A Cyclic Prefix OFDM System with Different Modulation Schemes Including Error Correction & Interleaving

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CERTIFICATE

This is to certify that the work entitled, "**A Cyclic Prefix OFDM System with Different Modulation Schemes Including Error Correction & Interleaving**" submitted by Vipin Mittal (051087), Hiyaa Tiwari (051038) and Karan Chawla (051065) in fulfillment for the award of degree of Bachelor of Technology in Electronics and Communication of Jaypee University of Information Technology has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree or diploma.

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Vipin Mittal　　Karan Chawla　　Hiyaa Tiwari

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LIST OF ABBREVIATIONS

- AWGN……………………….Additive White Gaussian Noise
- BPSK……………………......Binary Phase Shift Keying
- BER………………………….Bit Error Rate
- CIR…………………………Channel Impulse Response
- CP……………………………Cyclic Prefix
- CPE………………………...Common Phase Error
- DFT…………………………Discrete Fourier Transform
- FFT………………………....Fast Fourier Transform
- IFFT………………………...Inverse Fast Fourier Transform
- ISI……………………………Inter Symbol Interference
- MRC…………………....……Maximum Ratio Combining
- OFDM……………………….Orthogonal Frequency Division Multiplexing
- P/S…………………………..Parallel to Serial Converter
- S/P…………………………..Serial to Parallel Converter
- SC……………………………Sub Carrier
- WLAN……………………..Wireless Local Area Network

ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is a promising technique for high data rate wireless communications because it can combat intersymbol interference caused by the dispersive fading of wireless channels. A FDM channel is like water flow out of a faucet, in contrast the OFDM signal is like a shower. In a faucet all water comes in one big stream and cannot be subdivided. OFDM shower is made up of a lot of little streams.

The demand for high speed mobile wireless communications is rapidly growing. OFDM technology promises to be a key technique for achieving the high data rate capacity and spectral efficiency requirements for wireless communications of the near future which was a source of motivation for this project. Here in this paper, we simulate a cyclic prefix OFDM system with Binary Phase Shift Keying Modulation on each subcarrier. CP-OFDM system includes a repetition code and interleaving across subcarriers as well as a Rayleigh fading channel model with exponentially decaying power profile.

CHAPTER 1: INTRODUCTION

High speed communications over broadband wireless channels has emerged as a key feature of future communications systems due in part to the explosive interest in information technology applications, including wireless networks, mobile computing, high speed mobile internet, and video transmission over wireless channels. The demand for higher information capacity in these and other similar applications has motivated the use of broadband wireless channels in order to provide wider bandwidth and higher data rates.

OFDM is a widely recognized modulation technique for high data rate communications over wireless links. Because of its capability to capture multipath energy and eliminate intersymbol interference, OFDM has been chosen as the transmission method for several standards, including the IEEE 802.11a wireless local area network (WLAN) standard in the 5-GHz band, the IEEE 802.11g WLAN standard in the 2.4-GHz band. Also, the OFDM-based physical layer is being considered by several standardization groups, such as the IEEE 802.15.3 wireless personal area network (WPAN) and the IEEE 802.20 mobile broad-band wireless access (MBWA) groups. The heightened interest in OFDM has resulted in tremendous research activities in this field to make the real systems more reliable and less costly in practice.

OFDM has been practically implemented in the United Kingdom in the form of digital Video broadcasting- Terrestrial (DVB-T) for quiet sometime now and it has been found useful there. In addition to that earlier this year this technology has given birth to a new concept known as "telemedicine" where doctor and patient can be in different parts of the globe but the patient can still consult the doctor. There can be nothing more to humanity! This is made possible by the high speed data transfer offered by this technique. We feel OFDM is a potential candidate for the physical layer of 4G mobile communication.

Here in this paper, we simulate a cyclic prefix OFDM system with Binary Phase Shift Keying Modulation on each subcarrier. CP-OFDM system includes a repetition code and interleaving across subcarriers as well as a Rayleigh fading channel model with exponentially decaying power profile.

CHAPTER 2: NICETIES

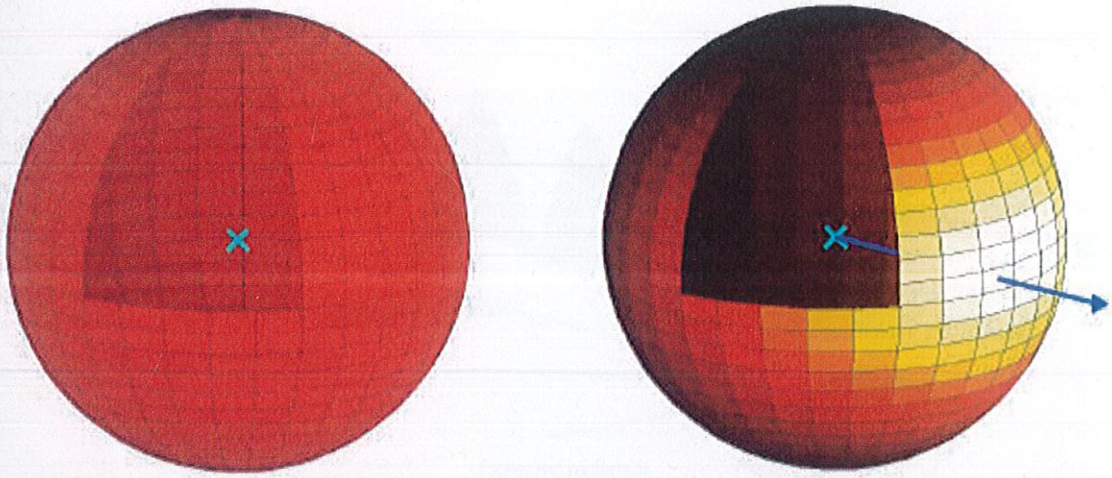
2.1 CHANNEL MODELLING:

In order to evaluate the effectiveness of a given channel coding and processing technique before actual implementation, some model of the channel must be developed that adequately describes the environment. Such analysis reduces the cost of developing a complex system by reducing the amount of hardware that has to be developed for evaluation of performance. By examining the details of how a signal is propagated from a transmitter to a receiver, we can effectively generate a better hardware of transmitter and receiver as physical processes can be judged which modify the transmitted signal.

It is usually described by three components: An input alphabet, an output alphabet and a transition probability 'p' (i,o).

2.2 PATH LOSS AND ATTENUATION:

During propagation, radio signals weaken with distance. This is due to the wave front of the radio signal expanding and thus reducing in power density. In free space, the propagating wave expands as a sphere and thus the power density reduces in proportion to the surface area of this sphere. If the signal is transmitted using a directional antenna, the signal still expands as a sphere, except that the energy density is concentrated to one or more areas (see Figure 2-1). If we transmitted the same energy from an omnidirectional as a direction antenna, the integrated energy over the surface area of the RF sphere, the energy would be the same. Figure 2-1 shows an expanding RF pulse, if we were to imagine a sinusoidal transmission (single frequency) it would be continuous stream of expanding spheres, with the power of these following a sinusoid waveform.



(a) (b)

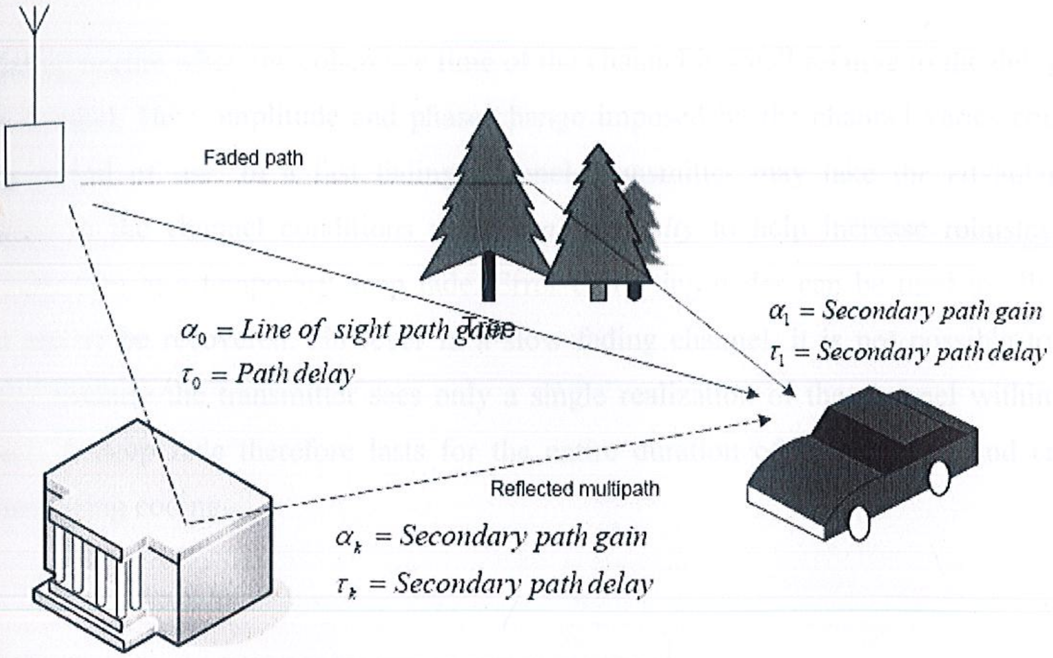
Figure 2-1, Expanding RF pulse from a central transmitter.

