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SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Channel Equalization Techniques for Amplify-and-Forward Cooperative Diversity Relaying Scheme

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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ABSTRACT

Spatial diversity is a technique used in wireless communication to combat the effect of fading. This diversity scheme generally requires more than one antenna at transmitting and/or receiving node(s). However, many wireless devices are limited to one antenna because of size or hardware complexity. Recently, a new class of method called *cooperative communication* has been proposed. This method enables single antenna mobiles in a multi-user environment to share their antennas and generate a virtual multiple-antenna transmitter that allows them to achieve transmit diversity.

Broadband wireless systems are emerging in order to provide high data rate services. However, the overall system performance will be degraded because of the frequency selectivity nature of the wireless channel. Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation technique which can mitigate inter-symbol interference (ISI) caused by the frequency selective fading.

OFDM possesses the advantages of frequency parallel transmission, high speed communication and efficient spectrum usage. By introducing OFDM transmission into the cooperative communication technique, the gains from both sides are combined. However, one prominent problem of OFDM is its sensitivity against carrier frequency offset which results from either Doppler shift or synchronization loss at the transmitter and receiver oscillators. This carrier offset causes inter-carrier interference (ICI). Hence, efficient ICI reduction techniques are necessary to improve system performance. In this thesis, we focus on two methods of ICI reduction techniques; namely, time- and frequency-domain equalizations.

In the frequency-domain equalization a correlative polynomial is used in the frequency domain to suppress the ICI. In time-domain equalization technique a window function is employed. MATLAB simulation of the two techniques shows that, the time-domain equalization scheme achieves better performance in ICI suppression compared to the correlative coding technique. In other words, time domain equalization technique offers better carrier-to-interference ratio (CIR) as compared to the correlative coding method.

Key words: Cooperative diversity, OFDM, ISI, ICI, CIR.

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LIST OF ACRONYMS

AaF	Amplify-and-Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CFO	Carrier Frequency Offset
CIR	Carrier-to-Interference Ratio
CP	Cyclic Prefix
DAB	Digital Audio Broadcasting
DaF	Decode-and-Forward
DVB	Digital Video Broadcasting
IFFT	Inverse Fast Fourier Transform
ERC	Equal-Ratio Combining
FDE	Frequency-Domain Equalization
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FRC	Fixed-Ratio Combining
ICI	Inter-Carrier Interference
ISI	Inter-Symbol Interference
MRC	Maximum-Ratio Combining
OFDM	Orthogonal Frequency Division Multiplexing
P/S	Parallel-to-Serial Converter
Pdf	Probability Density Function
QAM	Quadrature Amplitude modulations
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RMS	Root Mean Square
S/P	Serial-to-Parallel Converter
SC-FDE	Single Carrier Frequency Domain Equalizer
SNR	Signal-to-Noise Ratio
SNRC	Signal-to-Noise Ratio Combining
TDM	Time-Division Multiplexing
TDE	Time-Domain Equalization
WLAN	Wireless Local Area Network

CHAPTER ONE

INTRODUCTION

1.1. Background

Transmission over wireless channels suffers from fading induced by multipath propagation which causes random fluctuations in the received signal level. A common approach to mitigate the degrading effects of fading is the use of diversity techniques. Most popular diversity forms are *spatial diversity*, *temporal diversity*, and *frequency diversity*. Among these, spatial diversity is particularly attractive as it does not require additional time slot or frequency band, which contribute to the data rate reduction.

In particular, advances in the theory of *multiple-input multiple-output* (MIMO) systems have made it desirable to embed multiple antennas on modern wireless transceivers, in order to achieve spatial diversity gains. However, as the cost and size of wireless devices are limited for many applications, e.g., in sensor networks or cellular phones, placing multiple antennas on a single terminal may not be practical.

To overcome the above limitations of achieving MIMO gains in future wireless networks, we must think of new techniques beyond traditional point-to-point communications. The traditional view of a wireless system is that it is a set of nodes trying to communicate with each other. From another point of view, however, because of the broadcast nature of the wireless channel, we can think of those nodes as a set of antennas distributed in the wireless system. Adopting this point of view, nodes in the network can *cooperate together* for distributed transmission and processing of information and the resulting technique is called *cooperative communication* or *cooperative diversity*.

Cooperative communications is a new communication paradigm which generates independent paths, considering the mobile radio network, between a mobile user and base station by introducing a relay channel. The relay channel can be thought of as an auxiliary channel to the direct channel.

Therefore, if the terminals share their antennas and other resources (such as time, frequency, etc.) to create a "*virtual array*" through distributed transmission and signal processing, sets of wireless terminals benefit by relaying messages for each other to propagate redundant signals over multiple paths in the network. The redundancy allows the ultimate receivers to essentially average channel variations resulting from fading, shadowing, and other forms of interference [4].

In mobile radio communication, the fading channels exhibit frequency selectivity. In the frequency-selective fading, coherence bandwidth of the channel is smaller than the bandwidth of the signal so that different frequency components of the signal experience decorrelated fading. Viewed in the time domain, an inter-symbol interference (ISI) appears at the receiver side when the channel is frequency selective. ISI leads to high probability of errors and, hence, the system's overall performance becomes very poor.

Multi-carrier modulation is one physical-layer technique that has recently gained much popularity due to its robustness in dealing with ISI. Multicarrier modulation splits a high data rate stream into a number of low-rate streams modulating separate orthogonal frequencies and combining the data received on the multiple channels at the receiver. Orthogonal frequency division multiplexing (OFDM) is one example of multicarrier modulation system. The primary advantage of this technique is its ability to effectively combat the ISI effect due to frequency selective fading without the need for complex equalizers [30].

OFDM is essentially a discrete implementation of multicarrier modulation, which divides the transmitted bitstream into many different sub-streams and sends them over many different sub-channels. Typically, the sub-channels are orthogonal and the number of sub-channels is chosen such that each sub-channel has a bandwidth much less than the coherence bandwidth of the channel. Thus, ISI on each sub-channel is very small. For this reason, OFDM is widely used in many high data rate wireless systems, for example, digital audio broadcasting (DAB) [25], digital video broadcasting (DVB) [26], and the IEEE 802.11a and 802.11g standards [27] for wireless local area networks (WLAN).

A well known problem of OFDM, however, is its sensitivity to frequency offset between the transmitted and received signals, which may be caused by Doppler shift in the channel or by the difference between the transmitter and receiver local oscillator frequencies. This carrier frequency offset causes loss of orthogonality between sub-carriers and the signals transmitted on each other, leading to inter-carrier interference (ICI). The undesired ICI degrades the performance of the system.

Researchers have proposed various methods to combat the ICI in OFDM systems. The existing approaches that have been developed to reduce ICI can be categorized as frequency-domain equalization, time-domain windowing, and the ICI self-cancellation (SC) scheme. The first two methods are investigated in this thesis and their performances are evaluated.

1.2. Motivation

As mentioned in the previous section, the relaying nodes in cooperative communication forward redundant information for the purpose of spatial diversity. Moreover, the cooperative mechanism enlarges the communication coverage, enhances the capacity and improves the transmission performance. Two primary kinds of relaying schemes that are used in cooperative communication are the *amplify-and-forward* (AaF) relaying and the *decode-and-forward* (DaF) relaying. In the former scheme, the relay amplifies the received signal and forwards to the receiver, and in the latter the relay decodes and forwards the received symbols to the receiver.

OFDM, on the other hand, possesses the advantages of frequency parallel transmission, high speed communication and efficient spectrum usage. By introducing OFDM transmission into the cooperative communication domain, the gains from both sides are combined. In the following such a system is called *cooperative OFDM*. When transmitted through frequency-selective channels, OFDM can help cooperative communication to benefit from multipath diversity.

However, one of the main disadvantages of OFDM is its sensitivity against carrier frequency offset which causes ICI. Unless this ICI is mitigated, the performance of the cooperative OFDM will also degrade. Thus, efficient ICI reduction mechanisms are necessary for reliable communication. This work proposes the use of time- and frequency-domain equalization techniques in the cooperative OFDM scheme to eliminate the adverse effect of ICI. The performance of these two equalization methods is investigated.

1.3. Objectives

1.3.1. General Objective

The core objective of this thesis is to evaluate the performance improvement of cooperative OFDM wireless communication systems by employing different ICI equalization techniques. The performance of the ICI equalization techniques is measured in terms of reduction in the bit error rate (BER) and performance of the carrier-to-interference ratio (CIR) which is the ratio of the signal power to the power in the interference components.

1.3.2. Specific Objectives

- To combine cooperative communication with OFDM modulation technique and compare BER performance with that of standard cooperative communication system.
- To explore the various ICI equalization techniques those are suitable for implementation in cooperative OFDM. Among the available ones, this work implements time- and frequency-domain equalization techniques.
- To compare performance between time-domain equalization, frequency-domain equalization and standard OFDM system.
- Finally, we determine a better equalization technique with larger CIR.

1.4. Methodology and Scope

1.4.1. Methodology

Reviewing literatures and other resources, which is the basis for this thesis work, is a preliminary step in order to achieve the desired objectives. Taking the ideas obtained in the literature survey, modeling a system which involves developing mathematical relationship that will relate frequency selective channel by incorporating OFDM in cooperative diversity was carried out. Following selection of appropriate model parameters, simulation of the overall system is performed using MATLAB software as a simulation tool. Subsequently, the performance of time and frequency domain equalization techniques was analyzed, results are interpreted and conclusions are drawn based on the results.

1.4.2. Scope

The performance evaluation which is carried out in this thesis work is based on simulation of the available equalization techniques using MATLAB. Frequency selective fading channel and two-user cooperation with Amplify and Forward relaying protocol are considered.

1.5. Related Work

As mentioned earlier, multi-antenna techniques are well appreciated in terms of boosting capacity and error performance. However, their application often encounters practical implementation problems when a larger number of antennas are to be deployed in a small mobile terminal [6]. To overcome this problem, cooperative relaying was proposed [3]-[4].

Cooperative communication based on OFDM is an attractive solution to achieve the Cooperative Diversity while overcoming the wireless channel frequency selectivity. A.A. Florea, H. Gacanin, and, F. Adachi try to compare cooperative OFDM relay network and cooperative single carrier frequency domain equalization (SC-FDE) relay network [5]. The results illustrate that cooperative OFDM relay network outperforms cooperative SC-FDE relay network in a frequency-selective fading channel.

In [14], a comprehensive study to give details on the performance of a single relay cooperative OFDM system under AaF and DaF relaying strategies on text message transmission was made. Results of BER simulation in AWGN and Raleigh fading channels shows that the AaF relaying protocol cooperative OFDM system outperforms with ERC scheme than DaF.

One of the main reasons to use OFDM is to increase the robustness against frequency selective fading and narrowband interference. However, the largest drawback of OFDM is its sensitivity to inter-carrier interference and many researches have been conducted to overcome this problem [9]-[15].

