PERFORMANCE ANALYSIS OF DIVERSITY COMBINING WITH OFDM

A Dissertation submitted in partial fulfilment of the requirements
for the award of the Degree of

MASTER OF ENGINEERING
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Submitted By

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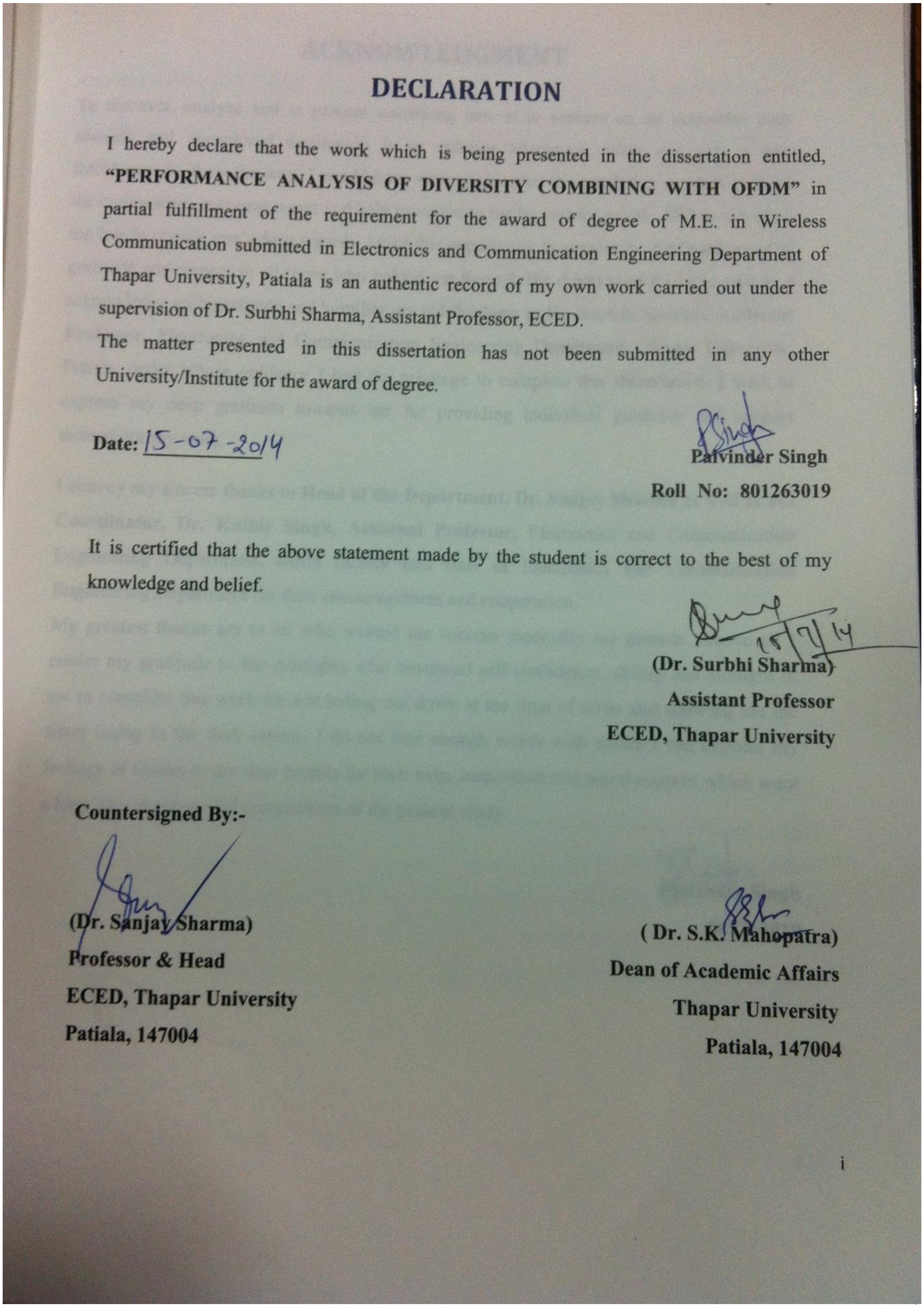

DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled, **"PERFORMANCE ANALYSIS OF DIVERSITY COMBINING WITH OFDM"** in partial fulfillment of the requirement for the award of degree of M.E. in Wireless Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of Dr. Surbhi Sharma, Assistant Professor, ECED.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

Wireless communications is the fastest growing segment of the communications industry. There is always a greater demand for capacity, reliability and also need to integrate voice, data and other type of traffic over radio channels. There are many ways to solve all these problems, such as OFDM, Spread spectrum techniques and Antenna arrays. In Wireless communications, the effect of channel fading and co-channel interference is very high. So we need diversity techniques which are used to mitigate all these effects. Indeed, diversity techniques at the receiver, in which two or more copies of the same information bearing signal are combined skillfully to increase the overall signal-to-noise ratio (SNR), still offer one of the greatest potential for radio link performance improvement to many of the current and future wireless technologies.

This dissertation develops a mathematical framework for analyzing the average bit error rate performance of selection diversity combining, maximal ratio combining and optimum combining schemes with binary phase-shift keying (BPSK) modulation over independent and identically distributed Rayleigh fading channel with OFDM as multiple access technique.

The need of high speed and reliable digital wireless communication which includes not only cellular phones but devices such as wireless modems, high definition television (HDTV) and digital radios. The need of high speed data transfer is catered by the orthogonal frequency division multiplexing (OFDM) and the performance of the system which is dictated by random fluctuations in the amplitude of the received signal is enhanced by using maximal ratio combining (MRC) and optimal combining (OC) diversity combining technique. Here we explore the system performance having receiver antenna diversity along with OFDM in Rayleigh fading environment. The performance of system is evaluated in terms of signal to noise ratio (SNR) and bit error rate (BER) probability. The simulation result shows that the performance ofOFDM system in Rayleigh fading in terms of SNR can be improved by using MRC and OC.

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LIST OF ABBREVIATIONS

DSP	Digital Signal Processing
VLSI	Very Large Scale Integration
BPSK	Binary Phase Shift Keying
MPSK	Multilevel Phase Shift Key
MQAM	Multilevel Quadrature Amplitude Modulation
SC	Selection Combining
SDC	Selection Diversity Combining
SD	Selection Diversity
MRC	Maximal Ratio Combining
ODC	Optimum Diversity Combining
BEC	Binary Erasure Channels
EGC	Equal Gain Combining
dB	Decibel
AWGN	Additive White Gaussian Noise
i.i.d.	Independent Identical Distribution
i.n.i.d	Independent Non Identical Distribution
PDF	Probability Density Function
CDF	Cumulative Density Function
GA	Gaussian Approximation

DE	Density Evolution
CEP	Conditional Error Probability
MGF	Moment Generating Function
STBC	Space Time Block Code
LOS	Line of Signal
NLOS	Non Line of Sight
SNR	Signal to Noise Ratio
SIR	Signal-to-Interference Ratio
SINR	Signal-to-Interference Noise Ratio
MMAC	Mobile Multimedia Access Communication
LTE	Long Term Evolution
UHF	Ultra High Frequency
LAN	Local Area Network
BER	Bit Error Rate
SER	Symbol Error Rate
SOI	Signal of Interest
CCI	Co-channel Interference

CHAPTER 1

INTRODUCTION

Wireless communications is one of the most active areas of technology development of our time. This development is being driven primarily by the transformation of what has been largely a medium for supporting voice telephony into a medium for supporting other services, such as the transmission of video, images, text, and data. Thus, similar to the developments in wireline capacity in the 1990s, the demand for new wireless capacity is growing at a very rapid pace. Although there are, of course, still a great many technical problems to be solved in wireline communications, demands for additional wireline capacity can be fulfilled largely with the addition of new private infrastructure, such as additional optical fiber, routers, switches, and so on. On the other hand, the traditional resources that have been used to add capacity to wireless systems are radio bandwidth and transmitter power. Unfortunately, these two resources are among the most severely limited in the deployment of modern wireless networks as Radio Bandwidth because of the very tight situation with regard to useful radio spectrum, and Transmitter Power because mobile and other portable services require the use of battery power, which is limited. These two resources are simply not growing or improving at rates that can support anticipated demands for wireless capacity. On the other hand, one resource that is growing at a very rapid rate is that of processing power. Moore's Law, which asserts a doubling of processor capabilities every eighteen months, has been quite accurate over the past twenty years, and its accuracy promises to continue for years to come. Given these circumstances, there has been considerable research effort in recent years aimed at developing new wireless capacity through the deployment of greater intelligence in wireless networks. A key aspect of this movement has been the development of novel signal transmission techniques and advanced receiver signal processing methods that allow for significant increases in wireless capacity without attendant increases in bandwidth or power requirements. But mobile radio channel places fundamental limitations on the performance of wireless communication systems. The transmission path between transmitter and receiver can vary from simple line of sight to one that is severely obstructed by buildings, mountains etc. unlike wired channels that are stationary and predictable, radio channel is extremely random and do not offer easy analysis. Even the speed of motion impacts how rapidly the signal level fades as a mobiles terminal moves in space. Modeling the radio channel has historically been one of the most difficult parts of mobile radio system design, and is typically done in a statistical fashion.

1.1 WIRELESS COMMUNICATION SYSTEM

In Figure (1.1), the data source generates an information signal that is to be transmitted at the receiver. After the message is generated by the data source which is processed at the transmitter end before being transmitted on a noisy channel. The processing is done to compensate the effect of various signal impairments caused by the channel and to enable the waveforms to be detected easily at the receiver end.

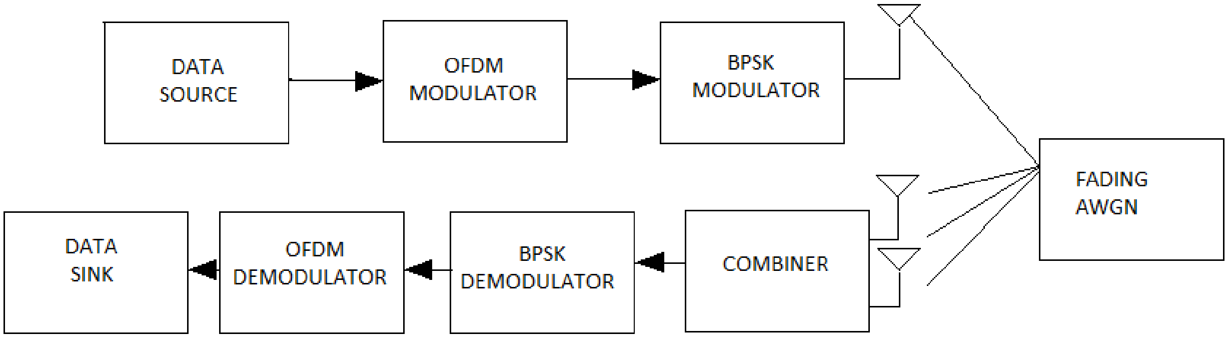


Figure 1.1: Block diagram of a wireless communication system [3]

The two main blocks at the transmitter end are OFDM and modulator. The message from data source is fed to OFDM modulator. Typically, the OFDM modulator is multicarrier modulation scheme that transmits the data by dividing the serial high data rate streams into a number of low data rate parallel data streams [3]. Orthogonal Frequency Division Multiplexing (OFDM) is a kind of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is then modulated by a low rate data stream at different carrier frequency. The conventional OFDM system makes use of IFFT and FFT for multiplexing the signals and reduces the complexity at the transmitter and receiver. These bits are then modulated using the BPSK modulator to transfer the signal waveforms to better withstand the channel impairments. Modulation is the method by which the message symbols are converted to waveforms that are compatible with the requirements imposed by the channel. The channel is the transmission medium, through which this waveform is transmitted. It is responsible for distortion the message signal and degrading the performance of the wireless communication system. The distortions in wireless channel are often due to noise (AWGN) and fading. After the degraded signal is received at the receiver, it is processed by the linear combiner and demodulator which try to obtain the original signal. The process at the receiver is the reverse of that at the transmitter. The received waveform is demodulated by the BPSK demodulator. The term data sink is used to describe a device or part of computer which is capable of accepting data signals from a data transmission device and storing data for future use. All this trouble is undertaken just to ensure that the correct information which is intelligible is imparted to the data sink.