The transmitter is shown as a ✖ in the cut away section. (a) For an omnidirectional antenna, the energy density is even in all directions. (b) For a high gain antenna, the energy is concentrated in one direction; it still however expands as a sphere.

2.3 MULTIPATH FADING:

Mathematically, Fading is modeled as a time-varying random change in amplitude and phase of transmitted signal. It is the distortion that a signal experiences.

If the path from the transmitter to receiver either has reflections or obstructions, we get fading effects. In this case, signal reaches the receiver from many different routes, each a copy of original. Each of these rays, called multipath signals/waves, has a slightly different delay and slightly different gain. This results in either constructive or destructive interference, amplifying or attenuating the signal power at receiver. Strong destructive interference is frequently referred to as a deep fade and thus SNR drops significantly.



$$h_c(t) = \sum_{k=0}^{K-1} \alpha_k \delta(t - \tau_k)$$

$$\alpha_k = Complex\ path\ gain$$

$$\tau_0 = Normalized\ path\ delay\ relative\ to\ LOS$$

$$\Delta_k = \tau_k - \tau_0\ \ difference\ in\ path\ time$$

Figure 2-2 Multipath Fading

2.3.1 ***SLOW AND FAST FADING***:

Slow and Fast fading refer to the rate at which the magnitude and phase change imposed by the channel on the signal changes. The coherence time is a measure of the minimum time when phase and magnitude of a signal decorrelate completely from its previous values.

Slow fading arises when the coherence time of the channel is large relative to delay constant of the channel. Here amplitude and phase change imposed by the channel can be considered roughly constant over the period of use. It is also caused by shadowing where a large obstruction obscures the main signal path between transmitter and receiver.

Fast fading occurs when the coherence time of the channel is small relative to the delay constant of the channel. Here amplitude and phase change imposed by the channel varies considerably over a period of use. In a fast fading channel, transmitter may take the advantage of the variations in the channel conditions using *time diversity* to help increase robustness of the communication to a temporary deep fade. Error correcting codes can be used to allow for the erased bits to be recovered. However in a slow fading channel, it is not possible to use time diversity because the transmitter sees only a single realization of the channel within its delay constant. A deep fade therefore lasts for the entire duration of transmission and can not be mitigated using coding.

2.3.2 ***FLAT AND FREQUENCY SELECTIVE FADING***:

As the carrier frequency of the signal is varied, magnitude of change in amplitude will vary. The *coherence bandwidth* measures the minimum separation in frequency after which two signals will experience uncorrelated fading. It is thus considered as the range of frequencies over which the signal remains flat.

In Flat fading, the coherence bandwidth of the channel is larger than bandwidth of the signal and therefore all frequency components of signal will experience the same magnitude of fading. In Frequency selective fading, the coherence bandwidth of the signal is smaller than the bandwidth of the signal and therefore all frequency components of signal will experience different and decorrelated magnitude of fading.

2.3.3 ***FADING RELATED TO PROBABILITY DISTRIBUTIONS***:

Various probability distributions give various models of fading implemented in different situations. The *Rayleigh Fading* model assumes that the magnitude of a signal that has passed through such a transmission medium will vary randomly according to a Rayleigh distribution.

This model is a reasonable model when there are many objects in the environment that scatter the radio signals before they arrive at the receiver. If there is a dominant line of sight, *Rician Fading* is more applicable which follows Rician probability distribution. *Nakagami Fading* is related to Gamma distribution and is considered to be the more general fading distribution because it matches empirical results for short ionosphere propagation. It occurs for multipath scattering with relatively larger time-delay spreads, with different clusters of reflected waves. Within any one cluster, phases of individual reflected waves are random, but time delays are approximately equal for all waves. Here the outer envelope of ach cluster is Rayleigh distributed.

2.4 DELAY SPREAD:

Delay spread is a measure of the spread in the time over which the multipath signals arrive. It is a measure of the time dispersion of a channel, and is very important in determining how fast the symbol rate can be in digital communications. A symbol is a period over which one or more groups of bits of information are sent. For a single carrier transmission, using Binary Phase Shift Keying (BPSK) as the modulation scheme, each symbol carries one bit of information. The symbol corresponds to the period required to send the phase information as 0° or 180°, which corresponds to the digital information of zero or one respectively. The faster the phase is varied the faster the symbol rate and the higher the data rate and bandwidth. For OFDM transmission, each symbol corresponds to a parallel transmission of many low bandwidth carriers. The symbol time in this case corresponds to the period over which the amplitude and phase of the data carriers is remained fixed corresponding to one data vector. Delay spread results in time blurring, where energy from previous data symbols becomes mixed in with current symbols. This causes interference, known as Inter- Symbol Interference (ISI), because previous symbols are uncorrelated, effectively adding noise to the signal. Single carrier transmissions are particularly prone to problems caused by delay spread as it normally sets the upper limit on symbol rate. This is because the bit error rate (BER) increases as the delay spread time becomes a significant fraction of the symbol time. Simple modulation schemes such as BPSK can tolerate a delay spread of approximately 10 - 20% of the symbol period; anymore and the BER is too high.

However, higher modulation schemes such as 16-QAM, 256-QAM, etc, which have a higher spectral efficiency, are much more sensitive to ISI and thus the delay spread must be less than several percent of the symbol period.

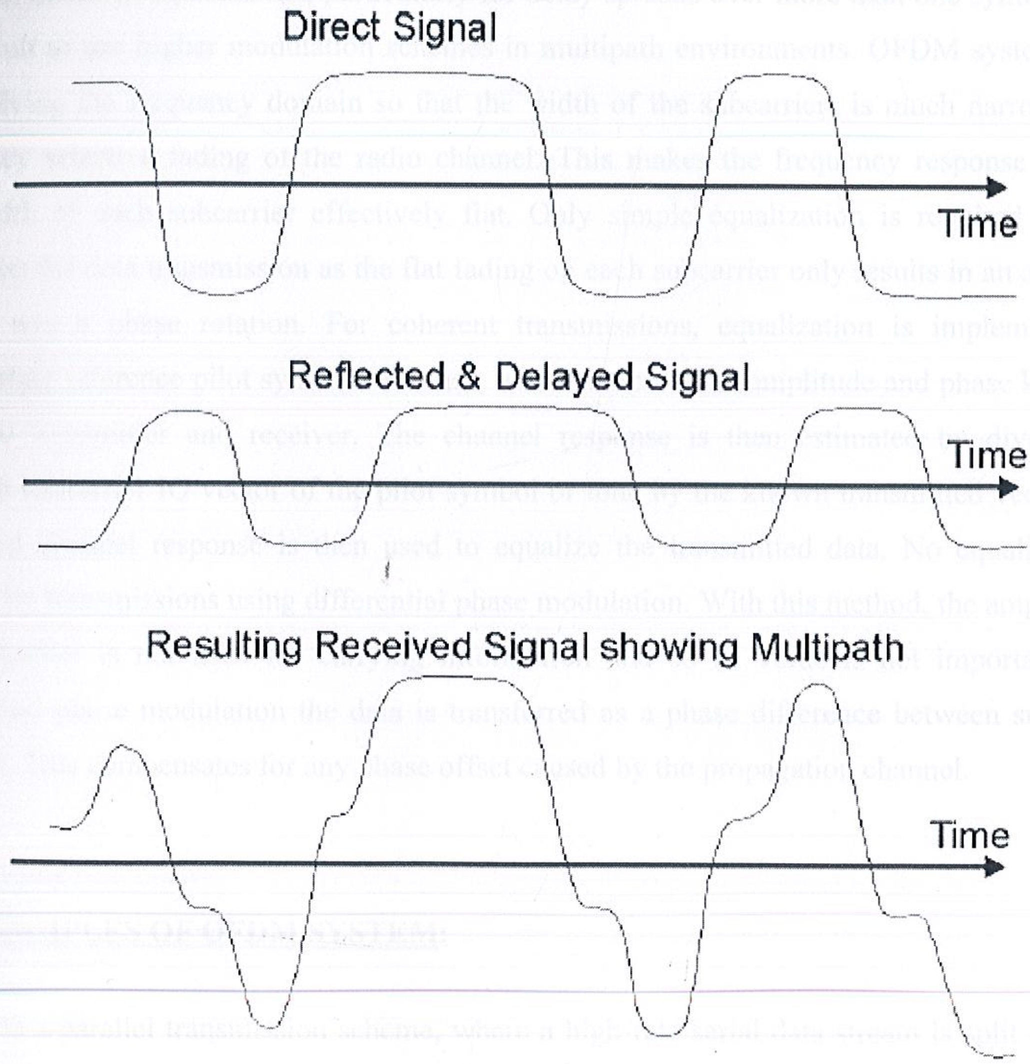


Figure 2-3 Multipath Delay Spread

2.5 EQUALIZATION:

One method to overcome the limitations of delay spread for single carrier transmission is to use equalization. The aim of equalization is to find an inverse filter that compensates for the ISI so that all the multipath signals become shifted and aligned in time, rather than being spread out. For example, the GSM phone system, which uses 270 k symbols/s (3.7 ms symbol period), can tolerate a delay spread of up to 15 ms. This is a delay spread of over four symbol periods. The problem with equalization is that it becomes increasing difficult, as the ISI is spread over more symbols. Errors in equalization, particularly for delay spreads over more than one symbol, make it difficult to use higher modulation schemes in multipath environments. OFDM systems work by resolving the frequency domain so that the width of the subcarriers is much narrower than frequency selective fading of the radio channel. This makes the frequency response over the bandwidth of each subcarrier effectively flat. Only simple equalization is required for each subcarrier for data transmission as the flat fading on each subcarrier only results in an amplitude scaling and a phase rotation. For coherent transmissions, equalization is implemented by transmitting reference pilot symbols or tones, which are set to an amplitude and phase known by both the transmitter and receiver. The channel response is then estimated by dividing the received subcarrier IQ vector of the pilot symbol or tone by the known transmitted vector. This measured channel response is then used to equalize the transmitted data. No equalization is needed for transmissions using differential phase modulation. With this method, the amplitude of the subcarrier is not used for carrying information and so its value is not important. With differential phase modulation the data is transferred as a phase difference between successive symbols. This compensates for any phase offset caused by the propagation channel.