In [9], the use of frequency-domain correlative coding with correlation polynomial F(D)=1-D in OFDM mobile communication systems to reduce the inter-carrier interference (ICI) caused by channel frequency errors is studied. Theoretical expression of carrier-to-interference power ratio

(CIR) has been derived and it is shown that such a simple coding method enhances system CIR by 3.5 dB, without reducing band-width efficiency.

In [10] and [15], the performance of time-domain equalization technique is compared with the existing frequency domain equalization technique and results showed that time domain windowing technique offers better (CIR) and BER is reduced compared to the correlative coding method. However, in the aforementioned three researches, employing the proposed ICI equalization methods on cooperative OFDM system was not considered. Therefore, this thesis tries to combine the technology of OFDM with cooperative diversity and perform comparison of time and frequency domain equalization techniques for amplify and forward cooperative relaying system.

1.6. Organization of the Thesis

The rest of this thesis is organized as follows. Chapter one provides a brief introduction. In this chapter the background behind cooperative communication and the motivation behind the thesis work are presented. Also, review of related works and objectives of the thesis are discussed. In Chapter two, we present the wireless channel fundamentals and give preliminary concepts about OFDM. The chapter covers basic theory of OFDM and focuses on system operation of OFDM system, advantages and disadvantages of OFDM. Chapter three gives a brief introductory about cooperative communication followed by a description of OFDM modulation technique applied on cooperative communication. Along with this, the drawbacks of OFDM and analysis of ICI is discussed and multipath channel with carrier frequency offset is briefly introduced. In addition, two types of equalization schemes for ICI cancellation are investigated. Chapter four presents simulation results with their discussions and implications. Finally, in Chapter five, conclusions drawn from our experiments and recommendations for future work that can be considered in order to extend this research work are discussed.

CHAPTER TWO

WIRELESS CHANNEL FUNDAMENTALS AND OFDM

2.1. Wireless Channel Fundamentals

2.1.1. Introduction

The performance of any communication system is eventually determined by the medium which the message signal passes through. This medium may be an optical fiber, a copper cable or a wireless link, is referred to as communication channel. There exists a large variety of channels, which may be divided into two groups. If a solid connection exists between transmitter and receiver, the channel is called a wired channel. If this solid connection is missing, this connection is called a wireless channel [8].

Wireless channels differ from wired channels due to their unreliable behavior. In wireless channels, the state of the channel may change within a very short time span. The random and severe behavior of wireless channels turns communication over such channels into a difficult task and puts fundamental limitations on the performance of wireless communication systems. The transmission path between the receiver and the transmitter can be altered from simple line-of-sight to one that is drastically obstructed by buildings, foliage and mountains. Even the speed of the mobile impacts how rapidly the signal level fads [8], [20].

2.1.2. Multipath Fading Channel

There are a lot of mechanisms behind the electromagnetic wave propagation, but they can be generally attributed to reflection, diffraction and scattering as shown in Figure 2.1. Reflections arise when the plane waves are incident upon a surface with dimensions that are very large compared to the wavelength. Diffraction occurs when there is an obstruction between the transmitter and the receiver antennas and as a result of this, there are secondary waves generated behind the obstructing body [8]. Scattering occurs when the plane waves are incident upon an object whose dimensions are on the order of a wavelength or less, and causes the energy to be redirected in many directions.

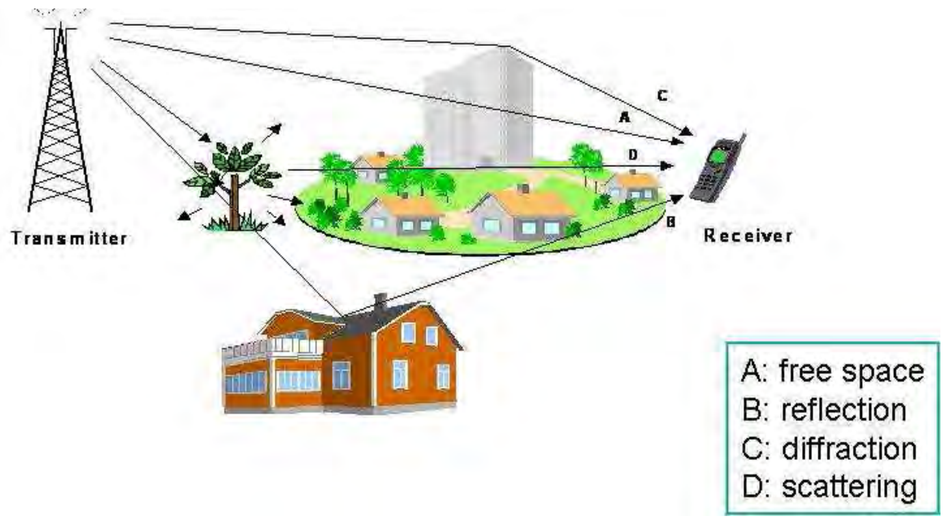


Figure 2.1 Wireless Propagation [8].

Signal multipath occurs when the transmitted signal arrives at the receiver via multiple propagation paths. Each of these paths may have a separate phase, attenuation, delay and Doppler frequency associated with it. Due to the random phase shift associated with each received signal, they might add up destructively, resulting in a phenomenon called *multipath fading or simply fading*.

2.1.3. Types of Fading

The fading phenomenon can be broadly classified into two different types: *large-scale fading* and *small-scale fading.*

- **Large-scale fading**: - Usually is defined as the average signal power attenuation or path loss due to motion over large areas. This depends on the presence of obstacles in the signal path, on the position of the mobile unit and its distance from the transmitter. The statics of large-scale fading provide a way of computing an estimate of path loss as a function of distance. This is normally described in terms of a mean-path loss and a log-normally distributed variation about the mean which is known as *shadowing*. Hence, the term large-scale fading correspond to the combined effects of path-loss and shadowing loss [8].
- **Small-scale fading:** - Refers to dramatic changes in signal amplitude and phase that can be experienced as a result of small changes in the spatial separation between a receiver and transmitter [8]. Small-scale fading manifests itself in two mechanisms:

1. *Frequency-spreading of the signal*: generated by the relative motion between the transmitter and the receiver and that results in the appearance of Doppler shift. If the multiple reflective paths are large in number and there is no line-of-sight signal component, the different Doppler frequencies and amplitudes of each paths implies that the envelope of the received signal is statistically described by a Rayleigh probability density function. This time-variant manifestation of the fading can be categorized as fast- or slow-fading as explained in Section 2.1.5.

2. *Time-spreading of the signal:* Generated by the multiple paths in the radio signal. Depending on the symbol duration with respect to this delay spread, frequency selective fading can appear and so signal distortion. This frequency-variant manifestation of the fading can be then categorized as frequency-selective or frequency-non-selective (flat) fading, further explained in Section 2.1.5.

The emphasis of this thesis is on small-scale fading. Large-scale fading is more relevant to issues such as cell-site planning. Small-scale multipath fading is more relevant to the design of reliable and efficient communication systems. Moreover, the term fading hereafter is used to refer to the small-scale fading.

2.1.4. Fading Parameters

As mentioned earlier, multipath components arrive at the receiver at slightly different times. If there is movement in the system, then there is also phase difference between the received components which leads to shift in the frequency. These multiple received copies apply constructive or destructive interference to the signal and create a standing wave pattern that shows rapid signal strength changes, frequency shifts or echoes.

Multipath propagation, movement and bandwidth are factors that influence the fading. Multipath delay nature of the channel is quantified by *delay spread* in the time domain and by *coherence bandwidth* in the frequency domain. The time-varying nature of the channel caused by movement is quantified by Doppler spread and coherence time [20].

✓ **Delay Spread:** The reflected parts arrive later than the original signal to the receiver. RMS delay spread (σ_τ) is the metric to characterize this delay in terms of second order moment of the channel power profile. Typical values are on the order of microseconds in outdoor and on the order of nanoseconds in indoor radio channels [2].

✓ **Coherence Bandwidth:** The channel power profile is coupled with channel frequency response through Fourier transform. Coherence bandwidth (B_c) is used to quantify the channel frequency response and it is inversely proportional to RMS delay spread. Coherence bandwidth is used to measure how flat the channel bandwidth is. Flatness is described as the close correlation between the two frequency components. This is important since a signal having a larger bandwidth (B_s) than (B_c) is severely distorted. For a 0.9 correlation, $B_c = 1/50\sigma_\tau$ [2].

✓ **Doppler Shift:** Movement causes shift in the signal frequency. When the stations are moving, the received signal frequency is different than the original signal frequency. Doppler shift is defined as the change in the frequency. Suppose a mobile is moving at velocity v as in Figure 2.2. The difference in path length of received signals is $l = d\cos\theta$ where

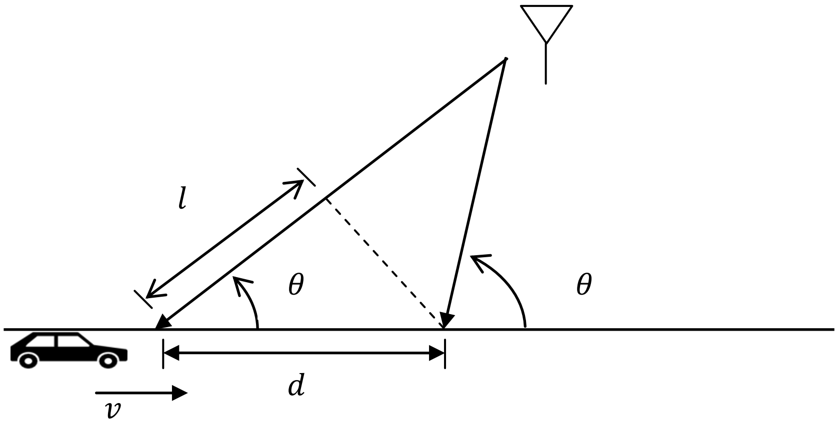


Figure 2.2 Doppler Effect.

$d = v\Delta t$. The phase change is

$$\Delta\emptyset = 2\mu l/\lambda \tag{2.1}$$

and Doppler shift is given by $$f_d = \frac{1}{2\mu}.\frac{\Delta\emptyset}{\Delta t} = \frac{v}{\lambda}.\cos\theta \tag{2.2}$$

From the Equation 2.2, one can see that if the movement is toward the signal generator, the Doppler shift is positive otherwise it is negative [2].

- ✓ **Doppler Spread:** A channel shows a time varying nature when there is a movement in either the source or destination or even objects in the middle. Doppler spread (B_D) is the measure of maximum broadening of the spectrum due to Doppler shift. Thereby B_D is $f_m = \frac{v}{\lambda}$ where f_m is the maximum Doppler shift.

- ✓ **Coherence Time:** The time domain dual of Doppler spread is coherence time T_c where $T_c \approx 1/f_m$ Coherence time identifies the time period wherein two received signal have high amplitude correlation.

2.1.5. Slow Fading vs. Fast Fading

The distinction between slow and fast fading is important for the modeling of fading channels and for the performance evaluation of communication systems [8]. This time variant behavior of the channel is due to motion (e.g., a receiver antenna on a moving platform).

