

# **Design and Simulation of COFDM for High Speed Wireless Communication and Performance Analysis**

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## **ABSTRACT**

Coded Orthogonal Frequency Division Multiplexing (COFDM) is one of the dominant techniques of present day wireless (mobile) communication. The main advantage of OFDM is that it makes the receiver highly robust against Multipath fading environments. Due to orthogonal properties of the sub-carriers used, OFDM also provides efficient spectrum utilization by use of single frequency networks (SFNs) and use of simple equalizers. OFDM has become the standard for physical layer implementation of various digital audio and video wireless communications such as DAB/DVB, wireless local access networks (WLANs) and wireless metropolitan area networks (WMANs). In this paper, we present a performance analysis of a (COFDM) using convolutional coding, interleaving with different digital modulation techniques in diverse transmission channels. The results show that COFDM is well suited for high speed data transmission in mobile environment and interleaving is essential for reducing bit error rate (BER) for high speed transmission.

## **General Terms**

Wireless (mobile) digital communication.

## **Keywords**

COFDM, multipath fading, channel coding, interleaving, bit error rate.

## **1. INTRODUCTION**

With the rapid growth of digital communication in recent years, the need for high-speed data transmission has increased. Over the last few years, there has been increasing demand on extending the services available on wired public telecommunications networks to mobile/movable non wired telecommunications users [1]. At present, in addition to voice services, only low-bit-rate data services are available to mobile users. However, demands for wireless broadband multimedia communication systems are anticipated within both the public and private sectors. Wired networks are cannot support extension to wireless mobile networks because mobile radio channels are more contaminated than wired data-transmission channels [1]. We also cannot preserve the high Quality of service in wired communications network.

The mobile radio channel is always characterized by multipath reception. The signal picked up by the receiver contains not only a direct line-of-sight (LOS) radio wave, but also a large number

of reflected radio waves that arrive at the receiver at different time's instants. Delayed signals are due to the result of reflections from terrain features such as trees, hills, mountains, vehicles, or buildings. These reflected, delayed waves interfere with the direct wave and cause intersymbol interference (ISI), which in turn causes significant degradation of network performance [1]. ISI occurs when a transmission interferes with itself and the receiver cannot decode the transmission correctly. As communication systems increase their information transfer speed, the time for each transmission necessarily becomes shorter. Since the delay time caused by multipath remains constant, this ISI becomes a limitation in high-data-rate communication. A wireless network should be designed to minimize these adverse multipath effects to avoid signal degradation.

To overcome such a multipath-fading environment with low complexity Equalizers and to achieve wireless broadband multimedia communication systems, this paper presents a detailed overview and simulation of the orthogonal frequency division multiplexing (OFDM) parallel data transmission scheme. OFDM is a kind of Multi Carrier Transmission system where a single data stream is transmitted over a number of subcarriers. Since many communication systems being developed use OFDM, it is a worthwhile research topic. Some examples of current applications using OFDM include GSTN (General Switched Telephone Network), Cellular radio, DSL & ADSL modems, DAB (Digital Audio Broadcasting) radio, DVB-T (Terrestrial Digital Video Broadcasting), HDTV broadcasting, HYPERLAN/2 (High Performance Local Area Network standard), and the wireless networking standard IEEE.

In this paper we designed and implemented an interleaving based channel coding technique for improved performance of OFDM system in different transmission channels.

In this paper we developed an OFDM transmission system based on IEEE 802.11a standard [5] [6]. The design consists of energy dispersal scrambler, QPSK/QAM symbol mapping, convolutional encoder (FEC), interleaving and OFDM signal generator (IFFT) in the transmitter side and in the receiver corresponding inverse operations is carried out. A frame based processing is used in this work. Bit error rate (BER) has been considered as the performance index in all analysis. The analysis has been carried out with simulation studies under MATLAB environment.

Following this introduction the remaining part of the paper is organized as follows. Section 2 provides brief overview of the COFDM system. This section explains the concept and introduces the OFDM system standard. In Section 3, the details of the modeling and simulation of the system using MATLAB is presented. Then, simulation results have been discussed in Section 4. Finally, Section 5 provides the conclusions.

