MULTICARRIER MODULATION FOR WIRELESS COMMUNICATION USING WAVELET PACKETS

A Thesis Submitted in Partial Fulfilment

of the Requirements for the Degree of

Bachelor of Technology
In
Electronics and Communication Engineering

by

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and

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Department of Electronics and Communication Engineering

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Under the aegis of
PROF. SARAT KUMAR PATRA

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DECLARATION

We hereby declare that the project work entitled "**Multicarrier Modulation for Wireless Communication using Wavelet Packets**" is a record of our original work done under **Dr. Sarat Kumar Patra**, Professor, National Institute of Technology, Rourkela. Throughout this documentation wherever contributions of others are involved, every endeavor was made to acknowledge this clearly with due reference to literature. This work is being submitted in the partial fulfillment of the requirements for the degree of Bachelor of Technology in Electronics and Communication Engineering at **National Institute of Technology, Rourkela** for the academic session 2008 – 2012**.**

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CERTIFICATE

This is to certify that the thesis entitled “Multicarrier modulation for wireless communication using wavelet packets” submitted by I. Indumati Anusha (108EC038) and Priyadarshini Mullick (108EC001) in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Electronics and Communication Engineering at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

Prof. Sarat Kumar Patra
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This is a research project and the fact that we have been able to complete it successfully owes a lot to a number of persons associated with us during this project.

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ABSTRACT

Success of OFDM has proved that Multi carrier modulation is an efficient solution for wireless communications. Wavelet Packet Modulation (WPM) is a new type of modulation for transmission of multicarrier signal on wireless channel that uses orthogonal wavelet bases other than sine functions. Though this modulation is over all similar to that of OFDM, it provides interesting additional features. In this thesis, a detailed study is given on Wavelets and WPM and the BER performance comparison between the OFDM systems and WPM systems and equalization techniques are analysed. The analysis is done for different types of wavelet generating families, various number of modulations QAM constellation points (16 to 64), and simulated over AWGN channel, and other Multipath fading channels.

Keywords: Wavelet packet modulation, Multicarrier Modulation, Orthogonal Frequency Division Multiplexing (OFDM), Bit error Rate (BER).

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LIST OF ABBREVIATIONS

CP	Cyclic Prefix
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
ICI	Inter Channel Interference
ISI	Inter Symbol Interference
LMS	Least Mean Square
OFDM	Orthogonal Frequency Division Multiplexing
QPSK	Quadrature Phase Shift Keying
RLS	Recursive Least Square
STFT	Short Time Fourier Transform
WPT	Wavelet Packet Modulation
WPT	Wavelet Packet Transform
ZF	Zero Forcing

Chapter 1

INTRODUCTION

1.1 Introduction

Although the principle of multicarrier modulation is not recent, its actual use in commercial systems started when the technology required to implement it became available at a reasonable cost. Similarly, the idea of using a better transform than Fourier's as the core of a multicarrier system has been recently introduced. However, very little interest has been given to the alternative methods. With the current demand for enhanced performance in wireless communication systems, it's high time we looked forward to the possible advantages that wavelet-based modulation could have over OFDM systems.

1.2 Motivation for Work

Several objectives motivate the current research on Wavelet Packet Modulation. Firstly, the characteristic of a multicarrier modulated signal is directly dependent on the set of waveforms of which it uses. Hence, its sensitivity to non-linear amplifiers, multipath channel distortion or synchronization error might give better values than an OFDM signal. Moreover, the greatest advantage of WPM lies in its flexibility. Also, new generation systems have to be designed to dynamically deploy the instantaneous propagation conditions. This has led to the study of reconfigurable systems that can optimize performance according to the current channel response. Wavelet theory has been considered by several authors as a good platform on which multicarrier waveform bases can be built. The binary division of the bandwidth is not suitable for multicarrier communication. Wavelet packet bases therefore appear to be a better choice to build orthogonal waveform sets that are used in communication.

1.3 Thesis Outline

Our project work is on reviewing the advantages of WPM in wireless communications. Theoretical background on this modulation scheme is first recalled. Issues of using such waveforms for multicarrier communication systems are underlined, and a comparison with OFDM is made. Special emphasis on the flexibility of this scheme is given. Chapter 1 gives an introduction to wavelets and wavelet transforms. Chapter 2 describes the wavelet packet modulation, its system architecture, its relative features with OFDM and multipath channel models. Chapter 3 reports the equalization algorithms and its complexity when employed for WPM. Performance results obtained are compared with those of classical OFDM scheme.

Chapter 2

BACKGROUND

2.1 Wavelets

A wavelet is a small wave whose energy is concentrated in time and gives a tool for the analysis of transient, or time varying phenomena. Though it has the oscillating wave like characteristic but also has the ability to allow time and frequency analysis at the same time with a flexible mathematical foundation. This is illustrated in figure 1 with the wave (sinusoid) oscillating with equal amplitude over $-\infty \leq t \leq \infty$ and therefore having infinite energy and with the wavelet having its finite energy concentrated around a point.

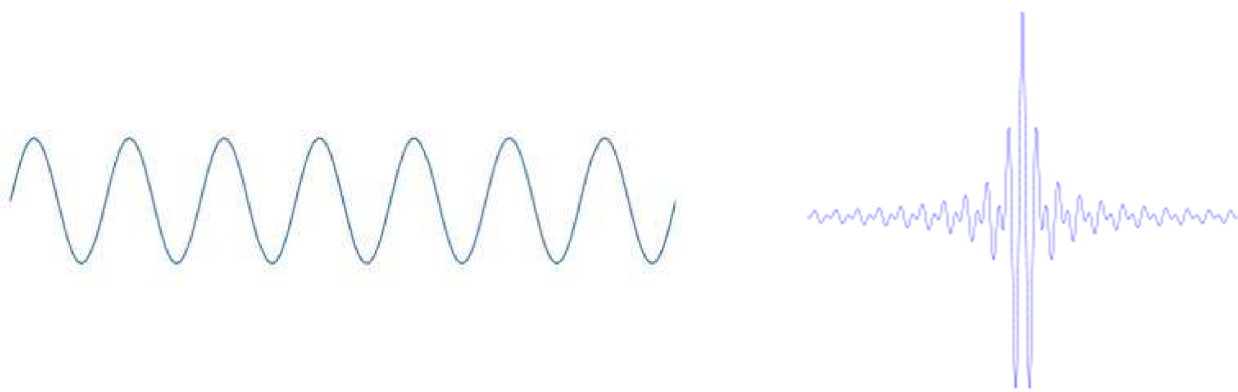

Figure 1 - A wave and a wavelet [8]

2.1.1 Wavelet Expansion

A signal F(t) can be better analyzed if expressed as a linear decomposition by

$$F(t) = \sum_l a_l \psi_l(t) \qquad \text{(Eq. 2.1)}$$

Where l is the integer index for the finite or infinite sum, a_l are the real valued expansion coefficients, and ψ_l is a set of real valued functions of t called the expansion set. The set is called a basis, if the expansion is unique.

For the wavelet expansion, we consider a two parameter system as

$$F(t) = \sum_j \sum_k a_{j,k} \psi_{j,k}(t) \qquad \text{(Eq. 2.2)}$$

Where both j and k are integer indices and $\psi_{j,k}(t)$ are the wavelet expansion functions that usually form an orthogonal basis.

The set of expansion coefficients $a_{j,k}$ are called discrete wavelet transform(DWT) and eq. 2.2 is known as inverse transform.

2.1.2 Types of Wavelets

- **Haar Wavelet**: The Haar wavelet is a sequence of square shaped functions which together form a wavelet family. The Haar wavelet is the simplest possible wavelet. The disadvantage of the Haar wavelet is that it is not differentiable since it is not continuous. But this property is an advantage for the analysis of signals which undergo sudden transitions.