Once the key factors involved in the time-variant manifestation are known, the next step is to describe when the channel defines a fast or slow fading:

- The terminology *fast fading* is used to describe a channel in which $\mathrm{T_s} \gg \mathrm{T_c}$ where $\mathrm{T_s}$ is the time duration of a transmission symbol, or similarly $\mathrm{B_s} \ll \mathrm{f_d}$ in the frequency domain, where $\mathrm{B_s}$ is the signal's bandwidth. $\mathrm{T_c}$ is the expected time duration over which the channel's response to a sinusoid is essentially invariant. The Doppler spread is inversely proportional to $\mathrm{T_c}$. Equation 2.3 shows one of the approximations for the relation between $\mathrm{T_c}$ and the Doppler frequency while Equation 2.4 is the geometric mean of this expression.

$$T_c \approx \frac{9}{16\pi f_d} \tag{2.3}$$

$$T_c \approx \sqrt{\frac{9}{16\pi {f_d}^2}} = \frac{0.423}{f_d} \tag{2.4}$$

- On the other hand, *slow fading* is said to happen when $T_s \ll T_c$, and so $B_s \gg f_d$ in the frequency domain. In this case, symbols are just attenuated in a higher or lower level depending on whether they are transmitted during a deep fading or not.

2.1.6. Frequency-selective Fading vs. Flat Fading

In a fading channel, the relationship between the *excess delay time* or *delay spread* and the symbol rate characterizes the signal dispersion, which is translated into frequency dependent fading in the frequency domain.

2.1.6.1. Flat Fading

The signal goes to flat fading if the channel bandwidth is greater than the signal bandwidth, i.e., $\mathrm{B_c} > \mathrm{B_s}$. Spectral shape of the signal remains unchanged but the gain changes. Narrow band signals fall into this category since their bandwidth is small as compared to the channel bandwidth.

There are various ways to reduce the fading distortion [28]. Spatial diversity is one way which leverages multiple independent channels. Multiple slightly separated antennas in space are used to create independent paths to achieve uncorrelated channels. Since channels are independent (statistically) they have lower probability to experience fades at the same time. Space diversity is one of the most efficient diversity technique compared to time or frequency.

2.1.6.2. Frequency Selective Fading

If channel bandwidth is smaller than the signal bandwidth, then the channel will experience frequency selective fading. Spectral response of a radio signal will show dips due to the multipath. Channel bandwidth limits the signal bandwidth which leads to overlapping of the successive symbols in the time domain due to the convolution. Overall symbol duration becomes more than the actual symbol duration($\sigma_\tau > T_s$). This phenomenon is called ISI.

2.1.6.3. Inter-Symbol Interference

Is a form of distortion of a signal in which one symbol interferes with subsequent symbols; as a result of multipath propagation or the inherent non-linear frequency response of a channel which makes communication less reliable. In practice, communications channels have a limited bandwidth, and hence transmitted pulses are spread during transmission. This pulse spreading can result in an overlap of pulses over adjacent time slots, as shown in Figure 2.3. The signal overlap may result in an error at the receiver resulting in ISI.

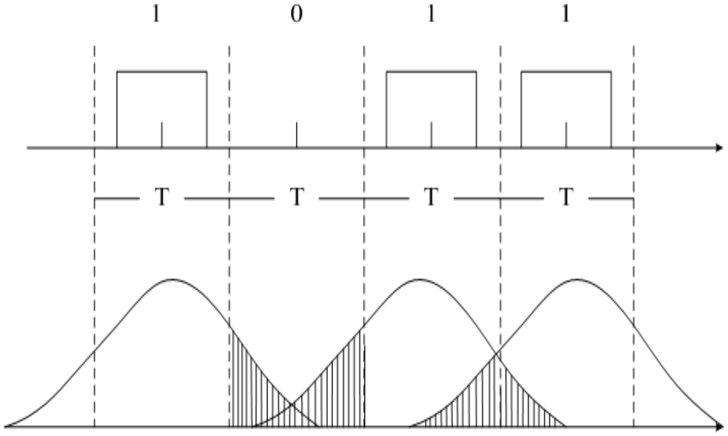


Figure 2.3 Inter-symbol interference

There are several ways to combat ISI [28]; OFDM is the widely used one. In OFDM, each subcarrier undergoes flat fading since its bandwidth is less than the coherence bandwidth. Therefore ISI is eliminated within an OFDM symbol. A portion of the OFDM symbol (cyclic prefix), larger than the coherence bandwidth, is appended to the symbol to overcome the ISI between symbols. Next, a multicarrier modulation technique called OFDM will be discussed.

2.2. The OFDM Principle

2.2.1. Introduction

OFDM is a technique for transmitting data in parallel by using a large number of modulated sub-carriers. These sub-carriers (or sub-channels) divide the available bandwidth and are sufficiently separated in frequency (frequency spacing) so that they are orthogonal. The orthogonality of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, although their spectra overlap.

The separation between carriers is theoretically minimal so there would be a very compact spectral utilization. OFDM systems are attractive for the way they handle ISI, which is usually introduced by frequency selective multipath fading in a wireless environment. Each sub-carrier is modulated at a very low symbol rate, making the symbols much longer than the channel impulse response. In this way, ISI is diminished. Moreover, if a guard interval between consecutive OFDM symbols is inserted, the effects of ISI can completely vanish. This guard interval must be longer than the multipath delay. Although each sub-carrier operates at a low data rate, a total high data rate can be achieved by using a large number of sub-carriers. ISI has very small or no effect on the OFDM systems hence an equalizer is not needed at the receiver side.

In the OFDM system, Inverse Fast Fourier Transform/Fast Fourier Transform (IFFT/FFT) algorithms are used in the modulation and demodulation of the signal. The length of the IFFT/FFT vector determines the resistance of the system to errors caused by the multipath channel. The time span of this vector is chosen so that it is much larger than the maximum delay time of echoes in the received multipath signal.

OFDM is generated by firstly choosing the spectrum required, based on the input data, and modulation scheme used. Each carrier to be produced is assigned some data to transmit. The required amplitude and phase of the carrier is then calculated based on the three modulation scheme (typically differential BPSK, QPSK, or QAM).

Then, the IFFT converts this spectrum into a time domain signal. The FFT transforms a cyclic time domain signal into its equivalent frequency spectrum. Finding the equivalent waveform, generated by a sum of orthogonal sinusoidal components, does this. The amplitude and phase of the sinusoidal components represent the frequency spectrum of the time domain signal.

2.2.2. Block Diagram of OFDM

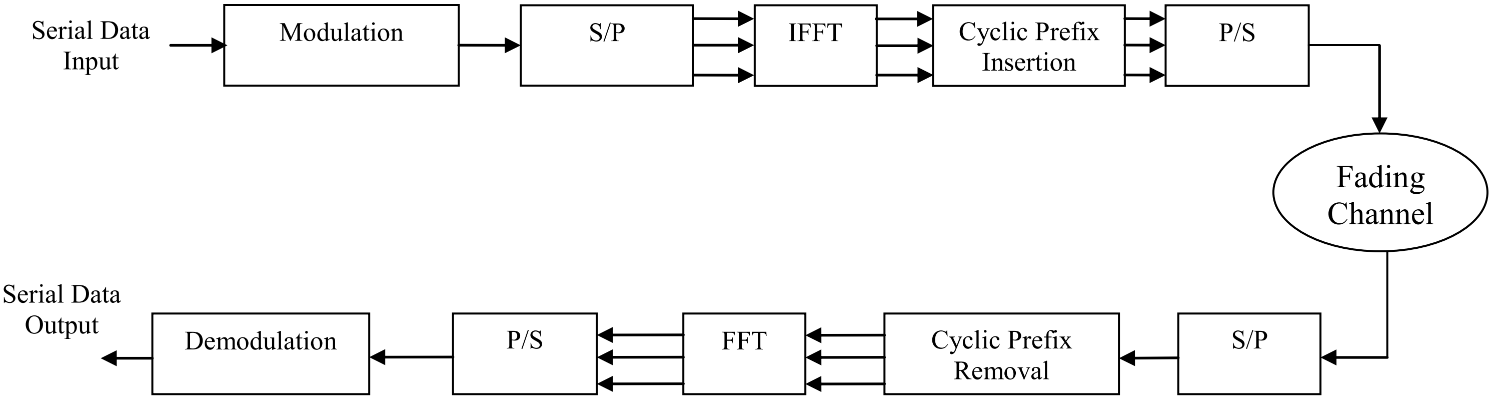


Figure 2.4 Basic OFDM transmitter and receiver block diagram

The schematic diagram of the complete structure of an OFDM transceiver system is shown in Figure 2.4. The blocks on the top row correspond to components in the transmitter and the bottom row to the receiver. The basic components of the system model are also described in this section.

Modulation: A baseband OFDM symbol can be first generated in the digital domain before modulating on a carrier for transmission. The generated symbols are mapped to signal mapper using known modulation schemes. Here, any kind of modulation scheme can be used like BPSK, QPSK, 8PSK, 8QAM etc.

Serial-to-Parallel Conversion (S/P): A serial bit stream is converted into several parallel bit streams to be divided among the individual carriers. Once the bit stream has been divided among the individual sub-carriers, each sub-carrier is modulated as if it was an individual channel before all channels are combined back together and transmitted as a whole.

IFFT at the transmitter and FFT at the receiver: OFDM transmits a large number of narrowband carriers, closely spaced in the frequency domain. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as FFT.

Inverse FFT at the transmitter and FFT at the receiver are key components in the OFDM performing linear mappings between N complex data symbols and N complex OFDM symbols result in robustness against fading multipath channel. This is achieved by transforming the high data rate stream into N low data rate streams, each experiencing flat fading during transmission over a wireless channel.

Suppose the data to be sent is $x(0), x(1), x(2), \ldots, x(N-1)$, where N is the total number of sub-carriers.

The signal after IFFT is

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x(k) \exp\left(j2\pi k \frac{n}{N}\right) \qquad (2.5)$$

At the receiver side the data is recovered by performing FFT on the received signal

$$R(k) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} x(n) \exp\left(-j2\pi k \frac{n}{N}\right), k = 0,1, \ldots, N-1 \qquad (2.6)$$

Cyclic Prefix: Signals arriving at a receiver by different paths show different time delays which result in ISI. An OFDM system with a multipath capability allows for the constructive combination of these signals. This is achieved by inserting a guard interval a cyclic prolongation of the useful symbol duration of the signal by replicating part of the OFDM time-domain waveform from the back to the front. The FFT window, i.e. the time period for the OFDM demodulation, is then positioned in such a way that a minimum of ISI occurs. The duration of the guard period should be longer than the delay spread of the multipath environment.

In an OFDM transmission, we know that the transmission of cyclic prefix doesn't carry extra information. The signal energy is spread over time $T_d + T_{CP}$ whereas the bit energy is spread over time T_d i.e. $E_s(T_d + T_{CP}) = E_b T_d$. Where, T_d is data symbol duration, T_{CP} is cyclic prefix duration and E_s and E_b are signal energy and bit energy respectively.