1.2 ROLE OF OFDM AND DIVERSITY TECHNIQUE

In a mobile communication channel while transmitting signal from a transmitter end to a receiver end through a channel, the signal not only confront noise and distortion but the presence of multipath propagation also dictates the propagation. In analog communication this multipath propagation results in echoes (in Audio communication) and shadows (in case of Visual communication), which can be tolerated by our ears and eyes respectively. But in case of digital communication these multipath propagations leads to linear channel distortion which manifest as inter symbol interference (ISI). This is because multipath leads to multiple copies of same signal reflected from various obstacles lying within the path while travelling through the channel. These multiple copies arrive at the receiver with different time delays. Thus one symbol pulse delayed affects one or more adjacent symbols causing ISI. To combat the effect of ISI, two highly effective tools are equalization and OFDM [1]. Fast fading frequency selective channels are the most serious challenges to mobile wireless communications, because firstly they introduce ISI and secondly the channel characteristics are also time varying. However to combat the ISI time domain equalization techniques can be applied but they need training data to either the channel parameters or estimate equalizer parameters. Since the parameter estimation of channels or equalizers cannot work properly and effectively unless the parameters stay constant between successive training periods. As a result these kinds of equalizers are unable to confront such channels having fast fading response. Now OFDM can convert a frequency-selective channel into a parallel group of flat channels and hence converting a fast fading and frequency selective channel into a parallel bank of fast flat-fading channel [3].

The receiver diversity is a very effective tool to mitigate the effect of this fast flat-fading. The receiver diversity can be achieved by transmitting the same data over more than one path in order to nullify the effect of fading. Here is description of BER two most popular diversity techniques MRC and OC. The motive behind using OFDM along with MRC is to divide a broadband frequency channel into a number of narrowband sub-channels. MRC is preferred over other linear combiners due to its best performance amongst the others [5]. Then these sub-channels experience flat fading instead of frequency selective fading, as it is found in case of broadband channels and to mitigate the effect of flat fading we can use diversity or equalization techniques can be easily applied [4]. While in case of presence of interferers OC is best amongst all other diversity combiners [9]. Among the advanced wireless standards such as Wi-Fi (IEEE 802.11n), WiMAX (IEEE 802.16e) and cellular LTE (long-term evolution) these all have adopted OFDM and MIMO technologies to achieve much higher data rates and better coverage area.

1.2.1 OFDM MODEL

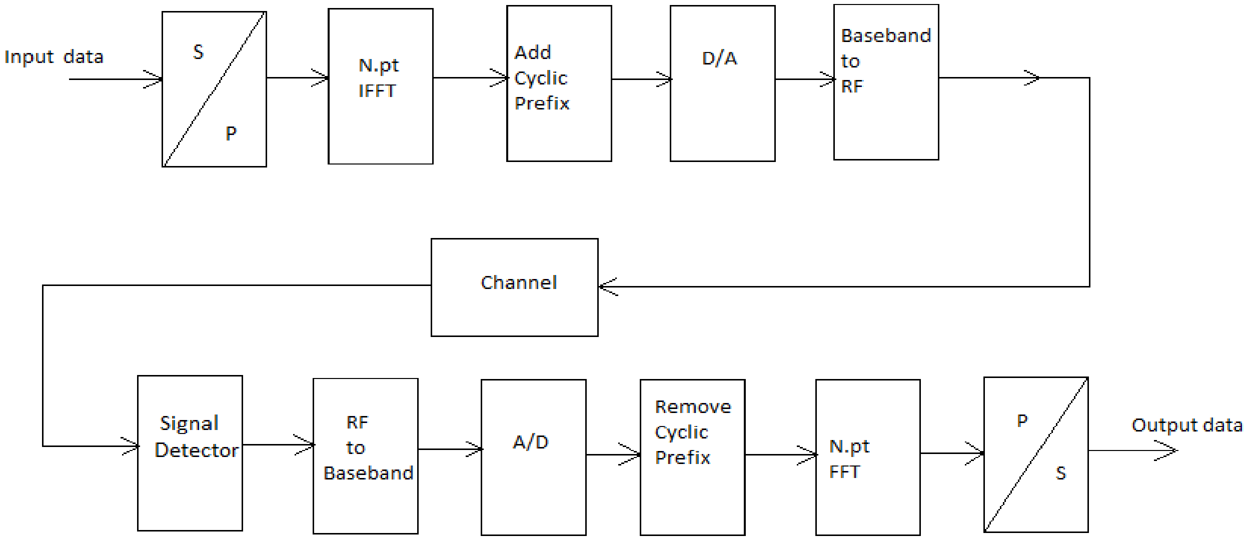


Figure 1.2: Block diagram of OFDM model [1]

As described in Figure 1.2 the input data is firstly converted from analogue to digital by A/D converter, then these serial data streams are converted to parallel data stream by using P/S(parallel to serial converter). The serial data stream of L length is now grouped into N number of blocks of parallel data streams having length of M bits each. Each of these M bit blocks are then fed to a N point Inverse Fast Fourier Transformer (IFFT) block. This block provides N number of sub-carriers which are providing N number of sub channels having different carrier frequencies as equivalent to N number of different local oscillators in analog signal. These sub channels are also orthogonal to each other in order to minimize the interference between them and to utilize the available bandwidth in the best possible way. After the division and applying IFFT to the blocks of signal a cyclic prefix (CP) is added to each of the block at both ends. This CP consists of nearly one fourth bits of the block itself and is added to each of the blocks both at the starting end and at the last end of each block, this addition of extra bits leads to minimizing the effects of inter-symbol-interference (ISI). It also converts the linear convolution between channel and transmitter data to the circular conversion which is easier to implement. After the addition of CP to the blocks of parallel data stream is again converted to serial data stream. The serial data is again converted to analog signal and transmitted through single antenna.

Now the data is transmitted over the channel, where it faces noise, attenuation and channel delay spread due to which multipath propagation occurs. At the receiver end the signal is detected by detector and then fed to analog to digital converter which gives us the digital format of received data which is in serial form, parallel to serial converter gives back parallel blocks and feed it to CP remover where additional cyclic prefix is removed. After then data is fed to FFT block to get the original data bits from each carrier. The parallel data is again converted back to serial bitstream and hence original data bits are obtained at the output.

OFDM is of great interest by researchers and research laboratories all over the world. Also, it is expected to be used for wireless broadband multimedia communications. Data rate is really what broadband is about. The new standard specifies bit rates of up to 54 Mbps. Such high rate imposes large bandwidth, thus pushing carriers for values higher than UHF band. For instance, IEEE802.11a has frequencies allocated in the 5 and 17 GHz bands. This project is oriented to the application of OFDM to the standard IEEE 802.11a, following the parameters established for that case. OFDM can be seen as either a modulation technique or a multiplexing technique. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrowband interference. In a single carrier system, a single fade or interferer can cause the entire link to fail, but in a multicarrier system, only a small percentage of the subcarriers will be affected. Error correction coding can then be used to correct for the few erroneous subcarriers. The concept of using parallel data transmission and frequency division multiplexing was published in the mid-1960s. Some early development is traced back to the 1950s. A U.S. patent was filed and issued in January 1970 [3]. In a classical parallel data system, the total signal frequency band is divided into N non-overlapping frequency subchannels. Each sub channel is modulated with a separate symbol and then the N subchannels are frequency-multiplexed.

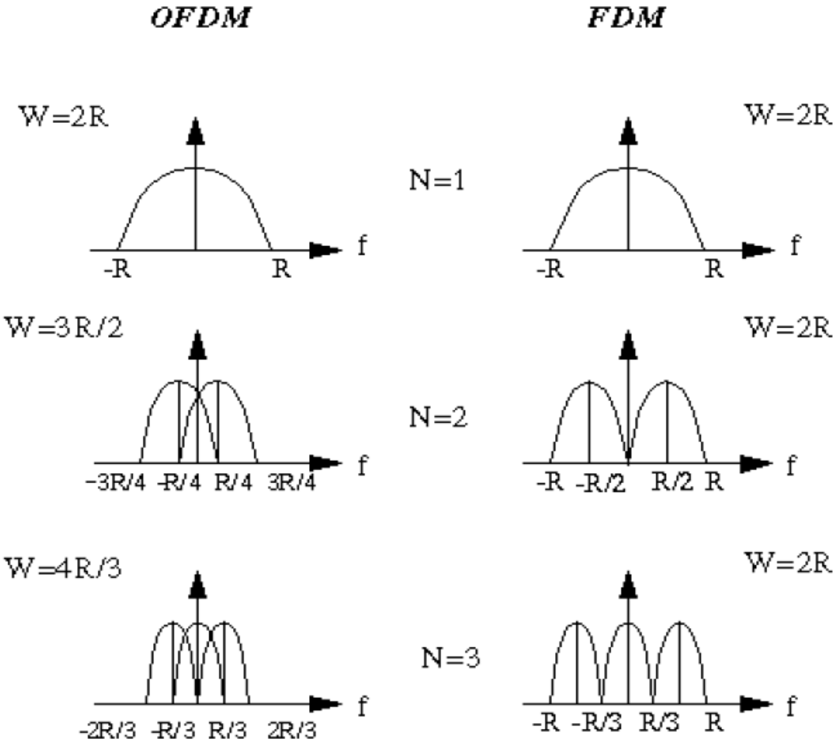
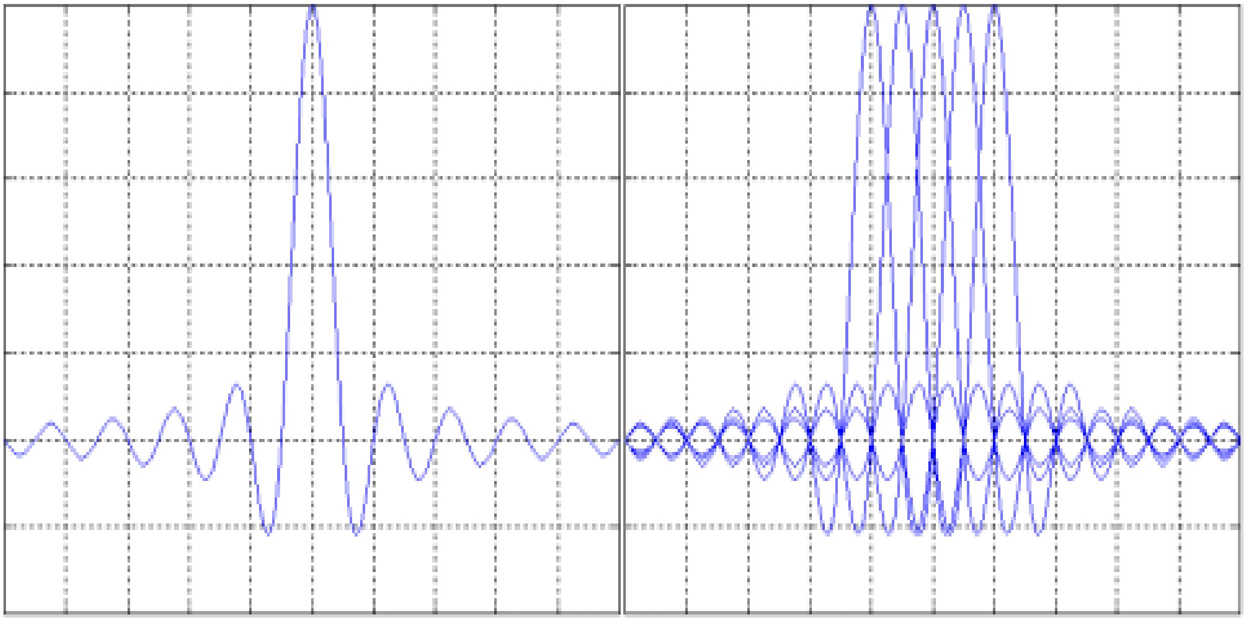


Figure 1.3: Concept of OFDM signal [3]

Figure 1.3 illustrates the difference between the conventional non overlapping multicarrier technique and the overlapping multicarrier modulation technique. As depicted, by using the overlapping multicarrier modulation technique, we save almost 50% of bandwidth. To realize the overlapping multicarrier technique, however we need to reduce crosstalk between subcarriers, which means that we want orthogonality between the different modulated carriers. The word orthogonal indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. In a normal frequency-division multiplex system, many carriers are spaced apart in such a way that the signals can be received using conventional filters and demodulators. In such receivers, guard bands are introduced between the different carriers and in the frequency domain, which results in a lowering of spectrum efficiency. It is possible, however to arrange the carriers in an OFDM signal so that the sidebands of the individual carriers overlap and the signals are still received without adjacent carrier interference. To do this, the carriers must be mathematically orthogonal. The receiver acts as a bank of demodulators, translating each carrier down to DC, with the resulting signal integrated over a symbol period to recover the raw data. If the other carriers all beat down the frequencies that, in the time domain, have a whole number of cycles in the symbol period T, then the integration process results in zero contribution from all these other carriers.



