Mitigating the Effects of Mobility and Synchronization Error in OFDM Based Cooperative Communication Systems

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Declaration

This thesis is my original work and has not been submitted to any other university for examination.

Signature:................................. Date:........................

Bereket Babiso Yetera

This thesis report has been submitted for examination with our approval as University supervisors.

Signature:.. Date:................................

Dr. Kibet P.Langat

Signature:... Date:................................

Dr. Edwrad N.Ndungu

DEDICATION

To you, Dad, I dedicate this thesis.

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Thanking the Almighty God at first, I would like to express my deepest gratitude to all people around me who have made this thesis possible and my graduate studies pleasant.

I wish to express my gratitude to my advisors, Dr. Kibet Langat and Dr. Edward Ndungu for their enthusiasm, inspiration, and great efforts to explain things clearly and simply. Throughout the development of my thesis, they provided encouragement, sound advice, good teaching, and lots of great ideas. I am also thankful to them for carefully reading and commenting on countless revisions of this manuscript.

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ACRONYMS

AAF	Amplify-and-Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BC	Broadcast
BPSK	Binary Phase Shift Keying
CFO	Carrier Frequency Offset
CDMA	Code Division Multiple Access
CE	Channel Estimation
CF	Compress-and-Forward
CIR	Channel Impulse Response
CO-OFDM	Cooperative OFDM
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
C-DF	Correctly-Decode-and-Forward
CSI	Channel State Information
DAF	Decode-and-Forward
DFT	Discrete Fourier Transform
ESNRC	Extended SNR Combiner
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FD	Frequency Domain
ICI	Inter-carrier Interference
ICI-R	ICI-Removal
ISI	Inter-symbol Interference
IFFT	Inverse Fast Fourier Transform
ML	Maximum Likelihood
MRC	Maximum Ratio Combiner

OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
SC	Self Cancellation
SER	Symbol Error Rate
SNR	Signal-to-noise Ratio
SINR	Signal to Interference plus Noise Ratio
TD	Time Domain

ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is a promising technique for mobile wireless communications because of its good performance under multipath propagation environments. The concept of cooperative communication is currently under intensive research. It uses antennas of other terminals in the network to create virtual Multiple Input Multiple Output (MIMO) systems, providing capacity gains similar to those of MIMO systems.

However, OFDM based communication systems suffer from Carrier Frequency Offset (CFO) due to Doppler shift, and frequency synchronization error at the transmitter-receiver oscillators. And this CFO disturbs the subcarriers by making them lose their orthogonality, which in turn causes a severe problem in wireless communications called Subcarrier Leakage or Inter-Carrier Interference (ICI). Due to complex relaying at the channel and the combining techniques used at the receiver the issue of ICI will become worse in the case of cooperative communication.

In this thesis, OFDM based cooperative communication system is studied and developed and also a model to mitigate the effects of Doppler shift and frequency synchronization error in an OFDM communication system is developed. The system uses orthogonal frequency division multiplexing as a transmission technique. In the design of OFDM, maximum likelihood estimation is used to compensate for the effects of carrier frequency offset. Performance comparison is also done for maximum likelihood estimation with the most common carrier frequency estimation method called the self-cancellation estimation method and proved that it overweighs the self-cancellation estimation series.

In designing the cooperation system, the channels between the source node, the cooperating node and the destination (base station) are modeled containing thermal noise, Rayleigh fading, Rician fading and path loss. Amplify-and-Forward (AAF) cooperation protocol is used at the cooperating node when the system is in cooperation mode. Depending on the channel state between the source network access node and the cooperating network access node, the cooperating node turns its cooperation switch to either ON or OFF state. For a relatively short distance between the cooperating nodes, when compared to the distance between them and the base station, AAF has a better performance than Decode-and Forward (DAF) protocol, unless an error correcting code is simulated. The wireless communication links, the link between the source node and the base station and the link between the cooperating node and the base station, are assumed to have six different propagation paths. Next, the system performance is investigated (bit-error-rate against signal-to-noise-ratio) for different types of signal combination techniques. The performance of different combination protocols at the receiver is simulated and Maximum Ratio Combiner (MRC) is found to have better performance. However, for immobile wireless sensor networks Extended SNR (ESNR) combiner has also better performance. The system has also showed that with any kind of combination protocol at the receiver it is possible to achieve second order diversity. Matlab application software package was used to perform the simulations.

CHAPTER ONE

Introduction

1.1 Research Background:

During the last two decades, the wireless communications have experienced a huge growth in both capacity and variety. This growth is going to shrink the world to a small village in which users with different requirements are efficiently accommodated anywhere and at any time. This will result in an increased demand for new services that provide higher bit rate and higher capacity. It is expected that the wireless communication systems of the near future will require data rates up to a few hundreds of mega bits per second (Mbps), which are able to deliver bandwidth hungry applications such as web browsing and video streaming. The required data rate of the next generation wireless communication systems will be achieved by efficiently increasing the amount of the allocated bandwidth and using more advanced technologies, both in hardware and software.

One of the major themes in today's broadband systems is the use of the Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a modulation scheme suitable for frequency selective channels and for providing high speed data transmission, which makes it one of the promising solutions for the next generation wireless communications. However, there is a need for more developments of OFDM systems in terms of complexity reduction and adaptation, therefore reconfigurable solutions are needed to achieve the user requirements. This is necessary because the end users require lightweight, compact size and power efficient devices besides the high bit rate capabilities.

Furthermore, combining the communication systems with the new techniques such as Multiple-Input-Multiple-Output (MIMO) or cooperative communication can also enhance the capacity and the bit rate of the emerging systems. Also MIMO transmissions have been extensively studied as a means to improve spectral efficiency in wireless networks. While MIMO techniques offer tremendous advantages, their performance strongly depends on the number of antenna elements, spatial fading correlations between antennas, the presence of line of sight component, etc. Especially, multiple antennas in small handsets/cellular phones are unattractive for the achievement of transmit/receive diversity due to the limitation on size, power, hardware and price. The advantages of MIMO techniques can be achieved via cooperative communication.

Cooperative networks are created via the help of relay terminals which are willing to help the communication of any source-destination pair. End to end spectral efficiency of a wireless network can be increased with the aid of cooperative strategies. The concept of node cooperation brings a new form of diversity. Transmit and/or receive diversity can be achieved even with single antenna terminals. By this way, the need for costly multiple transceiver circuitry diminishes. Furthermore, spatial fading correlation of a cooperative diversity scheme is expected to be much less than spatial fading correlation of Multi-Antenna Elements (MAE) co–located at a terminal.

In a cooperative communication system, each wireless user is assumed to transmit data as well as act as a cooperative agent for another user. One of the key components in such a cooperative relay network is a forwarding method used by a relay terminal. Amplify and Forward (AAF) and Decode and Forward (DAF), and purge and forward (PG) are the main forwarding schemes which can be used in the cooperative relay networks. A relay terminal using the AAF scheme amplifies and forwards the signal received from its immediate predecessor in the network. A relay terminal using the DAF scheme decodes re-encodes and forwards the signal received from its immediate predecessor in the network. The use of either AAF or DAF at a relay terminal achieves different performance results under given Signal to Noise Ratio (SNR) conditions.

1.1.1 Cooperative Communication

In any wireless communication networks where there are more than two network access terminals, it is possible to form a virtual MIMO system by pooling the resources of those wireless access terminals. The MIMO system formed in this way is called cooperative communication system. In this system, an access terminal with information to transmit over the air link searches for an ideal access terminal in the network in order to form cooperation. Once it locates any ideal access terminal, it transmits the information to the intended destination and the ideal access terminal for cooperation. Upon receiving the information, the cooperating access terminal (the ideal access terminal) will condition the received signal depending on the cooperation protocol it has and re-transmits it to the intended destination. At the intended destination, the receiver combines the signals coming from the source access terminal and the cooperating access terminal by using any type of combination technique.

In cooperative communication system, shown in figure 1.1, the two most common cooperative relaying protocols are AAF and DAF. In AAF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low-cost implementation. However, the noise is also amplified at the relay. In DAF, the relay attempts to decode the received signals. If successful, it re-encodes the information and retransmits it. If some relays cannot fully decode the signal, they will be discarded.

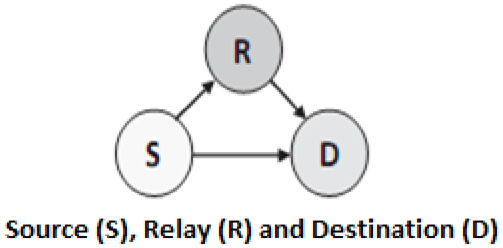

Figure 1.1 Simple Cooperative Communication System Diagram.

1.1.2 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a modulation technique that allows for high data rates over multipath channels. OFDM can also be seen as a multiplexing technique in the form of Orthogonal Frequency Division Multiple Access (OFDMA), which allows many users to share the orthogonal bands. OFDM mitigates the effect of multipath channel by essentially dividing the source spectrum into many narrow sub-bands that are transmitted simultaneously. The bandwidths of the sub-bands are designed to be narrow enough so that the channel exhibits a flat fading over each sub-band.

In OFDM, the source bit-stream is split into N parallel streams, which are modulated using N sub-carriers. Because of using many sub-carriers, the symbol duration Ts becomes N times larger. This reduces the effect of Inter Symbol Interference (ISI) in multipath channels, and thereby reduces the equalization complexity. In case of Frequency Division Multiplexing (FDM), frequency guard bands between the sub-carriers and a couple of filters are needed in the receiver side in order to decompose these carriers. On the other hand, if these sub-carriers are orthogonal, a very simple equalization method is able to decompose the carriers without requiring frequency guard bands or filters. To make the sub-carriers orthogonal, their frequencies must be located at $f_m = {}^{mB}/_{N}$, where m is an integer and B is the total available bandwidth. Basically, the sub-carriers can be generated using N local oscillators that oscillate at frequencies f_m [1]; however, the hardware cost of implementing N oscillators for one system is very high. A much easier alternative implementation is accomplished digitally using Inverse Discrete

Fourier Transform (IDFT), which is applied on the block of *N* symbols so that the resulting time domain carriers become orthogonal. In practical implementation, the block length *N* is chosen to be a power of 2 and the IDFT is realized efficiently as Inverse Fast Fourier Transform (IFFT), which speeds up the multiplication operation. Orthogonality condition in time domain requires all the sub-carriers to have an integer number of cycles during the symbol duration. For a certain carrier in frequency domain, at the maximum of each sinc shaped carrier, the contributions from other carriers must be zero as shown in Figure1.2 [2]. Orthogonality allows the carriers to overlap each.

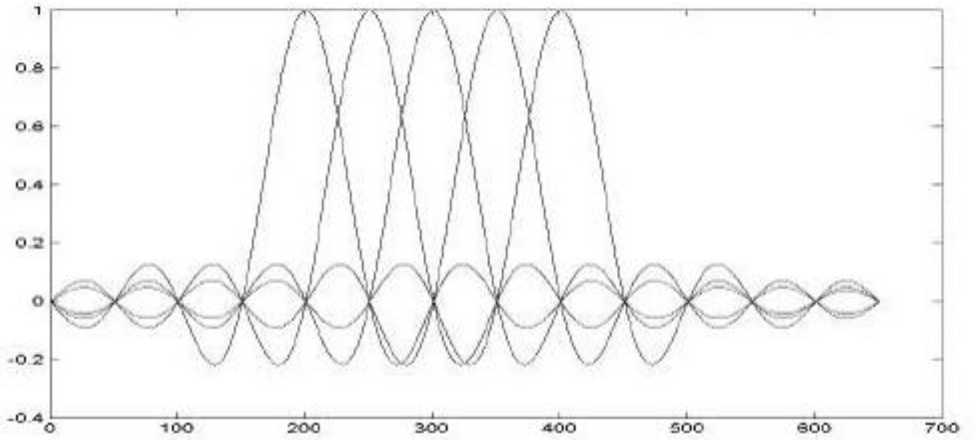

Figure1.2 Orthogonal Frequency Division Multiplexing

1.1.3 OFDM Based Cooperative Communication and MIMO Cellular Relay Networks: approaches and issues

The continually increasing number of users and the rise of resource-demanding services require a higher link data rate than the one that can be achieved in current wireless networks. Wireless cellular networks, in particular, have to be designed and deployed with inevitable constraints on the limited radio resources such as bandwidth and transmit power [2]. As the number of new users increases, finding a solution to meet the rising demand for high data rate services with the available resources has became a challenging research problem. The primary objective of such research is to find solutions that can improve the capacity and utilization of the radio resources available to the service providers. While in traditional infrastructure networks the upper limit of the Source–Destination (S–D) link's data capacity is determined by the Shannon capacity [4], advances in radio transceiver techniques such as MIMO architectures and cooperative or relay-assisted communications have led an enhancement in the capacity of contemporary systems.

In the MIMO technique the diversity relies on uncorrelated channels, and is achieved by employing multiple antennas at the receiver side, the transmitter side, or both, and by sufficiently separating the multiple antennas (of same polarization) [5]. The MIMO technique can be used to increase the robustness of a link as well as the link's throughput. Unfortunately, the implementation of multiple antennas in most modern mobile devices may be challenging due to their small sizes.

Cooperative diversity or relay-assisted communication has been proposed as an alternative solution where several distributed terminals cooperate to transmit/receive their intended signals. In this scheme, the source wishes to transmit a message to the destination, but obstacles degrade the S–D link quality. The message is also received by the relay terminals, which can retransmit it to a desired destination, if needed. The destination may combine the transmissions received by the source and relays in order to decode the message.

The limited power and bandwidth resources of the cellular networks and the multipath fading nature of the wireless channels have also made the idea of cooperation particularly attractive for wireless cellular networks [6]. Moreover, the desired ubiquitous coverage demands that the service reaches the users in the most unfavorable channel conditions (e.g., cell-edge users) by efficient distribution of the high data rate (capacity) across the network [7, 8]. In conventional cellular architectures (without relay assistance) increasing capacity along with coverage extension dictates dense deployment of Base Stations (BSs) which turns out to be a cost-wise inefficient solution for service providers. A Relay Station (RS), which has less cost and functionality than the BS, is able to extend the high data rate coverage to remote areas in the cell under power and spectral constraints [10–11].

By allowing different nodes to cooperate and relay each other's messages to the destination, cooperative communication also improves the transmission quality [14]. This architecture exhibits some properties of MIMO systems; in fact a virtual antenna array is formed by distributed wireless nodes each with one antenna. Since channel impairments are assumed to be statistically independent, in contrast to conventional MIMO systems, the relay-assisted transmission is able to combat these impairments caused by shadowing and path loss in S–D and Relay–Destination (R–D) links. To this end, an innovative system has been proposed in which the communication between transmitter and receiver is done in multiple hops through a group of relay stations. This cooperative MIMO relaying scheme creates a Virtual Antenna Array (VAA) [15] by using the antennas of a group of RSs. These RSs transmit the signal received from the BS (or previous hops) cooperatively on different channels to the receiving terminal (downlink case) or the signal that the transmitting terminal wants to send to the BS (uplink case). This system can be modeled as a MIMO system although the real receiver (downlink) or transmitter (uplink) only has one antenna. Since the relaying Mobile Stations (MSs) introduce additional noise and there is a double Rayleigh channel effect, the scheme is expected to perform below the corresponding MIMO diversity gain when used for spatial multiplexing.