The relationship between symbol energy and the bit energy is as follows:

$$\frac{E_s}{N_0} = \frac{E_b}{N_0} \left(\frac{n.DSC}{n.FFT}\right) \left(\frac{T_d}{T_d + T_{CP}}\right) \qquad 2.7$$

Where $n.DSC$ is number of used subcarriers and $n.FFT$ is FFT size.

Expressing in decibels,

$$\frac{E_s}{N_0}dB = \frac{E_b}{N_0}dB + 10log_{10}\left(\frac{n.DSC}{n.FFT}\right) + 10log_{10}\left(\frac{T_d}{T_d+T_{CP}}\right) \qquad 2.8$$

Parallel-to-Serial Conversion (P/S): Once the cyclic prefix has been added to the sub-carrier channels, they must be transmitted as one signal. Thus, the parallel to serial conversion stage is the process of summing all sub-carriers and combining them into one signal. As a result, all sub-carriers are generated perfectly simultaneously.

2.2.3. Advantages and Disadvantages of OFDM

OFDM Advantages:

- Spectral efficiency: the orthogonal sub-channels are closely spaced and overlap infrequency
- Ability to combat ISI caused by multipath delay spread
- Robust against frequency selective fading channels
- Efficient implementation by IFFT/FFT

OFDM Disadvantages:

- Sensitivity to frequency offset (due to Doppler shift and frequency synchronization problems): results in ICI
- High Peak to average power ratio (High power transmitter amplifiers need linearization, Low noise receiver amplifiers need large dynamic range)
- Capacity and power loss due to guard interval (Bandwidth and power loss due to the guard interval can be significant)

CHAPTER THREE

COOPERATIVE COMMUNICATION

3.1. Introduction

The introduction and rapid development of MIMO systems has promised significant improvements in reliability and throughput for wireless communication; by utilizing multiple antennas at both the transmitter and the receiver side. This technique is clearly advantageous for cellular base stations, but not feasible for mobile devices, due to their sizes and power constraints [1].

An alternate to this is a newly developed technique known as cooperative diversity. Cooperative communication is a new spatial diversity technique; the aim of it is to promote the benefit of spatial diversity to the single antenna system. The basic idea is that some single antenna mobile users in the networks can share their antennas to generate a virtual multiple – antenna transmitter that allows them to achieve transmit diversity [31].

3.2. Cooperative Communication

Cooperative communication was first studied by Van der Meulen [36]. He introduced the concept of relay channel model, which consists of a source, destination and relay; and whose major purpose was to facilitate the information transfer from source to destination. Later, Cover and El Gamal [38] deeply investigated the relay channel model, and provided a number of fundamental relaying techniques.

In conventional communication, data is transmitted between the source and destination without a users providing assistance to one another (Figure 3.1). However, there are many neighboring nodes in a practical wireless communication network, which could be of great assistance. When one node transmits its data, all the nearby nodes overheard its transmission [17].

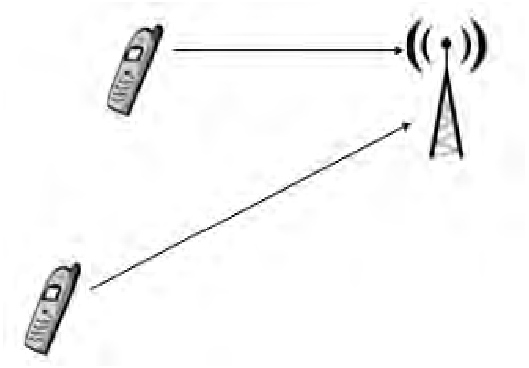


Figure 3.1 Conventional communication.

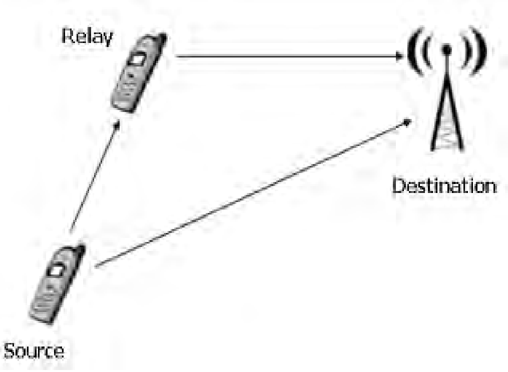


Figure 3.2 Cooperative communication.

Cooperative communication aims to process and forward this overhead information to the respective destination to create spatial diversity, which can in result increase the system performance. The concept of the cooperative communication is suggested in figure 3.2 [4].

As depicted in Figure 3.2, the source S is transmitting data to the destination D, while the relay station (another mobile user) R is also hearing the transmission. The relay station also process and forward this message to the destination, where both of the received signals are combined. As both copies of the signals are transmitted through independent paths, this results into spatial diversity.

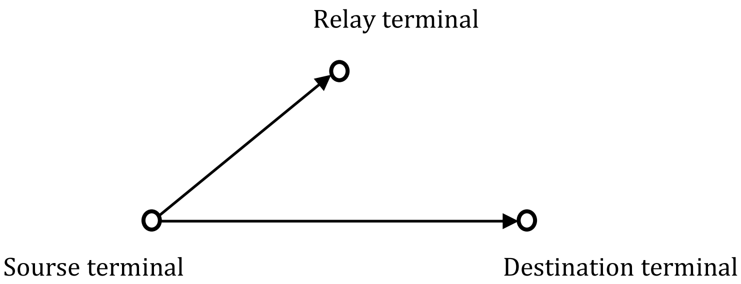
3.2.1. Half-duplex versus Full-duplex Relaying

A relay is said to be half-duplex when it cannot simultaneously transmit and receive in the same band. In other words, the transmission and reception channels must be orthogonal. Orthogonality between transmitted and received signals can be in time domain, in frequency domain, or using any set of signals that are orthogonal over the time-frequency plane.

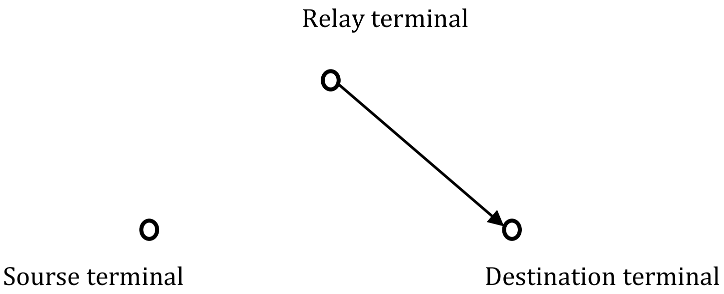
If a relay tries to transmit and receive simultaneously in the same band, then the transmitted signal interferes with the received signal. In theory, it is possible for the relay to cancel out interference due to the transmitted signal because it knows the transmitted signal. In practice, however, any error in interference cancellation can be disastrous because the transmitted signal is typically 100-150dB stronger than the received signal as noted in [1]. Due to the difficulty of accurate interference cancellation, full-duplex radios are not commonly used. Hence, in this thesis we will consider half duplex relaying.

3.2.2. Cooperative Transmission Stages

Cooperative communication takes place in two stages. In the first stage, the source transmits signals intended for the destination in a broadcast manner. The relay and the destination receive faded noisy versions of these signals. In the second stage, the relays retransmit a processed version of their received signals to the destination, and the destination combines the signals received in the two stages.



(a) Stage I



(b) Stage II

Figure 3.3 Cooperative Relaying model.

3.2.3. Cooperative Transmission Protocols

Cooperative transmission protocols describes that how the received data is processed at the relay station, before forwarding it to the destination. Next, we will see two types of cooperative relaying schemes.

A. Amplify-and-Forward Transmission

In AaF the received signal is amplified and retransmitted to the destination. The destination combines signals received from the relay and source, decodes the combined signal and makes a final decision. 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 X is received at both the relay (R) and destination (D) as

$$R_{SR}(n) = \sqrt{P}H_{SR}(n)X(n) + n_{SR}\ , \tag{3.1}$$

and $$R_{SD}(n) = \sqrt{P}H_{SD}(n)X(n) + n_{SD} \tag{3.2}$$

Where H_{SR} and H_{SD} are the channel gains between source and relay and source and destination, respectively. The terms n_{SR} and n_{SD} denote the additive white Gaussian noise with zero-mean and variance N_0, P is the transmission power 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. The relay does that by simply scaling the received energy and is denoted by

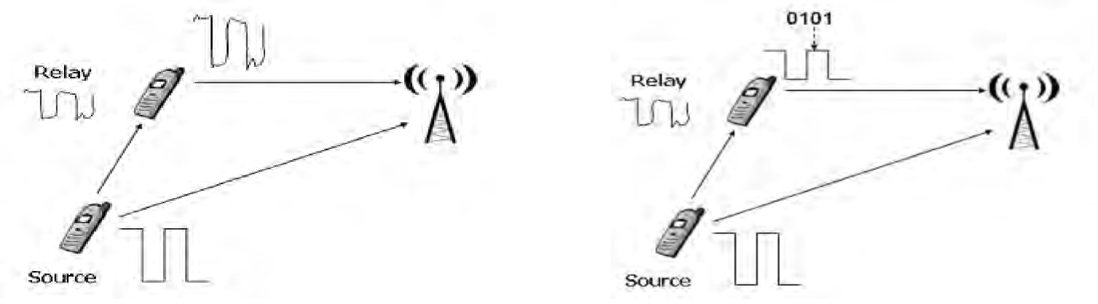
$$\beta = \sqrt{\frac{P}{PH_{SR}(n)+N_0}} \tag{3.3}$$

The destination received two copies from the signal X through the source link and relay link. There are different techniques to combine the two signals at the destination. This will be discussed in the next section.

B. Decode-and-Forward Transmission

In this relaying method, the relay decodes and re-transmits the signal to the destination (See part b of Figure 3.4). The destination then combines the messages it received from the source and destination, and decodes the combined signal. An error correcting code can be implemented at the relay station. This can help the received bit errors to be corrected at the relay station. However, this is only possible if the relay station has enough computing power [4].

In this paper, we focus our consideration on AaF protocol because of its low implementation complexity.



a. Amplify-and-Forward Technique b. Decode-and-Forward Technique

Figure 3.4 Cooperative Relaying Techniques [17]

3.3. Combining Types

The goal in combining is to process the multiple received signals so as to obtain a resulting signal of better quality or with better probability of successful reception than each of the received ones. The nature of the processing that is applied to each signal during combining depends on particular design goals.

3.3.1. Equal-Ratio Combining (ERC)

In equal gain combining, each signal branch weighted with the same factor irrespective of the signal amplitude. This is the easiest way to combine the signals, but the performance will not be that good in return [4].

$$R(n) = R_{SD}(n) + R_{RD}(n) \tag{3.4}$$

Where $R_{SD}(n)$ denotes the received signal from the sender and $R_{RD}(n)$ the one from the relay.