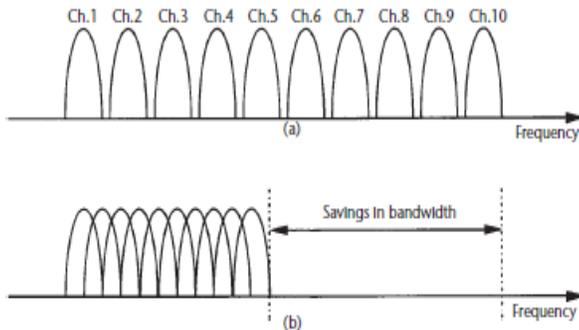
## 2. OVERVIEW OF COFDM SYSTEM

OFDM is derived from the fact that the high serial bit stream data is transmitted over large (parallel) number sub-carriers (obtained by dividing the available bandwidth), each of a different frequency and these carriers are orthogonal to each other. OFDM converts frequency selective fading channel into N flat fading channels, where N is the number of sub-carriers. Orthogonality is maintained by keeping the carrier spacing multiple of  $1/T_s$  by using Fourier transform methods, where  $T_s$  is the symbol duration. Since channel coding is applied prior to OFDM symbol generation which accounts for the term 'coded' in COFDM. Orthogonality between sub-carriers is maintained if sinusoids have integer number of cycles in  $T_s$  given by (1) below

$$\int_0^{T_s} \sin(2\pi f_c t) \sin(2\pi 2f_c t) dt = 0 \quad (1)$$

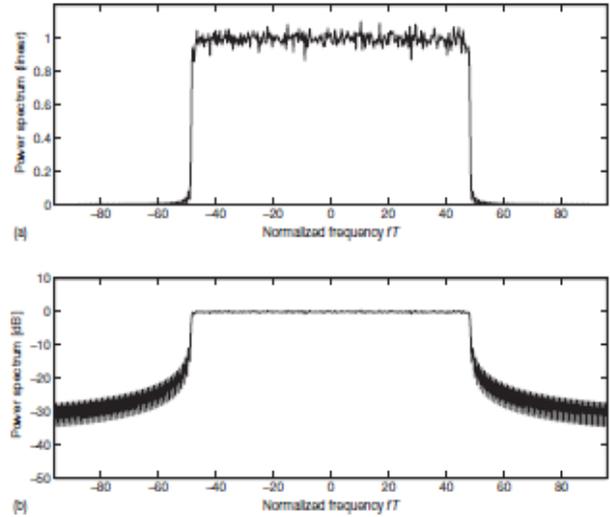
Where  $f_c$  is the sub-carrier frequency.

Frequency Division Multiplexing (FDM) divides the channel bandwidth into sub channels and transmits multiple relatively low rate signals by carrying each signal on a separate carrier frequency. To ensure that the signal of one sub channel did not overlap with the signal from an adjacent one, some guard-band was necessary which is an obvious loss of spectrum and hence bandwidth. But since carriers are Orthogonal to each other in OFDM therefore it offers bandwidth efficiency as no guard band is required as shown in Figure 1 below.



**Figure 1. Bandwidth conservation (a) FDM (b) OFDM [1].**

Figure 2 presents the power spectral density of OFDM signal for 97 subcarriers. It may be seen that the spectral shape is given by a sinc function. Also at the center frequency of each subcarrier, there is no crosstalk. Therefore, if we use FFT at the receiver and calculate correlation values with the center of frequency of each subcarrier, we recover the transmitted data with almost no crosstalk.



**Figure 2. Power Spectral Density of OFDM signal (a) On linear scale (b) Logarithmic scale [3].**

The COFDM system consists of three main elements. These are Channel coding/interleaving, IFFT and Guard interval/cyclic prefix. These technical aspects make the system resistant to ISI and multipath fading. Fig. 3 presents the basic block diagram of OFDM transmitter and receiver.

The basic principle of OFDM is to split a high-rate data stream into a number of lower rate streams to be transmitted simultaneously over a number of subcarriers. The relative amount of dispersion in time caused by multipath delay spread is decreased because the symbol duration increases for lower rate parallel subcarriers. The other problem to solve is the inter symbol interference, which is eliminated almost completely by introducing a guard time in every OFDM symbol. This means that in the guard time, the OFDM symbol is cyclically extended to avoid intercarrier interference [7].

The incoming data is first converted from serial to parallel and grouped into x bits each to be modulated by Quadrature Amplitude Modulation (QAM), Quaternary Phase Shift Keying (QPSK), or Binary Phase Shift Keying (BPSK). The required spectrum is then converted back to its time domain signal using an Inverse Fast Fourier Transform (IFFT), commonly used in most applications. The IFFT performs the transformation very efficiently, and provides a simple way of ensuring the carrier signals produced are orthogonal. The signals are then converted back to serial for transmission. A guard interval is inserted between symbols to avoid Inter symbol Interference (ISI) caused by multipath distortion. The discrete signals are converted back to analogue. Although it would seem that combining the inverse FFT outputs at the transmitter would create interference between subcarriers, the orthogonal spacing allows the receiver to perfectly separate out each subcarrier. The receiver performs the inverse process of the transmitter.