The combination of relaying and OFDMA techniques also has the potential to provide high data rate to user terminals everywhere, anytime. Interest in OFDM is therefore growing steadily, as it appears to be a promising air-interface for the next generation of wireless systems due, primarily; to its inherent resistance to frequency-selective multipath fading and the flexibility it offers in radio resource allocations. Likewise, the use of multiple antennas at both ends of a wireless link has been shown to offer significant improvements in the quality of communication in terms of both higher data rates and better reliability at no additional cost of spectrum or power [17]. These essential properties of OFDMA and MIMO, along with the effectiveness of cooperative relaying in combating large-scale fading and enhancing system capacity immediately motivate the integration of these technologies into one network architecture.

However, adequate and practical radio resource allocation (RRA) strategies have to be developed to exploit the potential gain in capacity and coverage improvement in the integration of relaying, OFDMA, and MIMO techniques [18].

1.2 Problem Statement

Wireless communications suffer from fading that result in poor link qualities or outages. On the other hand, the broadcast nature of wireless media provides for a natural way of cooperation between multiple nodes in a network, thereby alleviating the effect of fading. Cooperative relaying or cooperation diversity refers to the idea of cooperation between multiple nodes in order to enhance the overall link quality between the source and destination.

Next generation broadband multimedia communication systems integrate various functions and applications in the system and support large data rates with sufficient robustness to radio impairments. OFDM has the capability of supporting all the above requirements of the next generation communication systems. It is special case of multi-carrier communication system, where single data stream is transmitted over a number of lower sub-carriers. OFDM communication systems can be seen as either a modulation or multiplexing technique where the entire bandwidth is divided in to N sub channels which carry orthogonal subcarriers. One main reason to use OFDM is to increase the robustness against frequency selective fading or narrow band interference. This communication system is broadly considered as an effective approach for the future high speed wireless multimedia communication systems.

However, Synchronization issues and mobility of cooperating nodes pose a big challenge in OFDM based cooperative communication systems. The benefits of cooperative communication could easily be undone by improper synchronization. The problem arises because it would be difficult, from a complexity perspective, for multiple transmitting nodes to synchronize to a single receiver. And also the high mobility of cooperating nodes with respect to the transmitting node could introduce Doppler shift. Thus, these two issues: mobility and synchronization error, introduce Carrier Frequency Offset (CFO), which is the cause of Inter Carrier Interference (ICI) in OFDM based communication systems. Severe ICI could result in total damage of the transmitted signal in cooperative communication system.

1.3 Objectives

General objective:

- To mitigate the effects of high mobility and frequency synchronization error of transmitter-receiver oscillators in OFDM based cooperative communication systems.

Specific Objectives:

(i) Develop efficient adaptive carrier frequency offset estimation and equalization algorithms at the receiver.

(ii) Develop cooperation scheme (No-Cooperation, AAF) at the cooperating node.

(iii) Do performance analysis of the proposed and different CFO mitigation techniques of OFDM based communication systems in different modulation schemes.

1.4 Thesis Outline

The organization of this thesis is as follows:

Chapter 2 provides an overview of the fundamental background knowledge of our research in OFDM based cooperative communication system. The development history from MIMO to cooperative communication is introduced. It focuses on the infrastructure of the cooperative communication, but also AAF relay protocol and DAF relay protocol and others relaying techniques are reviewed. OFDM, which is a favorite multicarrier modulation technique in modern communication, possesses the advantage of frequency parallel transmission, high speed communication and efficient spectrum usage. The effects of CFO and familiar methods to mitigate CFO effects are discussed in this chapter. By integrating OFDM into cooperative communication, the gains from both are combined. Cyclic Prefix (CP)-OFDM is briefly reviewed in this chapter.

Chapter 3 discusses about the methodology. The first part shows the design parts of OFDM system. The signal and system model of the OFDM system is discussed in this part. Then, it is followed by the mathematical modeling of the maximum likelihood estimator which is used to combat the effects of carrier frequency offset. Section 3.3 discusses the design parameters and environmental aspects of cooperative communication system. Section 3.4 discusses the overall system development and designing. The overall system modeling is also discussed in this section.

In chapter 4, several simulations are performed and different results are obtained. This chapter investigates the BER performance of the system under different communication environment. Also in this chapter, the Maximum Likelihood (ML) method is compared with the most familiar CFO mitigation method, the self-cancellation method, in terms of BER.

Chapter 5 summarizes all main results of the thesis, draws overall conclusions and gives some recommendations for future work.

CHAPTER TWO

Literature Review

2.1 Introduction

Signal fading in multipath signal propagation environment is one of the major impairments to meet the demands of next generation wireless networks for reliable and high data rate services. To mitigate the effects of signal fading in wireless communication systems time, frequency, and spatial diversity techniques or their combinations can be used. Among different types of diversity techniques, spatial diversity is of special interest as it does not incur system losses in terms of delay and bandwidth efficiency [2].

Recently, cooperative diversity in wireless network has received great interest and is regarded as a promising technique to mitigate signal fading, which results in signal loss or fluctuation in the amplitude of the received signal [9]. Cooperative communication is a new wireless communication paradigm which generates independent paths between the user and the base station by introducing a relay channel. The relay channel can be thought of as an auxiliary channel to the direct channel between the source and destination. The basic idea behind cooperation is that several users in a network pool their resources in order to form a virtual antenna array which creates spatial diversity [3-5]. Since the relay node is usually at several or more wavelengths distant from the source, the relay channel is guaranteed to fade independently from the direct channel, which introduces a full-rank MIMO channel between the source and the destination. This cooperative spatial diversity leads to improvement of the communication performance in terms of Bit-Error-Rate (BER) performance and channel capacity [6, 18, 23].

OFDM, which is a favorite multi-carrier modulation technique in modern wireless communications, possesses the advantage of frequency parallel transmission, high speed communication and efficient spectrum usage. In addition, it also has the advantage of mitigating the effects of frequency selective channels. By integrating OFDM into cooperative communication, the gains from both are combined and results in improved system performance.

2.2 Orthogonal Frequency Division Multiplexing (OFDM): multi carrier modulation

2.2.1 History

Chang proposed the original orthogonal frequency division multiplexing principles in 1966, and successfully achieved a patent in January 1970 [4]. OFDM is a technique for transmitting data in parallel by using a large number of modulated sub-carriers. These sub-carriers divide the available bandwidth and are sufficiently separated in frequency so that they are orthogonal. The orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period.

In 1971, Weinstein and Ebert proposed a modified OFDM system [2] in which the Discrete Fourier Transform (DFT) was applied to generate the orthogonal subcarrier waveforms instead of the banks of sinusoidal generators. Their scheme reduced the size and implementation complexity of OFDM systems significantly, by making use of the Inverse DFT (IDFT) modules and the digital-to-analog converters. In their proposed model, baseband signals were modulated by the IDFT in the transmitter and then demodulated by DFT in the receiver. Therefore, all the subcarriers were overlapped with others in the frequency domain, while the DFT modulation still assures their orthogonality.

Cyclic prefix (CP) or cyclic extension was first introduced by Peled and Ruiz in 1980 [8] for OFDM systems. In their scheme, conventional null guard interval is substituted by cyclic extension for fully-loaded OFDM modulation. As a result, the orthogonality among the subcarriers was guaranteed. With the trade-off of the transmitting energy efficiency, this new scheme can result in a phenomenal ISI prevention from occurring. Hence, it has been adopted by the current IEEE standards. The paper in [5] introduced an equalization algorithm to suppress both ISI and ICI, which may have resulted from channel distortion, synchronization error, or phase error. In the meantime, [5] also applied Quadrature Amplitude Modulation (QAM) modulation, pilot tone, and trellis coding techniques in his high-speed OFDM system, which operated in voice-band spectrum.

In 1985, [10] introduced a pilot-based method to reduce the interference emanating from the multipath and co-channels. In the 1990s, OFDM systems were exploited for high data rate communications. In the IEEE 802.11 standard, the carrier frequency can go up as high as 2.4 GHz or 5 GHz. Researchers tend to pursue OFDM operating at even much higher frequencies nowadays. For example, the IEEE 802.16 standard proposes yet higher carrier frequencies ranging from 10 GHz to 60 GHz. However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes ICI [12]. The undesired ICI degrades the performance of the system. A number of authors have suggested different methods for ICI reduction. These methods are investigated in this thesis and their performances are evaluated.

Evolution of OFDM:

The evolution of OFDM can be divided into three parts. It consists of Frequency Division Multiplexing (FDM), Multicarrier Communication (MC) and Orthogonal Frequency Division Multiplexing.

I. Frequency Division Multiplexing

FDM has been used for a long time to carry more than one signal over a telephone line. FDM is the concept of using different frequency channels to carry the information of different users. Each channel is identified by the center frequency of transmission. To ensure that the signal of one channel did not overlap with the signal from an adjacent one, some gap or guard band was left between different channels. Obviously, this guard band will lead to inefficiencies which were exaggerated in the early days since the lack of digital filtering made it difficult to filter closely packed adjacent channels.

II. Multicarrier Communication

The concept of Multi carrier communications uses a form of FDM technologies but only between a single data source and a single data receiver. As multicarrier communication was introduced, it enabled an increase in the overall capacity of communications, thereby increasing the overall throughput. Referring to MC as FDM, however, is somewhat misleading since the concept of multiplexing refers to the ability to add signals together. MC is actually the concept of splitting a signal into a number of signals, modulating each of these new signals over its own frequency channel, multiplexing these different frequency channels together in an FDM manner; feeding the received signal via a receiving antenna into a de-multiplexer that feeds the different frequency channels to different receivers and combining the data output of the receivers to form the received signal.

III. Orthogonal Frequency Division Multiplexing

OFDM is simply defined as a form of multi-carrier modulation where the carrier spacing is carefully selected so that each sub-carrier is orthogonal to the other sub-carriers. Orthogonality can be achieved by carefully selecting the sub-carrier frequencies. One of the ways is to select sub-carrier frequencies such that they are harmonics to each other.

2.2.2 Working Principle and System Description of OFDM

OFDM is a combination of modulation and multiplexing. Multiplexing generally refers to independent signals, those produced by different sources. In OFDM the question of multiplexing is applied to independent signals but these independent signals are a sub-set of the one main signal. In OFDM the signal itself is first split into independent channels, modulated by data and then re-multiplexed to create the OFDM carrier. If the FDM system had been able to use a set of subcarriers that were orthogonal to each other, a higher level of spectral efficiency could have been achieved. The guard bands that were necessary to allow individual demodulation of subcarriers in an FDM system would no longer be necessary. The use of orthogonal subcarriers would allow the subcarriers spectra to overlap, thus increasing the spectral efficiency.

As long as orthogonality is maintained, it is still possible to recover the individual subcarriers signals despite their overlapping spectrums. By using OFDM almost half of the bandwidth is saved by overlapping the spectra. The main concept in OFDM is orthogonality of the sub-carriers. The "orthogonal" part of the OFDM name indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. It is possible to arrange the carriers in an OFDM Signal so that the sidebands of the individual carriers overlap and the signals can still be received without adjacent carrier‘s interference. In order to do this, the carriers must be mathematically orthogonal. The carriers are linearly independent (i.e. orthogonal) if the carrier spacing is a multiple of 1/Ts, where Ts is the symbol duration [26-29].

The orthogonality among the carriers can be maintained if the OFDM signal is defined by using Fourier transform procedures. The OFDM system transmits a large number of narrowband carriers, which are closely spaced. Note that at the central frequency of the each sub channel there is no crosstalk from other sub channels. In an OFDM system, the input bit stream is multiplexed into N symbol streams, each with symbol period Ts, and each symbol stream is used to modulate parallel, synchronous sub-carriers. The sub-carriers are spaced by 1/NTs in frequency, thus they are orthogonal over the interval (0, Ts). A typical discrete-time baseband OFDM transceiver system is shown in Figure 2.1. First, a serial-to-parallel (S/P) converter groups the stream of input bits from the source encoder into groups of $\log_2 M$ bits, where M is the alphabet of size of the digital modulation scheme employed on each sub-carrier. A total of N such symbols, X_m, are created. Then, the N symbols are mapped to bins of IFFT. These IFFT bins correspond to the orthogonal sub-carriers in the OFDM symbol. Therefore, the OFDM symbol can be expressed as

$$x(n) = 1/\sqrt{N} \sum_{m=0}^{N-1} X_m \, e^{j2\pi nm/N}, \quad 0 \leq n \leq N-1, \qquad (2.1)$$

where $X_m{}'s$ are the baseband symbols on each sub-carrier. The Digital-to-Analog (D/A) converter then creates an analog time-domain signal which is transmitted through the channel.

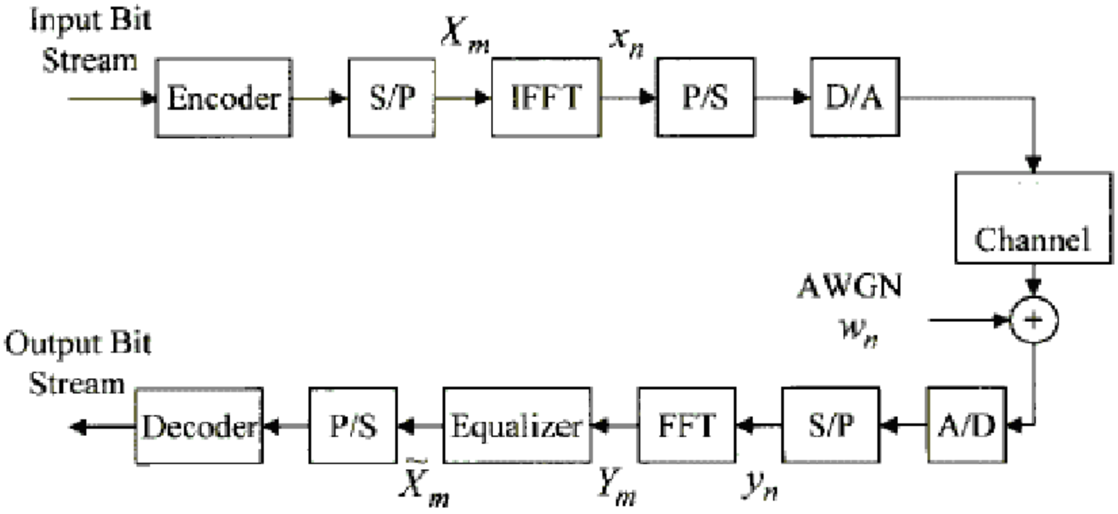

Figure 2.1 Baseband OFDM Transceiver System

At the receiver, the signal is converted back to a discrete N-point sequence $y(n)$, corresponding to each sub-carrier. This discrete signal is demodulated using an N-point FFT operation at the receiver. The demodulated symbol stream is given by:

$$Y(m) = \sum_{n=0}^{N-1} y(n)\, d_k e^{-j\left(\frac{2\pi mn}{N}\right)} + W(m), \quad 0 \leq \mathrm{m} \leq \mathrm{N}\text{-}1, \tag{2.2}$$

Where $W(m)$ corresponds to the FFT of the samples of $w(n)$, which is the Additive White Gaussian Noise (AWGN) introduced in the channel. The high speed data rates for OFDM are accomplished by the simultaneous transmission of data at a lower rate on each of the orthogonal sub-carriers. Because of the low data rate transmission, distortion in the received signal induced by multi-path delay in the channel is not as significant as compared to single-carrier high-data rate systems. For example, a narrowband signal sent at a high data rate through a multipath channel will experience greater negative effects of the multipath delay spread, because the symbols are much closer together. Multipath distortion can also cause ISI where adjacent symbols overlap with each other. This is prevented in OFDM by the insertion of a cyclic prefix between successive OFDM symbols. This cyclic prefix is discarded at the receiver to cancel out ISI. It is due to the robustness of OFDM to ISI and multipath distortion that it has been considered for various wireless applications and standards.