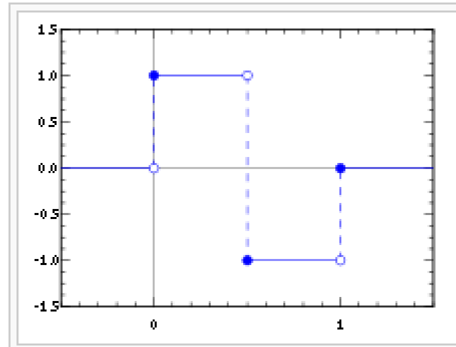

Figure 2 - The Haar wavelet [8]

The Haar wavelet's mother wavelet function can be described as

$$\Psi(t) = \begin{cases} 1 & 0 \le t < \frac{1}{2}, \\ -1 & \frac{1}{2} \le t < 1, \\ 0 & otherwise \end{cases} \qquad \text{(Eq.2.3)}$$

Its scaling function can be described as

$$\phi(t) = \begin{cases} 1 & 0 \le t < 1, \\ 0 & otherwise \end{cases} \qquad \text{(Eq.2.4)}$$

- **Coiflet:** Coiflets are discrete wavelets that have scaling functions with vanishing moments. The wavelet is near symmetric and has N/3-1 scaling functions and N/3 vanishing moments.

Figure 3- The Coiflet [8]

Mathematically, this looks like

$$B_k = (-1)^k \, C_{N-k-1} \qquad \text{(Eq.2.5)}$$

Where k is coefficient index; B is wavelet coefficient, C is scaling function coefficient and N is wavelet index.

- **Daubechies Wavelet:** The Daubechies wavelet is a set of orthogonal wavelets that defines a discrete wavelet transform and is characterized by a maximum

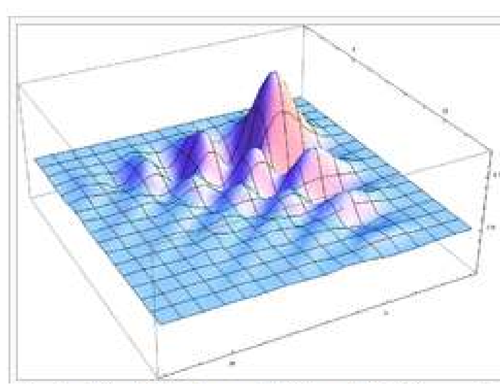

Figure 4- The Daubechies wavelet [8]

number of vanishing moments for a given support. Each wavelet type has a scaling function (also called father wavelet) that gives an orthogonal multi resolution analysis.

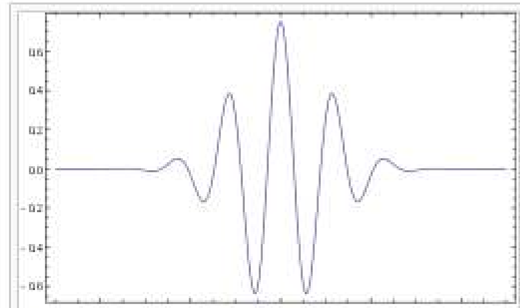

Figure 5. The Morlet Wavelet [8]

- **Morlet wavelet:** In mathematics, the Morlet wavelet was formulated by subtracting a constant from a plane wave and then localising it by a Gaussian window, given by

$$\Psi_\sigma(t) = c_\sigma \pi^{-1/4} e^{-1/2t^2}\left(e^{i\sigma t} - K_\sigma\right) \qquad \text{(Eq.2.6)}$$

And

$$c_\sigma = \left(1 + e^{-\sigma^2} - 2e^{-3/4\sigma^2}\right) \qquad \text{(Eq.2.7)}$$

2.2 Wavelet Transform

The Wavelet Transform has recently gained a lot of popularity in the field of signal processing since it has the capability to provide both time and frequency information simultaneously, hence it gives a time-frequency representation of the signal.

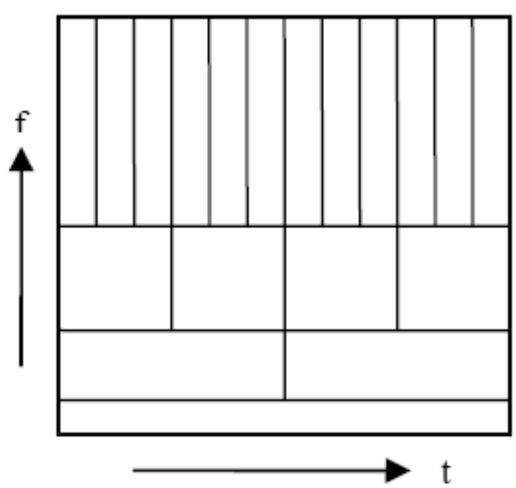

Figure 6 – Resolution of time and frequency in Wavelet Transform [9]

2.2.1 Discrete Wavelet Transform

A discrete wavelet transform (DWT) is a wavelet transform in which the wavelets are sampled discretely.

A general statement of the transform can be given by

$$G(t) = \sum_k c_{j_o}(k) 2^{j_o/2} \Phi(2^{j_o} t - k) + \sum_k \sum_{j=j_o}^{\infty} d_j(k) 2^{j/2} \psi(2^j t - k) \qquad \text{(Eq.2.8)}$$

Or

$$G(t) = \sum_k c_{j_o}(k)\, \Phi_{j_o,k}(t) + \sum_k \sum_{j=j_o}^{\infty} d_j(k) \psi_{j,k}(t) \qquad \text{(Eq.2.9)}$$

Where the choice of j_0 sets the coarsest scale whose space is spanned by $\phi_{j0,k}(t)$. The coefficients in this transform are called discrete wavelet transform of the signal g(t).

2.2.2 Wavelet transform vs. Fourier Transform

The traditional Fourier Transform only provides spectral information about a signal and only works for stationary signals while many real world signals are non-stationary and need to be processed in real time. The problem with Short Time Fourier Transform (STFT) can be attributed to the Heisenberg uncertainty principle which states that it is impossible for one to obtain the time instance at which frequencies exist but, one can obtain the frequency bands existing in a time interval. Also the resolution window used in STFT is of constant length whereas with Wavelet transform we can have multi resolution analysis i.e. we can

- Analyze the signal at different frequencies with different resolutions.
- Have good time resolution and poor frequency resolution at high frequencies.
- Have good frequency resolution and poor time resolution at low frequencies.

Also it is more suitable for short duration of high frequency and long duration of low frequency components. Wavelet transforms, unlike Fourier transform, do not have a single set of basis functions, which utilizes just the sine and cosine functions. Rather, they have an infinite set of possible basis functions. Thus wavelet analysis makes it feasible to acquire information that can be alienated by other time-frequency methods such as Fourier analysis.

2.3 Wavelet Packet Transform

Wavelet packet functions provide a basis, whose structure is extremely useful in decompositions and transforms making them well suited for the signal design problem in communications. These functions generalize standard wavelet bases and so inherit the properties that make their predecessors so attractive.

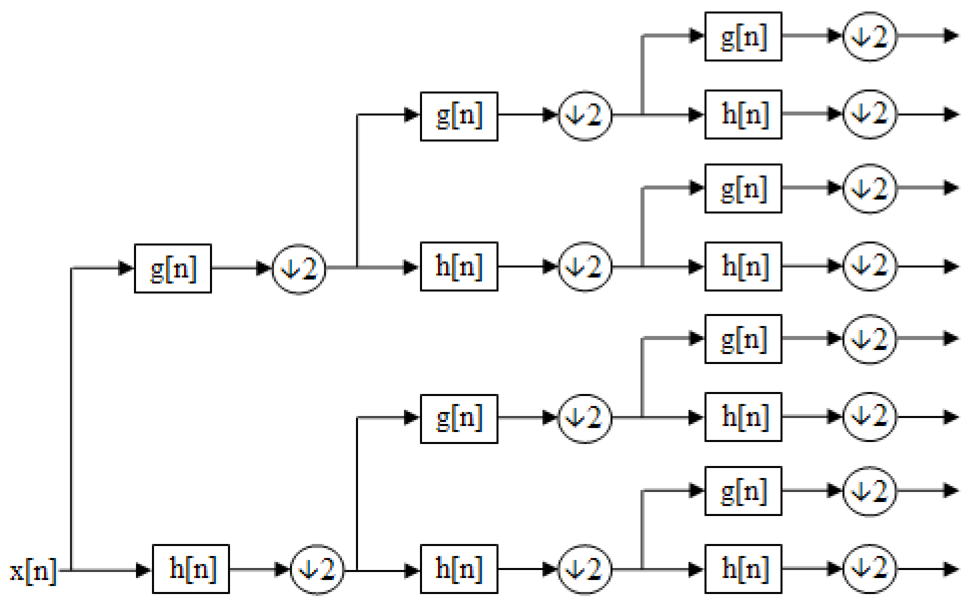

Figure 7: Wavelet Packets of 3 levels of decomposition of signal x[n] [3]

The theory of wavelets provides us that compactly supported wavelet can be derived from perfect reconstruction filter banks. Two channel filter banks split the given signal into the coarse version i.e. low frequency component and detail version i.e. high frequency component. This is then iterated successively on both the coarse and detailed versions at all scales. The cascaded two channel filter banks can be used to perform recursive decomposition of the signal being estimated and map its components into the frequency domain and each output point is a wavelet packet (WP) node and corresponds to a particular frequency band. So this decomposition of signal into coarse and detailed versions into different frequency bands with different resolutions is by successive high pass and low pass filtering of the signal.

