-OCCS presented in Chapter 3. 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 [25]
where the STFC symbols $\bar{s}_{Ai}$, $\bar{s}_{Bi}$, $\bar{s}_{Ci}$ and $\bar{s}_{Di}$ 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.4.1. 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 [25].

Denote $\bar{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, \ldots, h_{jkm,L_{jkm}}]^T$ to be the channel vector between two nodes $j$ and $k$, at the $m$-th Rx antenna of the destination node, where $j \in \{A,B,C,D\}$, $k \in \{A,B,C,D,d\}$, $m \in \{1,2,\ldots,N\}$, and $L_{jkm}$ represents the number of multipath in this link. 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.

### 4.2 Subband allocation for the 4-QOCCS

The transmission protocol in the proposed 4-QOCCS is presented in Fig. 4.1. From

\[
\begin{bmatrix}
\bar{s}_{Ai} & \bar{s}_{Bi} & \bar{s}_{Ci} & \bar{s}_{Di} \\
\bar{s}_{Bi} & \bar{s}_{Ai} & \bar{s}_{Di} & \bar{s}_{Ci} \\
\bar{s}_{Ci} & \bar{s}_{Di} & \bar{s}_{Ai} & \bar{s}_{Bi} \\
\bar{s}_{Di} & \bar{s}_{Ci} & \bar{s}_{Bi} & \bar{s}_{Ai}
\end{bmatrix}
\]
Eq. (4.1), it is clear that, in the proposed system, all nodes transmit signals simultaneously over four time slots. Thus, in the 4-QOCCS, we have to use four subbands to allow all the source nodes to receive and transmit the signals simultaneously (full duplex mode). Particularly, we propose a new subband allocation method for the 4-QOCCS that allows every source node in the system to work with the minimum number of subbands in each time slot to reduce the system complexity. 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) [44, 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.

Figure 4.1 Transmission protocol in the 4-QOCCS.

<table>
<thead>
<tr>
<th>Node A</th>
<th>( S_{A1} )</th>
<th>(-S_{B1}^*)</th>
<th>(-S_{C1}^*)</th>
<th>( S_{D1} )</th>
<th>( S_{A2} )</th>
<th>(-S_{B2}^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node B</td>
<td>( S_{B1} )</td>
<td>( S_{A1}^* )</td>
<td>(-S_{D1}^*)</td>
<td>(-S_{C1}^*)</td>
<td>( S_{B2} )</td>
<td>( S_{A2}^* )</td>
</tr>
<tr>
<td>Node C</td>
<td>( S_{C1} )</td>
<td>(-S_{D1}^*)</td>
<td>( S_{A1}^* )</td>
<td>(-S_{B1}^*)</td>
<td>( S_{C2} )</td>
<td>( S_{D2}^* )</td>
</tr>
<tr>
<td>Node D</td>
<td>( S_{D1} )</td>
<td>( S_{C1}^* )</td>
<td>( S_{B1}^* )</td>
<td>( S_{A1} )</td>
<td>( S_{D2} )</td>
<td>( S_{C2}^* )</td>
</tr>
</tbody>
</table>

The subband allocation for the 4-QOCCS is shown in Fig.4.2. Node \( A \) transmits signals using TFC 5 in the band group 1 (RF is in the range 3168 – 3696 MHz corresponding to the subband 1) and receives signals using TFC 6 in the band group 1 (RF in the range 3696 – 4224 MHz, subband 2) and TFC 5 in the second band group (4752 – 5280 MHz, subband 4). Node \( B \) transmits signals using TFC 6 in the band
group 1 and receives signals using TFC 5 and TFC 7 (RF in the range 4224 – 4752 MHz, subband 3) in the band group 1. Node C transmits signals using TFC 7 and receives via TFC 5 in the band group 1 and TFC 5 in the band group 2. Node D transmits signals using TFC 5 in the band group 2 and receives signals using TFC 7 and TFC5 in the first band group.

Figure 4.2  Subband allocation in the 4-QOCCS in four time slots.

### 4.3 Signal transmission procedure

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 Eq. (4.1) 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 chapter. Instead, this chapter addresses the full-duplex cooperative communication scheme for this quadruple and the decoding method.
As shown in Fig. 4.2, each source node in the proposed system transmits signals in one subband and receives signals from one partner in other subband during the first three time slots. This full rate transmission requires four time slots to transmit four MB-OFDM symbols. Details of the signals transmitted during four time slots are depicted in Table 4.1 and are explained as follows.

Table 4.1 Signal transmission between nodes during four time slots

<table>
<thead>
<tr>
<th>time</th>
<th>Node A</th>
<th>Node B</th>
<th>Node C</th>
<th>Node D</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>slot</td>
<td>Send</td>
<td>Receive</td>
<td>Send</td>
<td>Receive</td>
<td>Send</td>
</tr>
<tr>
<td>1st</td>
<td>$\tilde{s}_{A_1}$</td>
<td>$\tilde{s}_{B_1}$</td>
<td>$\tilde{s}_{C_1}$</td>
<td>$\tilde{s}_{D_1}$</td>
<td>$\tilde{s}_{A_1}$</td>
</tr>
<tr>
<td>2nd</td>
<td>$\tilde{s}_{C_1}^*$</td>
<td>$\tilde{s}_{D_1}^*$</td>
<td>$\tilde{s}_{A_1}^*$</td>
<td>$\tilde{s}_{D_1}^*$</td>
<td>$\tilde{s}_{A_1}^*$</td>
</tr>
<tr>
<td>3rd</td>
<td>$\tilde{s}_{D_1}^*$</td>
<td>$\tilde{s}_{C_1}^*$</td>
<td>$\tilde{s}_{B_1}^*$</td>
<td>$\tilde{s}_{C_1}^*$</td>
<td>$\tilde{s}_{D_1}^*$</td>
</tr>
<tr>
<td>4th</td>
<td>$\tilde{s}_{D_1}^*$</td>
<td>$\tilde{s}_{C_1}^*$</td>
<td>$\tilde{s}_{B_1}^*$</td>
<td>$\tilde{s}_{C_1}^*$</td>
<td>$\tilde{s}_{D_1}^*$</td>
</tr>
</tbody>
</table>

- First time slot

Nodes $A$, $B$, $C$ and $D$ broadcast the MB-OFDM symbols, $\tilde{s}_{A_1}$, $\tilde{s}_{B_1}$, $\tilde{s}_{C_1}$ and $\tilde{s}_{D_1}$, to all the nodes in the system using the subbands 1, 2 and 3 (in band group 1) and subband 4 (in the band group 2) respectively. Node $A$ receives $\tilde{s}_{B_1}$ from Node $B$ in the subband 2.
Node $B$ receives $\tilde{s}_{A_i}$ from Node $A$ in the subband 1. Similarly, Node $C$ receives the data $\tilde{s}_{D_i}$ from Node $D$ in the subband 4 and Node $D$ receives the symbol $\tilde{s}_{C_i}$ from Node $C$ in the subband 3. At this point, every source node has the information to construct the transmission for the second time slot of the QOSTFC in (4.1).