2.2.3 CFO and Its Effects on OFDM Signal

The OFDM systems are very sensitive to the carrier frequency offset and timing; therefore, before demodulating the OFDM signals at the receiver side, the receiver must be synchronized to the time frame and carrier frequency which has been transmitted. Of course, in order to help the synchronization, the signals that are transmitted, have the reference parameters that are used in receiver for synchronization. However, in order the receiver to be synchronized with the transmitter, it needs to know two important factors:

(i) Prior to the FFT process, where it should start sampling the incoming OFDM symbol from.

(ii) How to estimate and correct any carrier frequency offset (CFO)

After estimating the symbol boundaries in the receiver and when the presence of the symbol is detected the next step is to estimate the frequency offset, which is one of the objectives of this thesis.

When CFO happens, it causes the received signal to be shifted in frequency (δf); this is illustrated in the figure 2.1. If the frequency error is an integer multiple I of subcarrier spacing δf, then the received frequency domain subcarriers are shifted by δf X I [11].

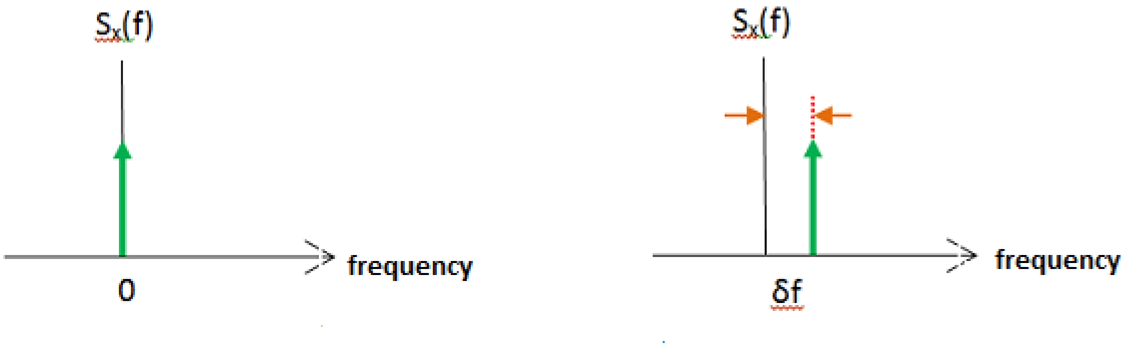

Figure 2.2 Effect of Carrier Frequency Offset

On the other hand, the subcarriers (SCs) will only be sampled at their peak, and this can only occur when there is no frequency offset. However, if there is any frequency offset the sampling will be done at the offset point, which is not the peak point [11]. This causes to reduce the amplitude of the anticipated subcarriers, which can result to raise the ICI from the adjacent subcarriers. Figure 2.3 shows the impact of carrier frequency offset (CFO).

It is necessary to mention that although it is true that the frequency errors typically arise from a mismatch between the reference frequencies of the transmitter and the receiver local oscillators, but this difference is avoidable due to the tolerance that electronics elements have [11].

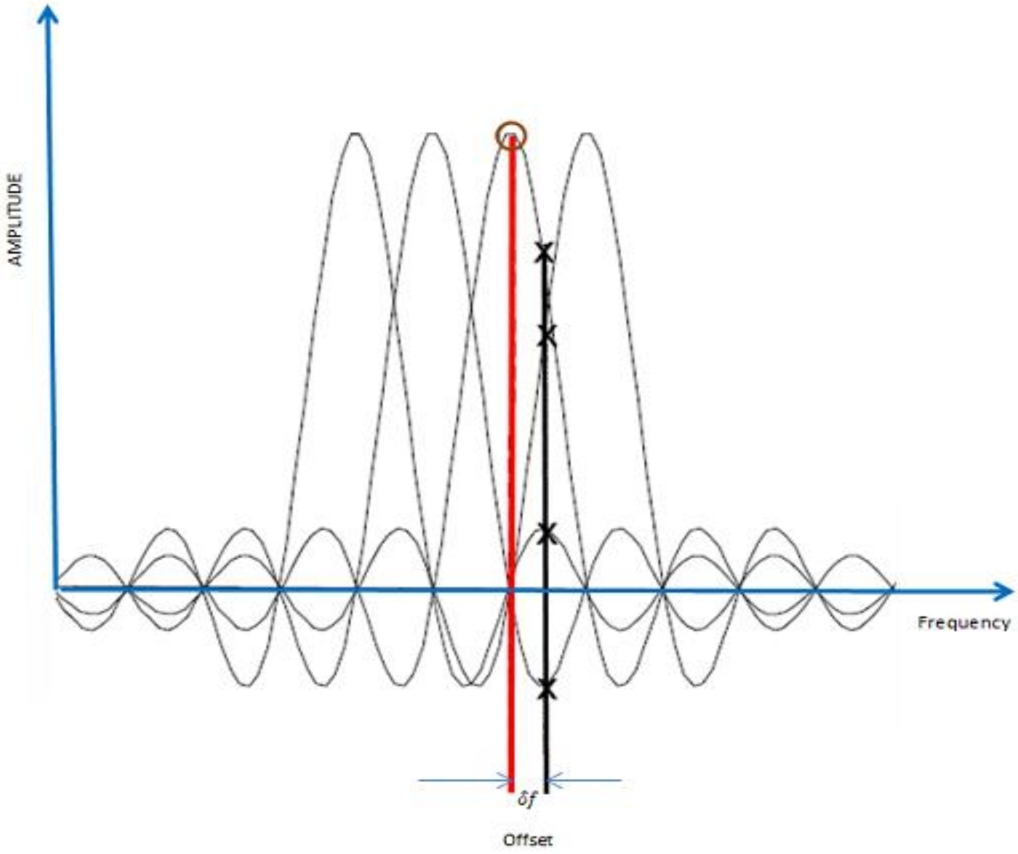

Figure 2.3 Frequency Offset

2.2.4 Inter Carrier Interference (ICI)

The inter-carrier interference is the main disadvantage of OFDM, however, is its susceptibility to small differences in frequency at the transmitter and receiver, normally referred to as carrier frequency offset [10]. This carrier frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by differences between the frequencies of the local oscillators at the transmitter and receiver.

The frequency offset is modeled as a multiplicative factor introduced in the channel. The received signal is given by,

$$y_n = x_n e^{j2\pi ftxnTs} + w(n)$$

$$y_n = x_n e^{j2\pi n\xi /N} + w(n) \qquad (2.3)$$

where ξ is the normalized frequency offset, and is given by $f_{tx}TsN$ and $w(n)$ is the noise.

The effect of this frequency offset on the received symbol stream can be understood by considering the received symbol Y(k) on the K-th sub-carrier [10].

$$Y(k) = X(k)S(0) + \sum_{l=0,l\neq k}^{N-1} X(l)S(l-k) + W(k), k = 0,1 \ldots, N-1, \qquad (2.4)$$

where N is the total number of subcarriers, $X(k)$ is the transmitted symbol for the k-th subcarrier, $W(k)$ is the FFT of $w(n)$, and $S(l-k)$ are the complex coefficients for the ICI components in the received signal [10]. The complex coefficients are given by:

$$S(l-k) = \frac{\sin(\pi(l+\xi-k))}{N sin(\frac{\pi(l+\xi-k)}{N})} \exp(j\pi\left(1-\frac{1}{N}\right)(l+\xi-k)) \qquad (2.5)$$

The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It serves as a good indication of signal quality. It has been derived in [10] and is given below. The derivation assumes that the standard transmitted data has zero mean and the symbols transmitted on the different sub-carriers are statistically independent.

$$CIR = \frac{|S(k)|^2}{\sum_{l=0,l\neq k}^{N-1}|S(l-k)|^2} \tag{2.6}$$

2.2.5 CFO Estimation and Compensation Techniques

Currently a few different approaches for reducing ICI have been developed. These approaches include the ICI self-cancellation and frequency-domain equalization scheme. In the following sections these methods will be discussed.

I. Self-cancellation scheme

Self-Cancellation method is studied most among other ICI reduction methods. The method is investigated by different authors in [10, 11]. It is also called as Polynomial Cancellation Coding (PCC) or (half-rate) repetition coding.

The main idea in self-cancellation is to modulate one data symbol onto a group of subcarriers with predefined weighting coefficients to minimize the average carrier to interference ratio (CIR). This is the main drawback of this method because it utilizes half of the available subcarriers for ICI reduction.

A. Cancellation in modulation

In an OFDM communication system, assuming the channel frequency offset normalized by the subcarrier separation is ξ and the ICI self-cancellation scheme requires that the transmitted signals be constrained such that

$$X(1) = -X(0), X(3) = -X(2), \dots\dots\dots.., X(N-1) = -X(N-2)\,, \tag{2.7}$$

then the received signal on subcarrier k can be written as in (2.4).

The first term in the right-hand side of (2.4) represents the desired signal. The second term is the ICI component. The sequence $S(l-k)$ is defined as the ICI coefficient between l-th and k-th subcarriers, which can be expressed as (2.5).

Using (2.5), this assignment of transmitted symbols allows the received signal on subcarriers k and k + 1 to be written as [10, 11]:

$$Y'(k) = \sum_{l=0, l=even}^{N-2} X(l)[S(l-k) - S(l+1-k)] + W(k) \tag{2.8}$$

$$Y'(k+1) = \sum_{l=0, l=even}^{N-2} X(l)[S(l-k-1) - S(l-k)] + W(k+1) \tag{2.9}$$

Where $W(k) and\, W(k+1)$ is the noise added to the received signal. And the ICI coefficient $S'(l-k)$ is denoted as [10, 11],

$$S'(l-k) = S(l-k) - S(l+1-k) \tag{2.10}$$

B. Cancellation in demodulation

ICI modulation introduces redundancy in the received signal since each pair of subcarriers transmit only one data symbol. This redundancy can be exploited to improve the system power performance, while it surely decreases the bandwidth efficiency. To take advantage of this redundancy, the received signal at the (k + 1)-th subcarrier, where k is even, is subtracted from the k-th subcarrier. This is expressed mathematically as [11]:

$$Y^{''}(k) = Y^{'}(k) - Y^{'}(k+1) \tag{2.11}$$

Subsequently, the ICI coefficients for this received signal become [11]:

$$S^{''}(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \tag{2.12}$$

Due to the repetition coding, the bandwidth efficiency of the ICI self-cancellation scheme is reduced by half. To fulfill the demanded bandwidth efficiency, it is suggested to use a larger signal alphabet size. This thesis showed that using maximum likelihood CFO estimation method can overcome the drawback of the self-cancellation scheme.

II. Frequency-Domain Equalization

Frequency domain equalization can be used to remove the effect of distortions causing ICI. In [38], frequency domain equalization is used to remove the fading distortion in an OFDM signal where a frequency non-selective, time varying channel is considered. Once the coefficients of the equalizer are found, linear or decision feedback equalizers are used in frequency domain.

One interesting point here is how the coefficients are calculated. Since ICI is different for each OFDM symbol, the pattern of ICI for each OFDM symbol needs to be calculated. CFO is estimated through the insertion of frequency domain pilot symbols in each symbol. A pilot symbol is inserted to adjacent a silence among two sub-blocks. This method is demonstrated in Figure 2.4.

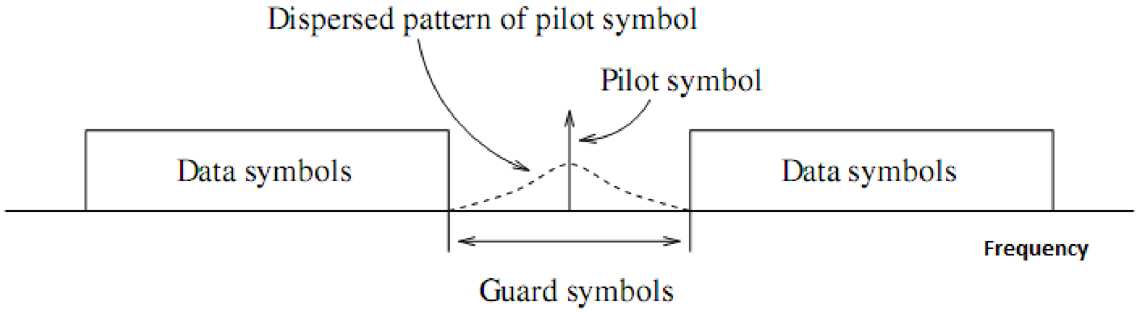

Figure 2.4 Dispersed Pattern of a Pilot in an OFDM Data Symbol.

Apart from pilot insertion method, a nonlinear adaptive filter in frequency domain is also used to reduce ICI [39]. This filtering is applied to reduce ICI due to the frequency offset. A nonlinear filter is used since it uses higher order statistics. However it converges slowly.

2.3 Cooperative Communication

2.3.1 Historical Background: from MIMO to cooperation

For spatial diversity, high data rates and reliable wireless transmissions can only be achieved for full-rank MIMO users [6, 15, 26]. To overcome the limitations of achieving MIMO gains in future wireless networks, it is appropriate to think of a new technology beyond the traditional point-to-point communication. This brought to the technology known as cooperative communication and networking, which allows different users or nodes in a wireless network to share resources (antennas) and to create collaboration by means of distributed transmission, in which each user's information is transmitted not only by the user but also by collaborating users [13]. Cooperative communication and networking is a new communication paradigm that promises significant capacity and multiplexing gain increases in wireless networks [14, 15]. It realizes a new form of spatial diversity to combat the detrimental effects of severe fading by mimicking the MIMO, while getting rid of the drawbacks of MIMO such as size limitation and correlated channels [3-5].

MIMO system designs comprise of multiple antennas at both the transmitter and receiver to offer significant increases in data throughput and link range without additional expenditure in frequency and time domain. Spatial diversity has been studied intensively in the context of MIMO systems. It has been shown that utilizing MIMO systems can significantly improve system throughput and reliability [2].

In the MIMO system, high data rates and reliable wireless communications are guaranteed by full-rank MIMO users. More specifically, full-rank MIMO users should have multiple antennas at the mobile terminal, and these antennas should see independent channel fades to the multiple antennas located at the base station. In practice, not all users can guarantee such high rates because they either do not have multiple antennas installed on their small-size devices, or the propagation environment cannot support MIMO because, for example, if there is not enough independent scattering. In the latter case, even if the user has multiple antennas installed full-rank MIMO is not achieved because the paths between several antenna elements might not be uncorrelated.