3.3.2. Fixed-Ratio Combining (FRC)

A much better performance can be achieved when fixed ratio combining is used. Instead of just adding up the incoming signals, the received signals are weighted with a constant ratio, which will not change a lot during the whole communication. The ratio should represent the average channel quality and therefore should not take account of temporary influences on the channel due to fading or other effects. The FRC can be expressed as

$$R_{\propto}(n) = \alpha_{SD} \cdot R_{SD}(n) + \alpha_{SRD} \cdot R_{RD}(n) \tag{3.5}$$

Where α_{SD} denotes the weight of the direct link and α_{SRD} the one of the multi-hop link [4].

3.3.3. Signal-to-Noise Ratio Combining (SNRC)

A much better performance can be achieved, if the incoming signals are weighted on an intelligent way. An often used value to characterize the quality of a link is the SNR, which can be used to weight the received signals [4].

$$R(n) = SNR_{SD} \cdot R_{SD}(n) + SNR_{SRD} \cdot R_{SRD}(n) \tag{3.6}$$

Where SNR_{SD} denotes the SNR of the direct link and SNR_{SRD} the one over the whole multi-hop channel.

3.3.4. Maximum-Ratio Combining (MRC)

The Maximum Ratio Combiner (MRC) achieves the best possible performance by multiplying each input signal with its corresponding conjugated channel gain. This assumes that the channels' phase shift and attenuation is perfectly known by the receiver. This combining technique is used in this work and mathematically it can be expressed as follows:

$$R(n) = H_{SD}^{*}(n)R_{SD}(n) + H_{RD}^{*}(n)R_{RD}(n) \tag{3.7}$$

3.4. Cooperative OFDM communication

Recently, cooperative communication has received much attention and has been considered as a promising technique to use the broadcast nature of the wireless channels to make communicating nodes help each other to gain from spatial diversity. The cooperative mechanism enlarges the communication coverage, enhances the capacity and improves the transmission performance. OFDM possesses the advantages of frequency parallel transmission, high speed communication and efficient spectrum usage. By introducing OFDM transmission into the cooperative communication domain, the gains from both sides are combined. When transmitted through multipath channel, OFDM can help that cooperative communication gain from multipath diversity.

3.4.1. System Model

Let us re-consider the wireless communication system scenario illustrated in Figure 3.3. As for the user cooperation protocol, we assume that the relay operates in AaF mode for simplicity. The information is transmitted via two time stages (i.e., TDM orthogonal channels [4]). The source transmits the data to the destination, while the relay is listening during the first stage. In the second stage, the relay sends the received data after processing to the destination as well, where the two received signals are combined. In this thesis, OFDM is used as a modulation technique in the cooperative system to gain from its inherent advantages and combat frequency selective fading.

The block diagram of cooperative OFDM system is shown in Figure 3.5. It consists of three major nodes; namely, source, relay and destination. In source node, data is generated and the bits are mapped to symbols. The symbol sequence is converted to parallel format and IFFT is applied and the sequence is once again converted to the serial format.

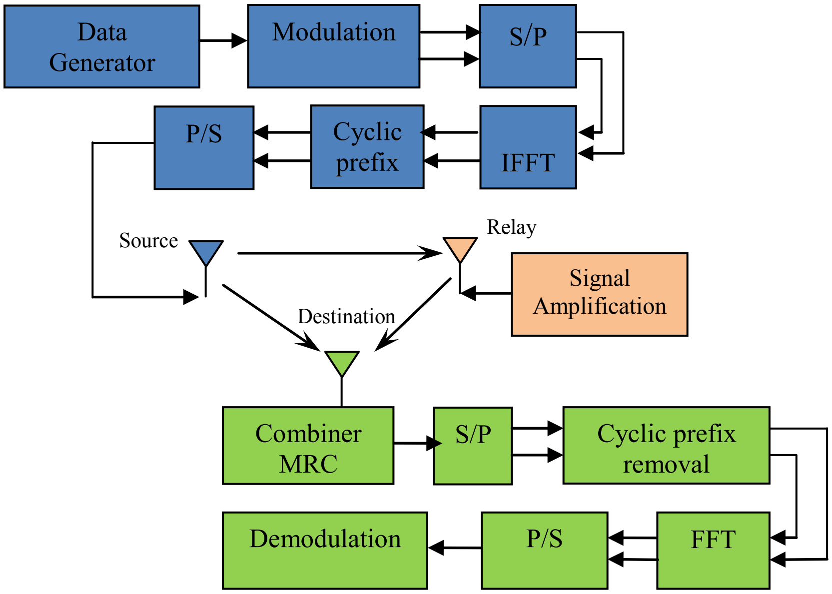


Figure 3.5 Block diagram of a Cooperative OFDM wireless Communication system.

Cyclic prefix is provided between the OFDM symbols by copying the last samples of the IFFT output. The CP is essentially a guard interval, which serves to eliminate interference between OFDM symbols. At the destination, the receiver receives two signals, one directly transmitted from sender and another one via relay. In relay unit, it receives transmitted signal from sender, it amplifies the signal and re-transmits. At the destination node, after the cyclic prefix removal, the received OFDM symbols are fast-Fourier-transformed, and the resulting symbols at the destination are used for the combination and detection.

Because of the amplification in the second cooperative transmission stage, the overall channel gain of the AF protocol should include the source to relay, relay to destination channel gains and amplification factor.

3.4.2. Relaying Phase

Consider the transmission of one block of data $\{\mathrm{X}(0), \mathrm{X}(1), \ldots, \mathrm{X}(\mathrm{N}-1)\}$ from source to destination using cooperative relaying, where N is the total number of sub-carriers. The discrete time representation of the signal after IFFT as given in Equation 2.5 is:

$$x(\mathrm{n}) = \sqrt{\mathrm{P}}\, \frac{1}{\sqrt{\mathrm{N}}} \sum_{\mathrm{k}=0}^{\mathrm{N}-1} \mathrm{X}(\mathrm{k}) \exp\left(\mathrm{j}2\pi\mathrm{k}\frac{\mathrm{n}}{\mathrm{N}}\right), n = 0,1, \ldots, N-1 \qquad (3.8)$$

P denotes the transmit power. And a cyclic prefix of length $\mathrm{N_g}$ samples is inserted in front of the data block and the signal is transmitted over a frequency selective fading channel.

Time slot 1: The received signal at the destination can be expressed, using the frequency domain representation as

$$R_D^1\,(n) = \sqrt{P_1}X(n)H_{SD}(n) + N_{SD}(n) \tag{3.9}$$

The received signal at the relay can be expressed as

$$R_R^1\,(n) = \sqrt{P_1}X(n)H_{SR}(n) + N_{SR}(n) \tag{3.10}$$

In which P_1 is the transmitted power at the source, $X(n)$ is the transmitted information symbol, and $N_{SD}(n)$ and $N_{SR}(n)$ are additive noise. In Equations (3.9) and (3.10), $H_{SD}(n)$ and $H_{SR}(n)$ are the channel coefficients from source to the destination and the relay respectively. They are modeled as zero-mean, complex Gaussian random variables with variances δ_{SD}^2 and δ_{SR}^2, respectively. The noise terms $N_{SD}(n)$ $N_{SR}(n)$ are characterized by zero mean complex valued Gaussian variable having variance of N_0.

Time slot 2: As illustrated in Section 3.2.3, during the second time slot, the relay terminal amplifies the received signal and forwards it to the destination with transmitted power P_2. The destination terminal receives a superposition of the relay transmission and the source transmission during the second time slot according to

$$R_D^2\,(n) = \frac{\sqrt{P_2}}{\sqrt{P_1|H_{SR}(n)|^2+N_0}}H_{RD}(n)R_R^1\,(n) + N_{RD}(n) \tag{3.11}$$

Where $H_{RD}(n)$ is the channel coefficient from the relay to the destination and $N_{RD}(n)$ is an additive noise. More specifically, by (3.10), the received signal $R_D^2\,(n)$ in this case is

$$R_D^2\,(n) = \frac{\sqrt{P_1P_2}}{\sqrt{P_1|H_{SR}(n)|^2+N_0}}H_{RD}(n)H_{SR}(n)X(n) + N'_{RD}(n) \tag{3.12}$$

Where $$N'_{RD} = \frac{\sqrt{P_2}}{\sqrt{P_1|H_{SR}(n)|^2+N_0}} H_{RD}(n) N_{SR} + N_{RD}(n) \tag{3.13}$$

Assume that the noise terms $N_{SR}(n)$ and $N_{RD}(n)$ are independent, and then the equivalent noise N'_{RD} is a zero-mean, complex Gaussian random variable with variance

$$\left(\frac{P_2|H_{RD}(n)|^2}{P_1|H_{SR}(n)|^2+N_0} + 1\right) N_0 \tag{3.14}$$

The channel coefficients $H_{SD}(n), H_{SR}(n)$ and $H_{RD}(n)$ are assumed to be known at the receiver, but not at the transmitter.

The destination combines the received signals during the two time slots based on maximum ratio combining (MRC). In MRC the signals at the output of diversity branches are combined linearly and the coefficients of the linear combination are selected to maximize the SNR. We consider a total transmitted power P such as

$$P_1 + P_2 = P \tag{3.15}$$

The combined signal is represented as

$$R(n) = R^1_{SD}(n) w_1(n) + R^2_{RD}\,(n) w_2(n) \tag{3.16}$$

Where $R_{SD}(n)$ *and* $R_{RD}(n)$ denote the received signals at the destination and $w_1(n)$ *and* $w_2(n)$ are the weights and are given by [5]

$$\begin{aligned} w_1(n) &= \frac{\sqrt{P_1} H^*_{SD}(n)}{N_0} \\ w_2(n) &= \frac{\frac{\sqrt{P_1 P_2}}{\sqrt{P_1|H_{SR}(n)|^2+N_0}} H^*_{SR}(n) H^*_{RD}(n)}{\left(\frac{P_2|H_{RD}(n)|^2}{P_1|H_{SR}(n)|^2+N_0}+1\right) N_0} \end{aligned} \tag{3.17}$$

Where $(.)^*$ denotes the complex conjugate operation. It is evident from (3.17) that the equalization weight for the second timeslot includes the channel gain between source and the relay as well. The combined signal is demodulated and the decision variables are decoded. We next describe inter-carrier interference and look at equalization techniques.

3.5. ICI and Methods of ICI Reduction

3.5.1. Introduction

As described earlier, in OFDM multipath interference can be effectively handled. However, there exists a problem with OFDM system, that is its sensitivity to frequency offset between the transmitted and received signals, which may be caused by Doppler shift due to relative motion between transmitter and receiver, or by the difference between the transmitter and receiver local oscillator frequencies. This carrier frequency offset causes loss of orthogonality between sub-carriers and then the signals transmitted on each carrier are not independent of each other. The orthogonality of the carriers is no longer maintained, which results in ICI [25].