(a) **(b)**

Figure 1.4: (a) Spectra of an OFDM subchannel and (b) OFDM signal [3]

Much of the research focuses on the high efficient multicarrier transmission scheme based on "orthogonal frequency" carriers. In 1971, Weinstein and Ebert applied the discrete Fourier transform (DFT) to parallel data transmission systems as part of the modulation and demodulation process. Figure 1.4 shows the spectrum of the individual data of the subchannel. The OFDM signal, multiplexed in the individual spectra with a frequency spacing b equal to the transmission speed of each subcarrier, is shown in Figure 1.4 and it also shows that at the center frequency of each subcarrier, there is no crosstalk from other channels. Therefore, if we use DFT at the receiver and calculate correlation values with the center of frequency of each subcarrier, we recover the transmitted data with no crosstalk. In addition, using the DFT-based multicarrier technique, frequency-division multiplex is achieved not by bandpass filtering but by baseband processing. Moreover, to eliminate the banks of subcarrier oscillators and coherent demodulators required by frequency-division multiplex, completely digital implementations could be built around special-purpose hardware performing the fast Fourier transform (FFT), which is an efficient implementation of the DFT. Recent advances in very-large-scale integration (VLSI) technology make high-speed, large-size FFT chips commercially affordable. Using this method, both transmitter and receiver are implemented using efficient FFT techniques that reduce the number of operations from N^2 in DFT down to N log N.

In the 1980s, OFDM was studied for high-speed modems, digital mobile communications, and high-density recording. One of the systems realized the OFDM techniques for multiplexed QAM using DFT and by using pilot tone, stabilizing carrier and clock frequency control and implementing trellis coding are also implemented. Moreover, various-speed modems were developed for telephone networks. In the 1990s, OFDM was exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL; 1.6 Mbps), asymmetric digital subscriber lines (ADSL; up to 6 Mbps), very-high-speed digital subscriber lines (VDSL; 100 Mbps), digital audio broadcasting (DAB), and high-definition television (HDTV) terrestrial broadcasting. The OFDM transmission scheme has the following key advantages:

- Makes efficient use of the spectrum by allowing overlap
- By dividing the channel into narrowband flat fading subchannels, OFDM is more resistant to frequency selective fading than single carrier systems are. Eliminates ISI and IFI through use of a cyclic prefix.

- Using adequate channel coding and interleaving one can recover symbols lost due to the frequency selectivity of the channel.
- Channel equalization becomes simpler than by using adaptive equalization techniques with single carrier systems.
- It is possible to use maximum likelihood decoding with reasonable complexity, as discussed in OFDM is computationally efficient by using FFT techniques to implement the modulation and demodulation functions.
- Optimum Pre-DFT Combining with Cyclic Delay Diversity for OFDM Based WLAN Systems
- Is less sensitive to sample timing offsets than single carrier systems are.
- Provides good protection against cochannel interference and impulsive parasitic noise.

In terms of drawbacks OFDM has the following characteristics:

- The OFDM signal has a noise like amplitude with a very large dynamic range, therefore it requires RF power amplifiers with a high peak to average power ratio.
- It is more sensitive to carrier frequency offset and drift than single carrier systems are due to leakage of the DFT.

1.3 MODULATION SCHEMES

After the signal has been input, it is modulated using a carrier to transform the signal into waveform that can better withstand the channel impairments. By modulating, we vary some parameter of the carrier according to the message signal and sent it over the channel. The basic band-pass modulation/demodulation techniques are divided into two parts:

Coherent Modulation

Non-coherent Modulation

In coherent modulation schemes, the information about the phase and frequency of the carrier is needed at the receiver for detection. It is more efficient in terms of the performance but the receiver design becomes more complex. In non-coherent modulation schemes, no information about the phase and frequency of the carrier is required for detection. In this scheme the receiver design is less complex but at the cost of degraded performance. A number of modulation schemes have been proposed in the past.

1.4 PROPAGATION CHARACTERISTICS OF RADIO CHANNELS

In an ideal radio channel, the received signal would consist of only a single direct path signal, which would be a perfect reconstruction of the transmitted signal. However in a real channel, the signal is modified during transmission in the channel. The received signal consists of a combination of attenuated, reflected, refracted, and diffracted replicas of the transmitted signal. On top of all this, the channel adds noise to the signal and can cause a shift in the carrier frequency if the transmitter or receiver is moving (Doppler Effect). Understanding of these effects on the signal is important because the performance of a radio system is dependent on the radio channel characteristics.

1.4.1 Attenuation

Attenuation is the drop in the signal power when transmitting from one point to another. It can be caused by the transmission path length, obstructions in the signal path, and multipath effects. Any objects, which obstruct the line of sight signal from the transmitter to the receiver, can cause attenuation. Shadowing of the signal can occur whenever there is an obstruction between the transmitter and receiver. It is generally caused by buildings and hills, and is the most important environmental attenuation factor. Shadowing is most severe in heavily built up areas, due to the shadowing from buildings. However, hills can cause a large problem due to the large shadow they produce. Radio signals diffract off the boundaries of obstructions, thus preventing total shadowing of the signals behind hills and buildings. However, the amount of diffraction is dependent on the radio frequency used, with low frequencies diffracting more than high frequency signals. To overcome the problem of shadowing, transmitters are usually elevated as high as possible to minimize the number of obstructions.

Table 1.1: Typical attenuation in radio channel [6]

Description	Typical Attenuation due to Shadowing
Heavily built-up Urban Center	20 dB variation from street to street
Sub Urban Area (fewer large buildings)	10 dB more power than built up urban center
Rural Open Area	20 dB more power than built up urban area
Terrain Irregularities and tree foliage	3-12 dB power variation

Typical amounts of variation in attenuation due to shadowing are shown in Table 1.1.

1.4.2 FADING

Radio waves propagate from a transmitting antenna and travel through free space undergoing absorption, reflection, refraction, diffraction and scattering. They are greatly affected by the ground, buildings, trees and other objects present in the path. All these things are responsible for the characteristics of the received signal. The two main factors which affect the reliability of a message over the channel are noise and fading. Noise in the communication system is generally modeled as AWGN because it is convenient to deal with noise of additive rather than multiplicative in nature. Noise affects the transmission over the channel by degrading the signal quality. Over the large distances the signal quality is shown to degrade even without the presence of AWGN. This degradation is known as fading [6] and the errors introduced by fading are much difficult to deal with as compared to the errors introduced by the noise. Fading is caused by multipath effect. Multi-path effect means that a signal transmitted from a transmitter may have multiple copies traversing different paths to reach a receiver. Thus, at the receiver, the received signal should be the sum of all these multi-path signals. Now because the paths traversed by these signals are different; some are longer and some are shorter. The one at the direction of line-of-sight must be the shortest. These signals interact with each other. If the signals are in phase, they would intensify the resultant signal; otherwise, the resultant signal is weakened due to out of phase. This phenomenon is called channel fading. In general, there are two criteria's to measure channel fading,

Doppler spread

Delay spread

Doppler spread

When a wave source and a receiver are moving relative to one another the frequency of the received signal will not be the same as the source. When they are moving toward each other the frequency of the received signal is higher than the source, and when they are approaching each other the frequency decreases. This is called the Doppler Effect. An example of this is the change of pitch in a car s horn as it approaches then passes by. This effect becomes important when developing mobile radio systems. The amount the frequency changes due to the Doppler effect depends on the relative motion between the source and receiver and on the speed of propagation of the wave [10]. The Doppler shift in frequency can be written as:

$$\Delta f \approx \pm f_o \frac{v}{c} \tag{1}$$

Delay spread

The received radio signal from a transmitter consists of typically a direct signal, plus reflections of object such as buildings, mountings, and other structures. The reflected signals arrive at a later time than the direct signal because of the extra path length, giving rise to a slightly different arrival time of the transmitted pulse, thus spreading the received energy. Delay spread is the time spread between the arrival of the first and last multipath signal seen by the receiver. In a digital system, the delay spread can lead to inter-symbol interference. This is due to the delayed multipath signal overlapping with the following symbols. This can cause significant errors in high bit rate systems, especially when using time division multiplexing (TDMA).

Table 1.2: Typical Delay Spread [10]

Environment or cause	**Delay Spread**	**Maximum Path Length Difference**
INDOOR(ROOM)	40 nsec-200 nsec	12m-60m
OUTDOOR	1 nsec-20 nsec	300m -6km

Table 1.2 shows the typical delay spread that can occur in various environments. The maximum delay spread in an outdoor environment is approximately 20 sec, thus significant intersymbol interference can occur at bit rates as low as 25kbps.

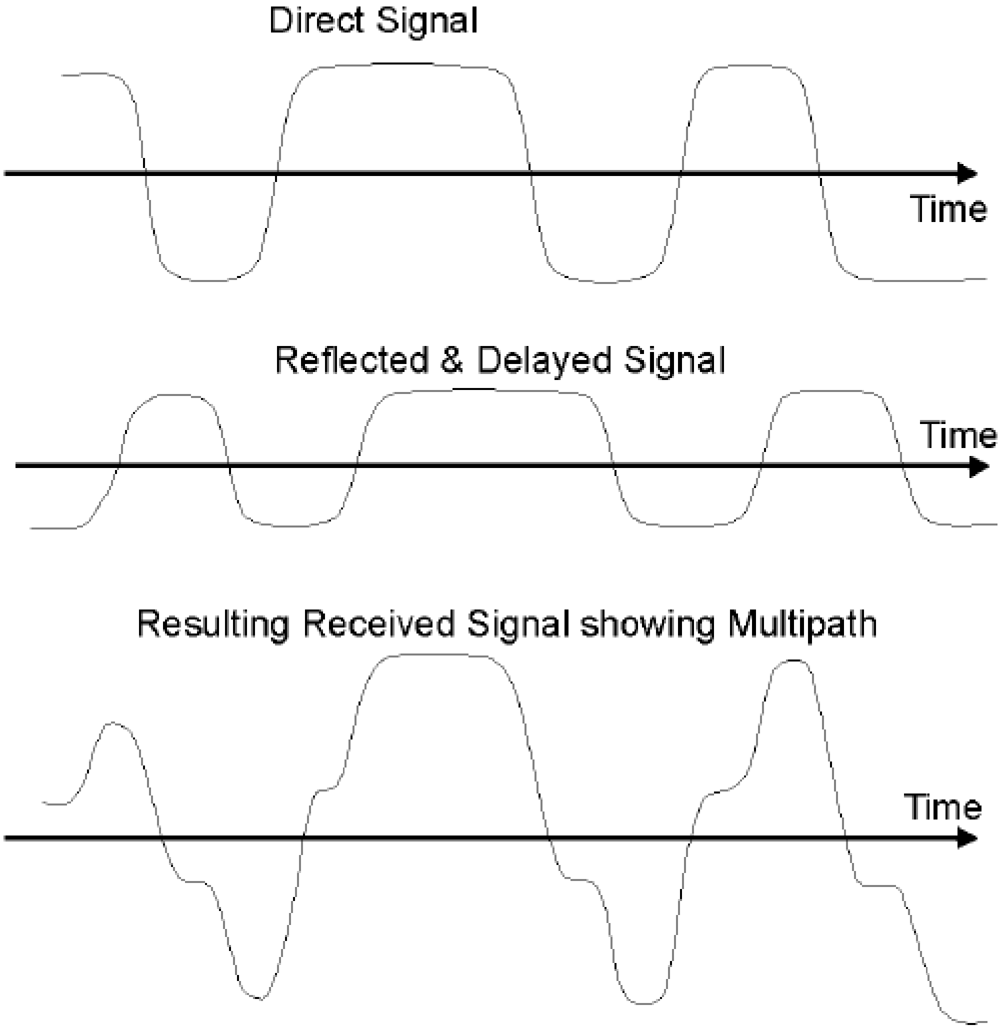


Figure 1.5: Multipath Delay Spread [3]

Figure 1.5 shows the effect of inter-symbol interference due to delay spread on the received signal. As the transmitted bit rate is increased the amount of inter-symbol interference also increases. The effect starts to become very significant when the delay spread is greater than ~50% of the bit time. Inter-symbol interference can be minimized in several ways. One method is to reduce the symbol rate by reducing the data rate for each channel (i.e. split the bandwidth into more channels using frequency division multiplexing). Another is to use a coding scheme, which is tolerant to intersymbol interference such as CDMA.