So wavelet packet transform is a wavelet transform where the signal is passed through more filters than DWT (Discrete Wavelet Transform). In the DWT, each level is calculated by passing

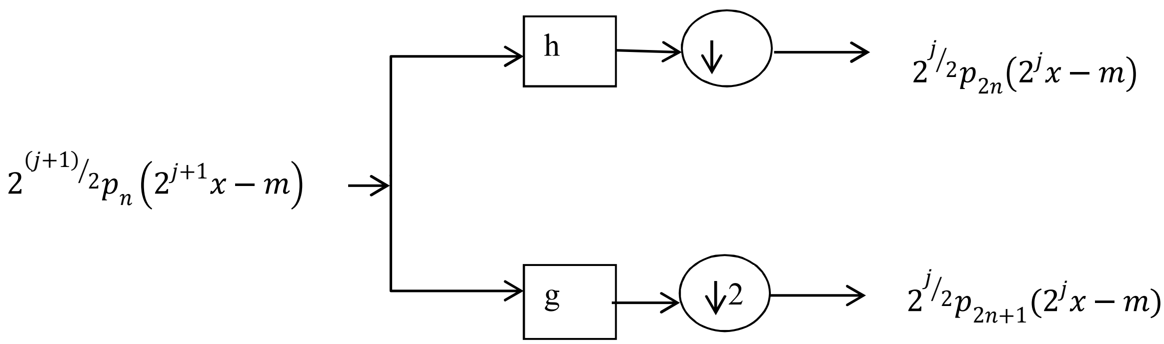

Figure 8: Wavelet packet decomposition by two-channel filter bank.[2]

only the previous approximation packet coefficients through low and high pass filters, unlike the WPT, where both the detail and approximation coefficients are decomposed to create the full binary tree. The number of successions or level of decompositions depends on the frequency resolution required. For n levels, 2^n different sets of wavelet packet coefficients are produced as opposed to (3n+1) sets for DWT. Downsampling process ensures that the overall number of coefficients is still same so that there is no redundancy.

The coefficients of the wavelet packet transform are not in the order of increasing frequency. Instead they are numbered on the basis of a sequential binary grey code value. For example if each coefficient in the level basis is numbered with a sequential decimal order (0001, 0010, 0011,...) the frequency ordering of the coefficients can be ordered by frequency by sorting them into Gray code value (0000, 0001, 0011, 0010, 0110,...). As they are in Gray code ordering, there is a need to change the frequency ordering of the output of wavelet packet node according to decimal order.

Hence this filter bank approximation of Wavelet Packet Transform makes it is suitable to finely identify the information in both high and low frequency bands and thus is an ideal processing tool for non-stationary time-variable signal.

Noise is primarily of high frequency and the signal of interest is primarily of low frequency. As this transform decomposes the signal into approximation and details coefficients, the detail coefficients containing much noise. So we simply reduce the details coefficients to denoise the signal before using them to reconstruct the signal. This approach is usually called thresholding. But the detail coefficients cannot be made zero as they contain some important features of the original signal which might be lost by reducing the coefficients. Hard thresholding and soft thresholding are the two different approaches which are usually applied to denoise the signal.

Chapter 3

WAVELET PACKET MODULATION

3.1 Introduction

The wavelet packet modulation (WPM) is a new type of multi-carrier modulation and has high bandwidth utilization, unique advantages in the capability of anti-disturbing and multi-rate transmission. It is considered as a tough contender to orthogonal frequency division multiplexing technique (OFDM).

3.2 Implementation of Wavelet Packet Modulation

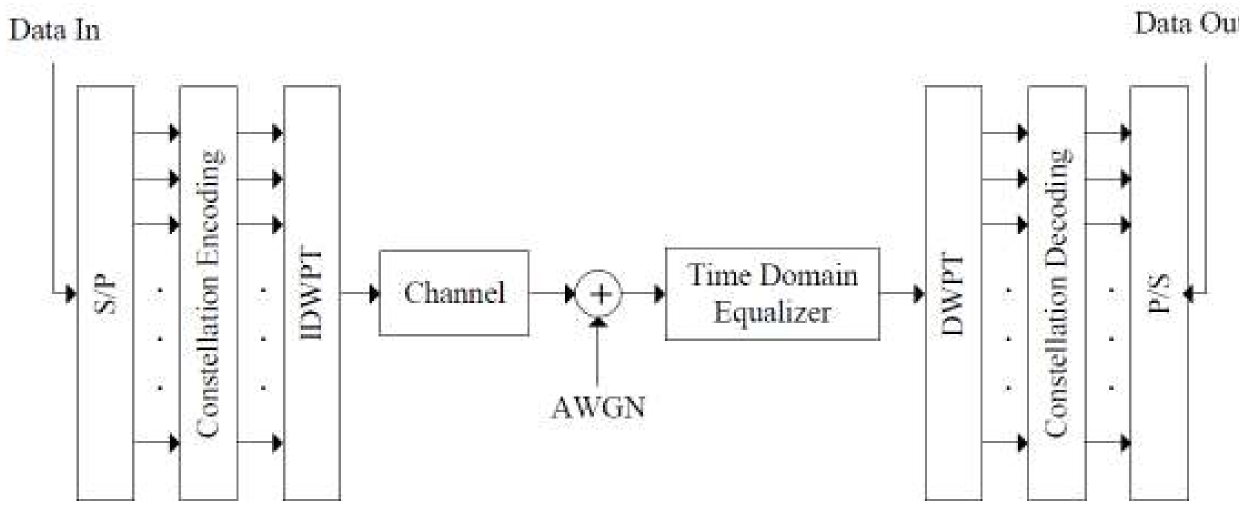

Figure 9: Block diagram of WPM (System Model) [2]

The simplified block diagram of the multicarrier communication system using wavelet packet transform is as shown in figure 9. The input data stream is divided into parallel lower data sub-streams by a serial to parallel (S/P) converter i.e. the data symbols design a block of N subcarriers that are first converted from serial to parallel to decrease symbol rate by a factor of N that is equal to the no. of sub-carriers. The signal transmitted on the channel is in the discrete domain, x[n], and is composed of successive modulated symbols, and each of this is constructed as the sum of M waveforms m[n] individually amplitude modulated with the constellation encoded symbol. So it can be expressed in the discrete domain as:

$$x[n] = \sum_s \sum_{m=0}^{M-1} a_{s,m} \varphi[n - sM] \qquad \text{(Eq.3.1)}$$

Where $a_{s,m}$ is a constellation encoded s^{th} data symbol modulating the m^{th} waveform T is denoting the sampling period, $\varphi_m[k]$ is non-null only in the interval [0, LT − 1] for any m{0..M − 1}.

In an AWGN channel, the waveforms $\varphi_m[k]$ should be mutually orthogonal to achieve the lowest probability of erroneous symbol decision i.e. $<\varphi_m[k], \varphi_n[k]> = \delta[m - n]$ where $<\cdot, \cdot>$ represents a convolution operation and $\delta[j] = 1$ if $j = 0$, and 0 otherwise. In OFDM, the discrete functions $\varphi_m[k]$ are the well-known M complex basis functions w[t]exp (j2π (m/M)kT) limited in the time domain by w[t] which is window function .These basis functions are sine-shaped waveforms that are equally spaced in the frequency domain, each having a bandwidth of 2π/M and are grouped in pairs of similar central frequency and usually modulated by a complex QAM encoded symbol. In WPM, the subcarrier waveforms are obtained by using the WPT. As in OFDM, the inverse transform is used to build the transmitted symbol while the forward transform allows retrieving the data symbol transmitted. Since wavelet theory has part of its origin in filter bank theory, the processing of a signal into wavelet packet coefficients through WPT is usually referred as decomposition while the reverse operation is called synthesis or reconstruction (i.e. from wavelet packet coefficients).