3.5.2. Multipath Channel with Carrier Frequency Offset (CFO)

A typical mobile radio channel is one suffering from severe multipath fading and the carrier frequency offsets lead to severe degradation of the bit error rate (BER) performance. In an OFDM system, as the signals in each channel are of low flow rate (or have larger symbol duration) channel can be considered as frequency flat. As aforementioned in chapter two, this is true when the coherence bandwidth of the channel is greater than the symbol rate. But, the real channel is frequency selective and the OFDM system exhibits diversity effect in a frequency selective channel. This is the major benefit in using OFDM system in a multipath fading channel.

To show the channel model with carrier frequency offset, let's consider a general multipath fading channel with carrier frequency offset.

In mobile radio environment, the time variant impulse response model of the multipath channel for one data block using discrete time domain index n is defined as [25]

$$h(n) = \sum_{m=0}^{M-1} h_m e^{\frac{j2\pi\varepsilon_m(n-n_m)}{N}} \tag{3.18}$$

N= the number of sub-carriers

M= number of paths

n_m= the delay samples

ε_m =is the normalized frequency offset of the m^{th} path which is given by $\varepsilon_m = \frac{f_{Dm}}{\Delta f} = \frac{f_c v}{c\Delta f}$

Where f_c is carrier frequency, v speed of the receiver, c speed of light, f_{Dm} Doppler frequency and Δf is frequency spacing. For each path, the amplitude of h_m is Rayleigh distributed.

Let us consider one path with amplitude of h_m , delay chip number n_m and the normalized frequency offset ε_m , the channel impulse response of the m^{th} path can then be expressed by

$$h(n) = h_m e^{\frac{j2\pi\varepsilon_m(n-n_m)}{N}} \tag{3.19}$$

Therefore, the corresponding frequency domain response can be obtained by FFT, which gives after some mathematical simplifications,

$$H_m(k) = h_m e^{\frac{-j2\pi\varepsilon_m n_m}{N}} * \frac{\sin(\pi(k-\varepsilon_m))}{N\sin(\frac{\pi(k-\varepsilon_m)}{N})} e^{(-j(1-\frac{1}{N})\pi(k-\varepsilon_m))} \tag{3.20}$$

The above equation is a function of n_m , ε_m , and k for a fixed N.

If all the paths are considered, $H(k)$ becomes

$$H(k) = \sum_{m=0}^{M-1} h_m e^{\frac{-j2\pi\varepsilon_m n_m}{N}} * \frac{\sin(\pi(k-\varepsilon_m))}{N\sin(\frac{\pi(k-\varepsilon_m)}{N})} e^{(-j(1-\frac{1}{N})\pi(k-\varepsilon_m))} \tag{3.21}$$

This equation expresses the ICI property with respect to the system frequency offset in the time variant multipath radio channel. However, it does not clearly show the structure on which ICI cancellation depends. Therefore, to make it simple and clear let us consider the effect of Carrier Frequency Offset (CFO).

The data at the receiver before FFT operation due to CFO is given by

$$r(n) = x(n)e^{j2\pi n\frac{\varepsilon}{N}} \tag{3.22}$$

$$x(n) = \sum_{k=0}^{N-1} X(k) * e^{\frac{j2\pi kn}{N}} \tag{3.23}$$

For OFDM systems, the received signal at sub-carrier l can be expressed from the FFT

$$R(l) = \frac{1}{N}\sum_{n=0}^{N-1} r(n) * e^{\frac{-j2\pi ln}{N}} \tag{3.24}$$

After a long mathematical calculation the received signal with CFO is given as

$$R(l) = x(l)I(-\varepsilon) + \sum_{k=0, l\neq k}^{N-1} x(k)I(l-k-\varepsilon) \quad where\ k = 0,1,2, \dots N-1 \tag{3.25}$$

Where N is the total number of sub-carriers, $x(k)$ is the modulated subcarrier and $I(l-k-\varepsilon)$ are the complex coefficients for the ICI components in the received signal.

$$I(l-k-\varepsilon) = \frac{\sin(\pi(l-k-\varepsilon))}{Nsin(\pi(l-k-\varepsilon)/N)} \exp\left(j\pi\left(1-\frac{1}{N}\right)(l-k-\varepsilon)\right) \tag{3.26}$$

As it is shown in eq.3.25, the first term is the desired part of the received signal whereas; the second term represents the sum of interferences resulting from other sub-carriers. This undesired part of the received signal can be canceled out using equalization techniques which is presented in the next topics.

3.5.3. Methods of ICI Reduction

As it was described earlier ICI is a special problem in the OFDM system. Therefore in order to mitigate this problem different equalization techniques can be employed:

- Frequency-domain equalization
- Time-domain equalization

In the frequency domain equalization technique, the frequency independent sub- channels are multiplied by a complex number. In time domain equalization technique, the time domain signals are multiplied by window function. In self cancellation, a symbol is modulated on two different sub-carriers with a 180^0 phase shift between them.

The main objective of this thesis is to investigate different methods of ICI reduction by applying them on Cooperative OFDM systems. In this project, we have focused on the problem of ICI reduction using windowing and frequency domain equalization and try to compare their performances.

3.5.3.1. Frequency-Domain Equalization

A simplified block diagram of the proposed binary phase-shift keying (BPSK)-OFDM system using correlative coding on source and destination node is shown in figure 3.6. The signal sequence before correlative coding is expressed by a_k, where k is the subcarriers' index with $k = 0,1,2,\dots,N-1$ and N is the total number of subcarriers. Considering BPSK modulation, a_k takes values of $-1,1$, that fulfill zero mean and independence conditions.

Denoting "D" as the unit delay of the subcarrier index k, the proposed coding with correlation polynomial $F(D) = (1-D)$ is performed as

$$b_k = a_k - a_{k-1} \tag{3.27}$$

Then the coded symbols b_k are modulated on N subcarriers. The symbol b_k takes three possible values $(-2,0,2)$. Equation (3.27) introduces correlation between the adjacent symbols (b_k, b_{k-1}), therefore the independence condition is no longer maintained. To avoid error propagation in the decoding procedure due to correlative coding, precoding (modulo 2) is performed before BPSK modulation, in a similar way to the duobinary signaling in single carrier communication systems [5].

Table 3.1 An example of $(1-D)$ correlative codes

a_k	-1	-1	1	-1	1	1	1	-1	-1	-1	-1	-1	1	-1	-1
b_k		0	2	-2	2	0	0	-2	0	0	0	0	2	-2	0

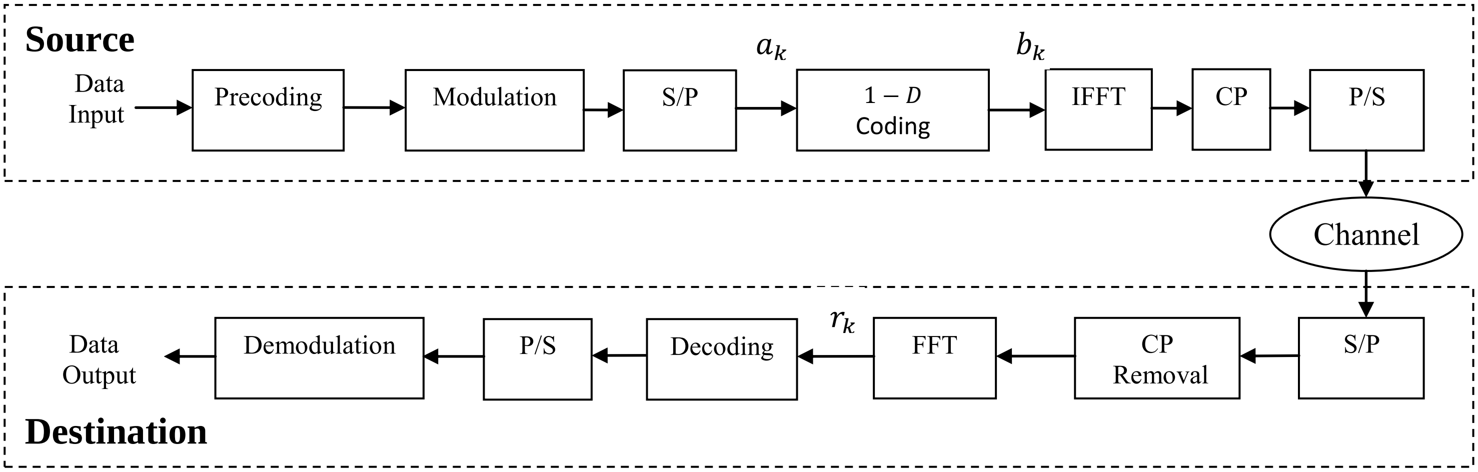


Figure 3.6 Block diagram of correlative coding scheme at the source and destination node

For an OFDM system with N sub-carriers, if the channel frequency offset normalized to the sub-carrier separation is denoted by ε as described in section 3.5.2., then the received signal on sub-carrier k can be derived as

$$r_k = \frac{1}{N}\sum_{n=0}^{N-1}\sum_{l=0}^{N-1} b_l\, e^{\frac{j2\pi nl}{N}}.e^{\frac{j2\pi n\varepsilon}{N}}.e^{\frac{-j2\pi nk}{N}}$$

$$r_k = \sum_{l=0}^{N-1} b_l I(l-k) \qquad (3.28)$$

The received signal r_k can be expressed as a sum of the desired signal C_k and the undesired ICI signal U_k

$$r_k = C_k + U_k \qquad (3.29)$$

Where $C_k = b_k I(0)$ and $U_k = \sum_{l=0,l\neq k}^{N-1} b_l I(l-k)$

The desired signal value C_k depends only on the signal transmitted on sub-carrier k, while U_k depends on the signals transmitted on all the other sub-carriers. Since $E[a_k] = 0$ for BPSK signals, we have $E[b_k] = 0$ from 3.27, leading to $E[C_k] = 0$ and $E[U_k] = 0$.

The average carrier power $E[|C_k|^2]$ and average $E[|U_k|^2]$ should be calculated separately to obtain the Carrier to Interference Ratio (CIR) expression. Since sequence a_k $(k = 0, \dots, N-1)$ fulfills the independence condition, it follows that

$$E[a_k a_{k-l}] = \begin{cases} E[(a_k)^2], & \text{for } k = l \\ 0, & \text{for } k \neq l \end{cases} \tag{3.30}$$

Therefore, we have

$$E[(b_k)^2] = E[(a_k - a_{k-1})^2] = 2\,E[(a_k)^2] \tag{3.31}$$

By using the approximation of $\sin\left(\frac{\pi\varepsilon}{N}\right) \approx \frac{\pi\varepsilon}{N}$ for $N \gg \pi\varepsilon$, we can get

$$E[|C_k|^2] = 2\left(\frac{\sin(\pi\varepsilon)}{\pi\varepsilon}\right)^2 E[(a_k)^2] \text{ and} \tag{3.32}$$

$$E[|U_k|^2] = E\left[\left|\sum_{l=0,l\neq k}^{N-1} b_l I(l-k)\right|^2\right]$$

$$= \sum_{\substack{l=0\\ l\neq k}}^{N-1} \sum_{\substack{p=0\\ p\neq k}}^{N-1} I(l-k)\, I^*(l-k) E\left[b_l b_p\right] \tag{3.33}$$

Simplifying the above equation will give as

$$E[|U_k|^2] = (2\sum_{l=1}^{N-1} |I(l)|^2 - \sum_{l=2}^{N-1}[I(l)I^*(l-1) + I(l-1)I^*(l)])E[(a_k)^2] \tag{3.34}$$

The CIR of an OFDM system with $1-D$ type correlative coding can be obtained by (3.32) and (3.34)

$$CIR = \frac{sin^2(\pi\varepsilon)/(\pi\varepsilon)^2}{\sum_{l=1}^{N-1}|I(l)|^2 - \frac{1}{2}\sum_{l=2}^{N-1}[I(l)I^*(l-1) + I(l-1)I^*(l)]} \tag{3.35}$$

3.5.3.2. Time-Domain Equalization

In time domain equalization technique, a window function is applied to the data in time domain obtained after IFFT operation. The window function proposed to use for ICI suppression is $1 - e^{j2\pi n/N}$ [15]. The application of the window function tapers the start and ends of waveform reducing the transients and consequently the spectral spreading. The application can be divided in two groups.