2.6 PRINCIPLES OF OFDM SYSTEM:

OFDM is a parallel transmission scheme, where a high-rate serial data stream is split up into a set of low rate substreams, each of which is modulated on a separate SC (FDM). Thereby, the bandwidth of the SCs becomes small compared with the coherence bandwidth of the channel; that is, the individual SCs experience flat fading, which allows for simple equalization. This implies that the symbol period of the substreams is made long compared to the delay spread of the time-dispersive radio channel. By selecting a special set of (orthogonal) carrier frequencies, high spectral efficiency is obtained because the spectra of the SCs overlap, while mutual influence among the SCs can be avoided. The derivation of the system model shows that by introducing a cyclic prefix, the orthogonality can be maintained over a dispersive channel.

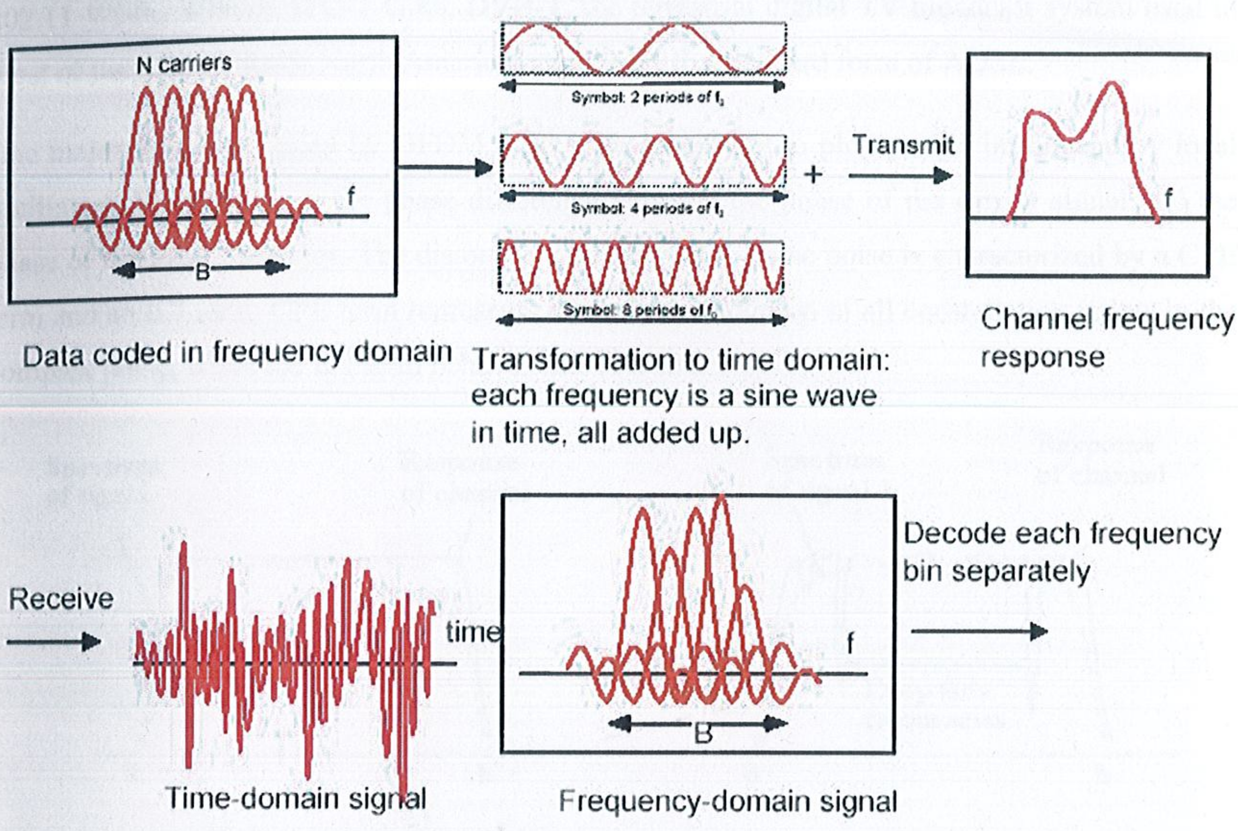


Figure 2-4 Orthogonal Frequency Division Modulation

2.6.1 ***ORTHOGONALITY***:

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. In Communications, multiple-access schemes are orthogonal when an ideal receiver can completely reject arbitrarily strong unwanted signals using different basis functions than the desired signal. One such scheme is TDMA, where the orthogonal basis functions are non-overlapping rectangular pulses ("time slots"). Another scheme is orthogonal frequency-division multiplexing (OFDM), which refers to the use, by a single transmitter, of a set of frequency multiplexed signals with the exact minimum frequency spacing needed to make them orthogonal so that they do not interfere with each other. Well known examples include a and g versions of 802.11 Wi-Fi; Wimax; ITU-T G.hn, DVB-T, the terrestrial digital TV broadcast system used in most of the world outside North America; and DMT, the standard form of ADSL.

One major limitation faced by OFDM is its high sensitivity to phase noise introduced by local oscillators. Phase noise is the phase difference between the phase of the carrier signal and the phase of the local oscillator. The distortion caused by this phase noise is characterized by a CPE term and an ICI term. CPE term represents the common rotation of all constellation points in the complex plane, while the ICI term behaves like AWGN.

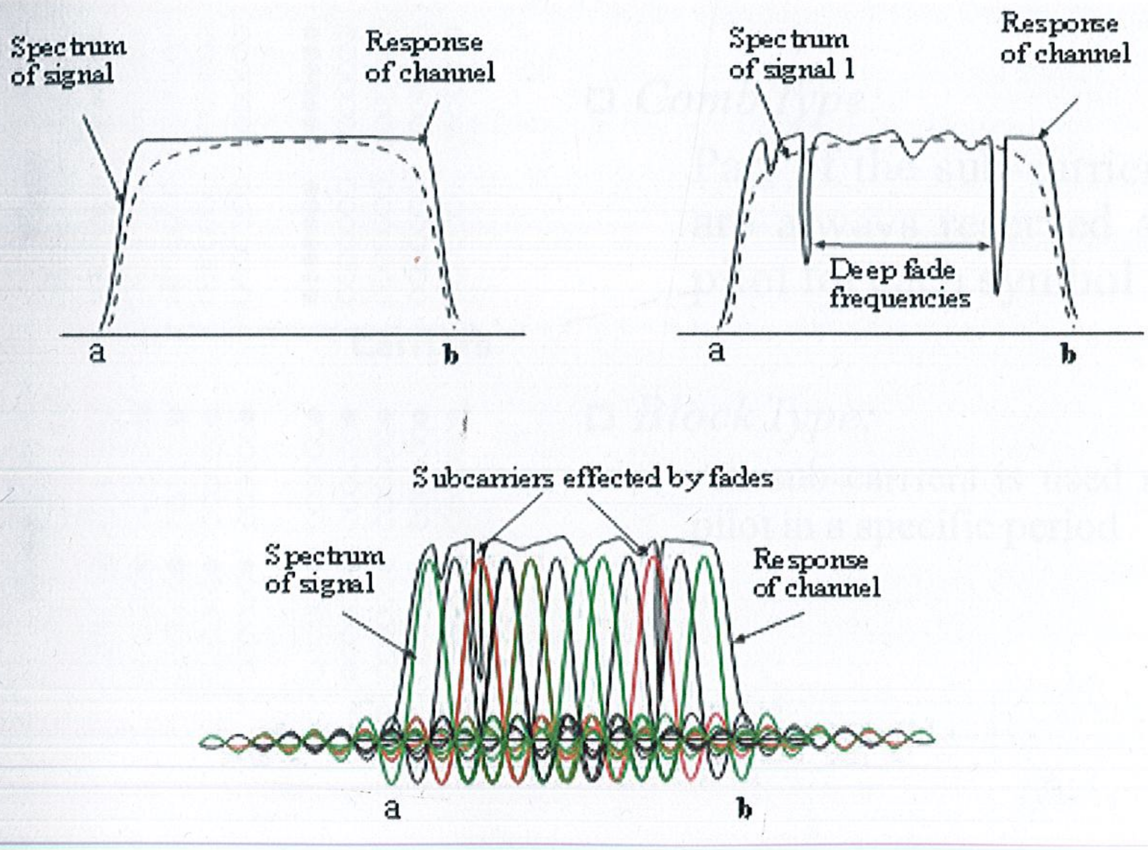


Figure 2-5 (a) Signal & Channel Frequency Response are well matched (b) Data lost due to Fading (c) With OFDM, only a small subset of data is lost due to fading due to a number of sub-carriers.