The important feature of the WPT is that the waveforms are longer than the transform size. Hence, WPM consists of a family of overlapped transforms. As they overlap in time domain the beginning of a next symbol is transmitted before the previous one(s) ends. The inter-symbol orthogonality is maintained as the waveforms are M-shifted orthogonally despite the overlap of consecutive symbols. Increased frequency domain localization can be made use provided by longer waveforms while the loss in system capacity is avoided that normally results from time domain spreading.

There are numerous alternative wavelet families that can be used but in this thesis we limit the performance analysis to only widely used wavelets as listed down in the table 1.

TABLE 1: Wavelet family Characteristics

Full Name	Abbreviated name	Vanishing Order	Length L_o
Haar	Haar	1	2
Daubechie	dbN	N	2N
Symlets	symN	N	2N
Coiflets	coifN	N	6N

3.3 Interesting features of WPM system compared to OFDM

From the system architecture point of view WPM provides interesting advantages.

- The dependence of wavelet packet transform on the generating wavelet is major asset as it achieves improved transmission integrity be exploiting the most common physical diversities- space, frequency and time diversities. This modulation provides signal diversity similar to spread spectrum systems. In practice, two different generating wavelets can modulate two signals that can be transmitted on same frequency band and also the interference suffered is reduced. The amount of interference between the two signals transmitted on same frequency band directly depends on the wavelets chosen. This characteristic can be used in cellular communications where different wavelets are used in adjacent cells so that they use same frequency bands in those cells and therefore reduce the inter-cell interference.
- There is no limitation in number of subcarriers in WPM unlike OFDM, where they are usually fixed at the time of design and is difficult to implement a FFT transform of a programmable size. In WPT the transform size is exponentially dependent on the number of iteration of the algorithm. So it is easy to configure them without increasing the overall complexity in implementation point of view. So this allows the change of transform on-the-fly.
- Semi-arbitrary division is another useful feature of WPT. OFDM only allows all the subcarriers of same bandwidth. But WPM gives the flexibility to choose subcarriers of different bandwidth. But as explained the previous chapter, increase in subcarrier bandwidth is bounded to decrease the corresponding symbol length as each subcarrier has the time-frequency plane area. This feature allows the WPM to be referred as multi-rate system as its transmission over the channel is effectively done at different symbol rates the throughput of the corresponding subcarrier remains constant due to constant bandwidth-duration of the subcarrier. This feature can be used of the systems that should support multiple data streams with different transport delay.
    - A channel that requires low transport delay can use subcarrier of greater bandwidth.

  - The signalling information that could be carried within narrower bandwidth employs narrow subcarriers, and could be used for the purpose of synchronization to take advantage of the longer symbols.

- In OFDM, the set of waveforms is by nature defined in the complex domain. WPM, on the other hand, is generally defined in the real domain but can be also defined in the complex domain, solely depending of the scaling and dilatation filter coefficients.

Altogether, WPM presents a much higher level of flexibility than current multicarrier modulation schemes and this makes it a candidate of choice for reconfigurable and adaptive systems for the next generation of wireless communication devices.

3.4 Channel Models

This thesis mainly studies Gaussian, Rayleigh and Rician fading and frequency selective channels.

In the AWGN channel, zero-mean white Gaussian noise is added to the transmitted signal s(*t*) , so the received signal can be represented as

$$y(t) = x(t) + w(t) \qquad \text{(Eq. 3.2)}$$

where w (t) is zero-mean white Gaussian noise with variance σ^2.

3.4.1 Small-scale fading and models for multipath fading channels

Fading is nothing but deviation of attenuation of a signal when passed through the radio channel. The type of fading experienced by the signal propagating through the channel depends on the nature of transmitted signal w.r.t. characteristics of the channel. Depending on the relation between signal parameters (bandwidth and symbol period) and channel parameters (Doppler spread and rms delay spread), different signals undergoes different types of fading. Time dispersion and frequency dispersion mechanisms of radio channel are responsible for four possible effects.

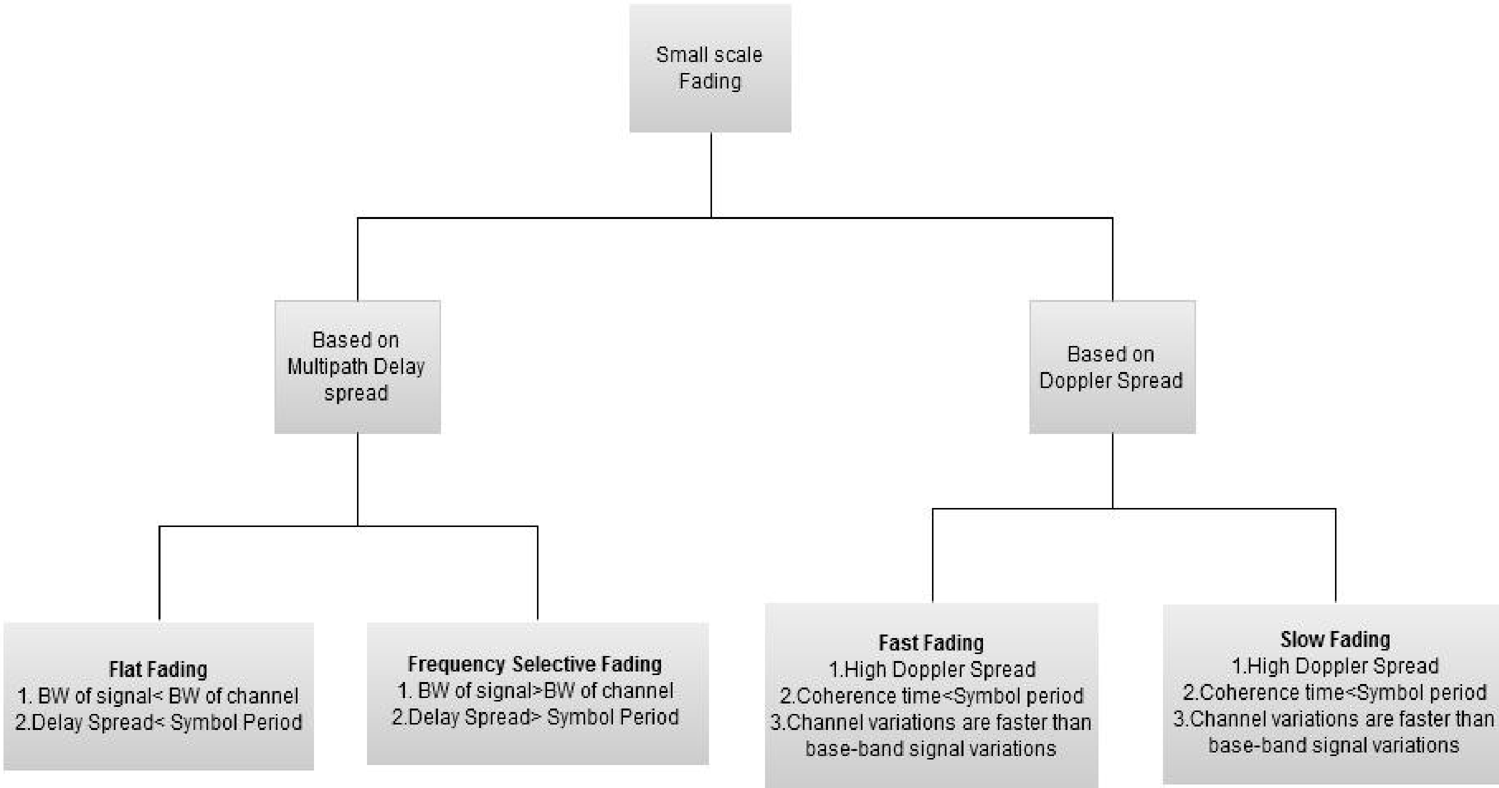

Figure 10: Types of Fading

3.4.1.1Rayleigh Fading Channel

Rayleigh distribution is generally used to describe statistical time varying received envelope of flat fading signal or an envelope of individual multipath component. The envelope of sum of two Gaussian noise signals in quadrature with each other obeys Rayleigh distribution.