The traditional view of a wireless system is that it is a set of nodes trying to communicate with each other. From a different viewpoint, and by considering the broadcast nature of the wireless channel, we can regard those nodes as a set of antennas geographically distributed in the wireless network. By adopting this point of view, nodes in the network can cooperate together for distributed transmission and for processing the information. The cooperating node acts as a relay node for the source node. Since the relay node is usually at several or more wavelengths distant from the source, the relay channel is guaranteed to fade independently from the direct channel. In this way, a full-rank MIMO channel between the source and the destination is obtained. In the cooperative communication setup, there is a-priori constraint for cooperative nodes receiving useful energy that has been emitted by the transmitting node. The new paradigm in user cooperation is that, by implementing the appropriate signal processing algorithms at the nodes of the network, multiple receiving terminals can process the transmissions coming from other nodes and can enhance the radio performance by relaying information for each other. The relayed information is subsequently combined at a destination node so as to create spatial diversity. This creates a network that can be regarded as a system implementing a distributed multiple antenna where collaborating nodes create diverse signal paths for each other [6].

2.3.2 Infrastructure: relays in cooperative communication

Cooperative relay communication is a new paradigm shift for the next generation wireless system that will guarantee high data rates to all users in the network. It is anticipated to be the key technology aspect in the fifth generation wireless networks [6].

In terms of research ascendance, the communication based on cooperative relays can be seen as related to research on the relay channel and on MIMO systems. The concept of user cooperation itself was introduced in two parts [5]. In these works, the authors proposed a two-user cooperation system, in which pairs of terminals in the wireless network are coupled to help each other forming a distributed two-antenna system. Cooperative communication allows different users or nodes in a wireless network to share resources and to create collaboration through distributed transmission and processing, in which each user's information is sent out not only by the user but also by the collaborating users [13]. Cooperative relay communication promises a significant capacity and multiplexing gain increase in the wireless system [14, 15]. It also realizes a new form of space diversity to combat the detrimental effects of severe fading. The way in which the relay processes and retransmits the signal, defines the cooperation method. These methods are:

I. Amplify and forward (AAF)
II. Decode and forward (DAF)
III. Compress and forward (CF)
IV. Coded cooperation (CC)

However, the first two schemes are the most familiar and common in cooperative communication system.

I. Amplify-and-Forward (AAF)

In AAF [5, 31], the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low cost implementation. But the noise is also amplified at the relay.

The AAF relay channel can be modeled as follows. The signal transmitted from the source, denoted as, x, is received at both the relay (r) and destination (d) as

$$y_{s,r} = \sqrt{E_s} h_{s,r} x + n_{s,r} \tag{2.13}$$

and

$$y_{s,d} = \sqrt{E_s} h_{s,d} x + n_{s,d} \tag{2.14}$$

Where $h_{s,r}$ and $h_{s,d}$ are the channel gains between source and relay and source and destination, respectively; they are modeled as Rayleigh flat fading channels. The terms $n_{s,r}$ and $n_{s,d}$ denote the additive white Gaussian noise with zero-mean and variance No. E_s is the transmission energy per bit at the source node. In this protocol, the relay amplifies the signal from the source and forwards it to the destination ideally to equalize the effect of the channel fading between the source and the relay [5]. The relay does that by simply scaling the received signal by a factor A_r that is inversely proportional to the received energy and is denoted by

$$A_r = \sqrt{\frac{E_s}{E_s h_{s,r} + N_o}} \tag{2.15}$$

The destination receives two copies of the signal x from source link and relay link. There are different techniques to combine the two signals at the destination. The optimal technique that maximizes the overall Signal-to-Noise Ratio (SNR) is the Maximal Ratio Combiner (MRC). Note that the MRC combining requires a coherent detector that has knowledge of all channel coefficients, and the SNR at the output of the MRC is equal to the sum of the received signal-to-noise ratios from all branches.

II. Decode and Forward (DAF) Protocol

Another protocol is termed as a decode-and-forward scheme, which is often simply called DAF protocol. In DAF, the relay attempts to decode the received signals. If successful, it re-encodes the information and retransmits it [17]. Although the DAF protocol has the advantage over the AAF protocol in reducing the effects of additive noise at the relay, the system complexity will be increased to guarantee correct signal detection.

Note that the decoded signal at the relay may be incorrect. If an incorrect signal is forwarded to the destination, the decoding at the destination is meaningless. It is clear that for such a scheme the diversity achieved is only one, because the performance of the system is limited by the worst link from the source-relay and source-destination [17].

Although DAF relaying has the advantage over AAF relaying in reducing the effects of noise and interference at the relay, it entails the possibility of forwarding erroneously detected signals to the destination, causing error propagation that can diminish the performance of the system. The mutual information between the source and the destination is limited by the mutual information of the weakest link between the source-relay and the combined channel from the source-destination and relay-destination [17,18].

Since reliable decoding is not always available, it also means that the DAF protocol is not always suitable for all relaying situations. The tradeoff between the time-consuming decoding, and a better cooperative transmission, finding the optimum hybrid cooperative schemes, that include both DAF and AAF for different situations, is an important issue for the cooperative wireless network design.

III. Compress and Forward (CF)

In Compress and Forward (CF) scheme, instead of decoding the source messages, the cooperating node helps the destination by forwarding a compressed version of its received signal. The transmission cycle is divided into two stages. During the first stage, both the cooperating node and the destination listen to the source node. In the second stage, the cooperating node quantizes its observations and sends the quantized data to the destination. In general, the correlation between the cooperating node and destination node observations can be exploited using Wyner-Ziv coding to reduce the data rate at the cooperating node [32]. During the second stage, new information is also sent by the source to further boost the total throughput.

A practical approach to the CF cooperative scheme is the Slepian-Wolf (SW) cooperation proposed in [36]. Slepian-Wolf cooperation exploits practical Slepian-Wolf codes in wireless user cooperation to help combat inter-user outage.

This type of cooperation scheme can be useful in the cases where the source-cooperating node link is very noisy since requiring the cooperating node to decode the message under these circumstances before starting to help the destination, may adversely affect the performance.

IV. Coded Cooperation (CC)

Coded Cooperation integrates cooperation into channel coding. In this method, portions of the user's codeword are sent through independent fading paths. The idea behind this is that each user tries to retransmit incremental redundancy to its partner. In the cases where this is not possible, the system switches to a non cooperative scheme. The big challenge in the CC method (for it to be efficient) is that it should be managed by the code design, to avoid the need of feedback between the users. A detailed description can be found in [20,21,22].

The data transmission period for each user is divided into two time segments of N1 and N2 bit intervals, respectively. N1 and N2 correspond to the size of portions in which the codeword was divided. Each portion is a codeword itself although weaker than the original. For the first interval, each user transmits a codeword consisting of the N1-bit code partition. Each user also tries to decode the transmission of its partner. If successful (determined by checking the CRC code), in the second frame the user calculates and transmits the second code partition of its partner, containing N2 code bits. Otherwise, the user transmits its own second partition, which also contains N2 bits. Thus, each user always transmits a total of N = N1 +N2 bits per source block over the two frames. The level of cooperation is defined as N2/N that is the percentage of the transmitted bits corresponding to the partner.

This method has the advantage that the amount of information sent remains the same, compared with a non-cooperative scheme. Furthermore, by trying to decode the partner's codeword, it has also an embedded method for measuring the quality of the inter-user channel to evaluate if it is worth cooperating. One disadvantage is that a complex protocol is needed to define whether there was cooperation or not. Other is that the processing load on the relay is higher compared with the AF case.

2.3.3 Advantages of Cooperative Communications

Cooperative communications are being studied as an alternative for generating virtual MIMO systems in cases where multiple antennas are not practical to implement in a single device, given their size or battery limitations. Providing the receiver of two uncorrelated faded versions of the signal increases the chances of the receiver to make a correct decision on the information received. As a result of spatial diversity, two important benefits can be identified by using cooperative communications: power efficiency and spectral efficiency.

In the case of power efficiency it may be argued that more power is needed because each user is transmitting for more than itself. However, the baseline transmit power from all users may be reduced because of the diversity i.e. lower SNR levels are required to achieve the same BER. Therefore it is expected that the net transmit power is reduced.

When it comes to the rate of the system, a counter argument can be that each user transmits its own bits plus the partner’s bits, which would decrease the rate of the system. However, due to diversity, the channel code rates can be increased, increasing the spectral efficiency of each user. Even in the cases where the different paths are correlated, the combination of correlated links provides also extra coding gains due to repetition of information.

Cooperative communications also offer the possibility of using different network topologies, providing higher flexibility. In some of these topologies, e.g. cooperative gateways and randomized cooperation are presented. The potential and challenges from the network topology point of view are also described.

In addition to the benefits resulting from cooperative diversity, there are also benefits related to the use of the relay itself. Higher coverage areas can be achieved by the efficient use of terminals that work both as user and as relays. These can translate in solutions for serving hotspots or providing better coverage in corporate buildings for example.

At the network level, studies have shown that diversity provided by MIMO space-time codes can improve performance at the medium access control (MAC), network and transport layers. This improvement in performance is also valid for cooperative systems.

2.4 OFDM Based Cooperative Communication

In wireless communication, antenna diversity has been intensively used to mitigate the effects of fading in the recent past years. Cooperative communication has become one of the promising cutting-edge techniques in providing solutions to the fading effects in wireless communication, as it maintains virtual antenna array without utilizing multiple antennas. Single carrier modulation schemes are usually used in cooperative communication in the case of the flat fading channel.

In beyond third generation and fourth generation wireless communication systems, fast moving terminals and scatterers are expected to cause the channel to become frequency selective. OFDM is a powerful solution for such channels. OFDM has a relatively longer symbol duration than single carrier systems which makes it very immune to fast channel fading and impulsive noise. However, the overall system performance may be improved by combining the advantages of cooperative communication and OFDM systems (CO-OFDM) when the source terminal has the above-mentioned physical limitations.

2.5 Challenges Encountered by Integrating OFDM in Cooperative Communication Systems

Synchronization issues and mobility of cooperating node pose a big challenge in OFDM based cooperative communication systems. The benefits of cooperative communication could easily be undone by improper synchronization. The problem arises because it would be difficult, from a complexity perspective, for multiple transmitting nodes to synchronize to a single receiver. And also the high mobility of cooperating nodes with respect to the transmitting node could introduce Doppler shift. Thus, these two issues, mobility and synchronization error, introduce CFO, which is the cause for Inter Carrier Interference in OFDM based communication systems. Severe ICI could result in total damage of the transmitted signal in cooperative communication system [23].

A handful of papers have been published in recent years describing OFDM based cooperative communication systems [7]-[10]. Most of them, however, are restricted in specific system structure.

In [1], ICI self-cancellation of the data-conversion method was proposed to cancel the ICI caused by frequency offset in the OFDM system. In [4], ICI self-cancellation of the data-conjugate method was proposed to minimize the ICI caused by frequency offset and it could reduce the peak average to power ratio (PAPR) than the data-conversion method. In [24], self ICI cancellation method which maps the data to be transmitted onto adjacent pairs of subcarriers has been described. But this method is less bandwidth efficient. It utilizes half of the subcarriers to mitigate the effects of CFO.

In addition, statistical approaches have also been explored to estimate and cancel ICI [6]. The problem with this approach is also it utilizes almost half of the subcarriers in order to deal with the effects of CFO.

In this thesis the OFDM based cooperative system is modeled and simulated under AWGN and fading channel. It is concerned with combating the effects of ICI induced by CFO by using cyclic prefix estimation and maximum likelihood method to compensate for the introduced CFO.

CHAPTER THREE

Methodology

3.1 Introduction

In this chapter an OFDM based cooperative communication system with AAF protocol is developed. In order to completely avert the effects of ISI from occurring, some redundant information is added into the OFDM symbols before transmission. The redundant information is called cyclic prefix (CP) and its length is made to vary depending on the channel state between the communicating parties. Maximum likelihood (ML) estimation is used to estimate and compensate for the CFO that occurs due to the Doppler shift and transmitter-receiver carrier frequency offset. ML estimation is compared with the self-cancellation estimation families and is found to be better in many aspects. The cooperating node is assumed to get the line-of-sight signal from the source and hence, the channel between the cooperating nodes is assumed to have Rician fading characteristics. The channels between the source node and the receiver and the cooperating node and the receiver as well are assumed to be frequency selective and Rayleigh fading. The cooperating node is to be only a few meters apart (up to 10 meters) from the source node. Therefore, the channel between the source node and the receiver and the channel between the cooperating node and the receiver are assumed to have the same characteristics. Hence, the CFO estimated at the receiver up on the arrival of the signal from the source node will be used to compensate the effects of CFO on the signal from the source and on a copy of the signal from the cooperating node.

In this chapter the methods of designing and modeling is described. First the underpinning part of the research, the design of OFDM system, is carried out. Then maximum likelihood estimation is integrated into the developed OFDM system in order to compensate for the effects of carrier frequency offset. Then the design of cooperative communication is carried out with amplification and forward cooperation scheme. Different scenarios are considered and most practical communication environment is assumed in designing the system. Finally the developed OFDM and cooperative communication systems are integrated.

3.2 Orthogonal Frequency Division Multiplexing System Design with Maximum Likelihood Estimation

3.2.1 Signal Model

The signal to be transmitted over the wireless channel must first be converted into OFDM symbols. In OFDM system with N subcarriers, N information symbols are used to construct one OFDM symbol. Each of the N symbols is used to modulate a subcarrier and the N modulated subcarriers are added together to form an OFDM symbol. Orthogonality among subcarriers is achieved by carefully selecting the carrier frequencies such that each OFDM symbol interval contains integer number of periods for all subcarriers. Using discrete-time baseband signal model, one of the most commonly used schemes is the IDFT-DFT based OFDM systems. Guard time, which is cyclically extended to maintain inter-carrier orthogonality, is inserted that is assumed longer than the maximum delay spread to totally eliminate inter-symbol-interference. In the presence of virtual carriers, only M out of N carriers is used to modulate information symbols. Without loss of generality, we assume that the first M carriers are used to modulate information symbol, while the last $N - M$ carriers are virtual carriers. The variable M varies depending on the channel information between the transmitting and receiving nodes. With symbol rate sampling, the discrete time OFDM model is

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} d_k \, e^{j\,2\pi nk\,/N} \tag{3.1}$$

where each d_k is used to modulate the subcarrier $e^{j2\pi k/N}$. Written in matrix form, we have

$$s = \boldsymbol{Wd} \tag{3.2}$$

where **W** consists of the first M columns of the IDFT matrix and **d** = [$d0$, · · ·, $dM-1$] is the symbol vector. In the presence of time dispersive channel, additive noise, and carrier frequency offset, the OFDM signal at the receiver is now,

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} H(k)\, dk e^{j\left(\frac{2\pi k}{N} + \Delta\omega . Ts\right)n} + \mathrm{z}[\mathrm{n}] \tag{3.3}$$

where $H(k)$ is the channel frequency response corresponding to subcarrier k, $z(n)$ is additive complex Gaussian noise, and $Ts= T/N$ is the symbol interval with T being the IDFT interval (or OFDM symbol interval, excluding the guard time, as often termed in the literature).Here the initial phase due to frequency offset is assumed to be zero (equivalently, the initial phase can be absorbed into $H(k)$).Notice if we define $\varphi = \Delta\omega \cdot Ts$, then φ and the frequency offset Δω differ only by a constant scalar, hence estimation of Δω is equivalent to estimation of the normalized phase shift φ.