- **Second time slot**

  We denote the decoded symbols at each nodes to be $\tilde{s}_{A_i}$, $\tilde{s}_{B_i}$, $\tilde{s}_{C_i}$ and $\tilde{s}_{D_i}$ which might not necessarily be equal to $s_{A_i}$, $s_{B_i}$, $s_{C_i}$ and $s_{D_i}$ due to the erroneous decoding processes at the source nodes. In the second time slot, Nodes $A$, $B$, $C$ and $D$ transmit the decoded symbol $-\tilde{s}_{A_i}^*$, $-\tilde{s}_{B_i}^*$, $-\tilde{s}_{D_i}^*$ and $\tilde{s}_{C_i}^*$ to the destination in the subbands 1, 2, 3 and 4 respectively. In this time slot, Node $A$ receives the signal $\tilde{s}_{C_i}^*$ from Node $D$ and Node $B$ receives $-\tilde{s}_{D_i}^*$ from Node $C$. Node $C$ receives $\tilde{s}_{A_i}^*$ from Node $B$ and Node $D$ receives $-\tilde{s}_{B_i}^*$ from Node $A$.

- **Third time slot**

  Nodes $A$, $B$, $C$ and $D$ transmit the signal $-\tilde{s}_{C_i}^*$, $-\tilde{s}_{D_i}^*$, $\tilde{s}_{A_i}^*$ and $\tilde{s}_{B_i}^*$ 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 $-\tilde{s}_{D_i}^*$ from Node $B$ and Node $B$ receives $-\tilde{s}_{C_i}^*$ from Node $A$. Node $C$ and Node $D$ exchange the signals, thus Node $C$ receives $\tilde{s}_{B_i}^*$ from Node $D$ and Node $D$ receives $\tilde{s}_{A_i}^*$ from Node $C$.

- **Fourth time slot**

  Nodes $A$, $B$, $C$ and $D$ transmit the symbol $\tilde{s}_{D_i}$, $-\tilde{s}_{C_i}$, $-\tilde{s}_{B_i}$ and $\tilde{s}_{A_i}$ to the destination in the subband 1 to 4 respectively. The destination is able to decode the MB-OFDM symbol $\tilde{s}_{A_i}$, $\tilde{s}_{B_i}$, $\tilde{s}_{C_i}$ and $\tilde{s}_{D_i}$ after four time slots (cf. Fig. 4.1). The decoding procedure for 4-QOCCS is presented in the next section.
4.4 Decoding metrics

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

\[\begin{align*}
\mathbf{r}_{1m} &= \mathbf{h}_{adm} \cdot \mathbf{s}_A + \mathbf{h}_{blm} \cdot \mathbf{s}_B + \mathbf{h}_{cdm} \cdot \mathbf{s}_C_i + \mathbf{h}_{dml} \cdot \mathbf{s}_D + \mathbf{n}_{1m} \\
\mathbf{r}_{2m} &= -\mathbf{h}_{adm} \cdot \mathbf{s}_A + \mathbf{h}_{blm} \cdot \mathbf{s}_B - \mathbf{h}_{cdm} \cdot \mathbf{s}_C + \mathbf{h}_{dml} \cdot \mathbf{s}_D + \mathbf{n}_{2m} \\
\mathbf{r}_{3m} &= -\mathbf{h}_{adm} \cdot \mathbf{s}_C_i - \mathbf{h}_{blm} \cdot \mathbf{s}_C + \mathbf{h}_{cdm} \cdot \mathbf{s}_B + \mathbf{h}_{dml} \cdot \mathbf{s}_A + \mathbf{n}_{3m} \\
\mathbf{r}_{4m} &= \mathbf{h}_{adm} \cdot \mathbf{s}_D - \mathbf{h}_{blm} \cdot \mathbf{s}_C - \mathbf{h}_{cdm} \cdot \mathbf{s}_B + \mathbf{h}_{dml} \cdot \mathbf{s}_A + \mathbf{n}_{4m}
\end{align*}\]

where \(\mathbf{h}_{jkm} = FFT(\tilde{h}_{jkm})\), \(\mathbf{n}_{mm} = FFT(\tilde{n}_{mm})\), while \(\tilde{n}_{mm}\) \((t = 1, 2, 3, 4)\) 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 \(\mathbf{h}_{jkm} = [h_{jkm,1}, h_{jkm,2}, \ldots, h_{jkm,N_m}]^T\) and \(\mathbf{n}_{mm} = [n_{mm,1}, n_{mm,2}, \ldots, n_{mm,N_m}]^T\). For the ease of illustration of the decoding algorithms, we also assume that the information transmitted from the source nodes can be error-free decoded by their partners as mentioned in Section II (in our simulations, the most general cases where erroneous decoding can happen at the source nodes are considered).

The ML decoding will be applied to decode the symbols. Unlike the 4-OCCS, 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 (4.1) in the similar manner of the QOSTBC in [25]. Specifically, the MB-OFDM symbols \(\tilde{s}_{A_t}\) and \(\tilde{s}_{D_t}\), \(\tilde{s}_{B_t}\) and \(\tilde{s}_{C_t}\) can be decoded in pairs, rather than jointly, as mentioned in Table 4.2.
Table 4.2 Decoding metrics for the 4-QOCCS with PSK or QAM modulation