1.5 TYPES OF FADING

On the bases of relative motion and distance between the transmitter and receiver the fading can be classified in following categories

Large scale fading: This type of fading is seen over large distance and caused by shadowing introduced by obstacles where a large obstruction such as a hill or large buildings obscures the main signal path between transmitter and receiver. The amplitude change caused by shadowing is often modeled using log-normal distribution. Large scale fading is also called shadowing fading.

Small scale fading: Small scale fading is observed over smaller distances as compared to large scale fading. In this fading their we observe rapid fluctuations in amplitude, phases or multipath delays in small scale fading, different replicas of same signal are created by reflection, diffraction and scattering, small scale fading can further categorized as:

- Fast or slow fading
- Frequency selective fading

Small scale fading models that are widely used to depict the fading environment are:

- Rayleigh fading
- Rician fading
- Nakagami fading

1.5.1 Rayleigh Fading

In a radio link, the RF signal from the transmitter may be reflected from objects such as hills, buildings, or vehicles. This gives rise to multiple transmission paths at the receiver. The relative phase of multiple reflected signals can cause constructive or destructive interference at the receiver. This is experienced over very short distances (typically at half wavelength distances), thus is given the term *fast fading*. These variations can vary from 10-30 dB over a short distance. Figure 6 shows the level of attenuation that can occur due to the fading.

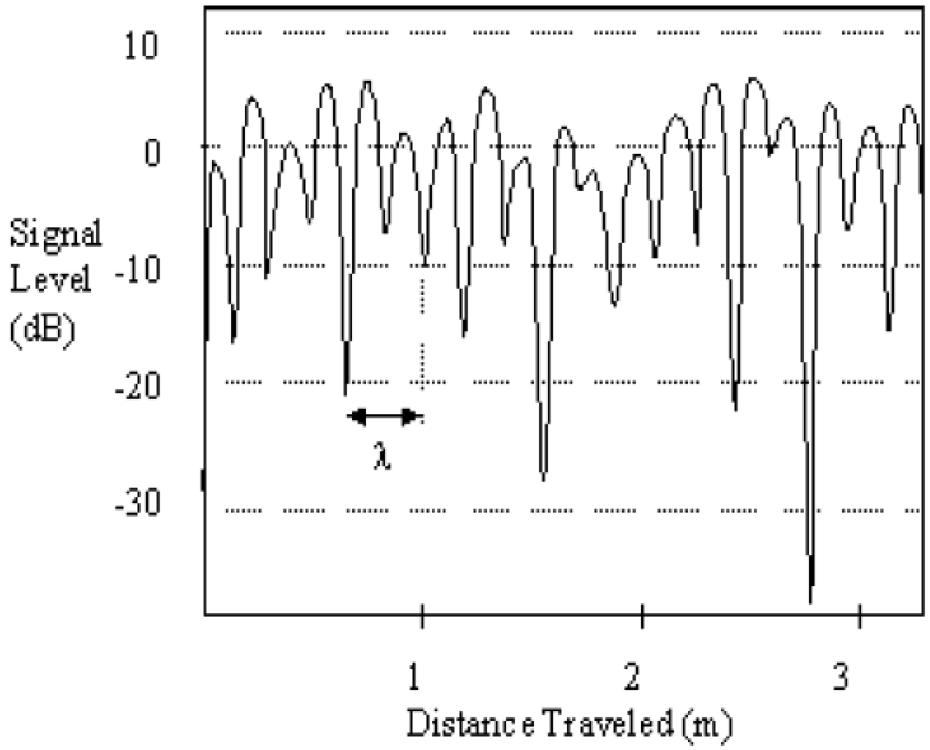


Figure 1.6: Typical Rayleigh fading while the Mobile Unit is moving (900 MHz) [10]

The Figure 1.6 shows the Rayleigh distribution is commonly used to describe the statistical time varying nature of the received signal power. It describes the probability of the signal level being received due to fading.

Table 1.3: Cumulative distribution for Rayleigh distribution [11]

Signal Level (dB about median)	**Probability of Signal Level being less than the value given(%)**
10	99
0	50
-10	5
-20	0.5
-30	0.05

Table 1.3 shows the probability of the signal level for the Rayleigh distribution [11]. In Rayleigh model the statistical time varying behavior of received signal of a flat fading signal or the envelope of individual multipath component. The envelope of a Rayleigh distributed signal can be assumed to be sum of two quadrature Gaussian noise signals. The probability density function of Rayleigh distribution is given by

$$p(r) = \begin{cases} \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right), & 0 \leq x \leq \infty \\ 0 & , 0 < x \end{cases} \tag{2}$$

Where σ is defined as the rms value of the received signal before envelope detection, and σ^2 is time average power of the received signal.

1.5.2 Rician fading

The Nakagami-n distribution is also known as Rice distribution [6]. When there is dominant stationary (non fading) signal component present, such as line-of-sight path, the small scale fading envelope distribution is Rician. This is often used to model propagation paths consisting of one strong direct LOS component and many random weaker components. For a multipath fading channel containing a seculars or LOS component, the complex envelope of the received signal can be given by a Rician distribution

$$p_z(x) = \begin{cases} \frac{x}{\sigma^2} e^{-\frac{(x^2+A^2)}{2\sigma^2}} \; I_o\left(\frac{Ax}{\sigma^2}\right), & A \geq 0, x \geq 0 \\ 0, & x < 0 \end{cases} \tag{3}$$

Where A denotes the peak amplitude of dominant or LOS signal and $I_o(.)$ is the 0th order modified Bessel function of first kind. The Rician distribution is often described in terms of a parameter K called Rician factor, which is defined as ratio between the deterministic signal power and the variance of the multipath or can also be defined as $K = \frac{A^2}{\sigma^2}$ is the relation between the power of LOS component and the power of Rayleigh component. For $K = 0$ we have Rayleigh fading and for $K = \infty$ we have no fading (that is channel with no multipath and only a LOS component). The fading parameter K is therefore a measure of severity of the fading: a small K implies severe fading, a large K implies relatively mild fading.

1.5.3 Nakagami Fading

The Rayleigh and Rician fading model described above fall short of describing long distance fading effects with sufficient accuracy. M. Nakagami observed this fact and then formulated a parametric Gama function which was inspired by this experiment in high frequency long distance propagation. The model proposed by Nakagami uses an adaptive m parameter to describe the fading conditions. It is shown that fading conditions less and more than Rayleigh and Rician fading can be accurately modeled by Nakagami fading. Nakagami fading model assumed that the signal that has passed through the channel will fade according to the Nakagami distribution. This means that the envelope of the channel response of Nakagami channel will be Nakagami distributed. The PDF for this can be given by

$$p_z(x) = \frac{m^m x^{2m-1}}{\Omega^m \Gamma(\mathrm{m})} e^{-\frac{mx^2}{\Omega}} \tag{4}$$

Where $\Gamma(\mathrm{m})$ the Gama function and m is is the shape factor with the constraint $(m \geq \frac{1}{2})$. Experimental and theoretical [7,8] works have shown that the Nakagami distribution is the best-fit distribution for data obtained from many urban multipath radio channel.

1.6 Diversity

Diversity combining is used to mitigate the effect of fading which consists of receiving redundantly the same information–bearing signal over two or more fading channels , then combining these multiple replicas at the receiver to increase the overall received SNR. The intuition behind this concept is to exploit the low probability of concurrence of deep fades in all the diversity channels to lower the probability of error and outage probability. So to improve the received signal quality and link performance over the small scale times and distances, Equalization, diversity and Channel Coding these three techniques are used. Array gain means a power gain of transmitted signals that is achieved by using multiple-antennas at transmitter and/or receiver, with respect to single antenna case. It can be simply called power gain. Diversity gain is the increase in signal-to-interference ratio due to some diversity scheme, or how much the transmission power can be reduced when a diversity scheme is introduced, without a performance loss. Diversity gain is usually expressed in decibel, and sometimes as a power ratio [10]. Now types of various diversities are discussed as given

1.6.1 FREQUENCY DIVERSITY

Frequency diversity is achieved by transmitting the same narrowband signal at different carrier frequencies, where the carriers are separated by the coherence bandwidth of channel. This technique requires additional transmit power to send the signal over multiple frequency bands. Also this technique consumes a large bandwidth as compared to other diversities, making it not suitable for already spectrum constraint environment. Thus it is not much popular among the other techniques.

1.6.2 POLARIZATION DIVERSITY

A method of achieving diversity is by using either two transmit antennas or two receive antennas with different polarization (e.g., vertically and horizontally polarized waves). The two transmitted wave follow the same path. There are two disadvantages of polarization diversity. First, you can have at most two diversity branches, corresponding to the type of polarization. The second disadvantage is that polarization diversity loses effectively half the power (3dB) because transmit or receive power is divided between the two differently polarized antennas.

1.6.3 TIME DIVERSITY

Time diversity is achieved by transmitting the same signal at different times, where the time difference is greater than the channel coherence time (the inverse of the channel Doppler spread). Time diversity does not require increased power but it does lower the data rate, since data is repeated in the time diversity slots rather than sending new data in those time slots. Time diversity can also be achieved through coding and interleaving [9].

1.6.4 Space Diversity

Another approach to achieve diversity is to use M antennas to receive M copies of the transmitted signal. The antennae should be spaced far enough apart so that different received copies of the signal undergo independent fading. Different from frequency diversity and temporal diversity, no additional work is required on the transmission end, and no additional bandwidth or transmission time is required. However, physical constraints may limit its applications. Sometimes, several transmission antennae are also employed to send out several copies of the transmitted signal. Spatial diversity can be employed to combat both frequency selective fading and time selective fading.

As mention above, diversity has long been recognized as a powerful communication receiver technique for mitigating detrimental effects of channel fading co-channel interference. The underlying premise is that if several uncorrelated replicas of a signal are received over multiple diversity paths with comparable signal strengths, then it is improbable that these signals will experience simultaneous deep fades. Diversity methods can be employed either at the base station (macroscopic diversity) or at the mobile station (microscopic diversity), although the antenna separation required differs for each case.

Diversity methods can be implemented by following ways:

- At the transmitter
- At the receiver
- At transmitter and receiver both

Space diversity reception methods can be classified into various categories.

- Selection combining diversity (SCD)
- Maximal ratio combining (MRC)
- Equal gain combining (EGC)
- Switched combing diversity (SWC)
- Generalized selection combining (GSC)
- Optimum diversity combining (OC)

Selection combining diversity (SC)

SC type system only process one of the diversity branches. Specially, in its conventional form, the SC combiner chooses the branch with the highest SNR. In addition, since the output of SC combiner is equal to the signal on only one of the branches, the coherent sum of the individual branch is not required. Therefore, the sum SC scheme can be used in conjunction with differentially coherent and non coherent modulation techniques since it does not require knowledge of the signal phases on each branch [11].

Threshold Combining

Selection combining for systems that transmit continuously may require a dedicated receiver on each branch to continuously monitor branch SNR. A simpler type of combining, called threshold combining, avoids the need for a dedicated receiver on each branch by scanning each of the branches in sequential order and outputting the first signal whose SNR is above a given threshold . Once a branch is chosen, the combiner outputs that signal as long as the SNR on that branch remains above the desired threshold. If the SNR on the selected branch falls below the threshold, the combiner switches to another branch.

Maximal ratio combining (MRC)

In Maximum Ratio Combining each signal branch is multiplied by a weight factor that is proportional to the signal amplitude. That is, branches with strong signal are further amplified, while weak signals are attenuated. In telecommunications, maximal-ratio combining is a method of diversity combining in which the signals from each channel are added together and the gain of each channel is made proportional to the RMS value of signal and inversely proportional to the mean square noise level in that channel. Different proportionality constants are used for each channel. It is also known as ratio-squared combining and pre-detection combining. Maximal-ratio-combining is the optimum combiner for independent AWGN channels [5]. In maximal ratio combining (MRC), the signals from all the receiver branches are weighted according to their individual SNRs and then summed. Here the individual signals need to be brought into phase alignment before summing.