2.6.2 ***PILOT SYMBOLS***:

A Pilot is a signal, usually a single frequency, transmitted over a communication channel for supervisory or control or reference purposes. A pilot tone of 19 KHz indicates that there is information at 19*2=38KHz. The receiver doubles the frequency of the pilot tone and uses it as a phase reference to demodulate information. Normally a guard band of ±4KHz is used to protect the pilot tone from interference. Pilots are used in OFDM for frame detection, carrier frequency offset estimation, and channel estimation. Figure below shows the two pilot structures of the system.

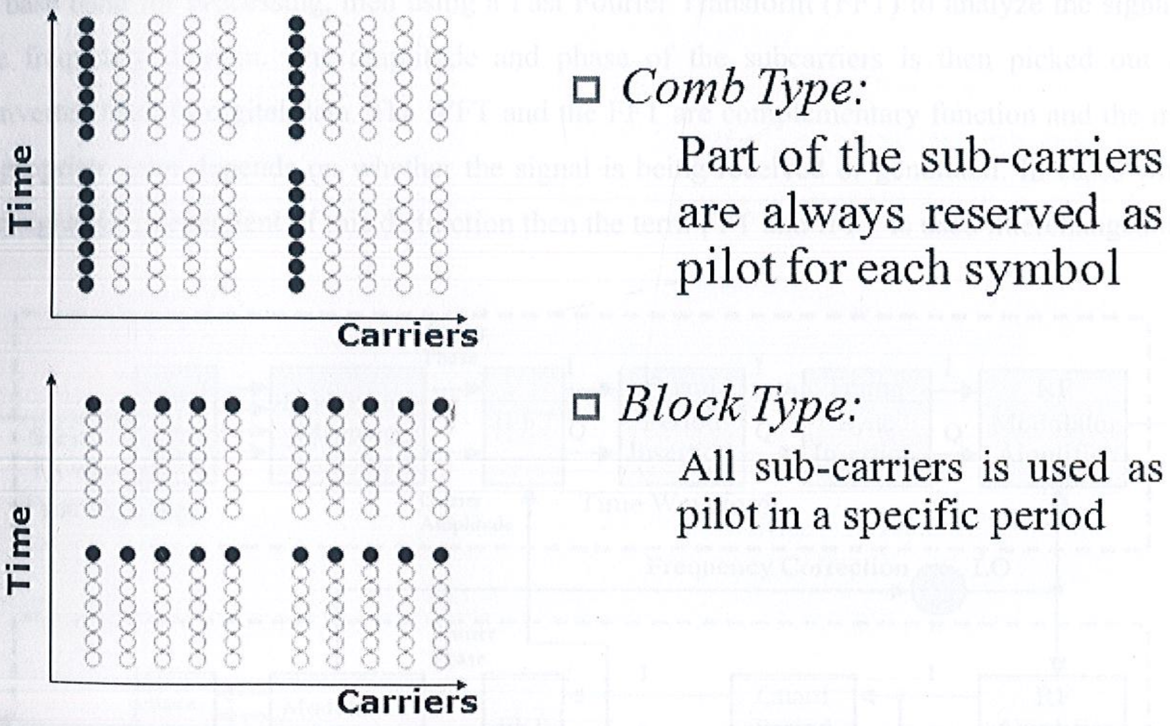


Figure 2-6 Pilot for Channel Estimation

2.6.3 *OFDM GENERATION & RECEPTION*:

OFDM signals are typically generated digitally due to the difficulty in creating large banks of phase lock oscillators and receivers in the analog domain. Figure below shows the block diagram of a typical OFDM transceiver. The transmitter section converts digital data to be transmitted, into a mapping of subcarrier amplitude and phase. It then transforms this spectral representation of the data into the time domain using an Inverse Discrete Fourier Transform (IDFT). The Inverse Fast Fourier Transform (IFFT) performs the same operations as an IDFT, except that it is much more computationally efficiency, and so is used in all practical systems. In order to transmit the OFDM signal the calculated time domain signal is then mixed up to the required frequency. The receiver performs the reverse operation of the transmitter, mixing the RF signal to base band for processing, then using a Fast Fourier Transform (FFT) to analyze the signal in the frequency domain. The amplitude and phase of the subcarriers is then picked out and converted back to digital data. The IFFT and the FFT are complementary function and the most appropriate term depends on whether the signal is being received or generated. In cases where the signal is independent of this distinction then the term FFT and IFFT is used interchangeably.

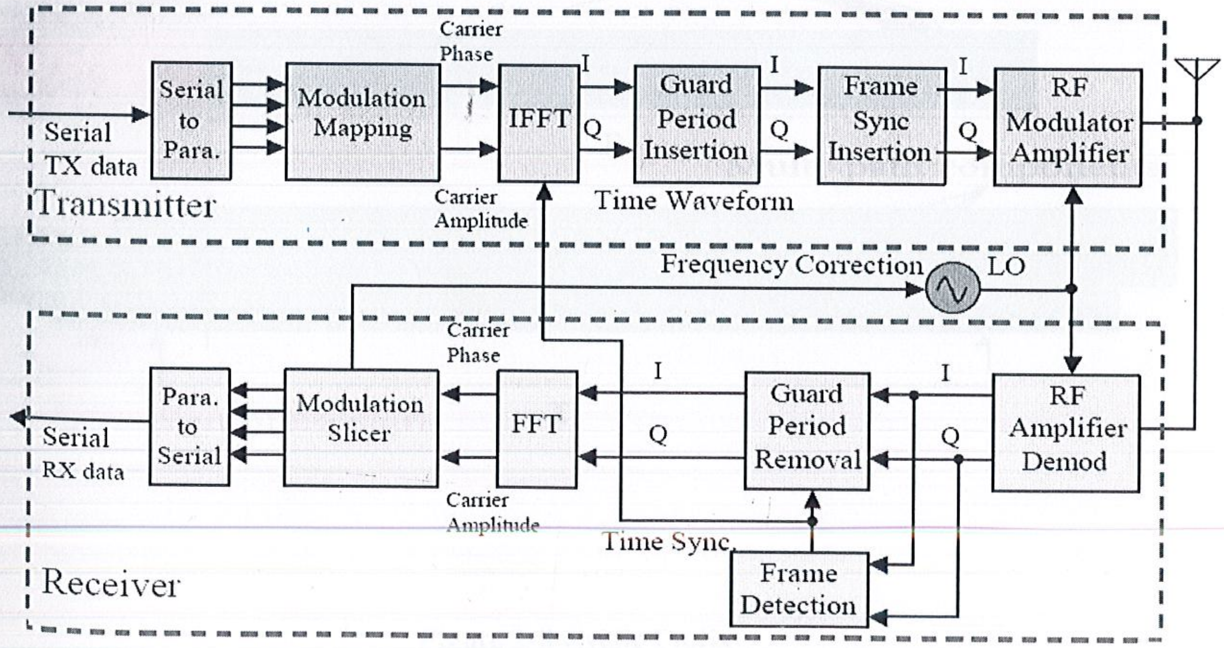


Figure 2-7 Basic OFDM Transceiver

2.6.4 *INTERLEAVING*:

Let's understand this concept with the help of an example. Suppose there are four families (each having four members) going on a holiday in there four cars. In each of the cars there is exactly one family. Now if unfortunately a car meets with an accident then one whole family will be finished. But suppose if they were to be seated differently i.e. if each car had exactly one member of each family and then the accident were to happen then no single family would be finished. The loss would be equal for all the families. This is certainly better. Same is with our data. If we send our data this way then we can eliminate some noise effect like burst noise effect.

2.6.5 *CYCLIC PREFIX*:

In an OFDM, the cyclic prefix is a repeat of the end of the symbol at the beginning. The purpose is to allow multipath to settle before the main data arrives at receiver. The receiver is normally arranged to decode the signal after it has settled because this is when the frequencies become orthogonal to each other. The length of cyclic prefix is equal to guard interval.

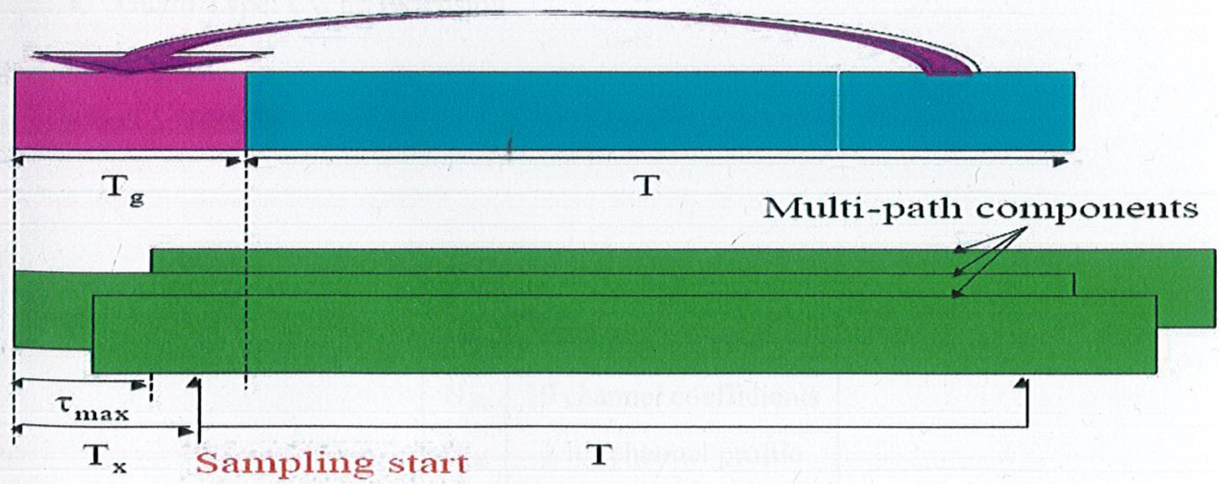


Figure 2-8 Cyclic Prefix

CHAPTER 3: PROCEDURE

Wireless multi-carrier transmission system is based on Orthogonal Frequency-Division Multiplexing (OFDM) including a simple channel coding scheme for error correction and interleaving across subcarriers for increased frequency diversity.