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Decoding Metric</th>
</tr>
</thead>
</table>
| $(\tilde{s}_A, \tilde{s}_D)$ | \[
\begin{align*}
\arg \min_{s_A, s_D \in C^{Nd}} & \left| \sum_{m=1}^{N} \left( \left( \sum_{j=A}^{D} | h_{jdm} | \cdot^2 \right) \cdot \left( | s_A | \cdot^2 + | s_D | \cdot^2 \right) \right. \\
+2 \Re \left\{ \left( -h_{Adm}^{*} \cdot \overline{r}_{1m} + h_{Bdm}^{*} \cdot \overline{r}_{2m} - h_{Cdm}^{*} \cdot \overline{r}_{3m} - h_{Ddm}^{*} \cdot \overline{r}_{4m} \right) \cdot \overline{s}_A + \left( -h_{Ddm}^{*} \cdot \overline{r}_{1m} + h_{Cdm}^{*} \cdot \overline{r}_{2m} \right. \\
+ h_{Bdm}^{*} \cdot \overline{r}_{3m} - h_{Adm}^{*} \cdot \overline{r}_{4m} \left. \right) \cdot \overline{s}_D + \left( h_{Adm} \cdot h_{Ddm}^{*} \right) \\
- h_{Bdm}^{*} \cdot h_{Cdm} - h_{Bdm} \cdot h_{Cdm}^{*} + h_{Adm} \cdot h_{Ddm} \cdot \overline{s}_A \cdot \overline{s}_D \right\} \right|_F^2 \\
\end{align*}
\]
| $(\tilde{s}_B, \tilde{s}_C)$ | \[
\begin{align*}
\arg \min_{s_B, s_C \in C^{Nd}} & \left| \sum_{m=1}^{N} \left( \left( \sum_{j=A}^{D} | h_{jdm} | \cdot^2 \right) \cdot \left( | s_B | \cdot^2 + | s_C | \cdot^2 \right) \right. \\
+2 \Re \left\{ \left( -h_{Bdm}^{*} \cdot \overline{r}_{1m} + h_{Adm}^{*} \cdot \overline{r}_{2m} - h_{Ddm}^{*} \cdot \overline{r}_{3m} - h_{Cdm}^{*} \cdot \overline{r}_{4m} \right) \cdot \overline{s}_B + \left( -h_{Ddm}^{*} \cdot \overline{r}_{1m} + h_{Cdm}^{*} \cdot \overline{r}_{2m} \right. \\
+ h_{Bdm}^{*} \cdot \overline{r}_{3m} + h_{Adm}^{*} \cdot \overline{r}_{4m} \left. \right) \cdot \overline{s}_C + \left( h_{Bdm} \cdot h_{Cdm}^{*} \right) \\
- h_{Adm}^{*} \cdot h_{Ddm} - h_{Adm} \cdot h_{Ddm}^{*} + h_{Bdm}^{*} \cdot h_{Cdm} \cdot \overline{s}_B \cdot \overline{s}_C \right\} \right|_F^2 \\
\end{align*}
\]

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 $n = 1, \ldots, N_D$, the decoding metrics for the $n$-th data subcarrier in MB-OFDM symbols $\tilde{s}_{A_i}, \tilde{s}_{B_i}, \tilde{s}_{C_i}$ and $\tilde{s}_{D_i}$ are as follows (the subscript $i$ is omitted for simplicity).
\[(s_A, s_D) = \arg\min_{s_A, s_D \in C} \sum_{m=1}^{N} \left( \left( \sum_{j=1}^{D} |h_{jdm,n}|^2 \right)(|s_A|^2 + |s_D|^2) \\
+2 \text{Re} \left\{ (-\tilde{h}_{Adm,n} r_{1m,n}^* - \tilde{h}_{Bdm,n} r_{2m,n}^* - \tilde{h}_{Cdm,n} r_{3m,n} \\
- \tilde{h}^*_D dm,n r_{4m,n}) s_A + (-\tilde{h}^*_D dm,n r_{1m,n}^* + \tilde{h}^*_{Cdm,n} r_{2m,n}^* \\
+ \tilde{h}^*_{Bdm,n} r_{5m,n} - \tilde{h}_{Adm,n} r_{4m,n}) s_D + (\tilde{h}_{Adm,n} \tilde{h}^*_D dm,n) \\
- \tilde{h}^*_{Bdm,n} \tilde{h}_{Cdm,n} - \tilde{h}_{Bdm,n} \tilde{h}^*_{Cdm,n} + \tilde{h}^*_{Adm,n} \tilde{h}^*_D dm,n \right\} \right) \]

\[(s_B, s_C) = \arg\min_{s_B, s_C \in C} \sum_{m=1}^{N} \left( \left( \sum_{j=1}^{D} |h_{jdm,n}|^2 \right)(|s_B|^2 + |s_C|^2) \\
+2 \text{Re} \left\{ (-\tilde{h}_{Bdm,n} r_{1m,n}^* + \tilde{h}^*_{Adm,n} r_{2m,n} - \tilde{h}^*_D dm,n r_{3m,n} \\
- \tilde{h}_{Ddm,n} r_{4m,n}) s_B + (-\tilde{h}^*_D dm,n r_{1m,n} - \tilde{h}^*_{Cdm,n} r_{2m,n} \\
+ \tilde{h}^*_{Bdm,n} r_{5m,n} + \tilde{h}_{Adm,n} r_{4m,n}) s_C + (\tilde{h}_{Bdm,n} \tilde{h}^*_C dm,n) \\
- \tilde{h}^*_{Adm,n} \tilde{h}_{Ddm,n} - \tilde{h}_{Adm,n} \tilde{h}^*_D dm,n + \tilde{h}^*_{Bdm,n} \tilde{h}^*_C dm,n \right\} \right) \]

4.5 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 be able to transmit signals in one subband, and receive signals in two other subbands (one subband at a time), while the destination node should 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.

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 a 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).

### 4.6 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. The simulation
parameters can be found on Table 4.3.

In order to fairly compare the error performance of non-cooperative and our two
previous cooperative communication schemes, namely the 2-OCCS and 4-OCCS, the
following constraints are applied to all simulations.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT and IFFT size</td>
<td>( N_{ff} = 128 )</td>
</tr>
<tr>
<td>Data rate</td>
<td>320 Mbps</td>
</tr>
<tr>
<td>Convolutional encoder’s rate</td>
<td>1/2</td>
</tr>
<tr>
<td>Convolutional encoder’s constraint length</td>
<td>( K = 7 )</td>
</tr>
<tr>
<td>Convolutional decoder</td>
<td>Viterbi</td>
</tr>
<tr>
<td>Decoding mode</td>
<td>Hard</td>
</tr>
<tr>
<td>STFC decoding at nodes</td>
<td>ML decoding</td>
</tr>
<tr>
<td>Transmitted MB-OFDM symbols</td>
<td>1200</td>
</tr>
<tr>
<td>Modulation</td>
<td>8PSK/16QAM/32QAM/64QAM CM1, 2, 3 &amp; 4</td>
</tr>
<tr>
<td>IEEE Channel model</td>
<td></td>
</tr>
<tr>
<td>Number of data subcarriers</td>
<td>( N_D = 100 )</td>
</tr>
<tr>
<td>Number of pilot subcarriers</td>
<td>( N_P = 12 )</td>
</tr>
<tr>
<td>Number of guard subcarriers</td>
<td>( N_G = 10 )</td>
</tr>
<tr>
<td>Total number of subcarriers used</td>
<td>( N_T = 122 )</td>
</tr>
<tr>
<td>Number of samples in ZPS</td>
<td>( N_{ZPS} = 37 )</td>
</tr>
<tr>
<td>Total number of samples/symbol</td>
<td>( N_{SYM} = 165 )</td>
</tr>
<tr>
<td>Number of channel realizations</td>
<td>100</td>
</tr>
</tbody>
</table>