The probability density function of Rayleigh distribution is given by

$$H(r) = \begin{cases} {r}/{\sigma^2}\; e^{r^2/\sigma^2} & (0 \le r \le \infty) \\ 0 & (r < 0) \end{cases} \qquad \text{(Eq. 3.3)}$$

So the received signal for a 2-path Rayleigh channel can be expressed as

$$y(t) = s(t) * h_1(t) * e^{j2\pi f_{d1} t} + s(t - \tau_s) * h_2(t) * e^{j2\pi f_{d2} t} + w(t) = u_1(t) + u_2(t) + w(t)$$

(Eq. 3.4)

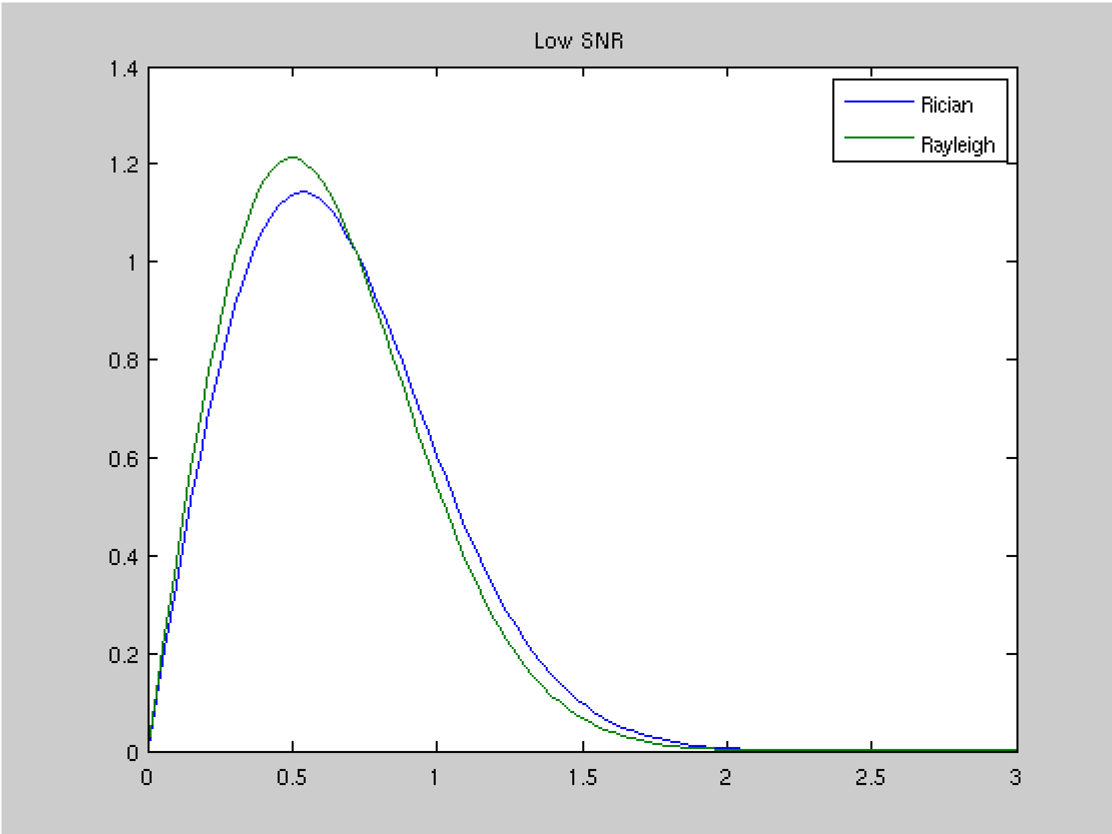

Figure 11: Rayleigh and Ricean pdf distribution

3.4.1.2 Rician Fading Channel

When a dominant stationary signal component like line of sight propagation path (nonfading) is present then the small scale envelope follows Rician distribution. In this case the multipath components arriving randomly are superimposed on dominant stationary signal. This has the effect of adding the random multipath to a dc component. As the dominant signal fades away, the composite signal resembles noise and Rician distribution degenerates to Rayleigh.

$$p(r) = \begin{cases} \frac{r}{\sigma^2} I_0\left({A_r}/{\sigma^2}\right) e^{-(r^2+A^2)/2\sigma^2} & (A \le 0, r \le 0) \\ 0 & (r > 0) \end{cases} \qquad \text{(Eq. 3.5)}$$

Chapter 4

EQUALIZATION

4.1 Introduction

Equalization compensates for inter symbol interference (ISI) created by multipath within time dispersive channels. ISI occurs if the modulation bandwidth is more than the coherence bandwidth of the radio channel and modulation pulses are spread in time. An equalizer within a receiver combats the average range of delay characteristics and expected channel amplitude.

Inter symbol interference caused by multipath in frequency selective time dispersive channels distorts the transmitted signal that results in bit errors at the receiver and hence, it is a major hindrance to high speed data transmission over mobile radio channels. Equalization is a technique used to minimize inter symbol interference. Equalizers must be adaptive in nature since the channel is generally time varying. A variety of adaptive equalizers can be used in radio channels, to cancel the interference while providing diversity. Since the mobile fading channel is time varying, equalizers must be adaptive in nature so that the time varying characteristics of the mobile channel is tracked by them.

4.2 Algorithms for Adaptive Equalization

There are three classic equalizer algorithms discussed under this sub topic, namely Zero Forcing (ZF) Algorithm, Least Mean Square (LMS) Algorithm, Recursive Least Square (RLS) Algorithm.

4.2.1 Zero Forcing (ZF) Algorithms

In a zero forcing equalizer, the equalizer coefficients are chosen such that they force the samples of the combined channel and equalizer impulse response to zero at all except one of the NT spaced sample points in the tapped delay line filter. By allowing the number of coefficients increase without limit, an infinite length equalizer with zero ISI at the output can be obtained.
If the frequency response of the channel is H(s), then the input is multiplied with the reciprocal of it , in order to cancel all ISI from the received signal. Thus, an infinite length, zero, ISI equalizer is as simple as an inverse filter that inverts the folded frequency response of the channel. Such an infinite length equalizer is usually implemented by a truncated length version.

$$H_{ch}(s)H_{eq}(s) = 1, \ |f| < \frac{1}{2T} \qquad \text{(Eq.4.1)}$$

When each of the delay elements provides a time delay equal to the symbol duration 7', the frequency response $H_{eq}(s)$ of the equalizer is periodic with a period equal to the symbol rate 1 / T. The combined response of the channel with the equalizer satisfies the Nyquist Criterion as shown in the above equation.

4.2.2 Least Mean Square (LMS) Algorithm

The Least Mean Square (LMS) algorithm, given by Widrow and Hoff in 1959 is an adaptive algorithm,that uses gradient-based method of steepest decent. Estimates of the gradient vector are used from the available data. LMS involves an iterative procedure that successively corrects the weight vector along the negative direction of the gradient vector that ultimately leads to minimum mean square error.

The principle used is the minimization of the mean square error (MSE) between the desired output and the actual output. The prediction error is given by

$$e_k = d_k - \tilde{d_k} = x_k - \tilde{d_k} \qquad \text{(Eq.4.2)}$$

To compute the mean square error at time instant k , we use

$$\mathcal{E} = E\,[e_k * e_k] \qquad \text{(Eq.4.3)}$$

The LMS algorithm minimizes the mean square error given in the above equation. Compared to other algorithms LMS algorithm is relatively simple; it neither requires correlation function calculation nor does it require matrix inversions.

4.2.3 Recursive Least square (RLS) Algorithm

The Recursive least squares (RLS) adaptive filter is an algorithm which recursively finds the filter coefficients to minimize a weighted linear least squares cost function that relates to the input signals.

The convergence rate of the gradient-based LMS algorithm is very slow, especially when the eigen values of the input covariance matrix have a very large spread. In order to achieve faster convergence, complex algorithms involving additional parameters are used. Faster converging algorithms are based least squares approach, in contrast with the statistical approach used in the LMS algorithm. That is, rapid convergence relies on error measures expressed in terms of a time average of the actual received signal instead of a statistical average. This leads to the family of powerful, complex, adaptive signal processing techniques known as recursive least squares (RLS), which aims at improving the convergence of adaptive equalizers.