The OFDM symbol in baseband is given by following (2):

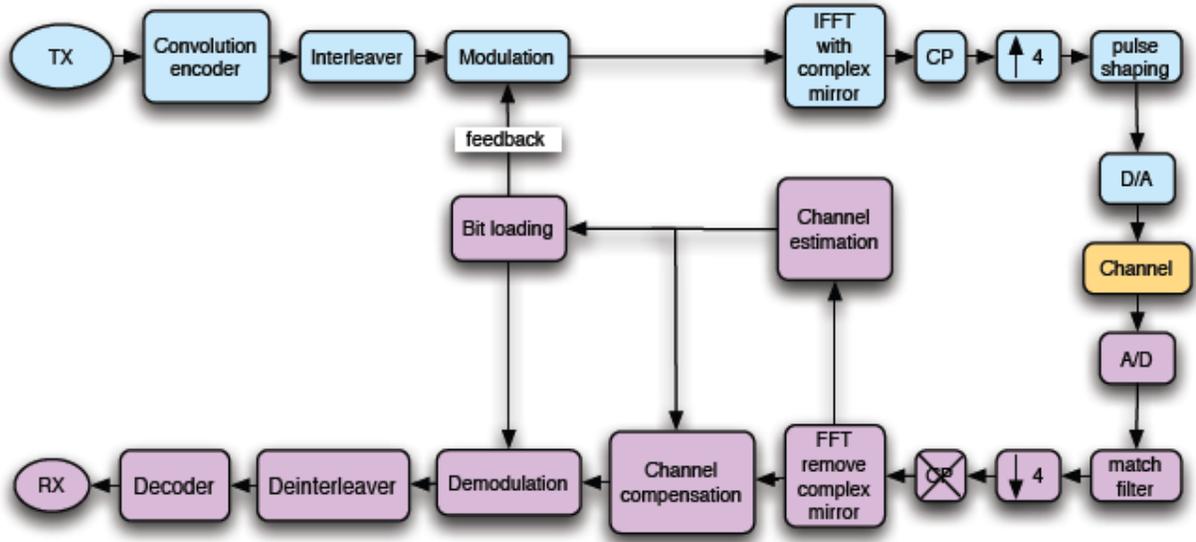


Figure 3. Block diagram of OFDM transmitter and receiver.

$$s_{bb}(t) = \sum_{k=0}^{N-1} \frac{1}{\sqrt{N}} \cdot (d_k e^{\frac{j2\pi kt}{T}}) \quad (2)$$

where N= no. of sub-carrier

### 2.1 Interpretation of IFFT & FFT

The Fast Fourier Transform is a very efficient mathematical method for calculating DFT. It can be easily implemented in integrated circuits at fairly low cost. With the advances in VLSI and DSP technology the implementation cost of OFDM is drastically reduced since heart of OFDM is merely IFFT/FFT operation. But the complexity of performing an FFT is dependent on the size of the FFT. The direct evaluation of an N-point DFT using the following formula (3):

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot e^{-\frac{j2\pi nk}{N}} \quad (3)$$

Where k = 0, 1, 2,.....,N-1.

DFT require N<sup>2</sup> complex multiplications and N\*(N-1) complex additions whereas use of FFT algorithm reduces the number of computations to the order of N/2\*log<sub>2</sub> (N) complex multiplications and N\*log<sub>2</sub> (N) additions. Moreover FFT algorithm works efficiently when N is a power of 2, therefore the number of sub-carriers is usually kept as power of 2. IFFT/FFT operation ensures that sub-carriers do not interfere each other. IFFT is used at the transmitter to obtain the time domain samples of the multicarrier signal. FFT is used to retrieve the data sent on individual sub-carriers. Therefore OFDM has a very simple implementation capability.

### 2.2 Guard time and Cyclic prefix

In order to overcome the problem of multipath fading environment and hence inter symbol interference ISI, it is common practice in OFDM technology to add guard interval between OFDM symbols. The guard interval is formed by a cyclic continuation of the signal so the information in the guard interval is actually present in the OFDM symbol. Guard interval makes the system robust against multipath delay spread. The guard interval is actually added by taking the copy of the last portion of the OFDM symbol and placing it at the start of the symbol as illustrated in Figure 4.

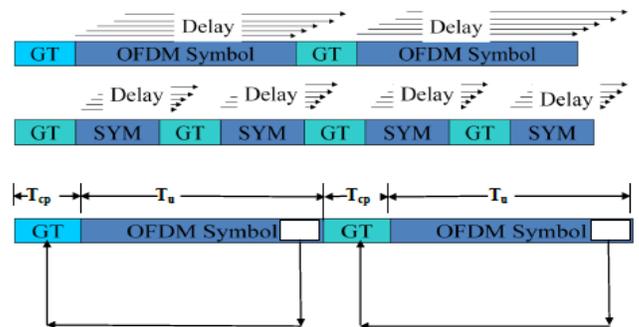


Figure 4. Guard time and Cyclic prefix.