- **Power constraint**: The total received power at each Rx antenna at the destination during each time slot needs to be the same in all systems. Therefore, the signal constellation points in the 2-OCCS (cf. Eq.(3.1)) are scaled down by a factor of \( 1/\sqrt{2} \). The signal constellation points in the 4-OCCS (cf. Eq.(3.4)) are scaled down by a factor of \( 1/\sqrt{3} \), while the factor is 1/2 for the case of the 4-QOCCS (cf. Eq.(4.1)).

- **Data rate constraint**: Different signal constellation mapping (QPSK/QAM) schemes are applied to guarantee that the proposed 4-QOCCS has at least the same or even higher spectral efficiency than the 2-OCCS and 4-OCCS in order
to evaluate the advantages of the proposed 4-QOCCS. For example, the 4-OCCS uses 32-QAM to achieve 4.5bits/s/Hz while the 4-QOCCS uses 64QAM to have 5bits/s/Hz, which is slightly higher than the 4-OCCS.

Figure 4.4 4-QOCCS vs. 2-OCCS and conventional MB-OFDM UWB with 3bits/s/Hz spectral efficiency.

Fig.4.4 compares the error performances of the three systems, namely the conventional MB-OFDM, 2-OCCS and 4-QOCCS, in the case where all nodes are equipped with one antenna. The spectral efficiency of all three systems is 3 bits/sec/Hz (8PSK modulation is used in all three systems). From Fig.4.4, 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. 4.5 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-PSK while the full rate 4-QOCCS uses 8PSK, thus they all have 3bits/s/Hz spectral efficiency. Fig.4.5 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 4.1, 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.

Figure 4.6 4-QOCCS vs. 4-OCCS with 5bits/s/Hz and 4.5bits/s/Hz spectral efficiency, respectively, and two-antenna destination node.

Fig.4.6 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-OCQS uses 64-QAM to achieve 4.5bits/s/Hz spectral efficiency. The full rate 4-OQCCS uses 32-QAM and it has 5bits/s/Hz spectral efficiency, which is even slightly higher than that in the 4-OCCS. From Fig.4.6, one can observe that the performance of 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.

### 4.7 Chapter summary

This chapter presents an order-4 quasi-orthogonal STFC cooperative communication scheme (4-QOCCS) for MB-OFDM UWB communication. A novel subband allocation scheme designed for this 4-QOCCS has also been illustrated in this chapter. In addition, the chapter compares the performance of the proposed 4-QOCCS with those of the 2-OCCS and 4-OCCS at a number of spectral efficiency values. From the simulation results, an important observation can be drawn that, at lower spectral efficiency, the 4-OCCS could be better than the 4-QOCCS, due to the full diversity brings more benefit than the full rate. Hence the full diversity might be more preferred in this case. However, at higher spectral efficiency, the 4-QOCCS can achieve better performance than the 4-OCCS, because the diversities of the 4-OCCS is neutralised by the high density modulation. Thus, the full rate might be more preferred in this case. The subsequent work covered in the next chapter would be the examination of the proposed schemes in the scenario where nodes might be erroneously decoded by their partners. Together with our analyses mentioned up to this point, this subsequent work shall provide a more comprehensive evaluation of the proposed cooperative communication schemes.
Chapter 5

Performance analysis of cooperative communication systems

One question that could be raised about cooperative communication is in which scenarios cooperative communication is useful, i.e. it performs better than non-cooperative communication. In this chapter, the exact BER lower bound performance of a non-OFDM cooperative communication system having two source nodes and one destination node will be derived first. We then evaluate the performance of a three-node MB-OFDM cooperative communication system and point out when the cooperative communication performs better than the conventional (non-cooperative) MB-OFDM system.

5.1 Three-node STBC cooperative communication system

In [55] and [56], the authors derived the exact BER performance of the AF and soft DF protocols in an one source-node, two-relay cooperative communication system where the distributed Alamouti STBC is implemented. However, to the best of our knowledge, an exact BER performance expression for a two-source node STBC cooperative communication network has not been derived, and the discussion on the
scenarios where a STBC cooperative communication system is better than a SISO system is still missing in the literature.

In the proposed two-source node STFC cooperative communication systems mentioned in the previous chapters, we are faced with two important questions: (i) would the cooperative communication still be useful if the SNR of the channels between source nodes are worse than the SNR of the channels between the source nodes and the destination node?, and (ii) what is the minimum value of the inter-node SNR for a given uplink SNR that would make cooperative communication beneficial? In this chapter, we will formulate the exact lower bound expression of the BER of a two-source node cooperative communication system to answer the above two questions.

5.1.1 System model

We consider a three-node cooperative communication system consisting of two source nodes $S_1$ and $S_2$ and one destination node $d$. The system model is depicted in Fig.5.1. The channels between the source nodes $S_1$, $S_2$ and the destination node $d$ are assumed to be independent Rayleigh fading channels. Additive Gaussian noise is assumed at all nodes in the system. The transmission can be divided into two time phases. In the first phase, $S_1$ and $S_2$ transmit their symbols $x_1$ and $x_2$ to the destination, as well as to each other. In the second phase, $S_1$ and $S_2$ decode the received signals (we denote the decoded symbols to be $\hat{x}_1$ and $\hat{x}_2$) and then transmit the signals $-\hat{x}_2^*$ and $\hat{x}_1^*$ to the destination respectively. Therefore, during the two phases, the following Alamouti code has been transmitted from $S_1$ and $S_2$ to $d$. 
Throughout this chapter, we refer the channels between the source nodes themselves to as the inter-node links, while the channels between the source nodes and the destination node are referred to as the uplinks. Assuming that the inter-node links have the same average SNRs, denoted as $\gamma_{ij}$, while all uplinks have the same average SNRs $\gamma_{up}$. For simplicity, we consider the BPSK modulation throughout this section. In order to formulate the BER expression of a non-OFDM cooperative communication system, we first consider the following two lemmas.