The least square error based on the time average is given as

$$J(n) \ = \sum_{i=1}^{n} \lambda_{n-1} \, e^{*}(i,n)e(i,n) \qquad \text{(Eq. 4.4)}$$

To obtain the minimum of least square error J (n) , the gradient of J (n) in equation (4.4) is set to zero,

$$\frac{\partial J(n)}{\partial w} = 0 \qquad \text{(Eq. 4.5)}$$

4.2.4 Comparison of Equalization Algorithms

RLS algorithms have similar convergence and tracking performances, much better than the LMS algorithm. However, these RLS algorithms usually have high computational requirement and complex program structures. Also, some RLS algorithms tend to be unstable.

Algorithm	*Number of Multiply Operations*	*Advantages*	*Disadvantages*
LMS	2N +1	Low computational complexity, simple Program	Slow convergence, poor Tracking
RLS	2.5N2 + 4.5N	Fast convergence, good tracking ability	High computational cornplexity

Table 2: Comparison of Various Algorithms for Adaptive Equalization

4.3 Types of Equalizers

In multicarrier systems, equalization is usually divided into pre- and post-detection equalizers, in accordance with their position respective to the core transform.

4.3.1 Pre-detection Equalizer

The objective of the pre-detection equalizer is different for an overlapping multicarrier and for an OFDM system making use of a cyclic prefix. While the equalization of WPM aims at minimizing the mean square error at its output, in the latter case, the equalizer attempts to shorten the perceived channel impulse response to a value lower than the cyclic duration.

4.3.2 Post - detection Equalizer

Post detection equalization is used in OFDM systems in the form of a single tap filter. These taps aim at inverting the channel transfer function in the frequency domain. For WPM, the structure of the post-detection equalizer is quite complex since it has to remove both ISI and ISCI. Hence, a combined time-frequency equalization structure is required.

4.4 Equalization problem of WPM

In OFDM, if the delay spread of the channel is shorter than the cyclic prefix, a pre-equalizer is not required. For longer delay spread, the pre-detection equalizer aims at shortening the apparent channel impulse response to a value lower or equal to the cyclic prefix duration. If it succeeds, the symbol at the input of the DFT is free from inter-symbol interference. For a channel with long impulse response, the length of the prefix required leads to a significant loss in capacity and transmit power. For WPM however, the use of a cyclic prefix is not possible as the successive symbols overlap. Hence it gives rise to both inter-symbol interference (ISI) and inter–symbols inter-carriers interference (ISCI) that have to be cancelled by the equalization scheme.

$$ISI_j(n) = \sum_{r=-\infty}^{\infty} x_j(r)\, h_{jjp}(n_j(n-r)) \qquad \text{(Eq. 4.6)}$$

$$ICI_j(n) = \sum_{\substack{k=0 \\ k\neq j}}^{M-1} \sum_{r=-\infty}^{\infty} x_j(r))\, h_{jjp}(n_j n - nkr) \qquad \text{(Eq. 4.7)}$$

Where $h_{jkp}(n) = h_k(n-p) * h_j^*(-n) = \sum_{m=-\infty}^{\infty} h_k(m-p)h^*j(m-n)$ and h_k is the sub channel impulse response. The power of IS1 and ICI, $\sigma^2_{ISIj,}$ σ^2_{ICIj} are determined, respectively, as

$$\sigma_{ISIj}^2 = \sum_{m=-\infty}^{\infty} |\, h_{jjp}(n_j m)\,|^2 \qquad \text{(Eq. 4.8)}$$

$$\sigma_{ICIj}^2 = \sum_{\substack{k=0 \\ k\neq j}}^{M-1} \sum_{m=-\infty}^{\infty} |\, h_{jkp}(n_k m)\,|^2 \qquad \text{(Eq. 4.9)}$$

So in multipath channels, equalization of WPM is more complex than that of OFDM. This is essentially because of the use of cyclic prefix that gives an edge to OFDM, when compared to overlapping multicarrier schemes such as WPM.

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Conditions of Simulation

Wavelet packet Decomposition is done using Simulink and later Wavelet Packet Modulation is done using Matlab Editor both of the package MATLAB R2009a. The composite signal taken for WPD comprises of pulse and sine waves have frequencies 5Hz and 10Hz respectively. The data signal undergoing WPM is digital with 128 carriers and 64 bit per each carrier and sample frequency of 2 KHz. All the simulations are done considering AWGN channel.