3.2.2 System Model

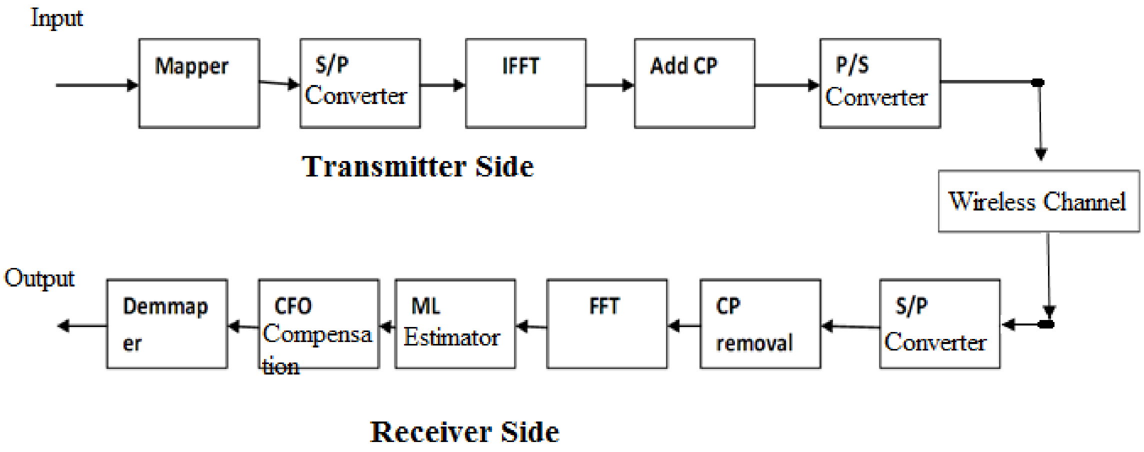

Figure 3.1 OFDM System

An OFDM system diagram is shown in figure 3.1 above. Upon receiving the bit stream to be transmitted the system performs modulation. Hence the bit stream will be converted into symbols. Then the system performs serial to parallel conversion. The number of parallel symbols should coincide with the number of available subcarriers. After the conversion, IFFT is performed to obtain OFDM symbol. The cyclic prefix (CP) is lastly added before transmission to minimize the inter-symbol interference (ISI) and to be used for CFO estimation at the receiver. The signal is converted by into series form before transmission; hence parallel to series converter is used. At the receiver, the process is reversed to obtain the decoded data. The CP is removed to obtain the data in the discrete time domain and then processed using the FFT for data recovery. Since the wireless channel is known to be fading and to introduce Doppler shift, the maximum likelihood (ML) estimator that comes immediately after the FFT block in the system is used to perform CFO estimation. Then using the estimated values of CFO inter carrier interference (ICI) that occurs during transmission will be compensated. Finally the symbols pass through the demapper (demodulation) in order to generate the received bit streams. The system is simulated using MATLAB simulation software and the system performance was evaluated by calculating the bit error rate.

3.2.3 Maximum Likelihood Estimation of CFO at the Receiver

This method has been presented in several papers in slightly varying forms [8, 9]. The training information required is at least two consecutive repeated symbols. The IEEE 802.11a preamble satisfies this requirement for both the short and long training sequence. Let the transmitted baseband signal be s_n, and then the complex baseband model of the passband signal y_n is

$$y_n = s_n e^{j2\pi f_{tx} nT_s}, \tag{3.4}$$

where f_{tx} is the transmitter carrier frequency and Ts is the sampling interval. After the receiver down-converts the signal with a carrier frequency f_{rx}, the received complex baseband signal r_n is

$$\begin{aligned} r_n &= s_n e^{j2\pi f_{tx} nTs} e^{-j2\pi f_{rx} nTs} + wn \\ &= s_n e^{j2\pi(\Delta f)nTs} + w_n \qquad (3.5) \end{aligned}$$

where $\Delta f = f_{tx} - f_{rx}$ is the carrier frequency offset and w_n the white Gaussian noise with variance No..

Let *D* denote the delay between the identical samples of the two repeated symbols. Then the frequency offset estimator is developed as follows: The cross-correlation of the two consecutive symbols is computed as,

$$\begin{aligned} c &= E[\textstyle\sum_{n=0}^{N-1} r_n\, r_{n+D}^*]) \\ &= E[\textstyle\sum_{n=0}^{N-1} (s_n\, e^{j2\pi\Delta f nTs} + w_n\,)\big((s_{n+D}\, e^{j2\pi\Delta f(n+D)Ts} + w_{n+D})^*\big)] \qquad (3.6) \end{aligned}$$

Since w_n is an additive white Gaussian noise with zero mean and variance of σ^2, the above equation will reduce to

$$c= \sum_{n=0}^{N-1} s_n \ \ s_{n+D}^{*} e^{j2\pi \Delta f nTs} \ e^{-j2\pi \Delta f(n+D)Ts}$$

$$= e^{-j2\pi \Delta f(D)Ts} \ \sum_{n=0}^{N-1} s_n \ \ s_{n+D}^{*}$$

$$c=e^{-j2\pi \Delta f(D)Ts} \ \sum_{n=0}^{N-1} |s_n|^2 \tag{3.7}$$

Hence, the maximum likelihood estimate gives us the frequency offset estimation as,

$$\Delta f = \frac{angle\ (c)}{2\pi DTs} \tag{3.8}$$

The ML estimation of frequency offset can also be derived after the discrete Fourier Transform (DFT) processing (i.e., in frequency domain). The received signal during two repeated symbols is (ignoring noise for convenience),

$$r_n=\frac{1}{N}\left[\sum_{k=-K}^{K} X_k \ H_k e^{\frac{j2\pi n\,(k+f_r)}{N}}\right], \quad \text{for n=0,1,........,2N-1,} \tag{3.9}$$

where X_k's are the transmitted data symbols, H_k is the channel frequency response for the k-th subcarrier, K is the total number of subcarriers, and f_r is the relative frequency offset to the subcarrier spacing. The DFT of the first symbol and for the *k*-th subcarrier is

$$R_{1,k} = \sum_{n=0}^{N-1} r_n \, e^{\frac{-j2\pi kn}{N}} \quad \text{, k=0,1,2,……,N-1,} \tag{3.10}$$

The DFT of the second symbol is derived as

$$R_{2,k} = \sum_{n=N}^{2N-1} r_n \, e^{\frac{-j2\pi kn}{N}}$$

$$= \sum_{n=0}^{N-1} r_{n+N} \, e^{\frac{-j2\pi kn}{N}}, \text{ k=0,1,2,…,N-1,} \tag{3.11}$$

But from equation (3.4) the received signal at the index n+N, which is $r_{n+N,}$ is given as

$$r_{n+N} = \frac{1}{N}\left[\sum_{k=-K}^{K} X_k \, H_k \, e^{\frac{j2\pi(n+N)(k+f_r)}{N}}\right]$$

$$= \frac{1}{N}\left[\sum_{k=-K}^{K} X_k \, H_k \, e^{\frac{j2\pi n\,(k+f_r)}{N}} e^{j2\pi(k+f_r)}\right], \text{ k=0,1,…N-1,} \tag{3.12}$$

But $e^{j2\pi(k+f_r)} = e^{j2\pi k} e^{j2\pi f_r}$, and $e^{j2\pi k} = 1$, for all integer values of k. Hence, equation (3.11) can be rewritten as

$$r_{n+N} = \frac{1}{N}\left[\sum_{k=-K}^{K} X_k \, H_k \, e^{\frac{j2\pi n\,(k+f_r)}{N}} e^{j2\pi f_r}\right]$$

$$= \frac{1}{N}\left[\sum_{k=-K}^{K} X_k \, H_k \, e^{\frac{j2\pi n\,(k+f_r)}{N}}\right] e^{j2\pi f_r}$$

$$r_{n+N}=r_n e^{j2\pi f_r} \quad , n=0,1,\ldots,2N-1, \tag{3.13}$$

Substituting equation (3.12) into equation (3.10) yields,

$$R_{2,k}= \ = \textstyle\sum_{n=0}^{N-1} r_n \, e^{j2\pi f_r} e^{\frac{-j2\pi kn}{N}}$$

$$R_{2,k}= \ e^{j2\pi f_r} \textstyle\sum_{n=0}^{N-1} r_n \, e^{\frac{-j2\pi kn}{N}}, \text{ k=0,1,2,.N-1}$$

$$R_{2,k} = R_{1,k} \ e^{j2\pi f_r}, \tag{3.14}$$

This, therefore, shows that every subcarrier experiences the same shift that is proportional to the frequency offset. The cross-correlation of the two subcarriers is obtained as follows:

$$\text{C}= \textstyle\sum_{k=-K}^{K} R_{1,k} \, R_{2,k}^{*}$$

$$= \textstyle\sum_{k=-K}^{K} R_{1,k} \left(R_{1,k} e^{j2\pi f_r}\right)^{*}$$

$$= e^{-j2\pi f_r} \textstyle\sum_{k=-K}^{K} R_{1,k} \left(R_{1,k}\right)^{*}$$

$$\text{C} = e^{-j2\pi f_r} \textstyle\sum_{k=-K}^{K} \left|R_{1,k}\right|^{2} \tag{3.15}$$

Thus, the frequency offset estimator governing equation is

$$f_r = \frac{-1}{2\pi}\text{angle(C)}, \tag{3.16}$$

$$\Delta f = \frac{-f_{sc}}{2\pi} \text{angle}(C), \tag{3.17}$$

This is quite similar in form to the time domain version of the ML estimation obtained in equation (3.7).

3.3 Cooperation Design

In this thesis it is set to obtain two-level (order-two) diversity through cooperative communication, meaning the source node will only pair to one cooperating node at a time. Hence, the sending node in the network is always paired to only one access node (cooperating node) in the network. The cooperating node always performs measurements on the link state between the message originating node and itself. If the link state allows cooperation to take place then the cooperating node runs its amplify-and-forward (AAF) protocol and performs signal conditioning on the information received from the information originating node. After conditioning the signal depending on the procedures of amplify-and-forward protocol the cooperating node retransmits it to its intended destination. The reason for choosing this cooperation protocol over the others is its simplicity; it does not consume much time to retransmit the received signal and its performance when incorporated to cellular communication systems.

3.3.1 Communication Channels and Environments

The channel between the source access node and the receiver and as well the channel between the cooperating access node and the receiver are assumed to have six independent fading paths, the worst case in wireless communication system simulation. These channels are also assumed to be frequency selective and time selective fading channels and have the characteristics of Rayleigh fading, figure 3.2 shows this. The Doppler shift due to the relative movement of the cooperating access node to the base station (the receiver) is assumed to be 20% less than that of the Doppler shift due to the relative movement of the source access node to the base station (the receiver). This is assumed because the source node is always forced to pair to a cooperating node with slightly slow mobility relative to its speed. As the mobility of the cooperating node approaches the speed of source node the link between the two nodes will get worse and the noise level will raise.

The source access node is assumed to be paired with a cooperating access node that is only a few wavelengths apart. And also the cooperating access node gets the line-of-sight (LOS) signal from the source access node. Hence, from figure 3.2 below, the channel between message originating node and the cooperating access node is assumed to be Rician and flat and slow fading.

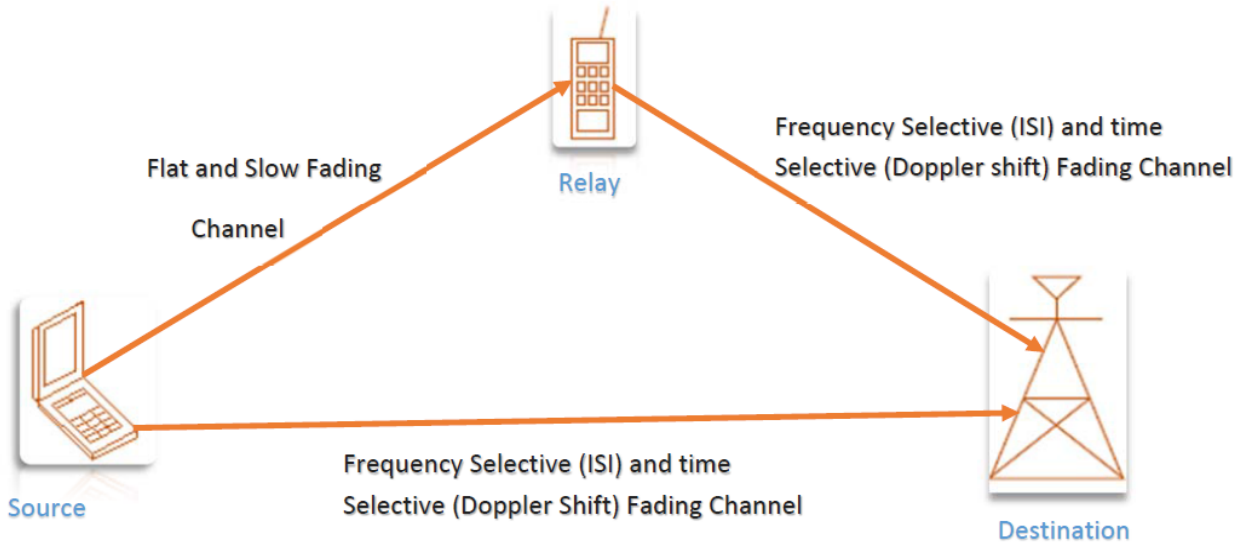

Figure 3.2 Communication Environment

3.4 Integration of OFDM with Cooperation Communication

3.4.1 Overall System Model and Design

Consider a three node OFDM based cooperative communication network with source node (SN), cooperating node (CN) and receiving node (RN). The SN broadcasts its signal over the fading wireless communication channel and both the CN and RN receive the signal. The CN amplifies and re-transmits the received signal depending on the link state between its node and the SN and also if the cooperating switch is on ON state by the time the signal arrives. Ideally it is assumed that the source and cooperating nodes are always near to each other and the cooperating node gets the LOS signal from the source node. Hence, the channel between the source node and the cooperating node assumed to have Rician fading characteristics. The channels between the source node and the receiving node and between the cooperating node and the receiving node are assumed to be frequency selective and Rayleigh fading.

Consider N OFDM subcarriers. In the first time slot, SN transmits one OFDM frame of duration (N+Ng)Ts, where Ts is one sample duration and Ng is the cyclic prefix(CP) length. The transmitted OFDM frame consisting of data symbols X[k], k=0,1,…,N-1, is given by

$$x[n] = \frac{1}{N}\sum_{k=-Ng}^{N-1} X[k]e^{\frac{j\pi\, 2nk}{N}} \qquad , \quad -Ng \leq n \leq N-l\,, \tag{3.18}$$

Let hsc[n], hsr[n] and hcr[n] denote the channel impulse response (CIR) of the source node to cooperating node, the source node to the receiving node and the cooperating node to the receiving node links, respectively. The received OFDM symbols at the cooperating and receiving nodes, during the first phase (time slot) ,will be

$$y_{sc}[n] = x[n] * hsc[n] + n_{sc}[n] \tag{3.19}$$

$$y_{sr}[n] = x[n] * hsr[n] + \ n_{sr}[n] \tag{3.20}$$

where * indicates linear convolution and $n_{sc}[n]$ is the white Gaussian noise signal at the cooperating node and $n_{sr}[n]$ is the white Gaussian noise signal at the receiving node, both white Gaussian noises with variance No. During the second time slot (or cooperation phase), the cooperating node will amplify the received signal by gain β and re-transmits it to the receiving node. Hence, the received signal at the receiving node in this second phase is

$$y_{cr}[n] = \beta y_{sc}[n] * hcr[n] + n_{cr} \tag{3.21}$$

$$= \beta(x[n] * hsc[n] + n_{sc}[n]) * hcr[n] + n_{cr} \tag{3.22}$$

where * denotes linear convolution and n_{cr} is the white Gaussian noise over the cooperating and receiving nodes link with variance No. The magnitude of the amplifying factor is determined based on the transmitted signal energy and the received signal energy:

Let $\xi = E[|x[n]|^2]$, then the energy of the signal received at the cooperating node is

$$E[|ysc[n]|^2] = E[|hsc[n]|^2]E[|x[n]|^2] + E[|nscn[n]|^2],$$

$$= E[|hsc[n]|^2]\xi + 2\mathrm{No}, \tag{3.23}$$

To re-transmit the data with the same power as the source node did, the cooperating node needs to amplify the received signal by a factor of

$$\beta = \sqrt{\xi \Big/ \mathrm{E}[|hsc[n]|^2]\xi + 2\mathrm{No}}, \tag{3.24}$$

The system is developed to support cooperation if and only if $\xi \gg \mathrm{E}[|hsc[n]|^2]\xi + 2\mathrm{No}$, otherwise the cooperating node turns its cooperation mode switch to OFF state.