Equal gain combining (EGC)

In an EGC receiver, the received signal carriers are first co-phased as in the case of MRC and are then equally weighted by their amplitudes. In other words, the branch weights are all set to unity. The possibility of producing an acceptable signal from a number of unacceptable inputs is still retained. The EGC receiver performance is superior to selection diversity performance and only marginally inferior as compared to MRC. EGC is often used in practice because of its reduced complexity relative to the optimum MRC scheme [34]. This is because the latter requires the knowledge of the fading amplitude in each signal branch while the former requires no such knowledge. The gain factor for an equal gain system can be written as

$$g_i = e^{-j\alpha_i} \quad , for\ i = 1, \dots \dots \dots \dots . M \tag{5}$$

With equal noise levels in each branch, the output SNR of EGC system is expressed as,

$$\rho_{out} = \frac{\frac{1}{2}\left(\sum_{i=0}^{M} X_i\right)^2}{\overline{M_n^2}} \tag{6}$$

Optimum diversity combining (OC)

In addition to combating multipath fading, space diversity can also be used in cellular radio systems to reduce the relative power of co-channel interferers (CCI’s) that are present at each element of the array. When operating in this scenario, the appropriate diversity scheme to employ is one that combines the branch outputs in such a way as to maximize the signal-to-interference plus noise (SINR) ratio at the combiner’s output. Under such conditions, this scheme, which is referred to as optimum combining (OC), will achieve a larger output SINR than MRC and is thus highly desirable even when the number of interferers exceeds the number of antenna array elements. This improved SINR efficiency can manifest itself in the cellular mobile radio application as a reduction in the number of base stations and/or an increased channel capacity through greater frequency reuse.

The difference between the RAKE receiver for MRC and that for OC lies in selection of the weight vector w. Specifically, for MRC the weights are selected for maximum instantaneous SNR at the combiner’s output, and thus $w = \frac{\alpha_d}{\sigma^2}$. For OC the weights are selected for maximum instantaneous SINR at the same location, and thus $w = R_{ni}^{-1}\alpha_d$ where R_{ni}^{-1} is the noise plus interference covariance matrix. For this receiver, the maximum instantaneous SINR at the combiner’s output is given by [13]

$$\Upsilon_{oc} = P_d \alpha_d^H R_{ni}^{-1} \alpha_d$$

Where the superscript H stands for the Hermitian (transpose complex conjugate) operation.

1.7 DISSERTATION ORGANIZATION

This dissertation includes five chapters. An outline of each chapter is given below:

Chapter 1st gives an introduction of wireless communication system, OFDM and diversity techniques. Some of the problems of wireless communications such as modulation and fading are also addressed in this chapter.

Chapter 2nd is dedicated to the literature survey. The research papers which are relevant to this dissertation are discussed here.

Chapter 3rd presents a study of selection combining (SC), maximal ratio combining (MRC) and OC. In this chapter simulated and analytically results of mean output SNR of SC, MRC and probability of error for SC, MRC and OC combining are calculated.

Chapter 4th includes meaningful results which are calculated analytically. In this chapter we have presented the analysis and result of probability of error for MRC-OFDM and OC-OFDM over i.i.d Rayleigh fading environment and comparison of the system has been done.

Chapter 5th concludes this dissertation, summarizing the major results and offering suggestions for further work on this topic.

CHAPTER 2

LITRATURE SURVEY

Cui *et al.* presented an analytical approach to derive bit error rate (BER) for Optimum Combining (OC) and Maximal Ratio Combining (MRC) in the presence of CCI. In this paper, analytical expressions of BER for OC in the presence of two interferers and for MRC in case of an arbitrary number of interferers are presented for DPSK signals over flat fading channel by assuming that the fading on each channel is independent. Furthermore, for a dual antenna communication system with correlated channel diversity, the BER expressions for OC and MRC in the presence of one co-channel interferer are also derived.

Annamalai *et al.* [12] derived the symbol error rate (SER) for maximal ratio combining (MRC) and equal gain combining (EGC) diversity by using multilevel quadrature amplitude modulation (MQAM) on arbitrary Nakagami fading channel. In this paper, MRC in independent and correlated fading and ECG in independent fading have been considered.

Winter [13] studied the Optimum signal combining for space diversity reception in cellular mobile radio systems. OC maximize the output SINR which is used not only to combat Rayleigh fading of the desired signal (as with MRC) but also to reduce the power of interfering signals at the receiver. Analytical and computer simulation techniques are used to determine the performance of optimum combining. Results show that optimum combining is significantly better than maximal ratio combining even when the number of interferers is greater than the number of antennas and showed that optimum combining increases the output signal-to-interference ratio at the receiver by several decibels. Thus, systems can require fewer base station antennas and/or achieve increased channel capacity through greater frequency reuse.

McKay *et al*. [17] considered the analysis of optimum combining systems in the presence of both co-channel interference and thermal noise. We address the cases where either the desired-user or the interferers undergo Rician fading. Exact expressions are derived for the moment generating function of the SINR which apply for arbitrary numbers of antennas and interferers. Based on these, we obtain expressions for the symbol error probability with M-PSK. For the case where the desired-user undergoes Rician fading, we also derive exact closed-form expressions for the moments of the SINR.

Villier [18] analyzed the performance of optimum combining in the presence of multiple equal power interferers and noise when the number of interferers is less than the number of antenna elements. Desired signal and interferers are subject to flat Rayleigh fading and the propagation channels are independent. An approximate expression of the probability density function (PDF) of the output signal-to-interference-plus-noise ratio (SINR), cumulative distribution function (CDF) of the SINR and the bit-error rate (BER) of some binary modulations has been derived.

Ahn *et al.* [19] analyzed the performance of maximum ratio combining (MRC) systems with imperfect channel estimation in the presence of co-channel interference (CCI) with an arbitrary power interference-to-noise ratio (INR). The maximum combining weights are the imperfect estimates of the desired user's fading channel coefficients and are assumed to be complex Gaussian distributed. The quantized measure for estimation error is the correlation coefficients between the true fading channel coefficients and their estimates. Exact closed form expressions are derived for the probability density function (PDF) of the signal-to-interference-plus-noise ratio (SINR), as well as performance metrics including outage probability and the average symbol error probability (ASEP) for some modulation formats. Simulation results demonstrate the accuracy of our theoretic analysis.

Shah [20] analyzed the performance evaluation of optimum combining in wireless communication with Rayleigh fading and cochannel interference. This paper considered binary phase shift keying (BPSK) modulation in a flat Rayleigh fading environment when the number of interferences is not less than the number of antenna elements. Closed form expression using hypergeometric functions are derived for outage probability and the average probability of bit error.

Yongpeng *et al.* [21] studies the optimum combining (OC) system with multiple arbitrary-power interferers and thermal noise in a flat Rayleigh fading environment. The main contribution of the paper is a concise performance analysis for the overload OC system where the number of interferers exceeds or is equal to the number of antennas elements. Simple closed-form formulas are derived for the moment generating function of the output signal-to-interference-plus-noise ratio (SINR) and the symbol error rate (SER) with M-ary phase shift keying (M-PSK). Based on the derived MGF, the closed-form explicit expressions for the moments of the output SINR are determined.

Aalo [22] studied the effect of cochannel interference on the performance of digital mobile radio systems in a Rayleigh fading environment. The average bit error rate (BER) of an antenna array system with an optimum combining scheme that maximizes the output signal-to-interference-plus-noise ratio is analyzed. BER expressions which are easy to evaluate numerically are derived for coherent binary phase-shift keying schemes in an environment with cochannel interference and noise. In this only one and two interferers are considered.

Shah [23] studied the performance of maximal ratio combining for space diversity reception in digital cellular mobile radio systems for communications in the presence of multiple cochannel interference (CCI) sources and is compared to optimum combining. Using a multivariate statistical analysis approach and assuming equal-power interference sources, analytical expressions are derived for the density function of the array output signal-to-interference ratio (SIR), the outage probability, and the average probability of bit error with maximal ratio combining. In this paper, Rayleigh fading is extended to the case when the SOI is subject to Rice fading.

Gowda *et al.* [25] evaluated Error performance of selection diversity (SD) receiver over non-identical fading channels, where the fading statistics of individual branches are different. Bit-error rate (BER) results are directly obtained from the cumulative distribution function (CDF), which drastically reduces the complexity of analysis and simplifies BER expressions. In particular, using this approach, we are able to generate unified simple, closed-form BER expressions for different modulation schemes under non-identical fading conditions in Rayleigh and Nakagami fading channels.

Romero-Jerez *et al.* [26] presented the average bit error rate (BER) of uncoded MIMO systems in Rayleigh fading channels with cochannel interference (CCI) and noise. Receiver schemes such as maximal ratio combining (MRC) and interference cancellation (IC) via null steering of the receive array radiation pattern has been considered. In these paper analytical expressions of the BER for different modulation techniques and comparison between the two proposed receiver schemes with fading and interference has been analyzed.

Zhong *et al.* [27] studied the ergodic capacity of multiple-input multiple-output (MIMO) systems with a single co- channel interferer in the low signal-to-noise-ratio (SNR). Exact analytical expressions for the minimum energy per information bit and wideband slope, are derived for Rayleigh and Rician fading channels. Results showed that the minimum energy per information bit is the same for both channels while their wideband slopes differ significantly and indicate that interference degrades the capacity by increasing the required minimum energy per information bit and reducing the wideband slope.

Yongpeng *et al.* [28] investigated optimum combining system of a Rician fading signal with unequal power Rician interferers and thermal noise. Based on the statistical characteristics analysis of the output SINR, it also derived a closed form upper bound for the symbol error probability of M-ary phase-shift keying.

Rao *et al*. [29] studied the statistical properties of the output signal to interference plus noise ratio (SINR) of a spatial combiner. Where the spatial weights used are either the Maximal Ratio Combiner (MRC) weights or the Optimum Combining weights. The channels are modeled as slow flat Rayleigh fading channels and multiple interferers are assumed present. In particular, the modified F-distribution is introduced to provide an exact characterization of a MRC receiver and to bound the performance of the OC receiver.

Raymond *et al.* [30] derived the asymptotic SER and outage probability of MIMO- OC systems with correlated Rayleigh-faded user channels and SIMO-OC systems with correlated Rician faded user channels. Results are based on new asymptotic expansions which derived for the CDF and PDF of the SINR at the OC output and obtained new closed-form performance results for unequal power, correlated Rayleigh and Rician co-channel interferer channel. For the MIMO-OC system, result showed that receive correlation decreases the array gain, hence increasing the SER at high SNR. For the SIMO-OC system, result showed that the Rician K factor increases the array gain, hence decreasing the SER at high SNR.

Burke *et al.* [31] analyzed the performance of Optimum combining (OC) and maximal ratio combining (MRC) by using a gain ratio. Using the receive carrier-to-interference plus noise ratio (CINR), the gain ratio CINR is evaluated in a flat Rayleigh fading communications system with multiple interferers. Exact analytical solutions derived for the probability density function (PDF) and the average gain ratio with one interferer. When more than one interferer is present, the PDF of the gain ratio is illustrated using Monte Carlo simulations and its mean value is shown in basic integral form. An upper bound to the gain ratio is derived providing a simple means to determine when OC will exhibit significant gains over MRC.

Goldsmith *et al.* [32] analyzed the closed-form analytical expressions for the outage probability of different diversity schemes, such as maximal ratio combining (MRC) and optimum combining (OC), and also for interference cancellation (IC). This is based on antenna beamsteering, which steers nulls in the array radiation pattern in the direction of the strongest interferers. At the receive antenna array, signal from the desired user has been assumed which is affected by Rice, Nakagami or Rayleigh fading, while CCI signals are assumed to experience Rayleigh fading. In this paper, Results showed that IC yields significantly better performance than MRC if the system is interference- limited and the number of dominant interferers is lower than the number of receive antennas, or when the output SINR is low.

CHAPTER 3

PERFORMANCE ANALYSIS OF DIVERSITY TECHNIQUES

The most suitable performance check for a diversity combining technique is BER with respect to changing SNR.