Some Assumptions:

- Usage of Cyclic Prefix
- Impulse response of the channel shorter than cyclic prefix.
- Slow fading effects so that the channel is time invariant over the symbol interval.
- Rectangular windowing of the transmitted pulses.
- Perfect Synchronization of transmitter and receiver.
- Additive, White, Gaussian Noise channel.
- Data Rate of OFDM signal: 1Mbps/carrier
- Guard Length: 16
- Guard Type: Cyclic Extension

Values of Constants:

N_{real}	10,000 OFDM symbols
N_c	128 subcarriers
N_{ch}	10 channel coefficients
C_{att}	2 for channel profile

1) **SYSTEM OVERVIEW:**

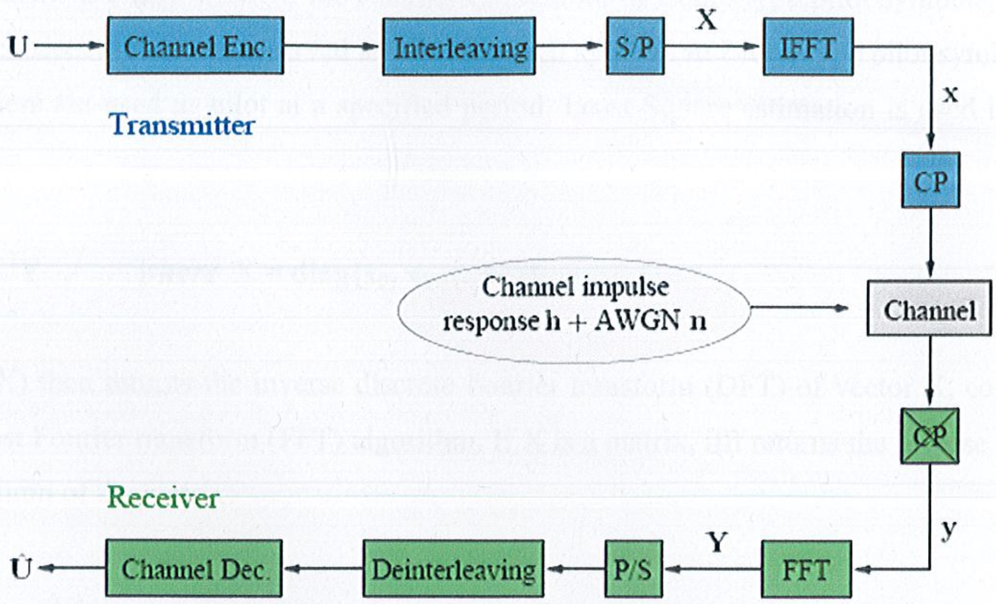


Figure 3-1 Basic Communication Model

2) **INPUT TO TIME DOMAIN:**

Digital data is transferred in an OFDM link by using a modulation scheme on each subcarrier. A modulation scheme is a mapping of data words to a real (In phase) and imaginary (Quadrature) constellation, also known as an IQ constellation. For example 16-QAM (Quadrature Amplitude Modulation) has 16 IQ points in the constellation constructed in a square with 4 evenly spaced columns in the real axis and4 rows in the imaginary axis. Maximum capacity of a channel of bandwidth, W signal power, S perturbed by AWGN of power, N is given by:

$$C = W \log_2(1 + S/N)$$

Interleaving is then done which arrange data in a non contiguous way in order to increase the performance. Data to be transmitted is typically in the form of a serial data stream. In OFDM, each symbol typically transmits 40 - 4000 bits, and so a serial to parallel conversion stage is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol.

Pilot symbols are then inserted for channel estimation. In Comb-type pilot symbols, part of the sub carriers are always reserved as pilot for each symbol. In Block-type pilot symbols, all sub carriers are used as pilot at a specified period. Least Square estimation is used in block types:

$$\mathbf{h}_{LS} = \mathbf{X}^{-1}\mathbf{Y} \qquad \textit{where} \quad \mathbf{X} = \mathbf{diag}\{x_0, x_1, \ldots, x_{N-1}\}$$

y = ifft(X) then returns the inverse discrete Fourier transform (DFT) of vector X, computed with a fast Fourier transform (FFT) algorithm. If X is a matrix, ifft returns the inverse DFT of each column of the matrix:

$$\mathbf{x(n) = 1/N} \sum_{k=0}^{N-1} X(k)\ \mathbf{e}^{\mathbf{j2\pi nk/N}} \qquad \textit{where} \quad \mathbf{n=0,1,\ldots,N-1}$$

3) GUARD INSERTION:

A Cyclic Prefix is then added to allow multipath to settle before the main data arrives at receiver. The undergoing process is: *message » IFFT » CP » FFT » message* as shown below:

$$\mathbf{X_f(n) = x(n + N)} \quad \textit{if} \quad \mathbf{n = - N_g, -N_g+1, \ldots, - 1}$$

$$\mathbf{= x(n)} \quad \textit{if} \quad \mathbf{n= 0, 1, \ldots, N-1}$$

4) CHANNEL MODEL:

A channel model is then applied to the transmitted signal. The model allows for the signal to noise ratio, multipath, and peak power clipping to be controlled. The signal to noise ratio is set by adding a known amount of white noise to the transmitted signal. Multipath delay spread then added by simulating the delay spread using an FIR filter. The length of the FIR filter represents the maximum delay spread, while the coefficient amplitude represents the reflected signal magnitude. If x-component consists of input signal, h-component channel response and w-component AWGN, then output component may be calculated as:

$$\mathbf{y_f = x_f(n) \otimes h(n) + w(n)}$$

5) GUARD REMOVAL:

The Cyclic Prefix is then removed at receiver end:

$$\mathbf{Y(n) = y_f(n)} \quad \textbf{\textit{where}} \quad \mathbf{n = 0, 1, 2, \ldots, N\text{-}1}$$

6) OUTPUT TO FREQUENCY DOMAIN:

Y = fft(X) returns the discrete Fourier transform (DFT) of vector X, computed with a fast Fourier transform (FFT) algorithm. If X is a matrix, fft returns the Fourier transform of each column of the matrix. If the length of X is less than n, X is padded with trailing zeros to length n. If the length of X is greater than n, the sequence X is truncated. When X is a matrix, the length of the columns is adjusted in the same manner:

$$\mathbf{X(k)} = \sum_{n=0}^{N-1} x(n)\,\mathbf{e}^{-j2\pi nk/N} \quad \textbf{\textit{where}} \quad \mathbf{k = 0, 1, \ldots N\text{-}1}$$

7) OUTPUT:

The receiver basically does the reverse operation to the transmitter. The guard period is removed. The FFT of each symbol is then taken to find the original transmitted spectrum. The phase angle of each transmission carrier is then evaluated and converted back to the data word by demodulating the received phase. The data words are then combined back to the same word size as the original data. Channel estimation and Deinterleaving is also performed in the same block. If W(k) is AWGN and I(k) is ICI then output may be calculated as:

$$Y(k) = X(k)\, H(k) + I(k) + W(k) \quad \textit{where} \quad k = 0, 1, \ldots, N-1$$

8) CHANNEL ESTIMATION & CALCULATION OF BER:

A channel model is useful in determining the mechanisms by which propagation in the indoor environment occurs, which in turn are useful in the development of a communication system. By examining the details of how a signal is propagated from the transmitter to the receiver for a number of experimental locations, a generic model may be developed that highlights the important characteristics of a given indoor environment. Generic models of indoor communications can then be applied to specific situations to describe the operation of a radio system, and may also be used to generate building designs that are particularly well-disposed to supporting radio communication systems. So Channel Estimation is done with the help of Pilot Symbols:

$$X_e(k) = \frac{Y(k)}{H_e(k)} \quad \text{where} \quad k = 0, 1, \ldots, N-1$$

In telecommunication, an **error ratio** is the ratio of the number of bits, elements, characters, or blocks incorrectly received to the total number of bits, elements, characters, or blocks sent during a specified time interval. The most commonly encountered ratio is the **bit error ratio** (BER) - also sometimes referred to as **bit error rate**. Analytical BER performance of binary antipodal transmission over $L \geq 1$ i.i.d. Rayleigh fading branches with MRC at receiver is calculated according to following formula:

$$P_b = \frac{1}{2^L}(1 - sum)^L \sum_{l=0}^{L-1} \binom{L-1+l}{l} \frac{1}{2^L}(1 + sum)^l$$

$$\textit{Where} \quad sum = \sqrt{\frac{1}{1+sig}} \quad \textit{where} \quad sig = \sigma_n^2$$

CHAPTER 4: RESULTS

We obtained the following graphical results:

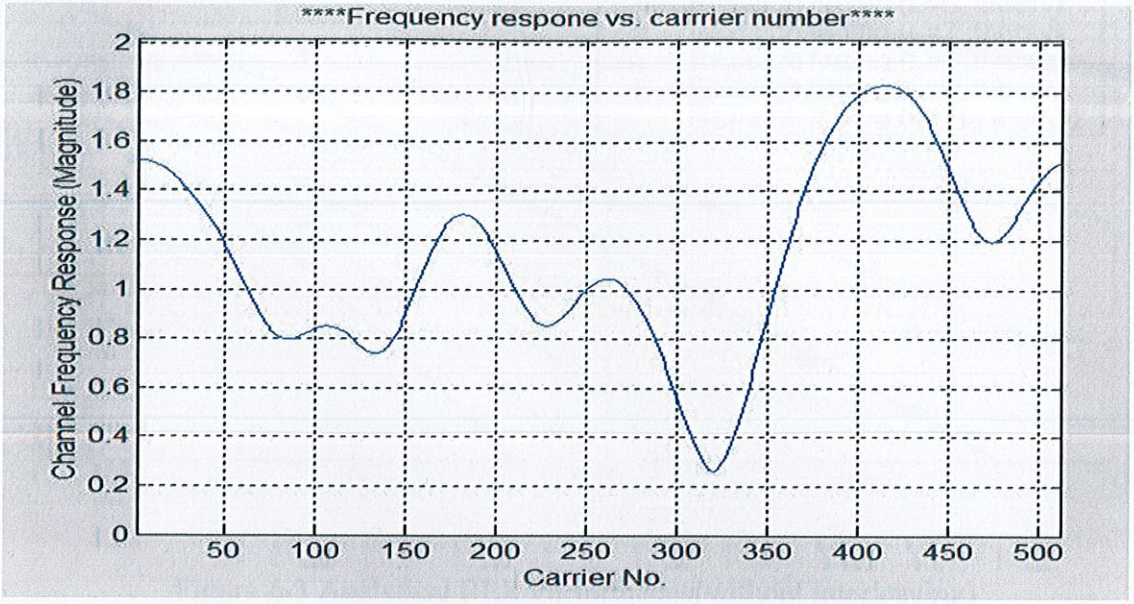


Figure 4-1 Frequency Response at code rate, R=1(without interleaving)

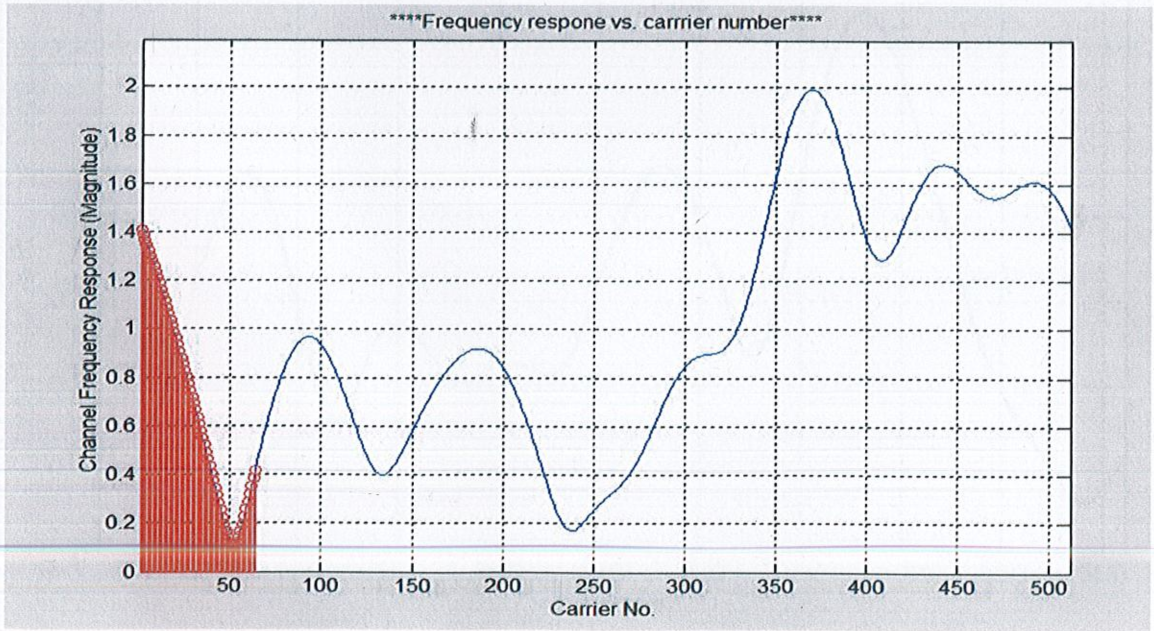


Figure 4-2 Frequency Response at code rate, R=1/64(without interleaving)

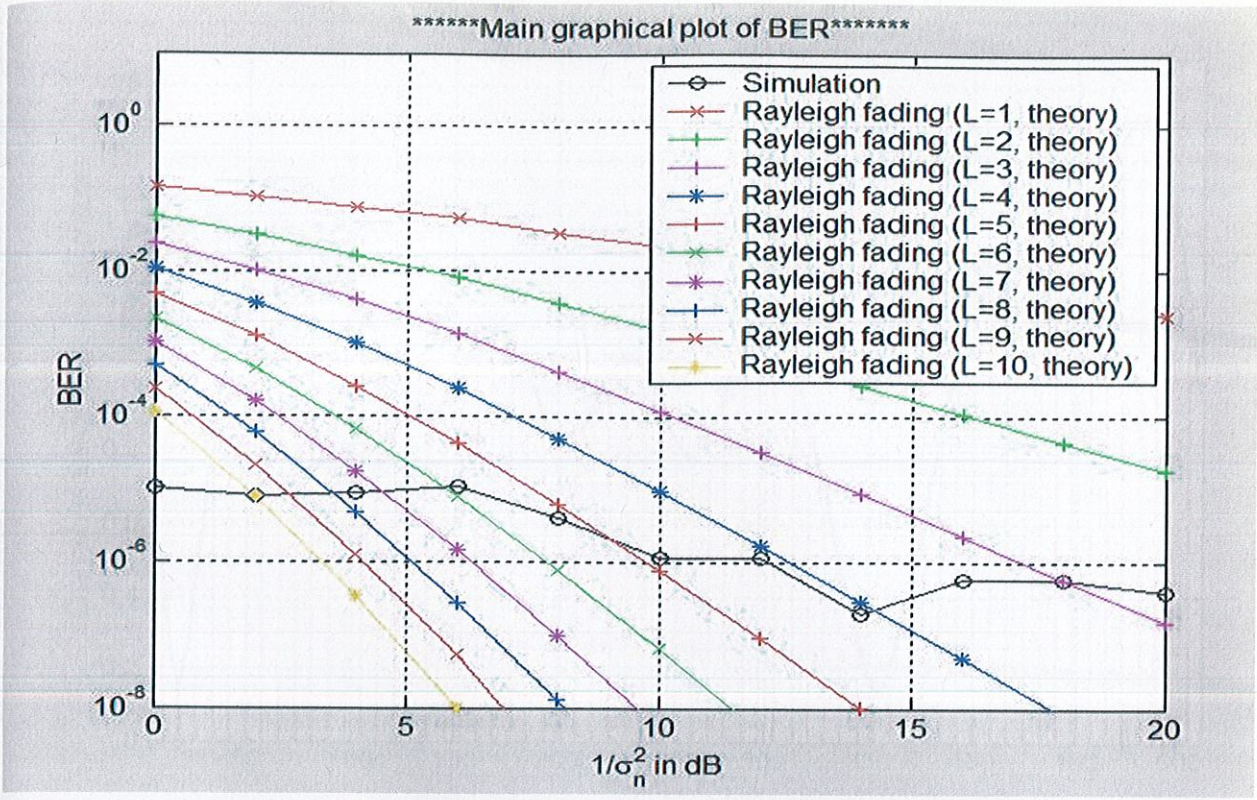


Figure 4-3 Analytical BER Performance(without interleaving)