The last T<sub>g</sub> portion of the symbol is appended and transmitted during the Guard time. T<sub>u</sub> is the OFDM symbol time without guard interval. T<sub>cp</sub> is the duration of the copied information in the guard interval using cyclic prefix. Therefore total OFDM symbol time T<sub>s</sub> = T<sub>u</sub>+T<sub>cp</sub>. Guard time needs to be greater than maximum delay spread otherwise ISI results. The guard time also eliminates the need of a pulse shaping filter, and it reduces the sensitivity to time synchronization problems. Cyclic prefix helps in maintaining orthogonality between sub-carriers by

converting linear convolution into circular convolution in multipath environment and also avoids ICI (Inter channel interference).

### 2.3 Convolutional coding and Interleaving

An OFDM system employs conventional forward error correction codes and interleaving for protection against burst errors caused by deep fades in the channel. Often it is concatenated with a block code for improving the performance. A Viterbi decoder for decoding a convolution code is easy to implement. Though coding improves the performance of the system, it decreases the spectral efficiency. Codes of different rates are used in conjunction with different modulation schemes to support different QoS. While error correction codes provide coding gain in the system, interleaving provides diversity gain. For OFDM, when a deep fade occurs in the channel the bits within the deep fade are erased. Interleaving the bits across different frequency bins distributes the energy within a symbol among different sub-carriers. Since distinct sub-carriers undergo different fading conditions, the probability that all the bits corresponding to a symbol are lost, decreases significantly. An uncoded OFDM system cannot exploit frequency diversity. Since in frequency selective fading channels, the sub-carriers separated by coherence bandwidth are independent of each other, the frequency diversity can be realized by spreading coded bits over different sub-carriers in such a way that adjacent bits are separated by coherence bandwidth. Coding and interleaving, diversity, equalization techniques decrease the irreducible error floors caused due to delay spread. An interleaver permutes symbols according to a mapping. A corresponding deinterleaver uses the inverse mapping to restore the original sequence of symbols. Interleaving and deinterleaving can be useful for reducing errors caused by burst errors in a communication system. A convolutional interleaver consists of a set of shift registers, each with a fixed delay. Figure 5 shows a convolutional encoder with constraint length  $L=7$ .

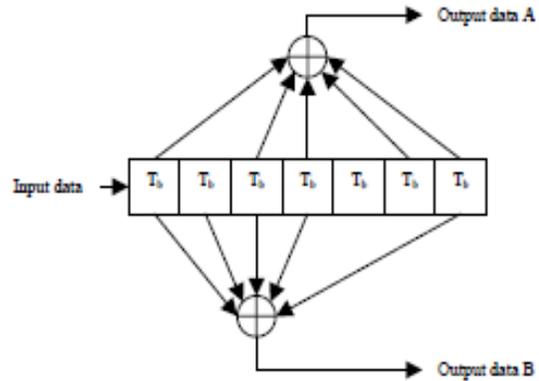


Figure 5. Convolutional encoder ( $L=7$ ) [7].

TABLE 2. PHYSICAL LAYER PARAMETERS

Data Rate (M bits/s)	Modulation	Coding Rate	Coded bits/subcarrier	Coded bits/OFDM	Data bits per OFDM signal
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16 QAM	1/2	4	192	96
36	16 QAM	3/4	4	192	144
48	64 QAM	2/3	6	288	192
54	64 QAM	3/4	6	288	216

### 2.4 OFDM physical layer parameters (IEEE 802.11a Standard)

The OFDM physical layer parameters as per IEEE 802.11a standard are as shown in Table I and Table II.

TABLE 1. PHYSICAL LAYER PARAMETERS

Parameter	Value
$N_{SD}$ : Number of data subcarriers	48
$N_{SP}$ : Number of pilot subcarriers	4
$N_s$ : Number of subcarriers, total	$52(N_{SD} + N_{SP})$
$\Delta_f$ : Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)
$T_{FFT}$ : IFFT/FFT period	$3.2\mu s (1/\Delta_f)$
$T_{PREAMBLE}$ : PLCP preamble duration	$16\mu s (T_{SHORT} + T_{LONG})$
$T_{SIGNAL}$ : Duration of the SIGNAL BPSK-OFDM symbol	$4.0\mu s (T_{GI} + T_{FFT})$
$T_{GI}$ : GI Duration	$0.8\mu s (T_{FFT}/4)$
$T_{GI2}$ : Training symbol of GI duration	$1.6\mu s (T_{FFT}/2)$
$T_{SYM}$ : Symbol interval	$4\mu s (T_{GI} + T_{FFT})$
$T_{SHORT}$ : Short training sequence duration	$8\mu s (10 * T_{FFT}/4)$
$T_{LONG}$ : Long training sequence duration	$8\mu s (T_{GI2} + 2 * T_{FFT})$