**5.1.2 BER expressions of SISO and Alamouti STBC systems**
Lemma 1 – BER expression of a SISO system

In the first phase, $S_1$ and $S_2$ need to exchange their messages in order to establish the Alamouti STBC. If the system is working on a half-duplex mode, this signal exchanging procedure requires two time slots. Denote $r_{ij}$ to be the signal transmitted from $S_i$ and received at $S_j$ ($i = 1, 2, j = 1,2$ and $i \neq j$). The signals received at the two source nodes during the first phase can be presented as follows

$$r_{ij} = h_{ij} x_i + n_{ij}$$  \hspace{1cm} (5.1)

where $h_{ij}$ is the Rayleigh channel coefficient of the inter-node link between $S_i$ and $S_j$, and $n_{ij}$ is the AWGN (Additive while Gaussian noise) at these nodes.

These transmissions can be treated as a Single-Input Single-Output (SISO) system. Thus the bit error probability between $S_i$ and $S_j$ for the BPSK modulation is [57]

$$P_{s_{ij}} = \frac{1}{2} \text{erfc}\left(\sqrt{\gamma_{ij}}\right)$$  \hspace{1cm} (5.2)

$P_{s_{ij}}$ could be simplified as:

$$P_{s_{ij}} = \frac{1}{2} \left( 1 - \frac{Y_{ij}}{\sqrt{1 + Y_{ij}}} \right)$$  \hspace{1cm} (5.3)

where $Y_{ij}$ is the average SNR of the inter-node link between $S_i$ and $S_j$. As a result, the decoding BER at each of the two source nodes $i$ and $j$, denoted as $BER_{s_{ij}}$, is equal to $P_{s_{ij}}$, thus
Lemma 2 – BER expression of the Alamouti STBC system

This lemma considers the case where the two source nodes are able to decode perfectly their partner. Intuitively, the considered two-source node cooperative communication system behaves similarly to the Alamouti STBC communication system. As mentioned in [3], the diversity order of a 2Tx, 1Rx Alamouti STBC system is equal to that of the maximal-ratio receiver combining (MRRC) technique with two antennas at the receiver. However, to make a fair comparison between the Alamouti STBC system and the MRRC system, the transmit power from each of the two antennas in the STBC case need to be scaled down by a factor of 2 in order to achieve the same total transmitted power as that transmitted from the single antenna in the MRC case. Therefore, the error probability for the two-Tx Alamouti STBC system in Rayleigh fading channels can be expressed as follows

\[ P_{Al} = p^2 [1 + 2(1 - p)] \]  

(5.4)

where

\[ p = \frac{1}{2} - \frac{1}{2} \left( 1 + \frac{2}{\gamma_{up}} \right)^{-\frac{1}{2}} \]  

(5.5)

Thus, we have
where $\bar{\gamma}_{up}$ is the average SNR of the uplink channels. As a result, the BER of a two-Tx Alamouti STBC system, denoted as $BER_{At}$, is equal to $P_{At}$

$$BER_{At} = P_{At}$$

5.1.3 Exact BER lower bound analysis

Since the decoding processes at the source nodes might not be perfect, in order to derive the exact lower bound of the BER of the STBC cooperative communication system, we divide the case of erroneous signal reception at the destination node into the following two complementary cases.

- Case one: errors occur in the uplinks (no matter if the inter-node links are correct or not). Intuitively, the bit error probability for this case is at least equal to that of the two-Tx Alamouti STBC, i.e.

  $$BER_1 \geq BER_{At}$$

  The equality occurs if the two source nodes are able to decode perfectly their partner.

- Case two: no errors occur in the uplink transmission. The probability for this case to be happened could be expressed as
\[ P_2 = 1 - P_1 = 1 - P_{Al} \]

Four following possible situations may occur between \( S_1 \) and \( S_2 \) in this case:

1) \( S_1 \rightarrow S_2 \) and \( S_2 \rightarrow S_1 \) are both incorrect;

2) \( S_1 \rightarrow S_2 \) and \( S_2 \rightarrow S_1 \) are both correct;

3) \( S_1 \rightarrow S_2 \) is correct and \( S_2 \rightarrow S_1 \) is incorrect; and

4) \( S_1 \rightarrow S_2 \) is incorrect and \( S_2 \rightarrow S_1 \) is correct.

Denote \( E_1, E_2, E_3 \) and \( E_4 \) to be these four events respectively. The total probability for these four events must be one. Assuming that these four events are equiprobable, i.e. each event occurs with a probability \( P_{E_i} = 0.25 \). The BER expression for each event is detailed as below.

- **\( E_1 \):** \( S_1 \rightarrow S_2 \) and \( S_2 \rightarrow S_1 \) are both incorrect. As the transmission between the two source nodes could be considered as a SISO system, the bit error probability for two BPSK symbols being erroneous simultaneously is \( P_{s_{ij}}^2 \). The two erroneous BPSK symbols cause two bit errors in the destination node (note that the uplinks are correct). Therefore the bit error rate caused by the event \( E_1 \) could be represented as

\[ BER_{E_1} = 2BER_{s_{ij}}^2 = 2P_{s_{ij}}^2 \]

- **\( E_2 \):** \( S_1 \rightarrow S_2 \) and \( S_2 \rightarrow S_1 \) both correct. This case does not cause any error at the destination, thus we do not need to consider the bit error rate in this case.

- **\( E_3 \):** \( S_1 \rightarrow S_2 \) is correct and \( S_2 \rightarrow S_1 \) is incorrect. The bit error rate caused by event \( E_3 \) could be represented as
\[ BER_{E_3} = P_{stij} \]

- \( E_4: S_1 \rightarrow S_2 \) is incorrect and \( S_2 \rightarrow S_1 \) is correct. Similarly to the event \( E_3 \), we have

\[ BER_{E_4} = P_{E_3}. \]

As a result, the lower bound of the BER of the proposed system, denoted as \( BER_{coop} \), is given below

\[
BER_{coop} = BER_1 + BER_2 \\
= P_{At} + 0.25(1 - P_{At}) (2P_{stij}^2 + 2P_{sij}) \\
= P_{At} + 0.5P_{sij} + 0.5P_{sij}^2 - 2P_{At}P_{sij}^2 - 2P_{At}P_{sij} \\
= P_{At} \left( 1 - 2P_{sij}^2 - 2P_{sij} \right) + 0.5P_{sij} \left( P_{sij} + 1 \right) \\
= \left( \frac{1}{2} - \frac{1}{\sqrt{1 + \gamma_{up}}} \right)^2 \left( 2 - \frac{1}{\sqrt{1 + \gamma_{up}}} \right) \left[ 1 - \left( 1 - \sqrt{\frac{\hat{y}_{ij}}{1 + \hat{y}_{ij}}} \right)^2 \right] - \left( 1 - \sqrt{\frac{\hat{y}_{ij}}{1 + \hat{y}_{ij}}} \right) \\
+ \frac{1}{4} \left( 1 - \sqrt{\frac{\hat{y}_{ij}}{1 + \hat{y}_{ij}}} \right) \left( \frac{3}{2} - \frac{1}{2} \sqrt{\frac{\hat{y}_{ij}}{1 + \hat{y}_{ij}}} \right)
\]