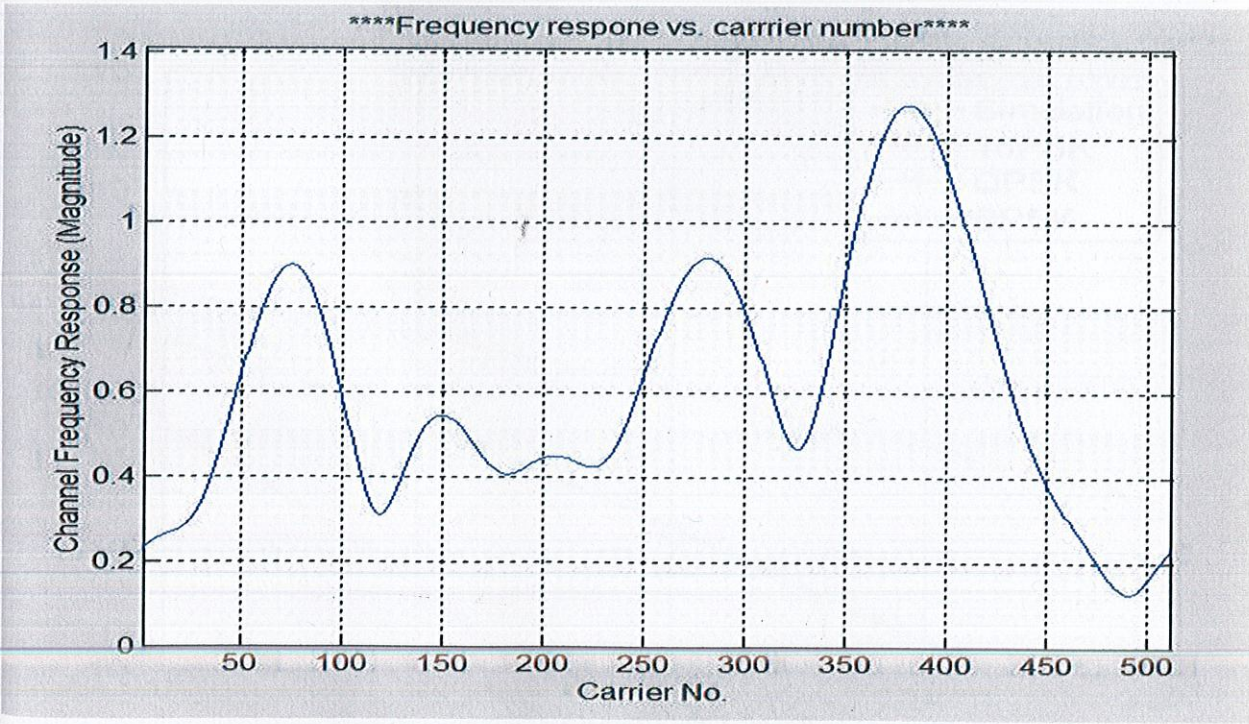


Figure 4-4 Frequency Response at code rate, R=1(with interleaving)

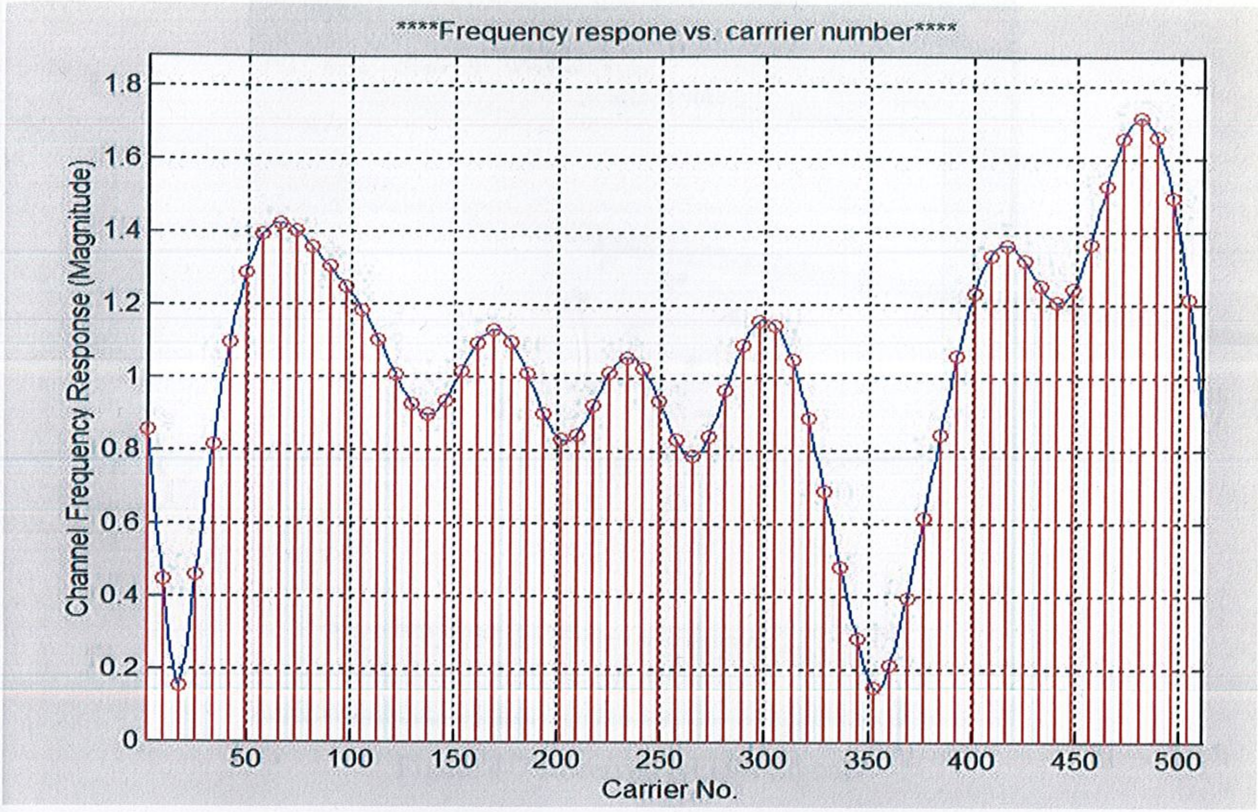


Figure 4-5 Frequency Response at code rate, R=1/64(with interleaving)