## 3. THE SIMULATION MODEL

Figure 6 presents the complete block diagram of the COFDM system which was modeled and simulated by us in MATLAB environment. The main objective of this simulation study is to evaluate the BER performance of the COFDM system using convolutional coding with interleaving. The simulation parameters are obtained from Table I and Table II. A frame based processing is used in this simulation model. The system model was exposed to AWGN channel, Rayleigh fading channel and Rician channel for performance analysis. The important blocks of the simulation model is discussed in detail as follows:

### 3.1 Energy dispersal scrambler

In order to ensure appropriate energy dispersal in the transmitted signal, the individual inputs of the energy dispersal scramblers shall be scrambled by a modulo-2 addition with a pseudo-random binary sequence (PRBS), prior to convolutional encoding.

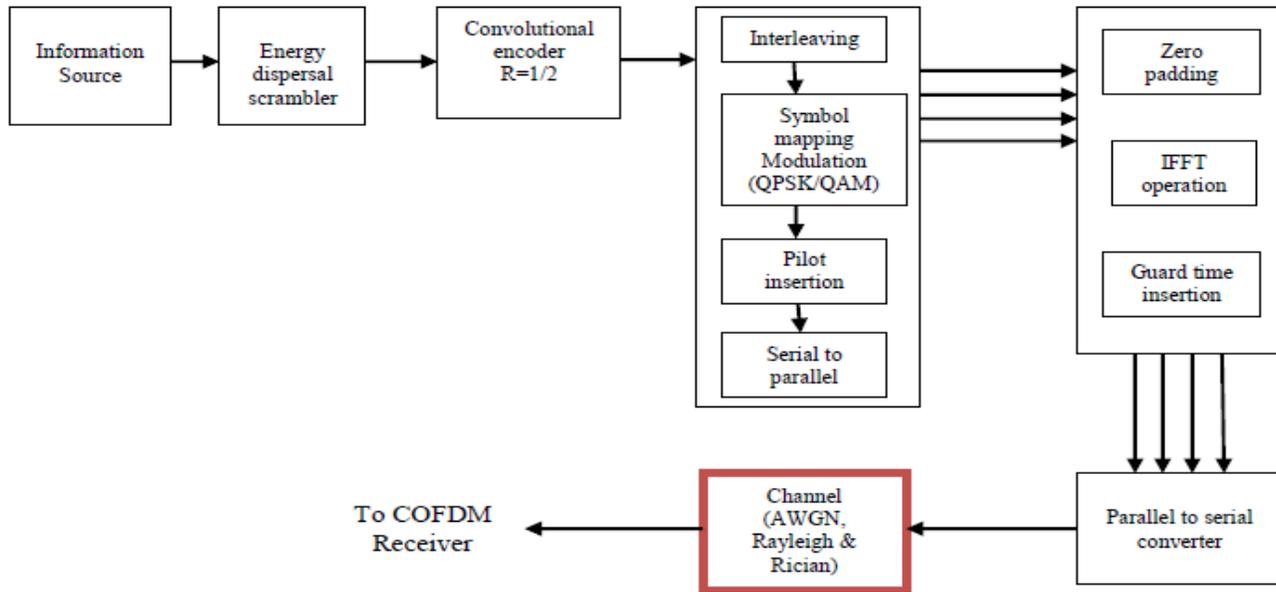


Figure 6. Block diagram of the COFDM system simulated.

### 3.2 Convolutional encoder

According to the OFDM standard, information data must be encoded with a convolutional encoder with coding rate  $R = 1/2$ ,  $2/3$ , or  $3/4$ , corresponding to the desired data rate. The convolutional encoder uses the industry-standard generator Polynomials, [133 ,171] of rate  $R = 1/2$  [7].