(5.7)

From (5.7), we can see that the BER system performance depends on the values of \( \hat{y}_{ij} \) and \( \hat{y}_{up} \). For a given \( \hat{y}_{up} \), the value of \( \hat{y}_{ij} \) could significantly affect the system performance (and vice versa). If \( \hat{y}_{ij} \) is lower than a threshold value, denoted as \( \hat{y}_{th} \), cooperative communication may have worse performance compared to a SISO system.

In order to find the threshold value, we equate the BER performance of the proposed system \( BER_{coop} \) to that of a SISO system \( BER_{siso} \) (cf. Eq.(5.3)) with same \( \hat{y}_{up} \) value.
For a given $\bar{\gamma}_{up}$, from Equations (5.7) and (5.8), we can calculate the threshold value $\bar{\gamma}_{th}$. If $\bar{\gamma}_{ij}$ is lower than $\bar{\gamma}_{th}$, the system may give up cooperation and use direct transmission instead to gain better performance.

5.1.4 Simulation results

![Graph showing BER vs. SNR](image)

Figure 5.2 Simulation of STBC cooperative communication vs. Eq. (5.7), with $\bar{\gamma}_{up} = \bar{\gamma}_{ij}$. 
Fig. 5.2 shows the BER curve of a STBC cooperative communication system obtained from (5.7) against the BER curve obtained from Monte-Carlo simulations. In this figure, uplinks and inter-node links are assumed to have the same SNR, i.e. $\bar{y}_{up} = \bar{y}_{ij}$, ranging from 0 to 30 dB. From Fig. 5.2, it is clear that the BER curve attained from the Monte-Carlo simulations is almost coincident with that calculated by equation (5.7).

![Plot of Equation (5.7)](image)

Figure 5.3 SISO system vs. STBC cooperative communication (Eq. (5.7)), with $\bar{y}_{up} = \bar{y}_{ij}$.

Fig.5.3 presents the BER calculated in (5.7) in comparison with the BER of a SISO system. Uplinks and inter-node links are still assumed to have the same SNR. Fig.5.3 clearly shows that when the SNR value of uplinks and inter-node links is lower than 5dB, the STBC cooperative communication performs worse than the SISO system. This
is because the decoding errors at the two source nodes have drowned the diversity advantage gained by the STBC. However, when the SNR value increases, the STBC cooperative communication starts to perform better than the SISO system.

![Figure 5.4 STBC cooperative communication vs. SISO system, $\bar{Y}_{up} \neq \bar{Y}_{ij}$.](image)

In the above two figures, uplinks and internode links are assumed to have the same SNR. In fact, their SNR values might be different. In Fig.5.4, we consider more practical scenarios where the uplinks have some given values of SNR (e.g. $\bar{Y}_{up}=5$, 15 and 25dB) while the SNR of the inter-node links ranges from 0 to 30dB. This figure plots groups of three curves, including the BER curve of a STBC cooperative communication system simulated by the Monte-Carlo simulations, the theoretical BER
curve of a STBC cooperative communication system calculated by Eq.(5.7), and the BER curve of a SISO system. The first two curves are almost coincident with each other, thus each group of curves looks as if it included only two curves. It is also noted that the SISO curves are in parallel with the horizontal axis due to the fact that the BER of a SISO system only depends on the SNR of the link between its source and destination, and does not depend on the SNR of the inter-node links (there is no inter-node link in this case).

From Fig.5.4, the BER of the STBC cooperative communication decreases when the inter-node SNR $\tilde{y}_{ij}$ increases. This is due to the fact that the decoding error probability at the two source nodes decreases when $\tilde{y}_{ij}$ increases. When $\tilde{y}_{ij}$ reaches a certain threshold value $\tilde{y}_{th}$, the STBC cooperative communication starts to perform better than the SISO system. The threshold value $\tilde{y}_{th}$ is determined by the intersection between the two curves of these two systems.

<table>
<thead>
<tr>
<th>Uplink SNR $\tilde{y}_{up}$ (dB)</th>
<th>$\tilde{y}_{th}$ observed from simulations (dB)</th>
<th>$\tilde{y}_{C}$ calculated by Eq.(5.8) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.4</td>
<td>5.2649</td>
</tr>
<tr>
<td>15</td>
<td>12.5</td>
<td>12.3625</td>
</tr>
<tr>
<td>25</td>
<td>22.2</td>
<td>22.0272</td>
</tr>
</tbody>
</table>

Table 5.1 summarises the threshold values $\tilde{y}_{th}$ corresponding to the uplink SNR $\tilde{y}_{up} = 5, 15$ and $25$ dB. The threshold values calculated from Eq. (5.8) are also included in this table as references.
From Table 5.1, we can see that the theoretical threshold values calculated by Eq. (5.8) are very close to those values observed in simulations. In other words, Eq. (5.7) and Eq. (5.8) can be used to calculate the threshold values for a relatively wide range of the uplink SNR $\bar{\gamma}_{up}$. If the uplink SNR $\bar{\gamma}_{up}$ is known at the source nodes, by substituting $\bar{\gamma}_{up}$ into (5.8), we can calculate the threshold value $\gamma_{th}$. The source nodes might also know the internode SNR value between themselves and their partner. Therefore, the source nodes could decide if cooperative communication should be used to improve the system BER performance (if $\bar{\gamma}_{ij} > \gamma_{th}$), or the non-cooperative mode should be used instead (if $\bar{\gamma}_{ij} < \gamma_{th}$).

Knowing whether cooperative communication could be useful before nodes actually engage in cooperation is important in numerous applications to keep system designs as simple as possible, while guaranteeing that, once nodes have decided to cooperate with each other, the implementation of cooperative communication would be definitely beneficial.

From the aforementioned analysis for a STBC, non-OFDM based cooperative communication system, we might conclude that, as opposed to our intuition, the implementation of cooperative communication could bring significant performance improvement (compared to non-cooperative communication) in various cases, but is not necessarily useful in all scenarios.