3.1 PERFORMANCE CRITERION

Probably the most common and best understood performance metric of a digital communication system is the average SNR (signal to noise ratio). Most often, this is measured at the output of the receiver and is thus related directly to the data detection itself. Of the several possible performance measures that exist, it is typically the easiest to evaluate and most often serves as an excellent indicators of the overall fidelity of the system. Although, the term noise in signal to noise ratio refers to the ever-present thermal noise at the input to the receiver, in the context of the communication system subject to fading impairment, the more appropriate performance metric is average SNR. The word average refers to a statistical averaging over the probability distribution of the fading. In simple mathematical terms, if denotes the instantaneous SNR (a random variable) of each branch then the average SNR at the diversity combiner output is

$$\overline{\xi} = \int_0^{\xi} \xi f_{\xi}(\xi)\, d\xi \tag{7}$$

Where $f_{\xi}(.)$ denotes the PDF of ξ. We can rewrite the equation (7) in terms of the MGF (moment generating function) associated with ξ, namely

$$\psi_{\xi}(g) = \int_0^{\xi} f_{\xi}(\xi) e^{-g\xi} d\xi \tag{8}$$

Now taking the derivative of equation (8) with respect to g, then again we the average SNR at the combiner's output that is

$$\overline{\xi} = \frac{d\psi_{\xi}(g)}{dg} | g = 0 \tag{9}$$

In other words, the ability to evaluate the MGF of the instantaneous SNR allows immediate evaluation of the average SNR via a simple mathematical operation differentiation. The second performance criterion is the average bit error rate. This metric can be evaluated by averaging the conditional error probability (CEP) over the PDF of combiner output SNR. Suppose the CEP is of the form

$$\epsilon_b(\xi) = aerfc\left(\sqrt{b\xi}\right) \tag{10}$$

Such as would be case for coherent detection of PSK signal or coherent detection of orthogonal FSK signal. Then the average probability of error can be written as

$$\epsilon_b = \int_0^{\xi} \epsilon_b(\xi) f_{\xi}(\xi)\, d\xi \tag{11}$$

3.2 PERFORMANCE ANALYSIS SELECTION COMBINING DIVERSITY (SC)

Selection combining (SC) is a combining mechanism used in conjunction with space diversity. SC type systems can process only one of the diversity branches. The combiner chooses output with the highest SNR that is the output of the SC combiner equal the signal on only one of the branches. The coherent sum (like MRC, EGC) of the individual branch signal is not required. This is equivalent to choosing the ith branch with the highest $r_i^2 + N_i$ if the noise power N_i=N is the same on all branches. Because only one branch is used at a time, SC is easy to implement because all that is needed a side monitoring station and an antenna switch at the receiver. However, it is not an optimal diversity technique because it does not use all of the possible branches simultaneously. The advantage of SC is it is simple because it controls switch. We don’t require perfect channel state information that is amplitude, phase, and delay. We don’t require many RF changes state like RF amplifiers, noise amplifiers, and power amplifiers. With ideal SC, the path output from the combiner has an SNR equal to the maximum SNR of all the branches. For $N-$branch diversity, the instantaneous symbol energy to noise ratio at the output of the SC is ξ_{sc}. ξ_{sc} can be written as

$$\xi_{sc} = \max[\xi_1, \xi_2 \dots \dots \dots \xi_N] \tag{12}$$

3.2.1 Calculate the average SNR, $\bar{\xi}_N$ at the combiner having N branches

To calculate the PDF for ‘N’ branches which is given by equation as following

$$f_{\xi_{sc}}(\xi_{th}) = \frac{N}{\xi_o}\left(1 - e^{-\frac{\xi_i}{\xi_o}}\right)^{N-1} e^{-\frac{\xi_{th}}{\xi_o}} \qquad (13)$$

To calculate the average output bit energy to noise ratio is given by

$$\bar{\xi}_{sc} = \int_0^\infty \xi_{sc}\, f_{\xi_{sc}}(\xi_{th}) d\xi_{th} \qquad (14)$$

Put the value of equation (13) into the equation (14) then we get

$$\bar{\xi}_{sc} = \int_0^\infty \xi_{th}\, \frac{N}{\xi_o}\left(1 - e^{-\frac{\xi_i}{\xi_o}}\right)^{N-1} e^{-\frac{\xi_{th}}{\xi_o}} d\xi_{th} \qquad (15)$$

$$\bar{\xi}_{sc} = \xi_o * \sum_{l=1}^{N} \frac{1}{l} \qquad (16)$$

With selection diversity we are seeing that the average SNR at the combiner is not increased linearly with increasing the number of receives antennas. This means that, with ‘2’ receive antennas, the average SNR, at combiner is 1.5 times average SNR, of each branch. With ‘3’ receive antennas, the average SNR at combiner is 1.833 times average SNR of each branch. With “4” receive antennas, the average SNR at combiner is 2 times average SNR of each branch. That is why we do not use this type of combining.

3.2.2 Probability of error, ϵ_e for selection diversity

To calculate the average probability of error at the combiner is computed by integrating the probability of error in AWGN channel over the Rayleigh distribution at the combiner which is given by [9]

$$\epsilon_e = \int_0^\xi Q\left(\sqrt{2N_o}\right) f_{\xi_{sc}}(\xi_{th}) d\xi_{th} \qquad (17)$$

Putting the value of equation (13) into equation (17), then ϵ_e becomes

$$\epsilon_e = \int_0^\xi \frac{erfc\left(\sqrt{N_o}\right)}{2} \frac{N}{\xi_o}\left(1 - e^{-\frac{\xi_i}{\xi_o}}\right)^{N-1} d\xi_{th} \qquad (18)$$

By solving the above equation by using Mathematica software and then we get the ϵ_e

$$\epsilon_e = \frac{1}{2}\sum_{l=0}^{N}(-1)^l\binom{N}{l}\left(1+\frac{l}{\xi_0}\right)^{\frac{-1}{2}} \tag{19}$$

3.3 PERFORMANCE ANALYSIS MAXIMUM RATIO COMBINING

In SC, the output of combiner equals the signal on one of the branches. In maximal ratio combining (MRC) the output is a weighted sum of all branches. The signals are co-phased and so $\alpha_l = \alpha_l e^{-j\theta_l}$ where θ_l is the phase of the incoming signal on the l^{th} branch.

3.3.1 Calculate the SNR at the combiner having N branches

The envelope of the combiner output will be $r = \sum_{l=0}^{N} \alpha_l r_l$. Assuming the same noise power spectral density (PSD) $\frac{N_o}{2}$ in each branch yields a total noise PSD $\frac{N_{tot}}{2}$ at the combiner output of $\frac{N_{tot}}{2} = \sum_{l=0}^{N} {\alpha_l}^2 \frac{N_o}{2}$. Thus the output SNR of the combiner is

$$\xi_{MRC} = \frac{r^2}{N_{tot}} = \frac{1}{N_o}\frac{\left(\sum_{l=0}^{N}\alpha_l r_l\right)^2}{\sum_{l=0}^{N}{\alpha_l}^2} \tag{20}$$

by using the Cauchy-Schwartz inequality. Then optimal weights yields ${\alpha_l}^2 = \frac{r_l^2}{N_o}$ and the resulting combiner SNR becomes

$$\xi_{MRC} = \sum_{l=0}^{N}\frac{r_l^2}{N_o} = \sum_{l=0}^{N}\xi_l \tag{21}$$

$$\xi_{MRC}=\mathrm{N}\xi_l \tag{22}$$

Where $\xi_l = \frac{r_l^2}{N_o}$ is the instantaneous SNR of each branch. Thus the SNR of the combiner's output is sum of the SNRs on each branch. Hence, the average combiner SNR and corresponding array gain increase linearly with the number of diversity branches N, in contrast to the diminishing returns associated with the average combiner SNR in SC given by equation (16). As with SC, the distribution of the combined output SNR does not remain exponential even when there is Rayleigh fading on all branches. Effective bit energy to noise ratio in a N receive antenna case is N times the bit energy to noise ratio for single antenna case.

3.3.2 Probability of Error with Maximal Ratio Combining

We know that, the PDF of ξ_l for independent identically distributed (i.i.d.) Rayleigh fading on each branch which is given by equation ξ

$$f(\xi_l) = \frac{1}{\xi_o} e^{-\frac{\xi_l}{\xi_o}} \qquad (23)$$

To calculate the moment generating function (MGF) of ξ_l becomes

$$M_{\xi_l}(g) = \int_0^{\xi} \frac{1}{\xi_o} e^{-\frac{\xi_l}{\xi_o}} e^{g\xi_l} d\xi_l \qquad (24)$$

$$M_{\xi_l}(g) = \frac{1}{1-\xi_o} \qquad (25)$$

For ‘N’ independent branches, The MGF function of equation (24) becomes

$$M_{\xi_{MRC}}(g) = \frac{1}{(1-g\xi_o)^N} \qquad (26)$$

$$f(\xi) = \frac{1}{2\pi l} \int \frac{1}{(1-g\xi_o)^N} \; e^{-g\xi} dg \qquad (27)$$

By solving the equation (26), we get

$$f_{\xi_{MRC}}(\xi) = \frac{1}{(N-1)!{\xi_o}^N} \xi^{N-1} e^{\frac{-\xi}{\xi_o}} \qquad \xi \geq 0 \qquad (28)$$

The average probability of bit error is obtained when we put the value of equation (22) into equation (17). Then the average probability of error ϵ_e becomes

$$\epsilon_e = \int_0^{\xi} \frac{erfc(\sqrt{\xi})}{2} \frac{1}{(N-1)!{\xi_o}^N} \xi^{N-1} e^{\frac{-\xi}{\xi_o}} \qquad (29)$$

By solving above equation we get

$$\epsilon_e = z^N \sum_{l=o}^{N-1} \binom{N-1+l}{l} (1-z)^l \qquad (30)$$

where $z = \frac{1}{2} - \frac{1}{2}\left(1 + \frac{1}{\xi_o}\right)^{-\frac{1}{2}}$

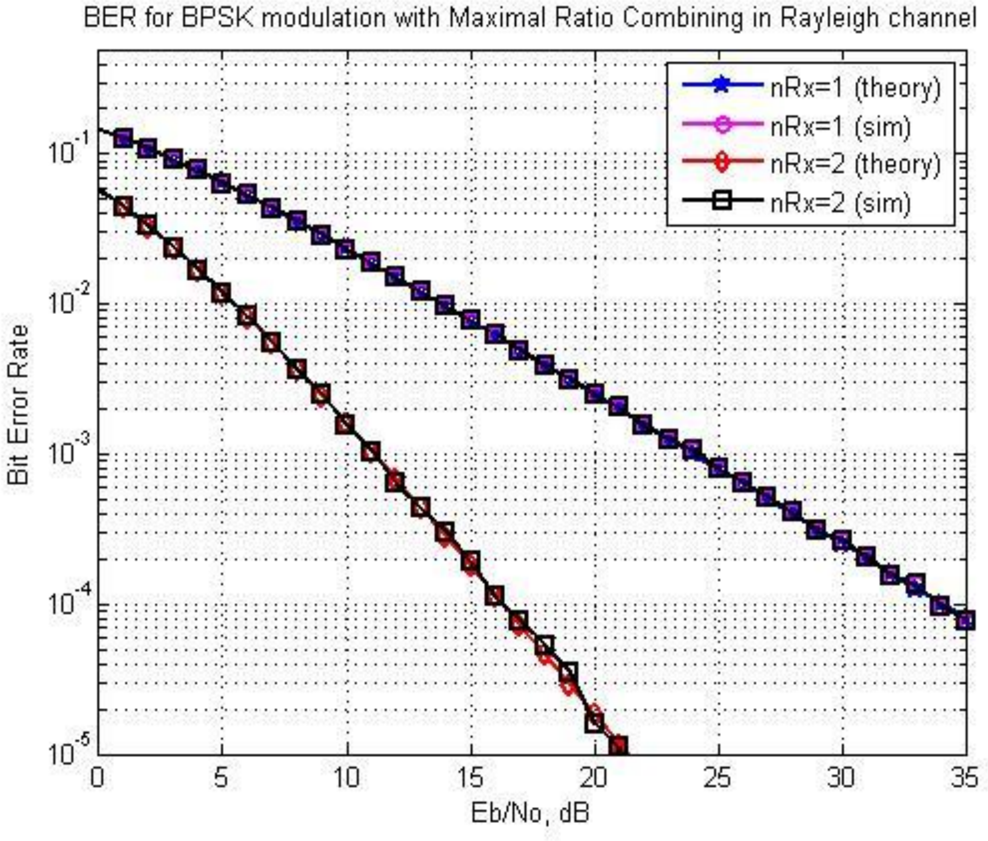


Figure 3.1: BER VS SNR of MRC using two receiver antennas

Table 3.1: BER improvement with increasing SNR

SNR (dB)	BER Single antenna	BER Double antennas
5	$10^{-1.50}$	$10^{-1.95}$
10	$10^{-1.85}$	$10^{-2.95}$
15	$10^{-2.20}$	$10^{-3.91}$
20	$10^{-2.85}$	$10^{-4.92}$

Table 3.1 shows the BER rate improvement with increasing SNR values with single and double antennas. As observed the BER performance can be enhanced by $10^{-4.92}$ from $10^{-2.85}$ using two antennas while keeping the SNR 20 dB. Thus with additional antennas better reception is possible at lower SNR values.