### 3.3 Interleaving

Frequency interleaving is used to eliminate the effects of selective fading. It offsets any deep fades that occur in the wireless channel by spreading the data bits over the sub-carrier channels. According to the standard, all data bits must be interleaved by a block interleaver with a block size corresponding to the number of bits in a single OFDM symbol, NCBPS. The interleaver is defined by a two-step permutation [7]. Just prior to modulation mapping, the first permutation is defined by the rule:

$$i = (\text{NCBPS}/16) (k \bmod 16) + \text{floor} (k/16) \quad (4)$$

Where  $k = 0, 1, \dots, \text{NCBPS}-1$ . The second permutation is defined by the rule:

$$j = s \times \text{floor} (i/s) + (i + \text{NCBPS} - \text{floor} (16 \times i/\text{NCBPS})) \bmod s \quad (5)$$

where  $i=0, 1, \text{NCBPS}-1$ .

### 3.4 Pilot symbol Insertion

The stream obtained after mapping is adjusted to carry 4 known data symbols which is also called pilot carriers. They are used to estimate the channel at the receiver. Typically the receiver compares the pilots received to the known data symbols and estimates the magnitude and phase of each channel tap. The channel response is obtained by interpolating the channel gains estimated.

### 3.5 FFT and IFFT

This sub-block is the heart of COFDM technology. These operations performing linear mappings between  $N$  complex data symbols and  $N$  complex OFDM symbols result in robustness against fading multipath channel. The reason is to transform the high data rate stream into  $N$  low data rate streams, each experiencing a flat fading during the transmission. Length of FFT/IFFT is taken to be 64.

### 3.6 Guard time insertion

This sub-block is responsible for making OFDM symbols resistant to inter symbol interference. It takes copy of last samples equal to guard interval (according to Table II) from each OFDM symbol and place it at the beginning of the OFDM symbol.

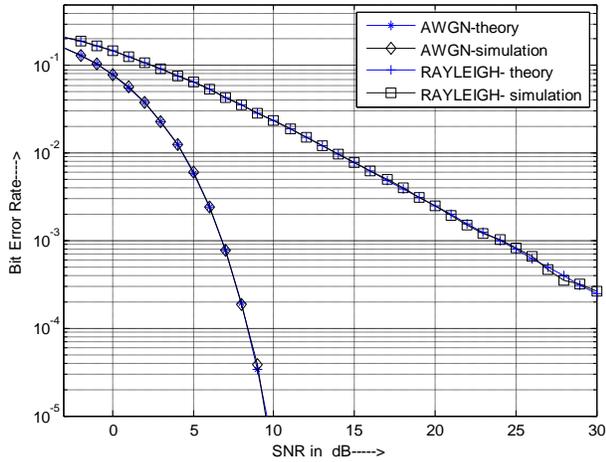
### 3.7 Viterbi decoding

For decoding the convolutional codes the Viterbi algorithm [4] will be used, which offers best performance according to the maximum likelihood criteria. The input to the Viterbi decoder will be hard-decided bits that are '0' or '1', which is referred to as a hard decision.

## 4. SIMULATION RESULTS AND DISCUSSION

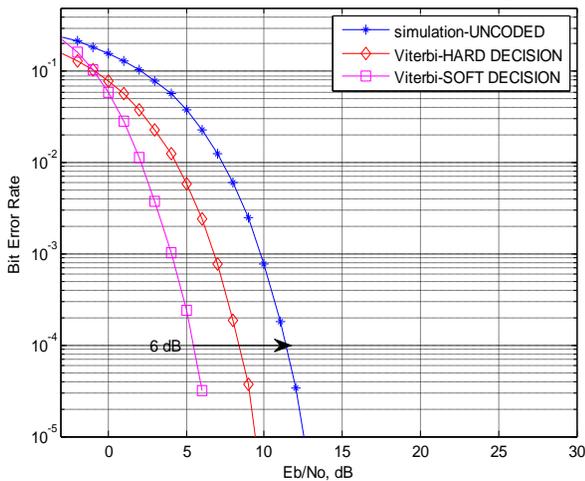
In this section we have presented the simulation results along with the bit error rate (BER) analysis for AWGN channel, Rayleigh fading channel and Rice channel. Three digital modulation techniques including BPSK, QPSK, 16-QAM, 32-QAM, 8-PSK, 16-PSK and 32-PSK were plotted to see the trade off between system capacity and system robustness. The standard BER of  $10^{-3}$  was used to determine the minimum performance of the OFDM system for voice transmission. Analysis was done by observing the simulation results.

Figure 7 presents the BER performance for QPSK in AWGN and Rayleigh fading channel. As can be seen from Figure 7 that both theoretical and experimental BER are in good agreement with each other. It is concluded that use of channel coding could improve the BER performance.