### 5.2 Performance evaluation of STFC MB-OFDM UWB cooperative communication systems

The above analysis for a STBC, non-OFDM cooperative communication system is
our motivation to further evaluate the performance of cooperative communication in the context of STFC MB-OFDM UWB systems. Chapters 3 and 4 have mentioned our proposed cooperative communication schemes for STFC MB-OFDM UWB, namely the 2-OCCS using the Alamouti STFC for a two source-node cooperative MB-OFDM UWB system, the 4-OCCS using a 3/4-rate OSTFC for a four source-node cooperative MB-OFDM UWB system, and the 4-QOCCS using a full-rate QO-STFC for a four source-node cooperative MB-OFDM UWB system. Simulation results in Chapters 3 and 4 have illustrated clearly the usefulness of the implementation of cooperative communication and STFCs in MB-OFDM UWB systems.

However, in all aforementioned results, it is assumed that SNR is the same in all links between nodes in the network. In fact, the SNR in the inter-node links and that in the uplinks might not be the same. The first case in Fig. 5.5 is a typical example for the case where the SNR in the inter-node links might be better than that in the uplinks, while the second case is a typical example for the reverse case. The SNR in the inter-node links significantly affects the decoding correctness at the cooperative nodes (i.e. source nodes), which in turns decides the usefulness of the implementation of cooperative communication.

In this section, we assess the performance of cooperative communication in a two-source node MB-OFDM UWB system, based on the 2-OCCS that is reviewed in Chapter 3, for various SNR values in the inter-node links for a given uplink SNR. The error performance of a conventional (i.e. non cooperative) MB-OFDM UWB system is plotted for the comparison purpose. We also evaluate the threshold SNR value of the inter-node links (hereafter referred to as the cooperative SNR value) at which cooperative communication starts to become beneficial.
5.2.1 Simulation results

The system model for the 2-OCCS has been introduced in Chapter 3. Thus, in this section, we only present the simulation results to examine the effect of the inter-node links on the overall system bit error performance.

To examine the performance advantage of cooperative communication, we ran several Monte-Carlo simulations for the 2-OCCS, and conventional MB-OFDM UWB system. Each run of simulations was carried out with 1200 MB-OFDM symbols. One hundred channel realizations of each channel model (CM1 and CM2) were considered for the transmission of each MB-OFDM symbol. In simulations, SNR (either $\tilde{y}_{ij}$ or $\tilde{y}_{up}$) 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 the non-cooperative and 2-OCCS systems, the following constraints are 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 $1/\sqrt{2}$.

• **Data rate constraint**: Same signal constellation mapping (QPSK) scheme are applied to the two systems to guarantee the same bit rate.

We assume the two uplinks have the same SNR, denoted as $\bar{\gamma}_{up}$. For each $\bar{\gamma}_{up}$, we vary the SNR value of the inter-node links, denoted as $\bar{\gamma}_{ij}$, and record the bit error rate of the 2-OCCS. Meanwhile, we also simulate the conventional SISO MB-OFDM UWB system with the same uplink channel condition, i.e. having the SNR equal to $\bar{\gamma}_{up}$ in the 2-OCCS. The two performances are then compared, and the cooperative SNR values for different $\bar{\gamma}_{up}$ values can be estimated.

Fig.5.6 (5.7) compares the error performances of the 2-OCCS and the conventional MB-OFDM with $\bar{\gamma}_{up}$ being 5, 10, 15, 20 and 25dB and $\bar{\gamma}_{ij}$ ranging from 0 to 30 dB in the channel model CM1 (CM2). The performance of the conventional MB-OFDM system (i.e. SISO MB-OFDM system) is presented as dotted lines which are in parallel with the horizontal axis. This is because the performance of the conventional MB-OFDM system does not depend on $\bar{\gamma}_{ij}$, but only on $\bar{\gamma}_{up}$. Therefore, the system bit error rate is constant for a given value of $\bar{\gamma}_{up}$. 
Figure 5.6 Cooperative communication vs. SISO MB-OFDM UWB in CM1.

Figure 5.7 Cooperative communication vs. SISO MB-OFDM UWB in CM2
These figures clearly show that the 2-OCCS provides a better error performance than the conventional system when $\tilde{y}_{ij}$ reaches a certain threshold, referred to as the cooperative SNR. The cooperative SNR value can be determined by the intersection between the two error performance curves of the SISO system and of the 2-OCCS corresponding to the same $\tilde{y}_{up}$. The cooperative SNR values are summarised in Table 5.2.

<table>
<thead>
<tr>
<th>Uplink SNR $\tilde{y}_{up}$ (dB)</th>
<th>CM1 Cooperative SNR $\tilde{y}_{ij}$ (dB)</th>
<th>CM2 Cooperative SNR $\tilde{y}_{ij}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.26</td>
<td>5.6</td>
</tr>
<tr>
<td>10</td>
<td>11.31</td>
<td>10.12</td>
</tr>
<tr>
<td>15</td>
<td>14.39</td>
<td>12.68</td>
</tr>
<tr>
<td>20</td>
<td>15.75</td>
<td>14.57</td>
</tr>
<tr>
<td>25</td>
<td>17</td>
<td>15.09</td>
</tr>
</tbody>
</table>

From Table 5.2, for a given $\tilde{y}_{up}$, the cooperative SNRs in CM2 are always smaller than those in CM1. Note that CM2 is much more dispersive than CM1 [48]. Comparison between the cooperative SNR values for CM1 and CM2 is presented in more detail in Fig.5.8. Clearly, the cooperative SNR values decrease significantly in the more dispersive channel model. This means that the threshold SNR value where the implementation of cooperative communication starts to become useful occurs earlier (that is, with a relatively lower $\tilde{y}_{ij}$) in the case of more dispersive channels.
Figure 5.8 $\bar{y}_{ij}$ vs $\bar{y}_{up}$ in CM1 and CM2.