5.2 Simulation Results

5.2.1 Wavelet Packet Decomposition

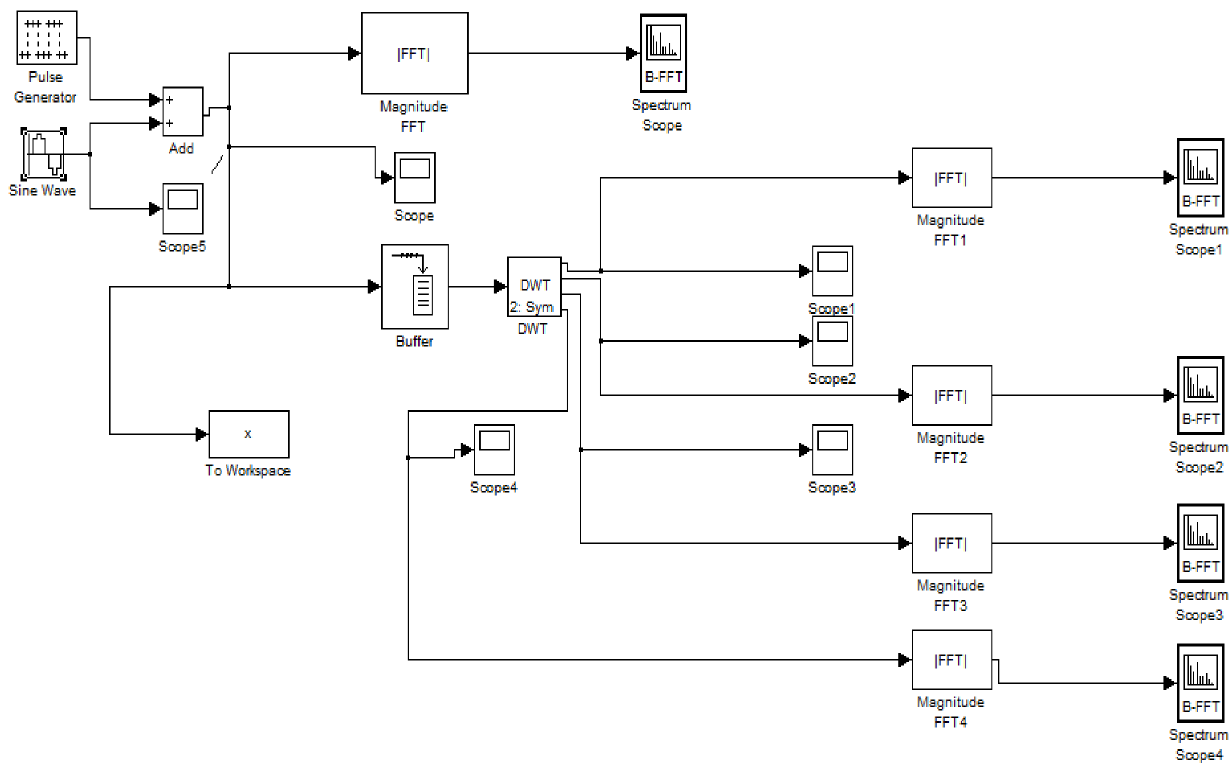

Figure 12: Model based design for Wavelet packet decomposition in Simulink

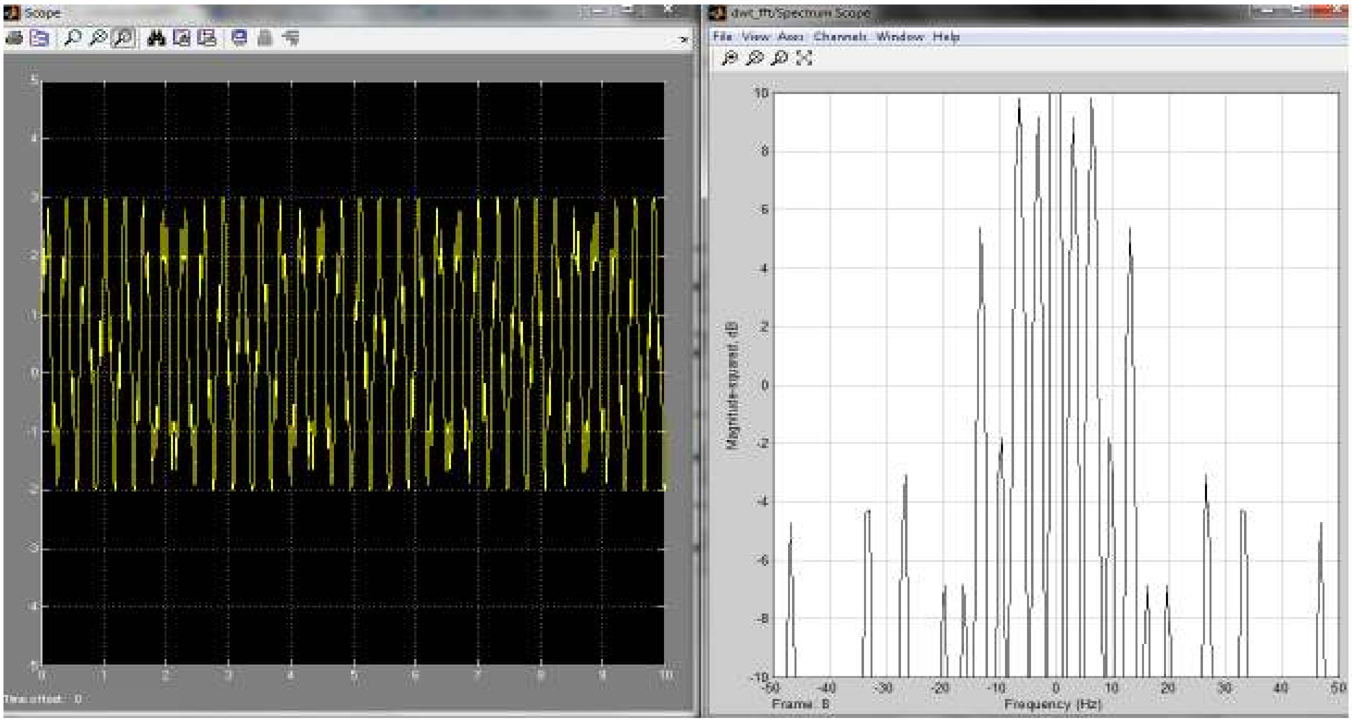

Figure 13: Composite input signal and its frequency response

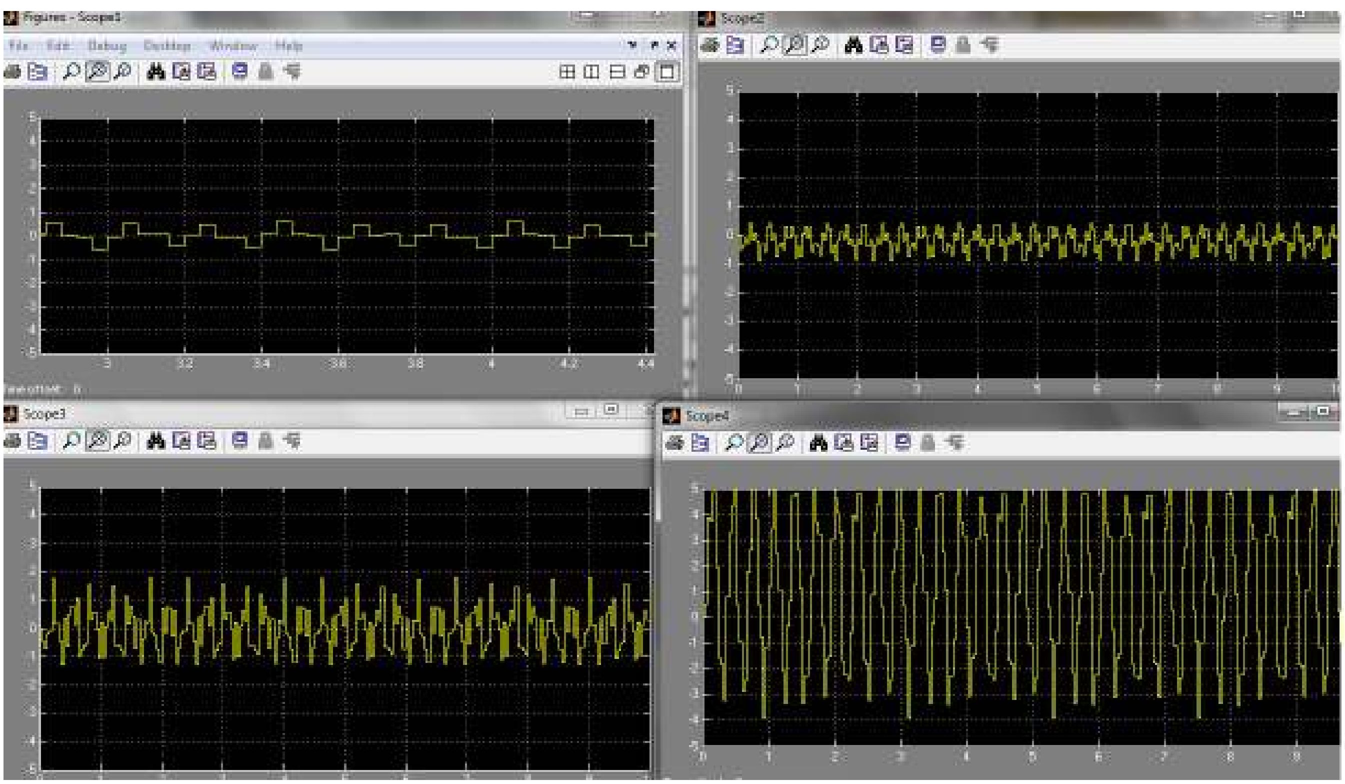

Figure 14: Decomposed Signals in time domain

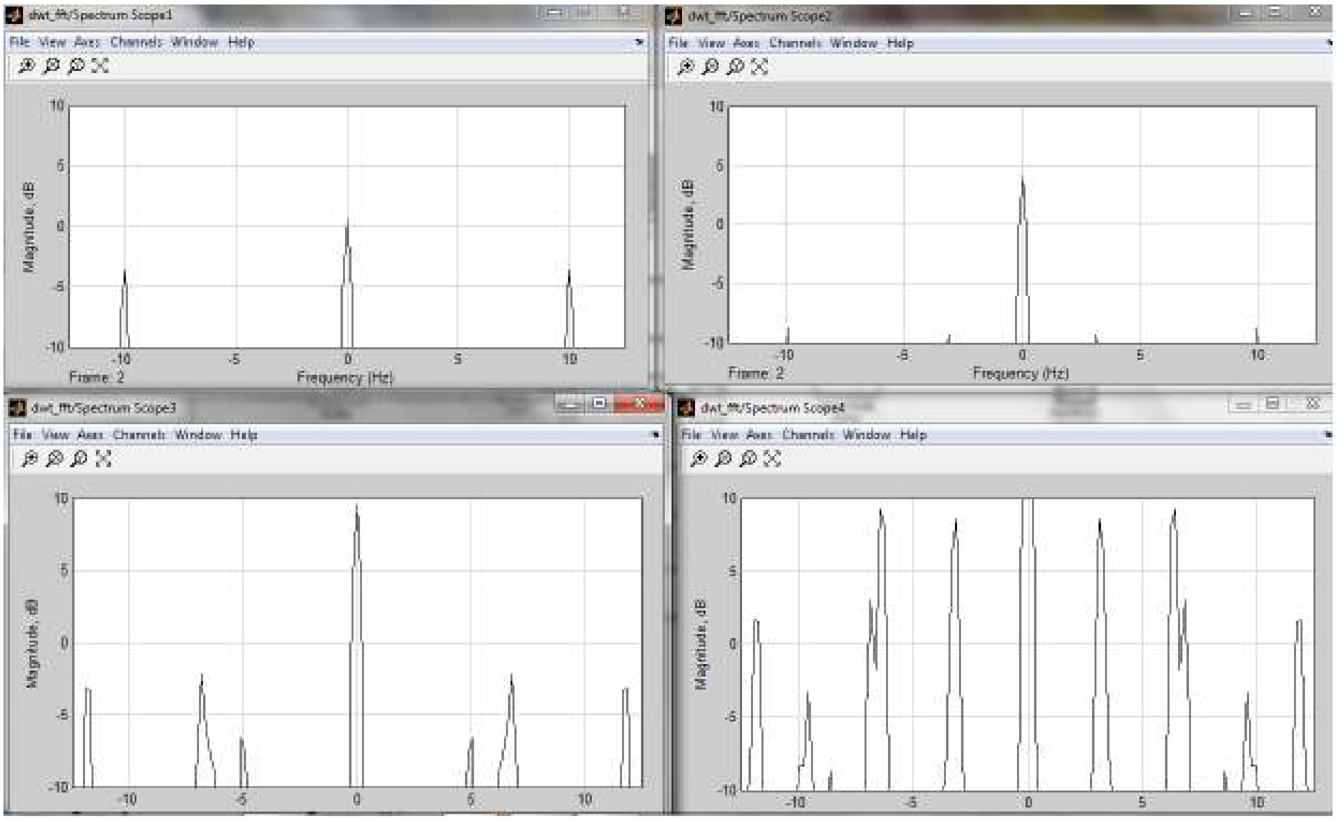

Figure 15: Frequency Response of decomposed signals

Inference: The above figures are for 2-level wavelet decomposition for composite signal consisting of Sine wave and Pulse wave of different frequencies. So the number of wavelet packet signals is four and are plotted in time and frequency domain.