**Figure 7. BER performance for QPSK modulation in AWGN & Rayleigh fading channel.**

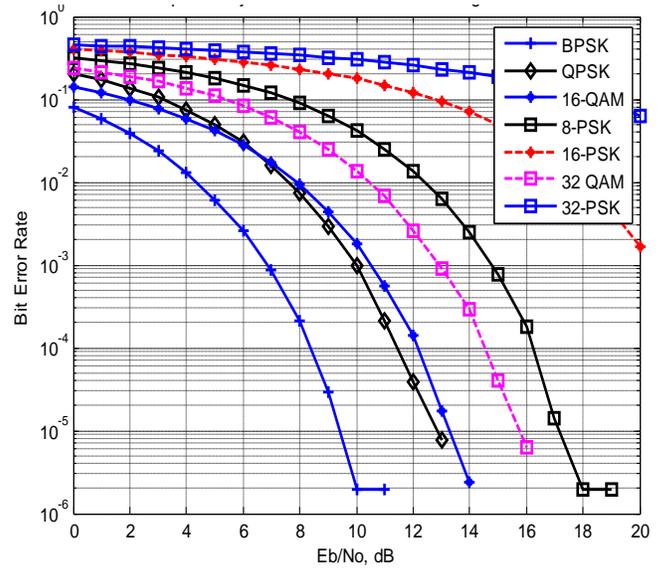
Figure 8 shows that to achieve a BER of  $10^{-4}$ , the coded BPSK with Viterbi 3-bit soft decision decoding gives a coding gain of 2.5 dB and 6 dB compared with Viterbi hard decision decoding & uncoded BPSK modulation, respectively. Convolutional code with constraint length  $L=3$ , code rate  $1/2$  and generator polynomial in octal (7, 5) was used as parameters for this simulation.



**Figure 8. BER performance for BPSK modulation in AWGN channel using Hard-Soft Viterbi decoding.**

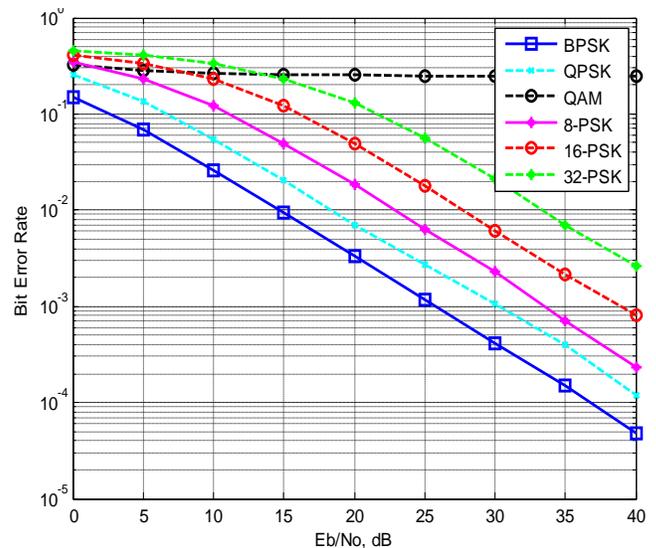
Figure 9 presents the effect of AWGN channel to the performance of COFDM system for different digital modulation techniques. It may be evaluated from the result that BPSK requires the least SNR for the same BER performance of  $10^{-4}$  and as we move towards higher modulation techniques higher transmitter signal power is required to achieve the same

performance. It also seen that QAM lower SNR values as compared to PSK.



**Figure 9. BER performance for BPSK, QPSK, 16-QAM, 64-QAM, 8-PSK, 16-PSK, 32-PSK modulation in AWGN channel.**

Fig. 10 presents the effect of Rayleigh fading channel to the performance of COFDM system for different digital modulation techniques. For this the system was exposed to fading channel with Doppler frequency 40 Hz (i.e.,  $v=48$  km/hr). It may be evaluated from the result that BPSK requires the least SNR for the same BER performance of  $10^{-4}$  and as we move towards higher modulation techniques higher transmitter signal power is required to achieve the same performance.



**Figure 10. BER performance for BPSK, QPSK, 8-PSK, 16-PSK, 32-PSK modulation in Rayleigh fading channel.**

Figure 11 presents the effect of Rician channel to the performance of COFDM system for different digital modulation techniques. For this the system was exposed to fading channel with Doppler frequency 40 Hz (i.e.,  $v=48$  Km/hr). It may be evaluated from the result that BPSK requires the least SNR for the same BER performance of  $10^{-4}$  and as we move towards higher modulation techniques higher transmitter signal power is required to achieve the same performance.