3.4 PERFORMANCE ANALYSIS OPTIMUM COMBINING

Space diversity provides an attractive means for improving the performance of mobile radio systems. With space diversity, the signals from the receiving antennas can be combined to combat multipath fading of the desired signal and reduce the relative power of interfering signals. In this chapter, mobile radio systems have considered space diversity only for combating multipath fading of the desired signal. Interference at each receiving antenna is assumed to be independent. Under this condition, MRC produces the highest output signal-to-interference-plus noise ratio (SINR) at the receiver. However, in most systems same interfering signals are present at each of the receiving antennas. Thus, the received signals can be combined to suppress these interfering signals in addition to combating desired signal fading which is referred as a optimum combining (OC). Thereby it achieved higher output SINR than maximal ratio combining and is thus highly desirable even when the number of interferers exceeds the number of antenna array elements. This improved SINR efficiency can manifest itself in the cellular mobile radio application as a reduction in the number of base stations and/or an increased channel capacity through greater frequency reuse [34].

Consider a system model that provides space diversity via an ‘N’-elements antenna array. Assume that the antenna elements of the array are placed sufficiently far apart so as to provide independent fading paths and all the interferers have equal power. Furthermore, the system employs binary phase shift keying modulation and channel is characterized by flat Rayleigh fading. At the receiver side, N-elements antenna array operates in the presence of ‘L’ co-channel interferers. Then the received signal vector $r(t)$ at the outputs of the array elements which is expressed as

$$r(t) = x_d s(t) + \sum_{k=1}^{L} x_k\, s_k(t) + n(t) \tag{31}$$

Where $s(t)$ and $s_k(t)$ are the desired and kth interfering signals respectively. x_d and $x_k (k = 1,2, \ldots \ldots . L)$ are assumed to be a mutually independent N-dimensional complex Gaussian vector with each component of vectors x_d and x_k having power P_s and P_I respectively and n(t) AWGN vector, each element of which has zero mean and variance. The desired signal $s(t)$ and the interfering signals are such that $s_k(t)$ are such that $E[s^2(t)] = E[{s_k}^2(t)] = 1$. Here we also assume that the coherence time of the channel is much larger than the duration of signals so that the propagation vectors may be considered as constant. It is known that the optimum weighting vector in the optimum combining for minimum mean square error between $s(t)$ and weighted and summed array output which is given by [20]

$$W_{oc} = R_{ni}^{-1} x_d \quad (32)$$

For this receiver, the maximum instantaneous SINR at the combiner's output is given by [21]

$$\xi_{oc} = x_d^H R_{ni}^{-1} x_d \quad (33)$$

Where the superscript 'H' stands for the Hermitian (transpose complex conjugate) operation and R_{ni} is a noise plus interference covariance matrix which is given by

$$R_{ni} = E\{[\sum_{k=1}^{L} x_k s_k(t) + n(t)][\sum_{k=1}^{L} x_k s_k(t) + n(t)]^H\} \quad (34)$$

$$R_{ni} = \sum_{k=1}^{L} x_k s_k(t) + \sigma_n^2 I \quad (35)$$

$$R_{ni} = V^H diag\{\xi_1, \xi_2, \dots \dots .. \xi_N\} \mathrm{V} \quad (36)$$

Where $\xi_1, \xi_2, \dots \dots .. \xi_N$ are eigen-values of R_{ni} .

3.4.1. Probability of error of Optimum Combining Receivers

Optimum combining (OC) will achieve a larger output SINR than MRC and is thus highly desirable even when the number of interferers exceeds the number of antenna array elements. This improved SINR efficiency can manifest itself in the cellular mobile radio application as a reduction in the number of base stations and/or an increased channel capacity through greater frequency reuse.

Single Interferer, Independent Identically Distributed Fading

In this case, only single interfere is considered. Then the received signal at the output of antenna array becomes

$$r(t) = x_d s(t) + x_I s_I(t) + n(t) \quad (37)$$

And from equation (34) becomes

$$R_{ni} = E\{[x_k s_k(t) + n(t)][x_k s_k(t) + n(t)]^H \} \tag{38}$$

$$R_{ni} = x_k {x_k}^H + \sigma_n^2 I \tag{39}$$

Therefore, the moment generating function (MGF) of ξ_{oc} at given ξ_o becomes from [22]

$$\psi_{oc}(g|\xi_1) = \left(\frac{\frac{\xi_1+1}{\bar{\xi}_s}}{\frac{\xi_1+1}{\bar{\xi}_s}-g}\right)\left(\frac{\frac{1}{\bar{\xi}_s}}{\frac{1}{\bar{\xi}_s}-g}\right)^{N-1} \tag{40}$$

Where $\bar{\xi}_s = \frac{P_s}{\sigma_n^2}$ is the average SNR for desired signal per antenna and $\xi_1 = \frac{x_k {x_k}^H}{\sigma_n^2}$ is the SNR of interference at the output of combiner. The PDF for SNR of interference

$$F(\xi_1) = \frac{1}{{\bar{\xi}_1}^M(M)} {\bar{\xi}_1}^M \, exp\left(-\frac{\xi_1}{\bar{\xi}_s}\right) \qquad \xi_1 \geq 0 \tag{41}$$

$$f(\xi_{oc}|\xi_1) = \frac{1}{2\pi i}\int \psi_{oc}(g|\xi_1) e^{-g\xi_{oc}} dg \tag{42}$$

$$f(\xi_{oc}|\xi_1) = \frac{(\xi_1+1){\xi_{oc}}^{(N-1)}}{\bar{\xi}_s} e^{\frac{-\xi_{oc}}{\bar{\xi}_s}} {}_1F_1\left[1; N; -\frac{\xi_1\xi_{oc}}{\bar{\xi}_s}\right] \tag{43}$$

$$f(\xi_{oc}) = \int \, F(\xi_{oc}|\xi_1)\, F(\xi_1) d\xi_1 \tag{44}$$

$$f(\xi_{oc}) = \frac{K_{N-1}(\bar{\xi}_s, \xi_{oc})}{(N-1)!} \int \left(1 + \bar{\xi}_1 \xi\right)_1 F_1\left(1; N; -\frac{\xi_1\xi_{oc}}{\bar{\xi}_s}\right) \xi^{N-1} e^{-\xi} d\xi \tag{45}$$

Where, $K_{N-1}\left(\bar{\xi}_s, \xi_{oc}\right) = \frac{1}{(N-1)!{\bar{\xi}_s}^N} e^{\frac{-\xi_{oc}}{\bar{\xi}_s}} {\xi_{oc}}^{(N-1)}$ (46)

Using the identity [26]

$$\frac{1}{(N-1)!^1} F_1(1; N; z) = \frac{1}{z^{N-1}}\left[e^z - \sum_{n=0}^{N-2} \frac{z^n}{n!}\right] \tag{47}$$

Now equation (44) becomes

$$f(\xi_{oc}) = \frac{K_{N-1}(\bar{\xi}_s, \xi_{oc})}{\left(1+\frac{\xi_1\xi_{oc}}{\bar{\xi}_s}\right)} \left[1 + N\xi_1 \frac{1+\frac{(N-1)\bar{\xi}_1\xi_{oc}}{N\bar{\xi}_s}}{1+\frac{\xi_1\xi_{oc}}{\bar{\xi}_s}}\right] \tag{48}$$

For N>>1 then above equation becomes

$$f(\xi_{oc}) = \frac{K_{N-1}(\bar{\xi}_s, \xi_{oc})}{\left(1+\frac{\xi_1\xi_{oc}}{\bar{\xi}_s}\right)} \left[1 + N\bar{\xi}_1\right] \tag{49}$$

BER for OC system over Rayleigh faded channel is given as:

$$\epsilon_e = \int_0^\infty \frac{1}{2} erfc\left(\sqrt{\xi_{oc}}\right) F(\xi_{oc}) d\xi_{oc} \tag{50}$$

Put the values of equation (49) into equation (50) then we get probability of error

$$\epsilon_e = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\xi}_s}{\bar{\xi}_s+1}} \sum_{k=o}^{M-2} \binom{2k}{k} \left(\frac{1}{4\left(\bar{\xi}_s+1\right)}\right)^K\right] - \frac{1}{2\Gamma(M)\left(-\bar{\xi}_1\right)^{M-1}} * \left\{\sqrt{\frac{\pi\bar{\xi}_s}{\bar{\xi}_1}} exp\left(\frac{\bar{\xi}_s+1}{\bar{\xi}_1}\right) erfc\left(\sqrt{\frac{\bar{\xi}_s+1}{\bar{\xi}_1}}\right) - \sqrt{\frac{\bar{\xi}_s+1}{\bar{\xi}_1}} \sum_{k=0}^{M-1} \frac{(2k)!}{k!} \left(\frac{-\bar{\xi}_1}{4\left(\bar{\xi}_s+1\right)}\right)^k\right\} \tag{51}$$

CHAPTER 4

DIVERSITY COMBINING WITH OFDM

The need of high speed data communication systems can also catered by two most powerful techniques of modern era, these are OFDM and diversity combining.

4.1 OFDM

The rapidly growing technology has made it possible for the communication systems to transfer data almost everywhere on this planet. But the limited bandwidth allocated to a large number of users restricts the bandwidth availability to the users. This scenario creates a technological challenge to develop the data transmission schemes which are bandwidth efficient. Multicarrier modulation is such a scheme that transmits the data by dividing the serial high data rate streams into a number of low data rate parallel data streams. Orthogonal Frequency Division Multiplexing (OFDM) is a kind of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is then modulated by a low rate data stream at different carrier frequency.

The conventional OFDM system makes use of IFFT and FFT for multiplexing the signals and reduces the complexity at the transmitter and receiver. Orthogonal Frequency Division Multiplexing is comprised of a combination of modulation and multiplexing. The original data signal is split into many independent signals, each of which is modulated at a different frequency and then these independent signals are multiplexed to create an OFDM carrier. As all the subcarriers are orthogonal to each other, they can be transmitted simultaneously over the same bandwidth without any interference which is an important advantage of OFDM. OFDM makes the high speed data streams robust against the radio channel impairments. OFDM is an efficient technique to handle large data rates in the multipath fading environment which causes ISI. With the help of OFDM, a large number of overlapping narrowband subcarriers, which are orthogonal to each other, are transmitted in parallel within the available transmission bandwidth. Thus, in OFDM, the available spectrum is utilized efficiently.

4.1.1 Bit Error Rate of OFDM-BPSK with Rayleigh Multipath Channel

A very popular digital modulation scheme, binary phase shift keying (BPSK) shifts the carrier sine wave 180° for each change in binary state. The BPSK is coherent as the phase transitions occur at the zero crossing points. The proper demodulation of BPSK requires the signal to be compared to a sine carrier of the same phase. The theoretical equation for bit error rate (BER) with Binary Phase Shift Keying (BPSK) modulation scheme

$$\epsilon_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{52}$$

In order to get the bit error rate for BPSK with Rayleigh fading channel which is of the form $y = rx + n$, assume that the channel is flat fading and is randomly varying in time. The noise, n has the Gaussian probability density function given by equation

$$f(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} \quad , r \geq 0 \tag{53}$$

Equation (52) gives the Bit error probability, however the presence of channel r, the effective bit energy to noise ratio is $\frac{|r|^2 E_b}{N_o}$. So the bit error rate probability for a given value of r is given by

$$\epsilon_{(b|r)} = \frac{1}{2} erfc\left(\sqrt{\frac{|r|^2 E_b}{N_o}}\right) = \frac{1}{2} erfc(\sqrt{\gamma}) \tag{54}$$

Where $\gamma = \frac{|r|^2 E_b}{N_o}$, so the error probability becomes

$$\epsilon_b = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{E_b}{N_o}}{\frac{E_b}{N_o}+1}}\right) \tag{55}$$

The total channel is a frequency selective channel [24], the channel experienced by each subcarrier in an OFDM system is a flat fading channel with each subcarrier experiencing independent Rayleigh fading. The BER for BPSK with OFDM in a Rayleigh fading channel should be same as the result obtained for BER for BPSK in Rayleigh fading channel. The following analysis shows that BER of OFDM is as same as the BPSK modulation in

Rayleigh fading. The BER rate goes on improving with increasing amount of SNR. The reported BER can be further reduced by using channel estimation or suitable diversity scheme.