In Fig.5.8, we also indicate two reference points A and B, where $\bar{y}_{up} = \bar{y}_{ij}$, for CM1 and CM2 respectively. Denote the $\bar{y}_{up}$ at these reference points to be $\bar{y}_{up}^A$ and $\bar{y}_{up}^B$. When the uplink SNR is lower than $\bar{y}_{up}^A$ (or similarly for $\bar{y}_{up}^B$ for CM1) (i.e. on the left side of the reference points), $\bar{y}_{ij}$ should be slightly higher than $\bar{y}_{up}$ in order for cooperative communication to have better performance than the conventional SISO system. For instance, given $\bar{y}_{up} = 5\text{dB}$, cooperative communication in MB-OFDM UWB will be useful if the inter-node SNR is not smaller than 6.2 dB in CM1 (or 5.6 in CM2). The first case in Fig.5.5 is an example for this scenario, where two source nodes are relatively closer than the destination. However, when the uplink SNR value is higher than the SNR at the reference point (right hand side of the reference point), cooperative communication is useful even when $\bar{y}_{ij}$ is smaller than $\bar{y}_{up}$. The second case in Fig.5.5 might be an example for this scenario where the two source nodes might actually be...
located further from each other than the destination. In the other words, when the uplink channel condition is better, cooperation between the noisy source nodes can still provide better performance than the non-cooperative system.

5.3 Chapter summary

This chapter analyses the usefulness of the STC cooperative communication in both OFDM and non-OFDM based systems. To do that, we first formulate the exact lower bound BER performance of the STBC cooperative communication in a non-OFDM based system. This theoretical lower bound BER expression fits very well with the simulated BER. By equalizing the BER expression of the STBC cooperative communication (i.e. virtual MIMO) system to that of a SISO (non-cooperative) system, the threshold SNR values can be estimated. These values indicate when cooperative communication is better than non-cooperative communication. We then evaluate the performance of cooperative communication in the context of MB-OFDM UWB (i.e. OFDM-based) system by simulations. Simulation results show that the STFC cooperative communication could be beneficial, compared to the SISO system, when the inter-node SNR reaches a certain threshold, defined as the “cooperative SNR”. A number of cooperative SNR values have been determined for different UWB channel models (CM1 and CM2) corresponding to several values of the uplink SNR for illustration. The results and observations derived in this chapter are important for many potential wireless, multi-source cooperative communication applications because they allow the source nodes to know whether or not they should cooperate with others.
Chapter 6

Conclusion

As wireless communication developed extremely fast during the last two decades, enhancing the performance and reducing the interference for wireless communication are some of the main research areas nowadays. In this thesis, we have proposed two cooperative communication schemes in STFC MB-OFDM UWB systems, namely the order-4 orthogonal cooperative communication scheme (4-OCCS) and the order-4 quasi-orthogonal cooperative communication scheme (4-QOCCS). In addition, we also analyse the usefulness of cooperative communication in both OFDM-based and non-OFDM based systems. This chapter is aimed to summarise the whole thesis and is organised as follows. Section 6.1 summarises the research contributions in this thesis. Section 6.2 discusses the future works regarding to the topic of this thesis. Section 6.3 provides a comprehensive conclusion for this thesis.

6.1 Research summary

In this section, we summarise the research activities and contributions in this thesis.

- We have provided a comprehensive literature review for three important techniques involving this thesis, namely cooperative communication, space-time codes and OFDM-based system. We also highlighted the recently proposed technique, which is the main motivation of this thesis, namely the order-2
cooperative communication scheme (2-OCCS) [4], for MB-OFDM UWB systems. Having known that the Alamouti STFC cannot be used for more than two cooperative nodes, we have the following research questions:

- Is it possible for more than two source nodes (up to four nodes for instance) to collaborate in the cooperative STFC MB-OFDM UWB system?

- Does a cooperative communication system always provide better performance than a non-cooperative one? If not, in what channel conditions should cooperative communication be used?

• A novel order-4 Orthogonal STFC cooperative communication scheme (4-OCCS) using a rate-3/4 orthogonal space-time frequency code (OSTFC) have been proposed as one of the potential solutions for the first question. This proposed scheme allows four source nodes to cooperate in a MB-OFDM UWB system to gain performance even better than the 2-OCCS.

• We have also proposed an order-4 quasi-orthogonal cooperative communication scheme (4-QOCCS) using a full rate quasi-orthogonal space-time frequency code (QOSTFC). It shows that the full rate transmission is able to achieve in a four-source node cooperative MB-OFDM UWB system and the performance of the 4-QOCCS could be better compared to the 4-OCCS when high density modulation is applied.

• To answer the second question, we have formulated for the first time the lower bound of the BER of a STBC, non-OFDM cooperative communication system, and provided the threshold SNR values of the inter-node links corresponding to different uplink conditions. It is shown that when the inter-node links are better than the threshold SNR, the cooperative communication could provide better performance than the SISO system. We have then evaluated the performance of
cooperative communication in the context of MB-OFDM UWB systems. Finally, the threshold SNR values for the cooperative MB-OFDM UWB system have been provided.

6.2 Future works

My possible further works regarding to the topic of this project are shown below:

- Express the exact BER lower bound of the STFC cooperative communication in MB-OFDM UWB systems.
- Apply higher order STFCs to enable more source nodes to cooperate in MB-OFDM UWB systems.
- Evaluate the usefulness of the higher order cooperative communication in MB-OFDM UWB systems.
- Develop a STFC cooperative communication system in the context of two-way relay networks.

6.3 Conclusion

In this thesis, we have proposed two cooperative communication schemes for four-source node MB-OFDM UWB systems, namely 4-OCCS and 4-QOCCS. In addition, we have performed an in-depth mathematical performance analysis for the STBC cooperative communication in a non-OFDM based system, and evaluated the performance of STFC cooperative communication in MB-OFDM based systems.

In the 4-OCCS, we have proved that it can provide significantly better error
performance compared to the 2-OCCS, which was proposed previously, with same transmission power and data rate. In the 4-QOCCS, we have shown that the 4-QOCCS has better performance than the 4-OCCS when high density modulation is applied.

After proposing these two schemes, we realised that the STBC/STFC cooperative communication does not always provide better performance than the non-cooperative communication, especially when the transmissions in the inter-node links are distorted. Thus, we have formulated for the first time the BER performance of a STBC, non-OFDM cooperative communication system. The overlap between the theoretical BER curve and the simulated one confirms the accuracy of our mathematical analysis. The analysis also indicates that the cooperative communication might only be useful when the inter-node SNR is higher than a threshold value, so called cooperative SNR. The cooperative SNR varies depending on the uplink condition (uplink SNR). We have extended this analysis in the context of MB-OFDM UWB systems, and evaluated the cooperative SNR values using the simulation approach.

Overall, in this thesis, we have deeply investigated the combination of three emerging techniques namely cooperative communication, OFDM and space-time codes. Though this area is not matured yet, the preliminary results and analysis mentioned in this thesis have illustrated its potential to the next generation wireless communication. It is believed that these promising techniques will continue to draw more research interests, and they will have a significant impact on the telecommunication industry.
Reference


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