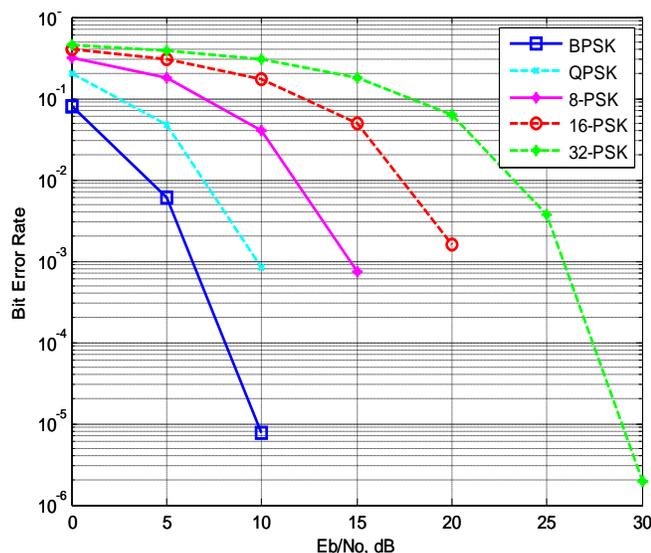


Figure 11. BER performance for BPSK, QPSK, 8-PSK, 16-PSK, 32-PSK modulation in Rician channel.

Fig. 12 finally presents the effect of interleaving in COFDM system in AWGN channel.

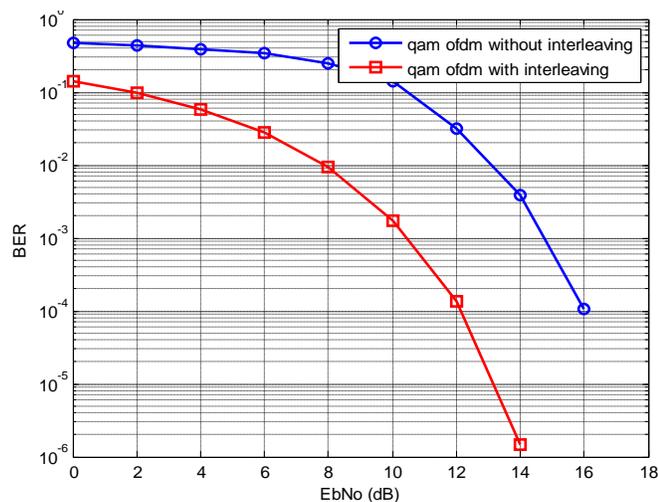


Figure 12. BER performance for COFDM using 16-QAM modulation with and without Interleaving.

It may be seen from the result that COFDM system with interleaving requires the SNR of 12 dB for the BER performance of  $10^{-4}$ . That is with interleaving we have a coding gain of about 4 dB.

## 5. CONCLUSIONS

This paper has outlined all the work done on studying the BER performance of COFDM under three different types of communication channels –Rayleigh, AWGN and Rician in wireless communications. It was concluded that AWGN is the ideal channel and Rayleigh fading channel is the worst one. Interleaving is essential for forward error correction to work properly. QAM modulation needs a lower SNR value compared with PSK modulation techniques. The results show that COFDM is well suited for high speed data transmission in mobile environment and interleaving is essential for reducing bit error rate (BER) for high speed transmission.

Also COFDM techniques are quickly becoming a popular method for advanced communications networks. Advances in VLSI technology have made it possible to efficiently implement an FFT block in hardware.

## 6. REFERENCES

- [1] Ramjee Prasad, "OFDM for wireless Communications systems", Artech House, 2004.
- [2] H. Harada & Ramjee Prasad, "Simulation and Software Radio for mobile communications", Artech House, 2003.
- [3] Henrik Schulze & Christian Luders, "Theory and Applications of OFDM and CDMA", John Wiley & Sons, Ltd, 2005.
- [4] John. G. Proakis, "Digital Communications", 3rd edition, McGraw-Hill, 1995.
- [5] IEEE 802. IF-1993, IEEE Standards for Local and Metropolitan Area Networks: Common Definitions and Procedures for IEEE 802 Management.
- [6] LAN/MAN Standards Committee of the IEEE Computer Society, Part 11: Wireless LANMedium Access Control (MAC) and Physical Layer (PHY) Specifications—High Speed Physical Layer in the 5 GHz Band, ANSI/IEEE Std 802.11.
- [7] Anibal Luis Intini, "Orthogonal Frequency Division Multiplexing for Wireless Networks", University Of California, Santa Barbara, Dec, 2000.
- [8] MATHWORKS. [Online]. [www.mathworks.com/Communications Toolbox/ Error Detection and Correction/ Channels/ AWGN channel & Fading channels](http://www.mathworks.com/Communications_Toolbox/Error_Detection_and_Correction/Channels/AWGN_channel_Fading_channels).
- [9] Anis Salwa Osman, "BER Performance of Orthogonal Frequency Division Multiplexing (OFDM)," Universiti Teknologi, Malaysia, Master's thesis December 2006.