Therefore, the received signal at the receiving node in two time slots is

$$y[n] = y_{sr}[n] + y_{cr}[n] \tag{3.25}$$

$$= x[n] * hsr[n] + n_{sr}[n] + \beta(x[n] * hsc[n] + n_{sc}[n]) * hcr[n] + n_{cr}$$

$$= x[n] * hsr[n] + \beta x[n] * hsc[n] * hcr[n] + \beta n_{sc}[n] * hcr[n] + n_{sr}[n] + n_{cr}[n]$$

Applying distributive property of convolution,

$$y[n] = x[n] * (hsr[n] + \beta hsc[n] * hcr[n]) + w[n] \tag{3.26}$$

Where, w[n]= $\beta n_{sc}[n] * hcr[n] + n_{sr}[n] + n_{cr}[n]$

The output on the k-th subcarrier is given by performing the discrete Fourier transform on the above equation (3.26),

Define $h_r[n] = hsr[n] + \beta hsc[n] * hcr[n]$, then equation (3.26) becomes

$$y[n] = x[n] * h_r[n] + w[n] \tag{3.27}$$

Then,

$$Y[k]=X[k]Hr[k] + W[k] \tag{3.28}$$

Where, $Hr[k] = Hsr[k] + \beta Hsc[k]Hcr[k]$, where Hsr[k] and Hsc[k] being the N-point DFTs of hsr[n] and hsc[n], respectively.

Equation (3.28) shows the amplitude of the transmitted signal is attenuated by a factor of Hr[k] and interfered by a signal W[k]. To reduce this attenuation of the signal amplitude and mitigate the interference at the destination this thesis used different types of combiners and analyzed the performance of each combiner. In the end MRC combiner has showed better performance and all the simulations on this thesis were performed using MRC combiner.

The schematic diagram below shows the overall system followed by its description.

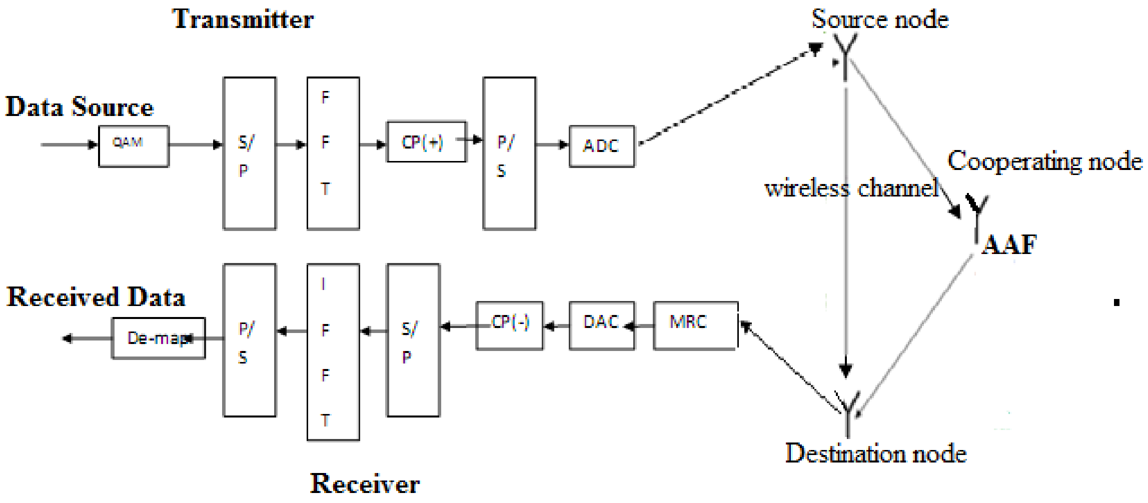

Figure 3.3 OFDM Based Cooperative Communication System

The transmitting node should always perform signal modulation whenever it has a signal to transmit. Hence the bit stream will be converted into symbols. Then the source node performs serial to parallel conversion. The number of parallel symbols should coincide with the number of available subcarriers. After the conversion, IFFT is performed to obtain OFDM symbol. The cyclic prefix (CP) is lastly added before transmission to completely avert inter-symbol interference (ISI) and minimize Inter Carrier Interference (ICI) at the receiving end. CFO estimation is also based on the CP added to the signal. Then the transmitter in the source node converts the parallel data into serial data and transmits it over the air link to the cooperating node and the receiving node. In this first phase, the cooperating node performs amplification of the received signal for re-transmission if the received signal passes the threshold quality for re-transmission. The cooperating node decides to cooperate depending on the state of the channel between the source and cooperating nodes. In the second phase, the receiver receives another copy of the signal from the cooperating node and combines it with the signal received from the source node directly. In this thesis different combiners were checked and tested under different conditions. And the MRC combiner is found to be better for the developed system structure. After obtaining the received signal by combining the direct signal and the signal from the cooperating node, the process that was undertaken in the main transmitting node is reversed to obtain the decoded data. The CP is removed to obtain the data in the discrete time domain and then processed using the FFT for data recovery. Since the wireless channel is known to be fading and to introduce Doppler shift, the ML estimator that comes immediately after the FFT block in the system is used to perform CFO estimation and compensation. Then using the estimated values of CFO, ICI that occurs during transmission will be compensated. Finally the symbols pass through the demapper (demodulation) in order to generate the received bit stream.

3.4.2 ML Estimator at the Receiver

In this thesis we assumed that the source node and the cooperating node to be separated only few meters apart (up to 10 meters maximum) and the cooperating node gets the LOS signal from the source node. This is due to the fact that the cooperating nodes need to be a few wavelengths apart in order to create a virtual MIMO system through spatial diversity [5]. In most cases, if the distance between the source and cooperating nodes is longer than 10 meter the level of the noise added to the transmitted signal will become pronounced and eventually surpass the threshold value. In addition to this, by limiting the distance between the two cooperating nodes to 10 meter, the channel characteristics of source node to destination and cooperating node to destination will be nearly the same. Hence, the carrier frequency offset estimated at the receiver upon the arrival of a signal from the source node will be used to compensate for the effects of CFO on both channels, the channel between the source node and the destination and the channel between the cooperating node and the destination. Meaning, there is no need to estimate the CFO that occurs over the cooperating node to destination channel. This minimizes computational time and complexity at the receiver side.

Moreover, when the distance between the cooperating nodes is limited to 10 meter range, there will be no need to deal with the issue of imperfect timing synchronization. Therefore, in these types of cooperative communication systems, perfect timing synchronization can be assumed between the cooperating nodes. And also, because the cooperating node is located far enough from the source node, there will be no spatial fading correlation between the channels from the source to the destination and from cooperating node to the destination. These reduce computational complexity at the cooperating node and at the intended destination.

CHAPTER FOUR

Simulation Results and Discussion

4.1 Simulation Results and Discussions

For simulation using MATLAB application software package, M-Quadrature Amplitude Modulation (M-QAM) scheme with M=4, where $\log_2$ (M) is the number of bits per symbol, is chosen and the total number of subcarriers is set to 64. These parameters are chosen because the current wireless communication systems, 3G and beyond, are based on them. The fading channel between the source node and the receiver and the fading channel between the cooperating node and the receiver are set to have six different signal propagation paths with 100Hz and 80Hz Doppler frequency, respectively. The 100Hz Doppler shift between the source node and the base station is the worst case in wireless communication system. The reason we chose 80Hz Doppler frequency between the cooperating node and the base station is that the source node is always assumed to select a cooperating node with relatively lower speed. Figure 4.1 below shows the transmitted and the received signal when there is no cooperation.

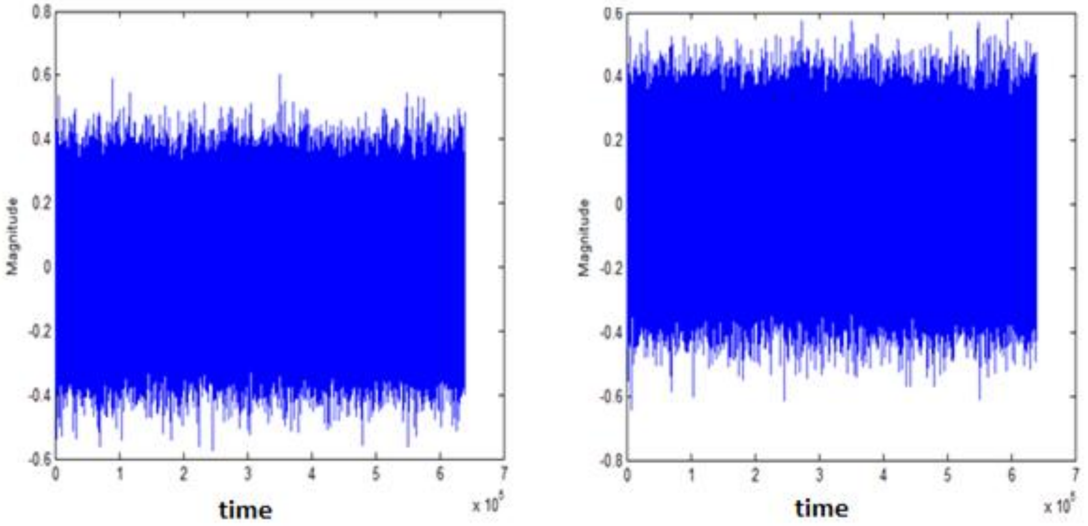

Figure 4.1 Transmitted and Received OFDM Signal, when there is no cooperation

Figure 4.2 shows the performance of the system when there is no cooperation, meaning, when there is no diversity. The broken curve in red color shows the system performance when there is no CFO. But, the broken curve in green color shows the effect of CFO with value of 0.2 in the system performance. This normalized value of CFO is chosen because most OFDM based wireless communication systems are simulated using 0.2 CFO value [8]. [8] Also shows that in most cases OFDM systems are affected by CFO that ranges in the interval [0, 0.5]. The system performance, for instance, at 40dB SNR is less that 10^{-4} when the system is CFO free. But, the system performance deteriorates to nearly 10^{-1} for the CFO value of 0.2.

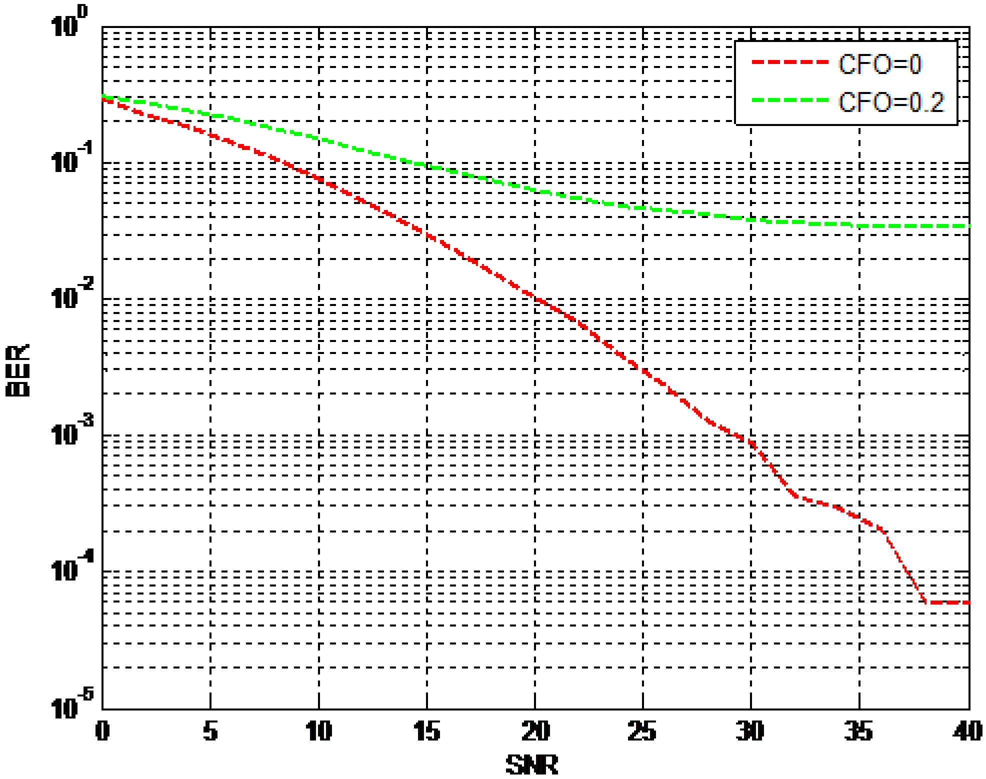

Figure 4.2 System Performance of OFDM System with no Cooperation.

This figure 4.2 shows the BER deteriorating as the system introduces more carrier frequency offset. However, the system performance should improve when carrier frequency estimation technique is incorporated at the receiver side of the system. Figure 4.3a shows the signal received at the cooperating node from the source node and figure 4.3b shows the performance of an ideal OFDM based cooperative communication system. For the case of an ideal cooperative communication system there is no need of mitigating the effects of mobility and frequency synchronization error as there is no inter carrier interference.