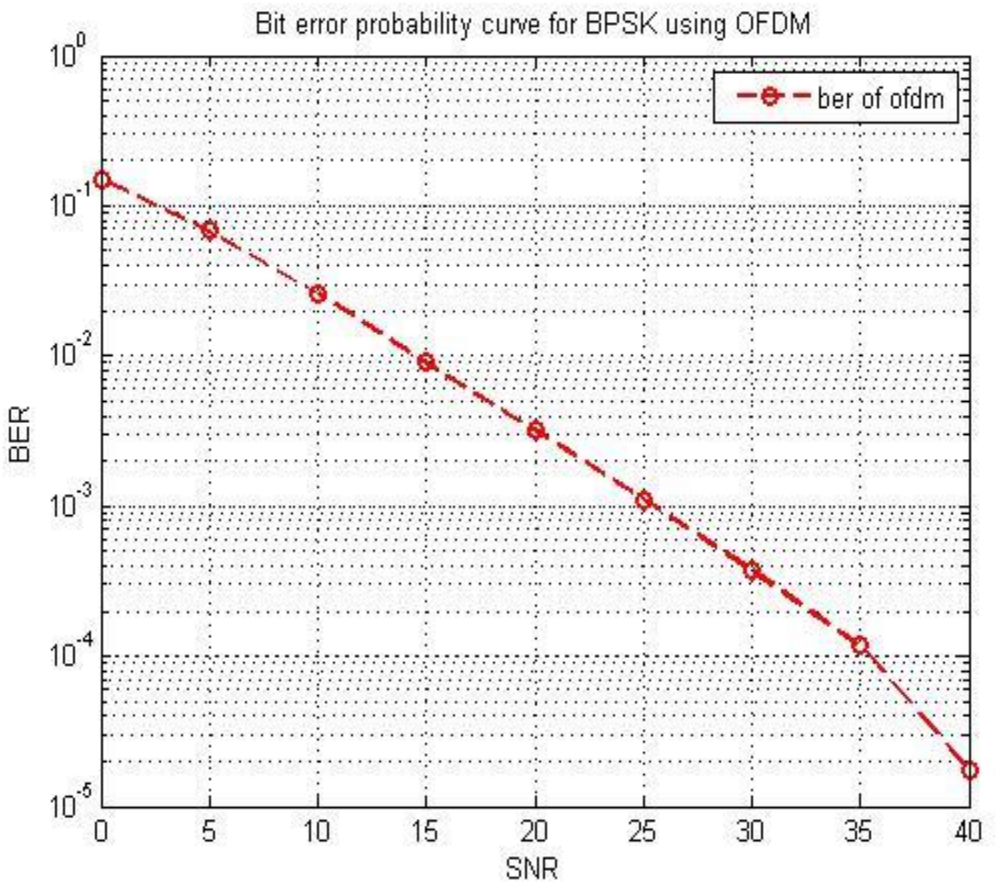


Figure 4.1: BER of OFDM with respect to SNR

Table 4.1: Analysis of BER of OFDM

SNR(dB)	BER
10	$10^{-2.18}$
20	$10^{-3.23}$
30	$10^{-4.28}$
40	$10^{-5.08}$

Here we observe the BER performance of BPSK modulation and OFDM -BPSK System over Rayleigh fading channel is analyzed. By increasing SNR from 10 dB to 20 dB we get BER improvement of $10^{-2.18}$ to $10^{-3.23}$ and by giving SNR 30 dB to 40 dB we get improved BER rate of $10^{-4.28}$ to $10^{-5.08}$OFDM is used to reduce inter- symbol interference problem. The simulation results show that the simulated bit error rate is improved with increasing SNR values.

4.2 BER PERFORMANCE OF MRC-OFDM SYSTEM

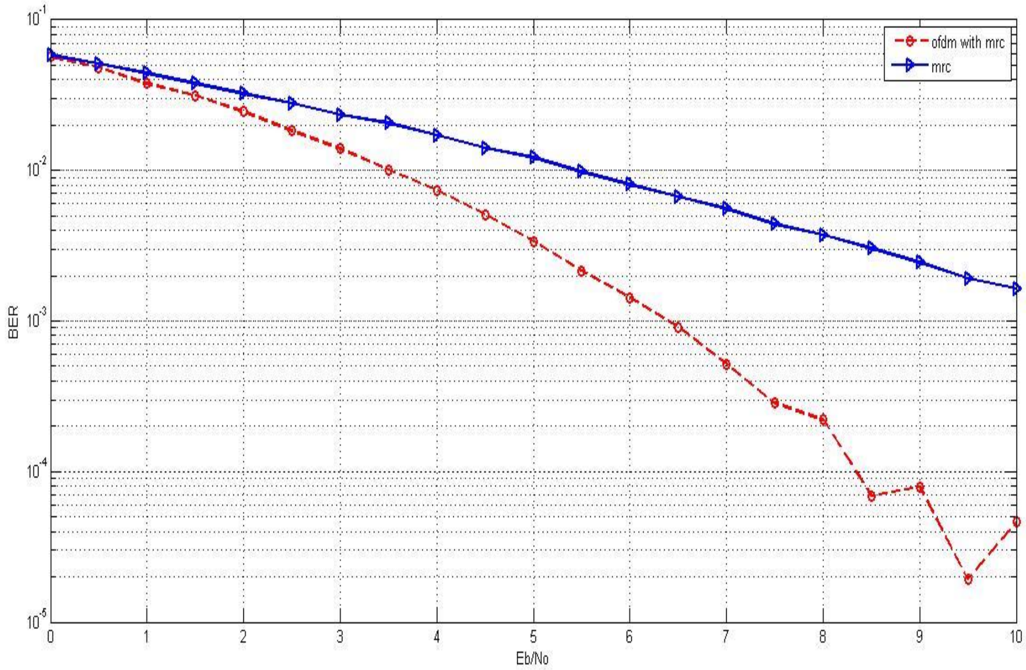


Figure 4.2: BER of MRC-OFDM system with respect to SNR

Table 4.2: Analysis of BER of MRC OFDM system with respect to SNR

SNR(dB)	BER (MRC)	BER(MRC- OFDM)
2	$10^{-1.79}$	$10^{-1.89}$
4	$10^{-1.93}$	$10^{-2.3}$
6	$10^{-2.2}$	$10^{-2.95}$
8	$10^{-2.63}$	$10^{-3.88}$
10	$10^{-2.93}$	$10^{-4.51}$

Thus Table 4.2 shows that with SNR of 2 dB we have BER of $10^{-1.79}$ with MRC alone and $10^{-1.89}$ with MRC-OFDM, with increasing SNR to 4 dB observations shows that BER improvement of $10^{-2.3}$ from $10^{-2.2}$ has been obtained. Thus here is the conclusion that with increasing SNR the BER rate improvement is more in case of MRC-OFDM system as compared to MRC system.

4.3 BER PERFORMANCE OF OC-OFDM

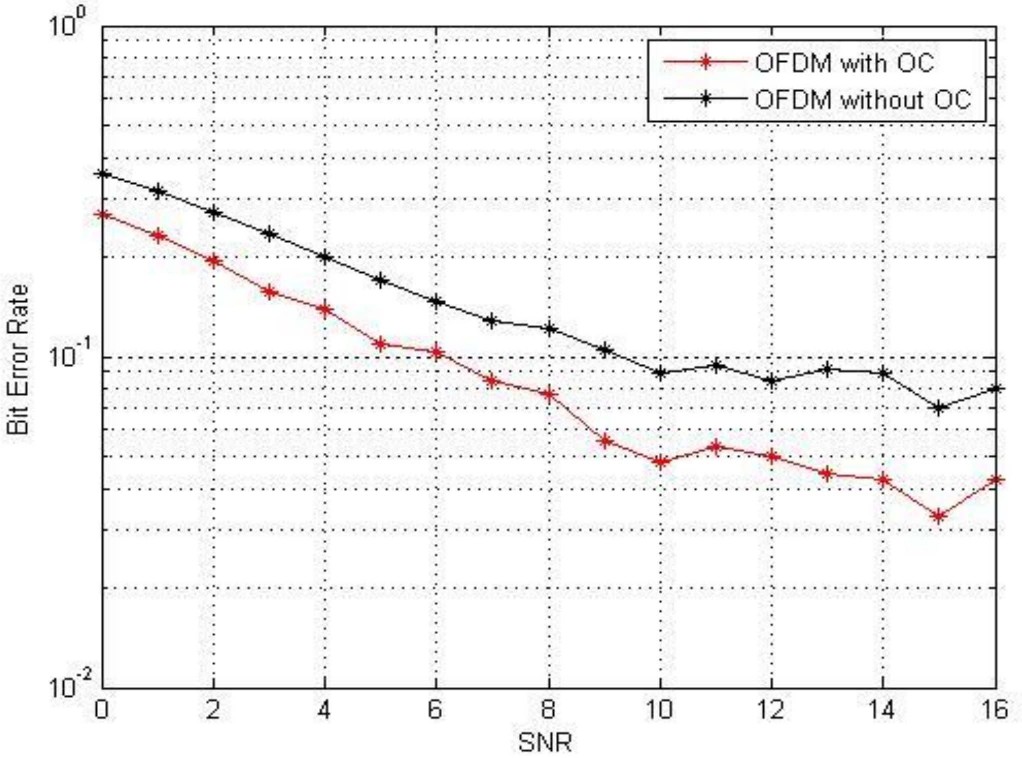


Figure 4.3: BER of OC-OFDM system with respect to SNR

Table 4.3: Analysis of BER of OC-OFDM with respect to SNR

SNR(dB)	BER (OC)	BER(OC- OFDM)
2	$10^{-0.82}$	$10^{-0.91}$
4	$10^{-0.90}$	$10^{-0.95}$
6	$10^{-0.95}$	$10^{-1.00}$
8	$10^{-0.97}$	$10^{-1.22}$
10	$10^{-1.1}$	$10^{-1.50}$

Table 4.3 shows the results of BER with respect to increasing SNR for an OC-OFDM system. As it is shown that with constant SNR of 2 dB BER get improved from $10^{-0.82}$ to

$10^{-0.91}$ and for 8 dB the BER rate improves from $10^{-0.97}$ to $10^{-1.22}$ by using OC-OFDM system as comparative to OC alone. Similar trends can be observed by varying the values of SNR. In the presence of multiple number of interferers and noisy environment, which is usual in modern cellular communication systems the OC is the best suitable diversity combining technique as compared to others [13]. Thus by deploying both OFDM and OC in communication system we have observed that we can have a high speed data transferring system with the least possible error within a noisy environment.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE OF WORK

5.1 CONCLUSION

Space Diversity combining techniques such as maximal ratio combining and optimum combining are very important part of the wireless communication system. It is used to mitigate the effect of fading. So that it helps to improve the performance of a system involving both noise and multipath propagation. OFDM is an efficient technique to handle large data rates in the multipath fading environment. OFDM makes the high speed data streams robust against the radio channel impairments such as ISI and ICI. In this dissertation, a comparison study of performance of OFDM along with MRC and OC has been done over the independent and identically distributed Rayleigh fading environment. The capability of OFDM to transform a broadband channel to smaller narrow band sub-channels and changing its properties leads to a more reliable channel conditions for diversity techniques such as MRC and OC. Such transformations thus leads to a solution for high data rate transmission system having capability of transferring data at much faster speed with least possible error. The performances of diversity combining working alone are compared to the diversity combining along with OFDM for the same modulation schemes. Observation shows that with SNR of 2 dB we have BER of $10^{-1.79}$ with MRC alone and $10^{-1.89}$ with MRC-OFDM, with increasing SNR to 4 dB, BER improvement of $10^{-2.3}$ from $10^{-2.2}$ has been obtained. In case of OC it has been observed that with constant SNR of 2 dB BER get improved from $10^{-0.82}$ to $10^{-0.91}$ and for 8 dB the BER rate improves from $10^{-0.97}$ to $10^{-1.22}$ by using OC-OFDM system as comparative to OC alone. It has been analysed that both the powerful techniques MRC and OFDM can perform well when employed with each other, these results are helpful in designing high data rate systems which are capable of working in wireless communication environment with least possible error rate and efficient utilization of spectrum . While in case of presence of number of interferers as it occurs in modern communication channels the OFDM-OC is the best suitable solution for optimal performance.

5.2 FUTURE SCOPE

In recent years, there has been a tremendous demand for reliable, high speed digital wireless communication. OFDM makes the high speed data streams robust against the radio channel impairments such as ISI and ICI. Diversity techniques such as MRC and OC are used to receive the data with minimum error rate despite the multipath propagation impairments. Thus both of these techniques can combined in order to get high data rate data transmission with least possible error in mobile networks, which can cater the need high data rate transmission to large number of mobile users in urban environment. Thus better quality of service can be provided to large number of users.

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