In the first group, windowing is used to reduce the sensitivity to linear distortions. In the second group, windowing is used to reduce the sensitivity to frequency errors. In this study the second approach is performed. In this case, the window function improves the spectral efficiency and reduces the BER of the OFDM system.

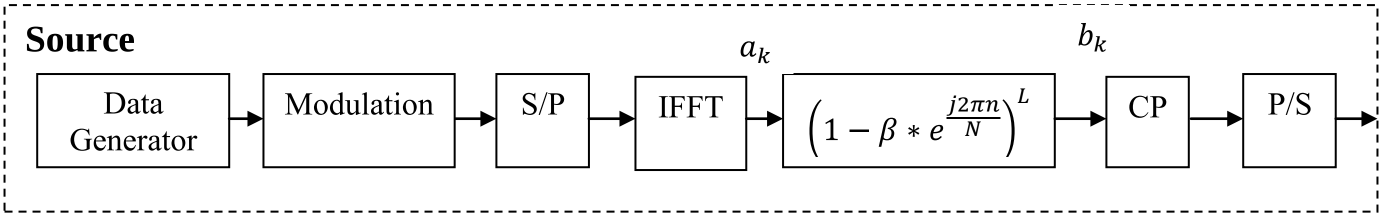


Figure 3.7 Time Domain Equalization on the source node

Let us consider β and L to be one.

Therefore the time domain windowing will become

$$W(n) = 1 - e^{j2\pi n/N} \tag{3.36}$$

The signal after time domain windowing is:

$$b_k = a_k\left(1 - e^{\frac{j2\pi n}{N}}\right) \tag{3.37}$$

The window function used is optimized to obtain a maximized Carrier to Interference Ratio (CIR). So, the order of the window function is optimized to be 1, assuming the modulation system to be BPSK. The time domain windowed signal at the receiver will be

$$r_k = C_k + U_k \tag{3.38}$$

Where

$$C_k = b_k I(-\varepsilon) \text{ and} \tag{3.39}$$

$$U_k = \sum_{l=0, l\neq k}^{N-1} b_k I(l-k-\varepsilon) \tag{3.40}$$

The theoretical CIR for the window function is given by

$$CIR = \frac{|I(-\varepsilon)|^2}{\sum_{l=0}^{N-1} |I(k-\varepsilon)|^2 - \sum_{l=0, l\neq k}^{N-1} Re[2I^*(k-\varepsilon)I(l-k-\varepsilon))]} \tag{3.41}$$

Later, by using this expression the two ICI reduction methods time and frequency domain equalization techniques are compared.

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

As it is presented in the previous chapters, two ICI reduction techniques has been chosen in order to improve the system performance. In this chapter, different simulation results are presented using appropriate parameters with brief discussions on the outputs. The simulation results are plotted in terms of BER and CIR. BPSK modulation is considered for the performance comparison. This is because BPSK is relatively less affected by carrier frequency offset as compared to higher order modulation techniques. Multipath Rayleigh fading is considered to give good reason for the performance under different environments.

Summary of parameters used for the simulations

- Channel: AWGN and flat and frequency selective Rayleigh fading
- Number of resolvable components: 3
- Number of FFT points, nFFT: 64
- Number of used subcarriers: 52
- FFT symbol period: 3.2ms
- Cyclic prefix ratio: 0.25
- RMS delay spread :100ns
- OFDM frame length: 4ms
- Modulation scheme: BPSK, QPSK, 16-QAM
- Normalized frequency offset (ε_m): 0.0 – 0.5
- Relaying type: AaF

The following assumptions are made together with the parameters presented above

- Perfect symbol timing synchronization at the destination (receiver)
- Carrier frequency offset is the frequency error normalized by subcarrier frequency spacing.

4.1. Performance Comparison of Cooperative Diversity with Non-cooperative Diversity Under flat fading Channel

The BER performance of cooperative half duplex communication system is shown in Figure 4.1. It is evident from this figure that:

- AaF cooperative diversity achieves diversity gain leading to the improvement in performance in terms of the average BER in comparison with non-cooperative network. This is valid for both simulation and theoretical results. At 10^{-3} BER the system with AaF cooperative diversity achieves a 10 dB SNR as compared to the non-cooperative communication system. The theoretical BER calculation is taken from [41].
- Comparing simulation results with that of theoretical, both for cooperation and non-cooperation, there is a discrepancy. One possible justification is that, theoretical results are based on high SNR approximations.

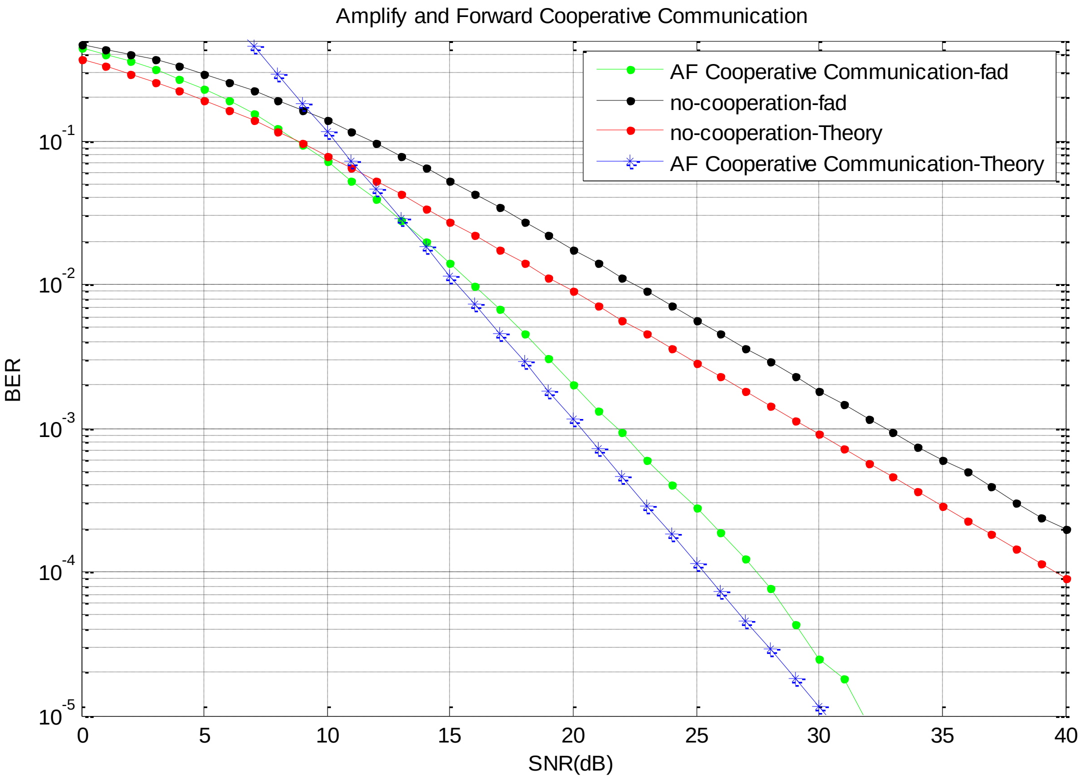


Figure 4.1 BER probabilities for AF Cooperative Communication.

4.2. BER Probability of Cooperative OFDM and Non-Cooperative OFDM System Under Frequency Selective Channel

In Figure 4.1 we have presented BER probability for cooperative without applying OFDM. Next, let us applying OFDM technique for cooperative diversity in a Rayleigh fading channel. Figure 4.2 shows BER performance comparison between cooperative OFDM and non-cooperative OFDM system. The result shows lower BER for cooperative OFDM as compared to non-cooperative OFDM system. Moreover the simulation result shows the fact that Cooperative Diversity achieves a slightly better performance gain over the non cooperative one. Moreover, comparing the results in Figure 4.2 and 4.1, the performance in frequency selective channel seems to perform slightly better; which is against intuition. However, one possible source of improvement, despite the channel condition, is the addition of OFDM block.

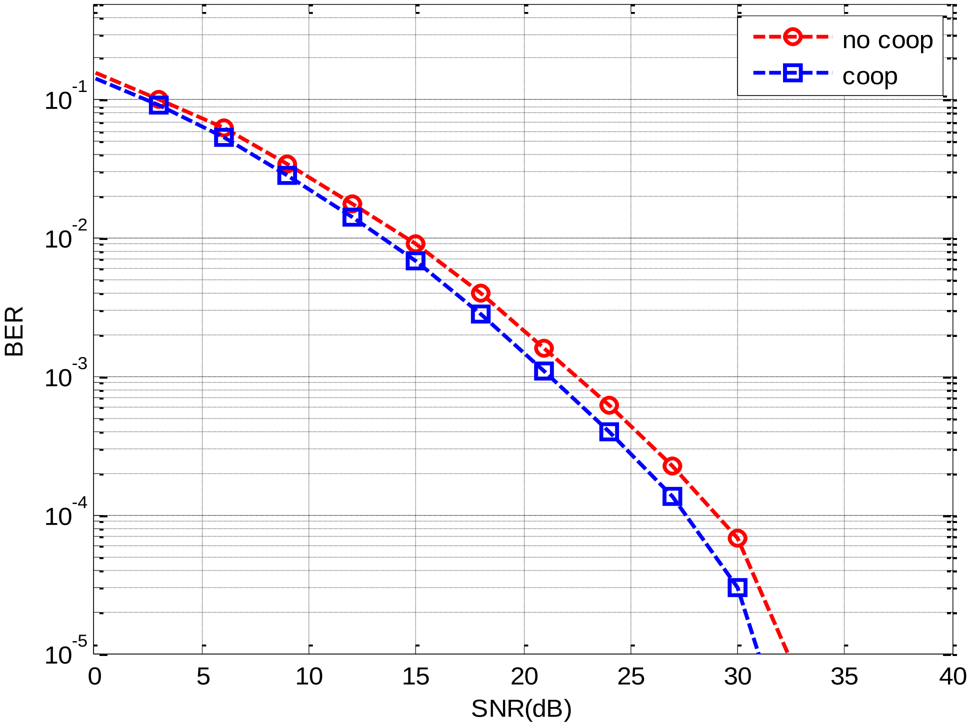


Figure 4.2 BER comparison of Cooperative OFDM and Non-cooperative OFDM System.