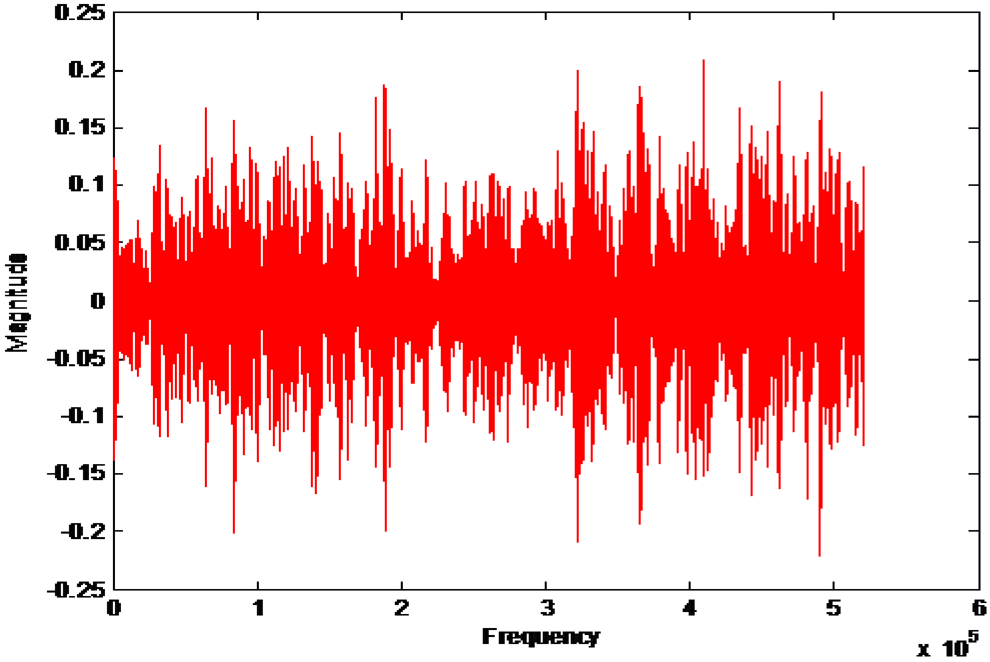

Figure 4.3a Signal Received at the Cooperating Node from the Source Node, 20dB SNR

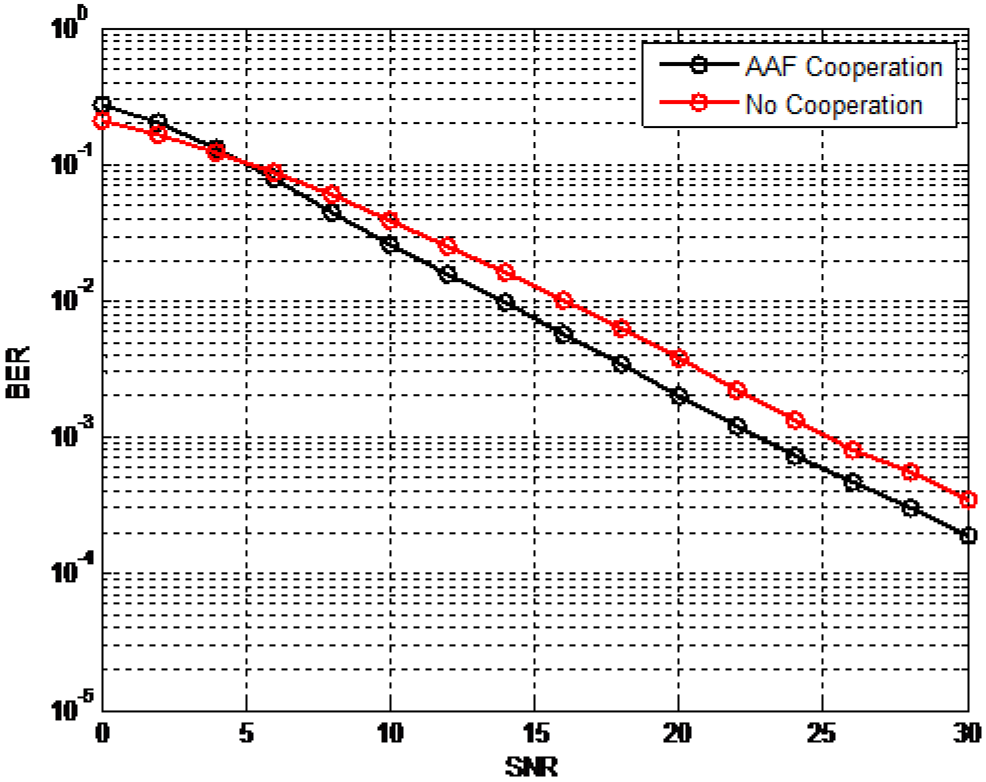

Figure 4.3b OFDM Based Cooperative Communication System Performance

The curve in red color in figure 4.3b shows the system performance when there is no cooperation, meaning when there is no copy of the message signal reaching the base station indirectly through other access node in the network. But the curve in black color in figure 4.3b shows how the system performance improves as cooperation is incorporated in the system.

From the simulation result in figure 4.3b, the BER of the system with cooperation improves as the SNR increases starting from 5dB. Hence, it can be concluded that at higher level of SNR cooperation results in a very improved system performance in terms of BER.

Figure 4.4 shows the effects of CFO deteriorating the performance of OFDM based second-order diversity cooperative communication system. Therefore, maximum likelihood estimation developed in the above session in chapter three to mitigate the effects of CFO is used to soothe the severity of CFO in the system. The simulation result shows how the system performance deteriorates for CFO =0.2.

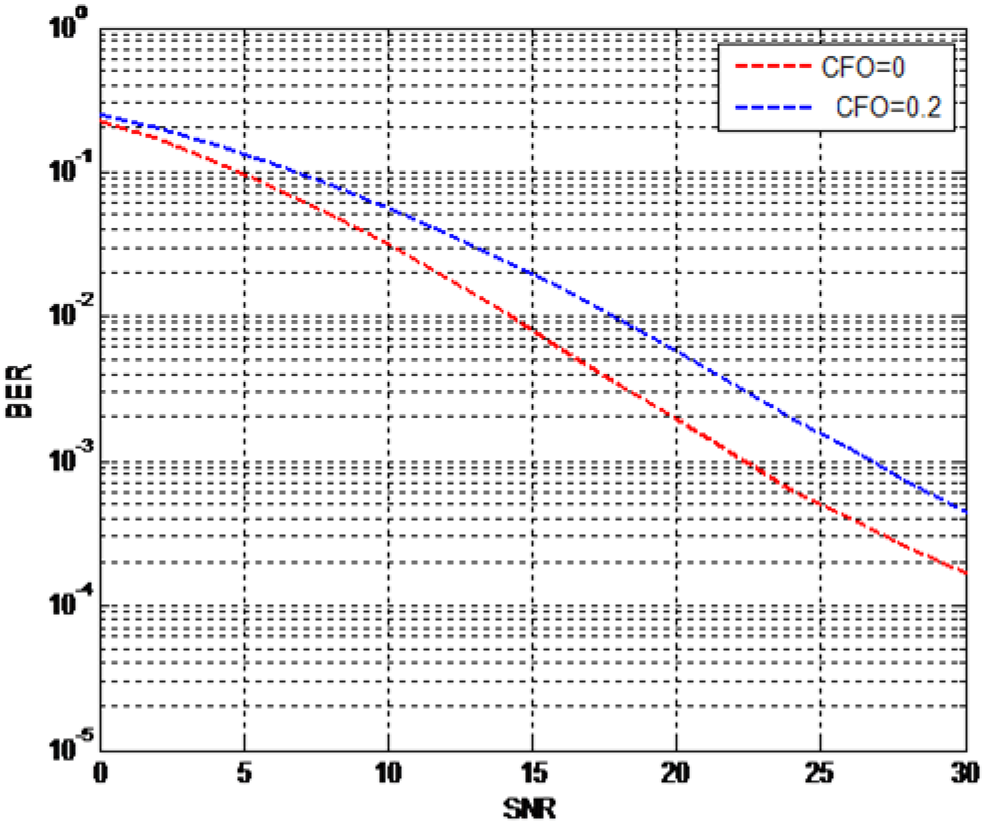

Figure 4.4 OFDM Based Cooperative System with CFO Effects for CFO=0.2

Figure 4.5 shows how the integration of ML estimation into the system improved the system performance. The simulation result compares the performance of the system with and without cooperation for CFO values of 0 and 0.2. The performance of the system with AAF cooperation in the environment where 0.2 carrier frequency offset introduced to the system has nearly the same performance with the system without cooperation and carrier frequency offset value of 0. This result shows how cooperation in wireless communication systems can significantly improve the performance in terms of BER against SNR.

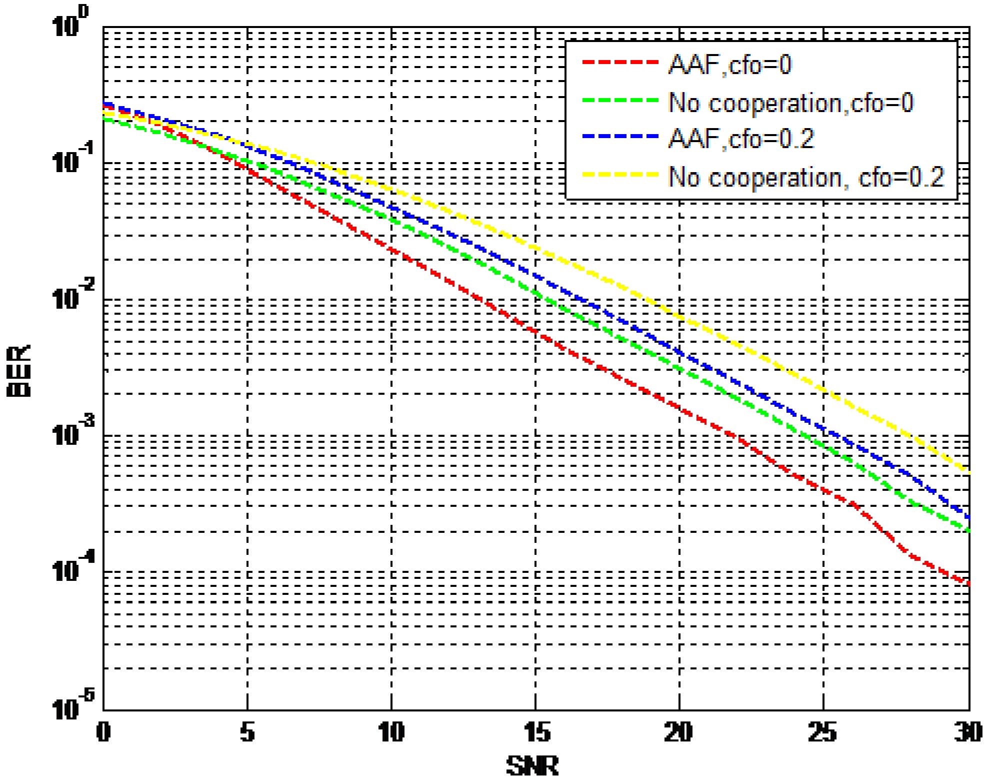

Figure 4.5 ML Estimation of CFO in Cooperative Communication System

4.2 Validation of the Simulation Results

The following simulation results from figure 4.6 to 4.8 show how the performance of cooperative communication system with ML estimation technique overrides the performance obtained from cooperative communication system with self-cancellation (SC) estimation technique.

The comparison between the ML estimation technique and the SC estimation technique is made for CFO values of 0.15, and 0.3 and for modulation types of QAM-4, QAM-16 and BPSK. In all of the simulation scenarios ML estimation and compensation technique has showed better performance. Especially, in the presence of small frequency offset and binary alphabet size, self cancellation does not offer much increase in performance. The maximum likelihood method gives the best overall results. This can also be seen in the work [22].

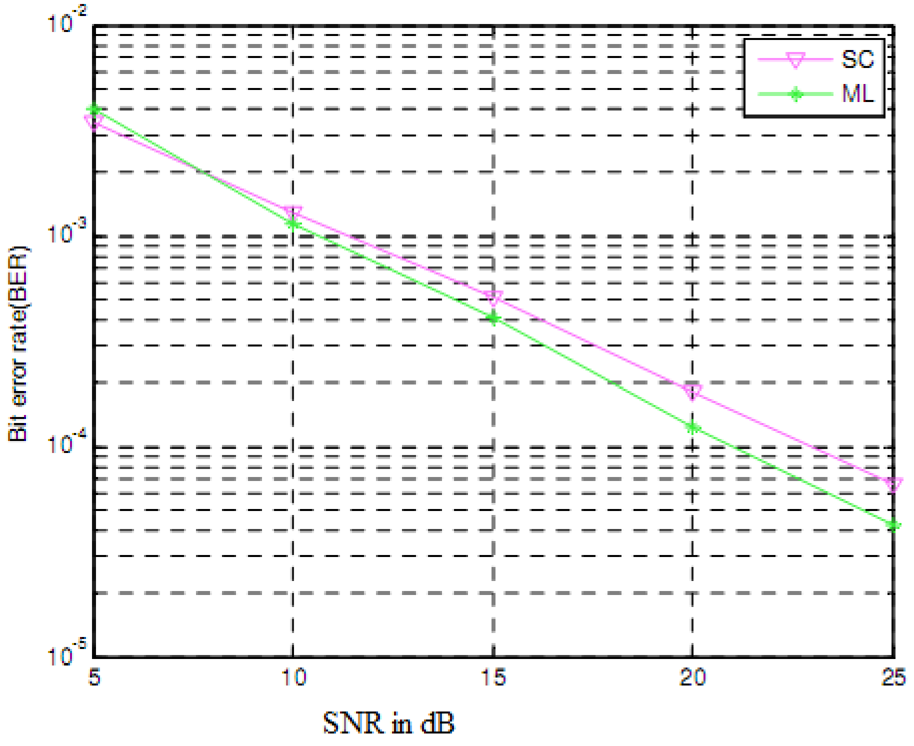

Figure 4.6 Comparison of ML with SC for CFO= 0.15 and 4-QAM

Figure 4.6 above shows simulation result of the cooperative communication system comparing ML and SC methods for carrier frequency offset value of 0.15 and 4-QAM modulation. The purple colored curve represents the performance curve of SC method and the green colored curve represents the performance of ML method. For this carrier frequency offset value and modulation type, the two methods showed nearly the same performance for SNR values of up to 10dB. But, thence the performance obtained from the ML method showed better performance in terms of BER.

Figure 4.7 shows that as the carrier frequency offset increases the overall result of ML method overrides the performance obtained from the SC method. Hence, it can be concluded that no matter how the modulation scheme is changed to the advance level, the ML estimation method shows better performance than the SC method in terms of BER as the carrier frequency offset increases. Performance of the ML method is represented by the black colored curve and the performance of the SC method is represented by the green color.