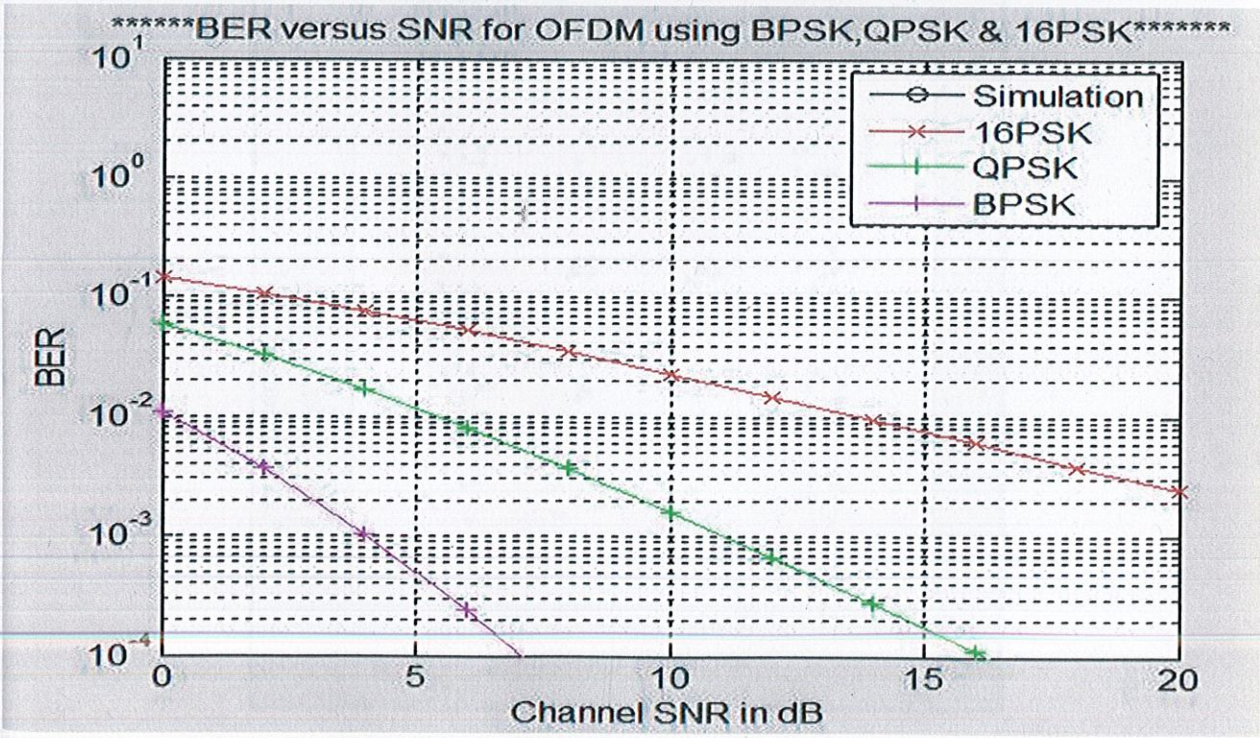


Figure 4-6 BER vs. SNR for OFDM using BPSK, QPSK & 16PSK

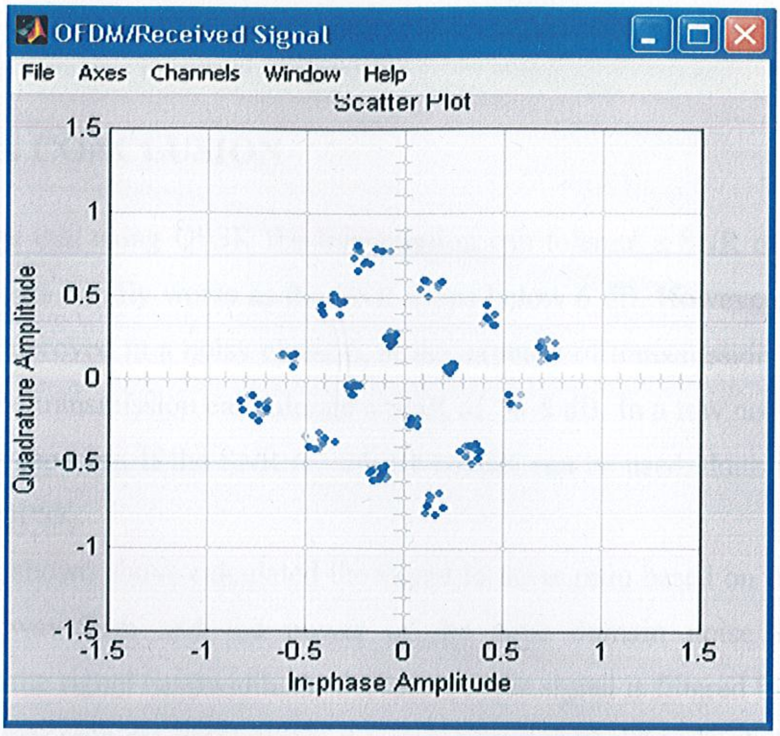


Figure 4-7 Received OFDM Signals

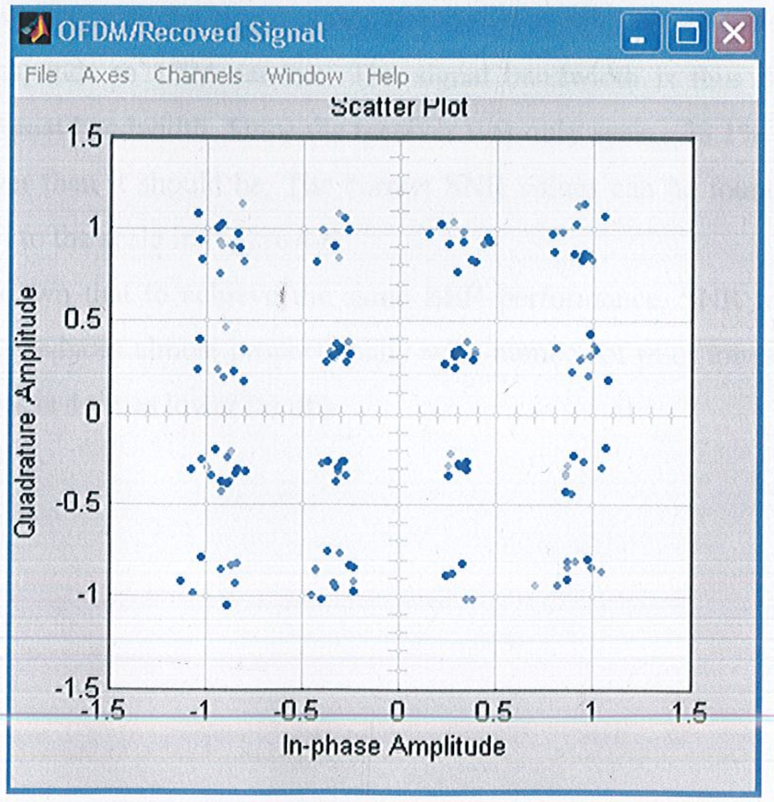


Figure 4-8 Recovered OFDM Signals

CHAPTER 5: CONCLUSION

The results show that using QPSK the transmission can tolerate a SNR of >10-12 dB. The bit error rate BER gets rapidly worse as the SNR drops below 6 dB. However, using BPSK allows the BER to be improved in a noisy channel, at the expense of transmission data capacity. Using BPSK the OFDM transmission can tolerate a SNR of >6-8 dB. In a low noise link, using 16PSK can increase the capacity. If the SNR is >25 dB 16PSK can be used, doubling the data capacity compared with QPSK.

The simulations shown above calculated the signal to noise ratio based on the power of the time domain signal waveform and the power of the time domain noise waveform, with no consideration of the signal bandwidth. At the receiver the signal is filtered by the FFT stage, thus making the receiver only see noise within the signal bandwidth. The simulations were performed using 800 carriers and generated using a 2048-point IFFT. The nyquist bandwidth is half the transmission sample rate as the signal is real (i.e. no imaginary components) and so the nyquist bandwidth corresponds to 1024 carriers. The signal bandwidth is thus 800/1024 = 0.781 or 78.1% of the nyquist bandwidth. Since the receiver was only seeing 78.1% of the total noise the error rate is lower than it should be. The correct SNR values can be found by adding 1.07 dB (10log10(0.781)) to the scale in Figure 4-6.

Also we noted down that to achieve the same BER performance, SNR must be higher. SNR performance loss reduces almost proportionally with number of pilot tones, thus the loss when using 4 pilot tones is 4 times lower (in db).

Table 5-1:

Subcarrier Modulation	Code Rate	SNR for BER=2*10^{-4}	Bit Rate(Mbps) at Guard period duration, 1/4	Bit Rate(Mbps) at Guard period duration, 1/32
BPSK	½	5.4	4.98	6.03
QPSK	½	16.3	8.71	10.56
16PSK	½	22.8	17.42	12.06

SNR Required and Bit Rate for a Selection of Coding & Modulation Schemes

Table 5-2:

Number of pilot symbols			BER 1×10^{-2}			BER 1×10^{-3}			BER 1×10^{-4}			BER 1×10^{-5}		
B	*Q*	*P*	*B*	*Q*	*P*	*B*	*Q*	*P*	*B*	*Q*	*P*	*B*	*Q*	*P*
1	1	1	1.55	2.5	2.7	1.2	2.4	2.9	1.0	2.4	3.0	0.8	2.35	3.2
2	2	2	0.6	1.3	1.5	0.35	1.3	1.6	0.2	1.2	1.7	0.15	1.2	1.7
3	3	3	0.3	0.85	1.0	0.2	0.8	1.1	0.15	0.8	1.1	0.12	0.7	1.1
4	4	4	0.2	0.65	0.8	0.15	0.6	0.8	0.1	0.6	0.8	0.10	0.45	0.8

B: BPSK Modulation

Q: QPSK Modulation

P: 16PSK Modulation

SNR Degradation (in db) in Performance for Different Modulation Schemes

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APPENDIX (BASIC STEPS AT MATLAB PLATFORM)

1) INFO VECTOR U:

Info symbols U_k carry the actual information to be transmitted and are regarded as independent and identically distributed (i.i.d.) random variables with antipodal representation {-1, +1}.

In first step, we generate vector U of length RN_c:

U = 2*round (rand (1, R*N$_c$)) - 1

2) CHANNEL ENCODING:

Channel encoding adds redundancy to info symbols in a structured fashion. For each info symbol U_k , encoder computes N code symbols$X_{k,1}$, ...,$X_{k,N}$. We apply simple repetition codes of rate R to info vector U so as to get a vector X of length N_c:

X = kron (U, ones(1,1/R))

3) INTERLEAVING:

Code symbols in vector X will be transmitted in parallel over the N_c orthogonal subcarriers. Here we spread code symbols $X_{k,1}$, ...,$X_{k,N}$ associated with info symbols U_k across entire system bandwidth instead of using N subsequent subcarriers. We use maximum distance pattern for interleaving X with an assumed N_c = 128 and R=4:

Index= [1 33 65 97 2 34 66 98 …… 96 128]

4) **OFDM MODULATION:**

The OFDM symbol X is converted into time domain via IFFT so as to get a vector x of length N_c. In addition, to avoid interference between OFDM symbols, guard interval of length N_{ch}-1 is required which is included by adding Cyclic-prefix to original vector. Here last N_{ch}-1 symbols of vector x are appended to x as a prefix to make total length of vector as $N_c + N_{ch}$-1:

X = ifft(X) * sqrt (N_c)

X = [x (end-N_{ch}+2 : end)x]

5) **CHANNEL MODEL:**

In channel model, we assume that channel coefficients are complex valued (i.e. we assume a baseband model) and the channel model is Rayleigh-fading channel model. Also channel impulse response changes only from one OFDM symbol to another. Here we first generate random channel impulse (CIR) response realization using specified channel powerprofile:

Var_ch = exp (- [0: N_{ch}-1] / c_att) *(c_att = 2 is assumed for powerprofile)*

Var_ch = Var_ch / sum (Var_ch) *(Normalized form)*

H = (sqrt(0.5) * (randn(1, N_{ch}) + j*randn(1, N_{ch})) .* sqrt(Var_ch) *(Random CIR)*

Then noiseless vector, y is calculated via convolution:

Y = conv (x, h)

Finally AWGN samples are added to y:

N = sqrt (0.5) * (randn (1, length(y)) + j * randn(1, length(y))

Y = Y + n * sqrt (0.5)

6) OFDM DEMODULATION:

The received vector y has a length (N_c + N_{ch}-1) + N_{ch}-1. We truncate vector y by removing last N_{ch}-1 symbols:

Y (end - N_{ch} + 2 : end) = [ ]

Then we remove Cyclic-prefix:

Y (1 : N_{ch} - 1) = [ ]

Finally we perform FFT to obtain received OFDM symbol Y :

Y = fft(y) / sqrt(N_c)

7) DEINTERLEAVING AND CHANNEL DECODING:

Here we first calculate channel frequency response via FFT of zero-padded CIR, h :

H = fft([h zeros(1, N_c - N_{ch})])

For coherent detection of info symbols U_k , derotation of received OFDM symbol Y is done :

Z = conj (H) .* Y

Next, deinterleaving is performed (assuming $N_c = 128$ and $R = 4$) :

Vm = [1 33 65 97; 2 34 66 98; ....; 32 64 96 128]

mittal = Z(Vm)

Since repletion code is used, all entries of Y that are associated with same info symbols U_k are optimally combined using MRC:

Z_mrc = sum(mittal, Z)

Finally estimates U_k are estimated based on vector Z_mrc:

U_{rec} = sign (real (Z_mrc))

8) CALCULATION OF BIT ERROR RATE (BER):

Bit errors are counted in current OFDM symbol and error counter is updated:

err_count = err_count + sum (abs (U_{rec} - U)) / 2

Final BER is next calculated:

Ber = err_count / (R * N_c * N_{real})