4.3. Carrier Frequency Offset Effect on BER Performance

4.3.1. BER Comparison Across Different Modulation Techniques

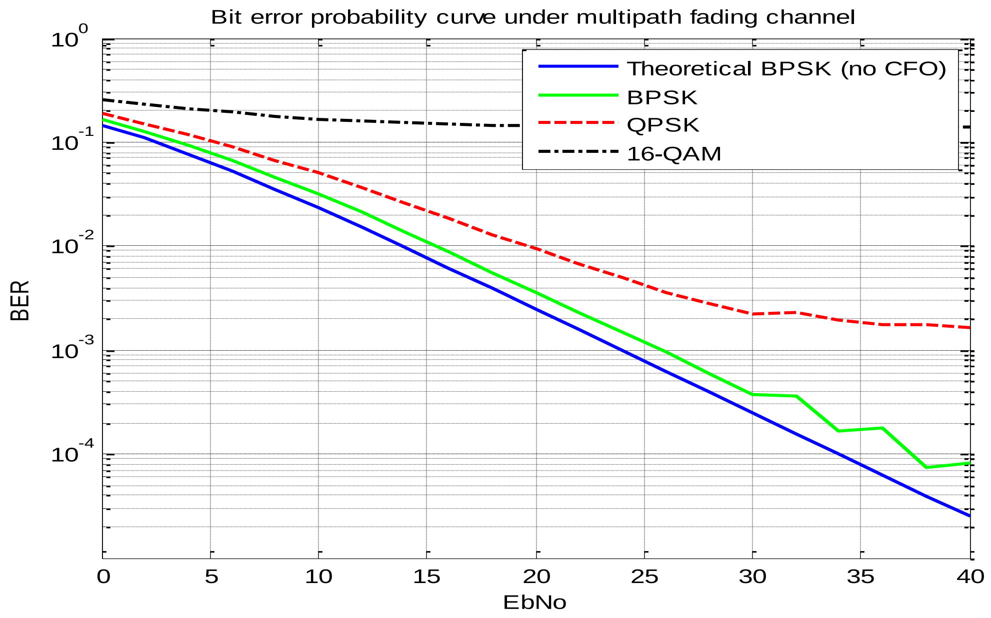


Figure 4.3 Effect of Carrier Frequency Offset on BER performance.

Figure 4.3 shows BER effect of carrier frequency offset comparison across different modulation techniques at 0.12 frequency offset. As it is clearly seen in the above figure the 16-QAM are more susceptible to carrier frequency offset than QPSK and BPSK. This is because the distance among the symbols in 16-QAM constellation is less than QPSK. Correspondingly BPSK is relatively less affected as compared to the others. The theoretical BER curves are plotted as a reference to show the effect of CFO. Therefore to achieve 10^{-3} BER, the OFDM system using 16-QAM modulation needs 32dB SNR, for QPSK modulation we need 13 dB and for BPSK an SNR of about 8dB is necessary. Finally, comparing Figures 4.2 and 4.3, we note that the performance slightly degrades in the latter; this loss is attributed to the presence of CFO.

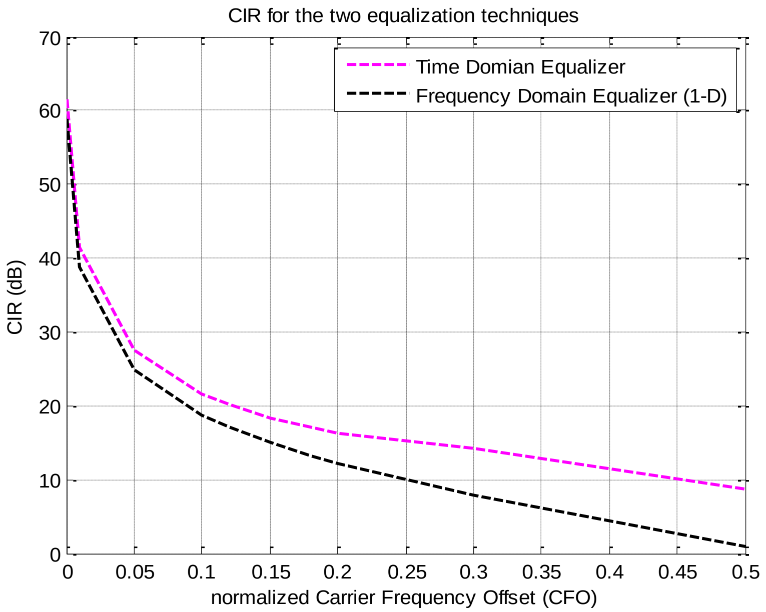


Figure 4.4 CIR comparison of TDE and FDE techniques.

4.3.2. Effect of Equalization Techniques on Carrier-to-Interference Ratio

Other than BER, CIR is another performance measurement used to investigate the effect of time-domain equalization and frequency-domain equalization. CIR serves as an indication of good quality. The CIR comparison of time domain equalizer and frequency domain equalizer are shown in the following figure. It can be seen that time domain equalization outperforms the frequency domain equalization technique.

From Figure 4.4, it can be observed that, when the normalized CFO is large enough, time-domain equalization technique outperforms frequency-domain equalization, due to its better capabilities in suppressing ICI and preventing error propagation through OFDM symbols. Additionally, when the normalized CFO is zero the TDE technique behaves like that of FDE. The effect of TDE can be clearly seen when the CFO value increases above 0.2.

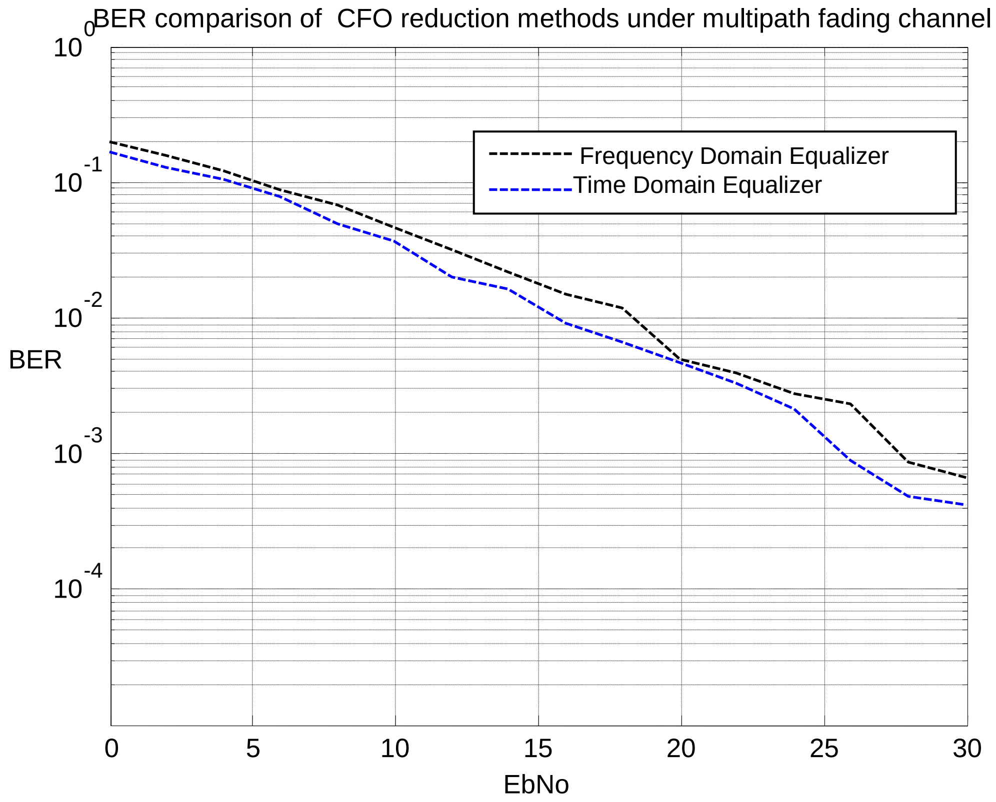


Figure 4.5 Comparison of ICI reduction Techniques in Rayleigh

4.4. BER Comparison of TDE and FDE

The BER performance measure of time domain equalization technique is compared with frequency domain equalization and standard OFDM system. In Figure 4.5 the performance is presented using Carrier Frequency Offset to be 0.12.

From the comparison of the average BER performance of the two ICI reduction techniques, the increase in frequency offset value results in the increase in BER and the TDE technique offers a better average BER performance compared to FDE technique. Although the two equalization techniques have comparable performances the TDE technique has a slightly reduced BER performance for a specified CFO.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The goal of this thesis is to implement OFDM as a modulation technique on cooperative diversity so that the performance of the communication system increases in terms of bit error rate and signal to noise ratio since OFDM is resistant to multipath fading and it allows high level of spectral efficiency. The basic idea behind cooperation is that several users in a network can share their resources in order to form a virtual antenna array which allows them to achieve transmit diversity. Over 3dB performance gain can be obtained with the employment of OFDM on Cooperative Communication in Rayleigh multipath channel as compared to the non-cooperative case.

OFDM is a very important modulation technique in wideband wireless communication and multimedia communication systems. The paper concentrates on reducing the effect of ICI using time-domain windowing equalization scheme and frequency-domain equalization scheme and comparing their result. This paper shows that the CIR for the TDE scheme is enhanced considerably compared to the FDE and the standard OFDM without any equalization. Such a technique will improve the performance of the OFDM systems.

The BER performances of TDE and FDE are reduced considerably compared to the standard OFDM without any equalization techniques. Even though the two ICI reduction techniques have comparable performances the time-domain equalization technique has a slightly reduced BER performance compared to that of frequency-domain equalization. Therefore, the TDE scheme outperforms the FDE, due to its better capabilities in suppressing ICI and preventing error propagation through OFDM symbols when the normalized frequency offset is large enough.

Recommendations for Future Work

Though all the impairments of OFDM systems have been analyzed in this thesis, only mitigation of frequency offset is implemented. Hence, other techniques such as pulse shaping, extended Kalman filter, and/or implementation of better equalization techniques can be applied for ICI reduction and to provide further improvement in performance.

Other than AaF relaying technique, different relaying techniques can be considered for better Cooperative Diversity gain; e.g., DaF, compress-and-forward and incremental relaying.

The cyclic prefix for OFDM can require up to 15~20% bandwidth overhead. It is desirable to develop techniques that eliminate or reduce the cyclic prefix for example one can implement multi symbol encapsulated (MSE) OFDM. In MSE-OFDM technique a number of conventional OFDM symbols without CP are grouped together. The group of symbols are protected by a single CP. CP in this case comprises of last few samples of the last OFDM symbol. As there is a single CP for a group of OFDM symbols the MSE-OFDM exhibits an improvement of bandwidth efficiency compared to the conventional OFDM.

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