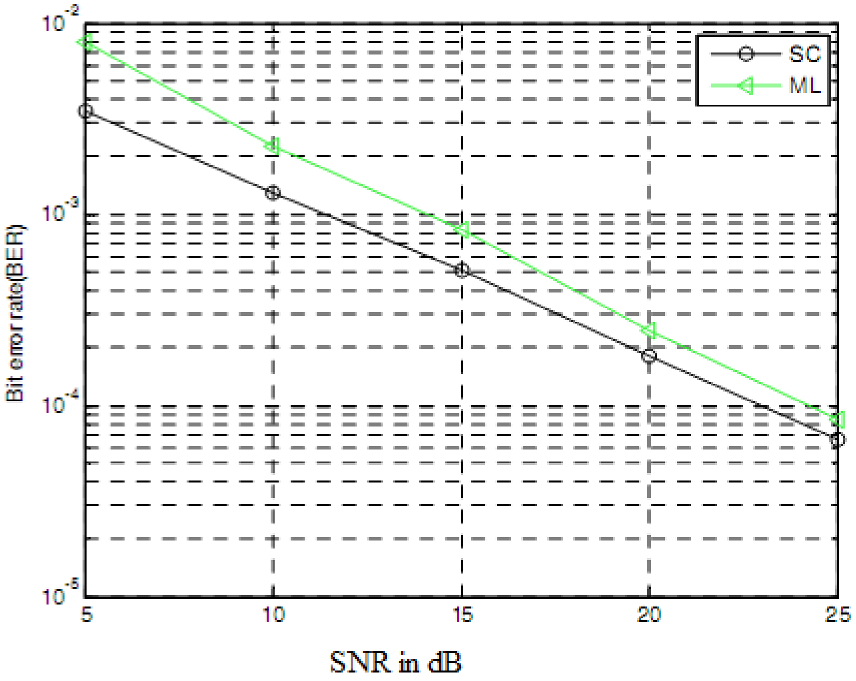

Figure 4.7 Comparison of ML with SC for CFO=0.3 and 64-QAM

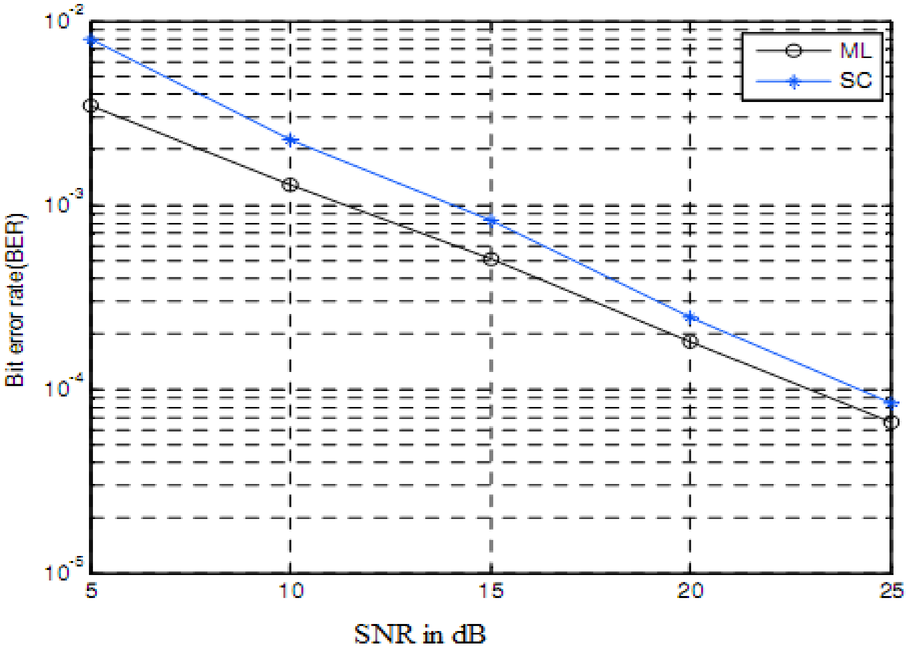

Figure 4.8 Comparison of ML with SC for CFO=0.15 and BPSK

CHAPTER FIVE

Conclusions and Recommendations

5.1 Conclusions

In cooperative systems, a group of single-antenna nodes transmit together as a ”virtual antenna array”, obtaining diversity gain without requiring multiple antennas at individual nodes. Research has been carried out in diverse aspects of cooperative systems, such as OFDM integration in the cooperative system, novel cooperative protocols, and pairing of the cooperating nodes. The engagement of cooperative systems with OFDM transmission, which has been extensively used in many advanced wireless communications systems, however, has received little attention. In particular, the application of OFDM-based cooperative transmission to facilitate the cooperation among multiple sources and multiple relays needs further investigations. This thesis tried to address some important aspects of cooperative OFDM systems and have presented useful analysis and methods

The thesis work considered the most practical scenarios in cooperative communication systems where the cooperating node gets line-of-sight signal from the source node. It has also investigated the effects of carrier frequency offset in amplify and forward cooperative communication system and how these effects are mitigated by using multi-carrier transmission along with maximum-likelihood estimation of CFO. The simulation results of the developed structure have also proved that better BER can be achieved if the cooperating node is restricted to be in a limited range of distance from the source node.

The links between the source node and the base station as well between the cooperating node and the base station are assumed to have six different propagation paths. The link between the source node and the base station is assumed to be Rayleigh fading. As well, the link between the cooperating node and the base station is assumed to be Rayleigh fading. But, the link between the cooperating nodes is assumed to have Rician fading for a reason that the cooperating node gets the line-of-sight signal from the source node. Simulation results showed that with these assumptions the performance of the cooperation system superseded the BER obtained from a system with no cooperation.

Furthermore, a significant bit error rate reduction was obtained by integrating maximum likelihood estimator into the cooperative communication system. And it is also proved that maximum likelihood estimation has better capability than self cancellation technique in dealing with the effects of carrier frequency offset. The comparison between the ML and SC was made in terms of BER.

5.2 Future Work

The work presented here constitutes only a small portion of what can be done in this fruitful area. Some of the problems that might be of interest for future research are as follows:

- Multiple-source multihop transmissions with co-channel interference

Realistic wireless networks could involve a large number of nodes with simultaneous transmissions from multiple sources. This could result in significant reductions in spectral efficiency as the nodes attempt to minimize interference during transmission. An essential element of the design of such networks is an efficient multiple access protocol in conjunction with the physical-layer cooperative strategies. One promising solution for efficient multiple access is to transmit a multicarrier signal with different users' data on different sub channels, implementing an OFDMA enabled interference avoidance protocol. Nodes can selectively decode and retransmit sub channels to create a natural reuse pattern of frequencies in a distributed fashion. Many interesting issues arise including determining a local assignment strategy for sub channels and an effective combining strategy at the destination with the consideration of co-channel interference. A very important consideration is the minimization of interference among the transmissions of the sources, as well as the transmissions of the relays.

- Synchronization for cooperative OFDM systems

Most of the previous research work in cooperative systems assumes ideal frequency and time synchronization among nodes. In a large-scale network without a fixed infrastructure, perfect synchronization among all the nodes might be difficult to achieve. Frequency offset and time offset can deteriorate the performance, especially in an OFDM system. When multiple distributed relay nodes transmit simultaneously to the destination, different transmission delays occur because of the different distances from the relay nodes to the destination. To avoid ISI, the time duration of the cyclic prefix of OFDM signals should be long enough to tolerate these transmission delays; the spectral efficiency, however, will decrease with the increase in the time duration of cyclic prefix. Achieving good performance with high spectral efficiency is very challenging, especially with decentralized control. Also, each relay node has a different frequency offset with the destination. The multiple frequency offsets must be compensated to eliminate their detrimental effects. How to minimize these synchronization errors is also a challenging problem.

- Realistic evaluation of cooperation in a networking context

Cooperative communications may involve multiple relay nodes transmitting simultaneously to a receiver. To facilitate such simultaneous transmissions and receptions, many different overheads, for example, overheads incurred in real implementations of the cooperative techniques at the physical layer and their interactions with higher layer protocols in a networking context, are incurred.

The application of OFDM based cooperation for routing and as an efficient multiple access schemes have been demonstrated in this work. The engagement of cooperative

OFDM transmission with realistic cross-layer interactions is an interesting subject for further investigations.

REFERENCES

[1] J. Niu and I-T. Lu, "Coded Cooperation on Block-Fading Channels in Single Carrier FDMA Systems" in *Proc. of IEEE GLOBECOM 2007,* pp. 4339-4343, Nov. 2007.

[2] Weinstein, S. and Ebert, P. "Data Transmission By Frequency-Division Multiplexing Using the Discrete Fourier Transform" *IEEE Trans. on Commun*. vol. 19 Issue: 5, pp.628 –634, 1971

[3] Qienfei Huang and MounirGhogho "Practical Timing and Frequency synchronization for OFDM-Based Cooperative Systems" *IEEETransactions on signal processing.* Vol58 :1-11 2010

[4] Kwnar.R, S. Malarvizhi and S. Jayashri "Time-Domain Equalization Technique for Inter Carrier Interference Suppression in OFDM Systems" *IEEE Trans. Commun.,* vol.4, pp. 78-86 2011

[5] O.Shin and Albert.M "Design of an OFDM Cooperative Space-Time Diversity System" IEEE. vol56: 2203-2214, 2007.

[6] Tiejun (Ronald) Wang, John G. Proakis, and James R. Zeidler, "Techniques for Suppression of Intercarrier Interference in OFDM Systems" *Wireless Communications and Networking Conference, IEEE* Volume1, Issue, 13-17(1): 39-44, 2005.

[7] Ali Ramadan M.Ali. "Channel Estimation and ICI Cancelation for Adaptive OFDM Systems in Doubly Selective Channel" *Otto-Von Guerickle University,* 2010.

[8] P. H. Moose, "A Technique for Orthogonal Frequency Division Multiplexing Frequency Offset Correction," *IEEE Trans. on Communications,* Vol. 42, No. 10,pp. 2908-2914, October 1994.

[9] J-J. van de Beek, M. Sandell, and P. O. Börjesson, "ML Estimation of Time and Frequency Offset in OFDM Systems," *IEEE Trans. on Signal Processing,* Vol.45, No. 7, pp. 1800-1805, July 1997.

[10] H. Cheon and D. Hong, “Effect of Channel Estimation Error in OFDM-Based WLAN," *IEEE Commun. Lett.*, vol. 6, no. 5, pp. 190-192, May 2002.

[11] L.dia, B.Gui, L.J. Cimini Jr., “Selective relaying in OFDM multihop cooperative networks,” *IEEE WCNC’2007*, pp. 963-968, March 2007.

[12] J. P. K. Chu, R. S. Adve, and A. W. Eckford, ”Fractional Cooperation Using Coded Demodulate-and-Forward,” in *Proc. of IEEE GLOBECOM 2007*, pp. 4323-4327, Nov. 2007.

[13] W. Zhang and K. B. Letaief, ”Bandwidth Efficient Cooperative Diversity for Wireless Networks,” in *Proc. of IEEE GLOBECOM 2007*, pp. 2942-2946, Nov.2007.

[14] M. R. Souryal and H. You, ”Quantize-and-Forward Relaying with M-ary Phase Shift Keying,” in *Proc. of IEEE WCNC 2008*, Mar. 2008.

[15] T. Wang, R. Wang, and G. Giannakis, ”Smart Regenerative Relays for Link Adaptive Cooperation,” *IEEE Trans. on Commun.*, vol. 56, Nov. 2008 .

[16] C. Hucher, G. R.-B. Othman, and A. Saadani, ”A New Incomplete Decode-and-Forward Protocol,” in *Proc. of IEEE WCNC 2008*, Mar. 2008.

[17] J. Laneman, ”Network Coding Gain of Cooperative Diversity,” in *Proc. of Milcom 2004*, vol. 1, pp. 106-112, Nov. 2004.

[18] S. Yiu, R. Schober, and L. Lampe, ”Distributed Space-time Block Coding” *IEEE Trans. on Commun.*, vol. 54, no. 7, pp. 1195-2006, July 2006.

[19] M. Levorato, S. Tomasin, and M. Zorzi, ”Coded Cooperation for Ad hoc Networks with Spatial Multiplexing,” in *Proc. of IEEE ICC 2007*, pp. 4746-4751,June 2007.

[20] M. Yu, J. Li, and R. S. Blum, ”User Cooperation Through Network Coding,” in *Proc. of IEEE ICC 2007*, pp. 4064-4069, June 2007.

[21] E. S. Lo and K. B. Letaief, ”Coded Cooperation For Improved Distance Spectrum and Diversity in Wireless Systems,” in *Proc. of IEEE GLOBECOM 2007*, pp. 4344-4348, Nov. 2007.

[22] J. Armstrong "Analysis of New and Existing Methods of Reducing Inter carrier Interference Due to Carrier Frequency Offset in OFDM" , *IEEE Trans. Commun.*, vol.47, pp. 365-369 2010

[23] Zhao, Y. and S. Häggman, "Intercarrier Interference Self Cancellation Scheme for OFDM Mobile Communication Systems," *IEEE Transactions on Communications*, 49(7): 1185-1191, 2001.

[24] J. Abouei, H. Bagheri, and A. K. Khandani, "An Efficient Adaptive Distributed Space Time Coding Scheme for Cooperative Relaying," in *Proc. of CISS 2008*, Mar. 2008.

[25] J. Liu and X. Cai,"Cooperative Communication Using Complementary Punctured Convolutional (CPC) Codes Over Wireless Fading Channels," in *Proc. Of IEEE WCNC2008*, Mar. 2008.

[26] K. G. Seddik and K. J. R. Liu, "Distributed Space-Frequency Coding Over Amplify- and-Forward Relay Channels," in *Proc. of IEEE WCNC 2008,* Mar. 2008.

[27] D. Chen and J. Laneman, "Modulation and Demodulation for Cooperative Diversity in Wireless Systems," *IEEE Trans. on Wireless Commun.*, vol. 5, no.7, pp. 1785-1794, June 2006.

[28] D. Chen and J. Laneman, "Non Coherent Demodulation for Cooperative Wireless Systems," in *Proc. of GLOBECOM 2004*, vol. 1, pp. 31-35, Nov.-Dec. 2004.

[29] D. Chen and J. Laneman, "Cooperative Diversity for Wireless Fading Channel Without Channel State Information," in *Proc. of 38th Asilomar Conf. on Sigs.,Sys. and Comp.*, vol. 2, pp. 1307-1312, Nov. 2004.

[30] M. R. Bhatnagar, A. Hjungnes, and L. Song, "Amplify-and-Forward Cooperative Communications Using Double-Differential Modulation Over Nakagami-m Channels," in *Proc. of IEEE WCNC 2008*, Mar. 2008.

[31] D. F. Crouse, C. R. Berger, S. Zhou, and P. Willett, "Optimal Memoryles Relays with Non-Coherent Modulation," in *Proc. of CISS 2008*, Mar. 2008.

[32] A. Cano, E. Morgado, and A. Caamano, and J. Ramos, ”Distributed Double Differential Modulation for Cooperative Communications Under CFO,”in *Proc. IEEE GLOBECOM 2007*, pp. 3437-3441, Nov. 2007.

[33] X. Deng and A. Haimovich, ”Power Allocation for Cooperative Relaying in Wireless Networks,” *IEEE Commun. Letts.*, vol. 9, no. 11, pp. 994-996, Nov.2005.

[34] M. M. Fareed and M. Uysal, ”Optimum Power Allocation for Fading Relay Channels,” in *Proc. of IEEE VTC 2007 Fall*, pp. 1157-1161, Sept 2007.

[35] L. Zhao and Z. Liao, ” On the Power Allocation for Cooperative Amplify-and-Forward Transmission,” in *Proc. of IEEE VTC 2007 Fall*, pp. 1162-1166, Sept2007.

[36] A. K. Sadek, H. Zhu, and K. J. R. Liu, ”A Distributed Relay-Assignment Algorithm for Cooperative Communications in Wireless Networks,” in *Proc. of IEEE ICC 2006*, vol. 4, pp. 1592-1597, June 2006.

[37] J. Ahn and H. S. Lee, “Frequency Domain Equalization of OFDM Signals Over Frequency Non-Selective Rayleigh Fading Channels," IEE Electron. Lett., vol. 29, no. 16, pp. 1476-1477, Aug. 1993.

[38] S. Chang and E. J. Powers, “Cancellation of Inter-Carrier Interference in OFDM Systems Using a Nonlinear Adaptive Filter," in Proc. IEEE Int. Conf. Commun., vol. 2, New Orleans, LA, pp. 1039-1043, 2000.

PUBLICATIONS

1. Y.B.Babiso, K.Langat and E.Ndungu, “Mitigating the Effects of Mobility and Synchronization Error in OFDM based Cooperative Communication Systems,” *International Journal of Advances in Telecommunications, Electrotechnics, Signals and Systems*, Vol.3, no.2, pp. 63-70, 2014.

2. Y.B.Babiso, K.Langat and E.Ndungu, “Maximum Likelihood CFO Estimation in OFDM Based Communication Systems,” *Proceedings of International Conference on Sustinable Research and Innovation*, vol. 5, pp. 285-289, 2014.