From the signal representation in frequency domain, we can infer that all the decomposed signals are in different frequency bands according to the wavelet approximate and detail filter, given the removal of DC component frequency.

5.2.2 Bit Error rate of WPM for different constellation encodings

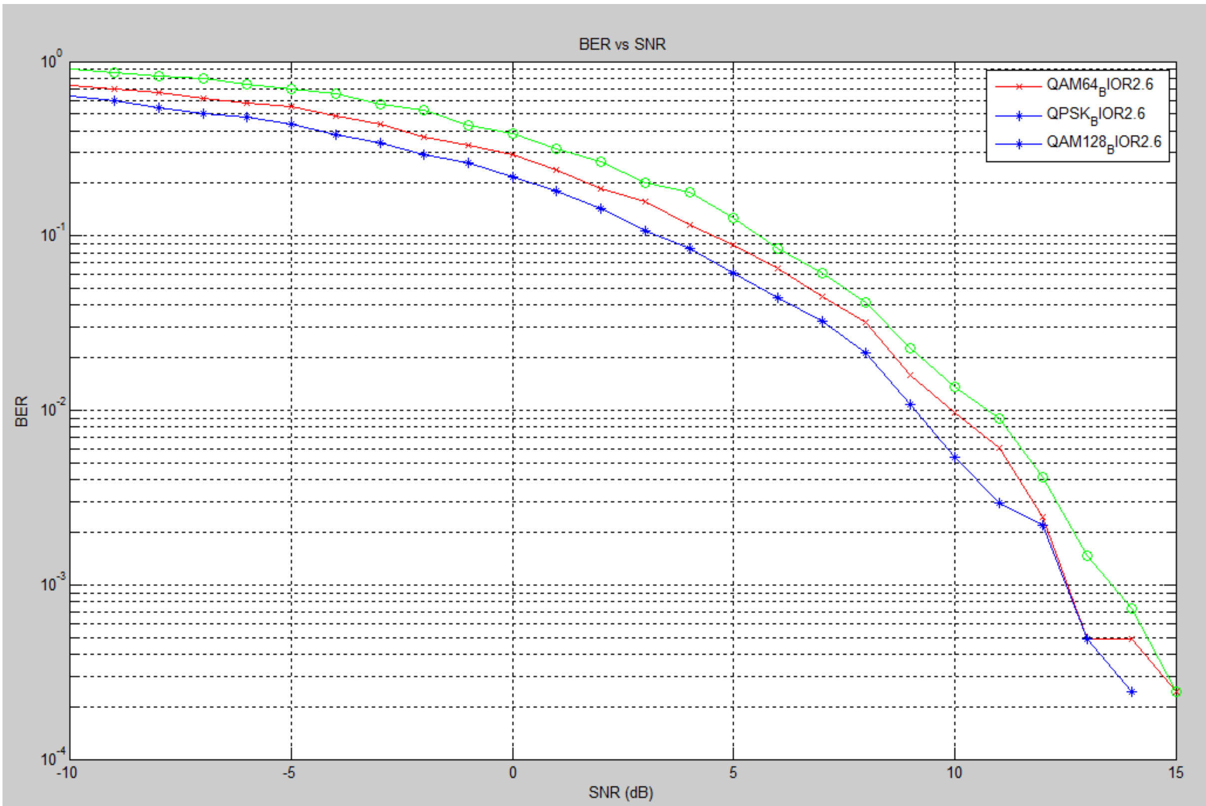

Figure 16: BER vs. SNR for different types of constellation Encoding in AWGN channel for haar wavelet

Inference

The above figure shows the Bit error rate for WPM using N-QAM for N=16, 64, 128 in the presence of white Gaussian noise for the haar wavelet. We can infer that QPSK (16 QAM) performance is better than other QAM encodings. So as the number of bits per symbol decreases the WPM system provides better BER performance.

5.2.3 Bit Error rate of WPM for different no. of carriers

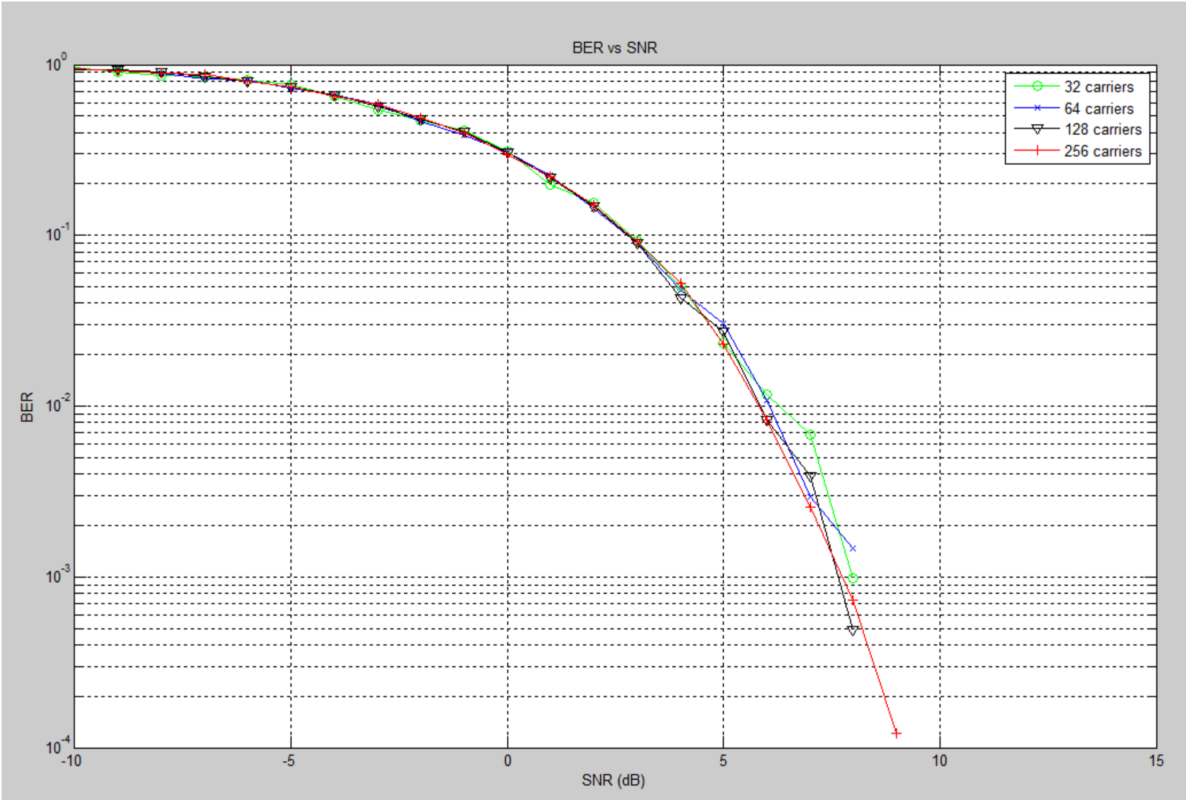

Figure 17: BER vs. SNR for different number of carriers for haar wavelet in AWGN channel

Inference

The above snapshot depicts that the BER performance for different number of subcarriers (32, 64, 128, and 256) is similar at lower SNR but as the signal power increases, it is better for large number of carriers. It is simulated for Haar wavelet and QPSK encoding.

5.2.4 BER performance of WPM for different wavelet families

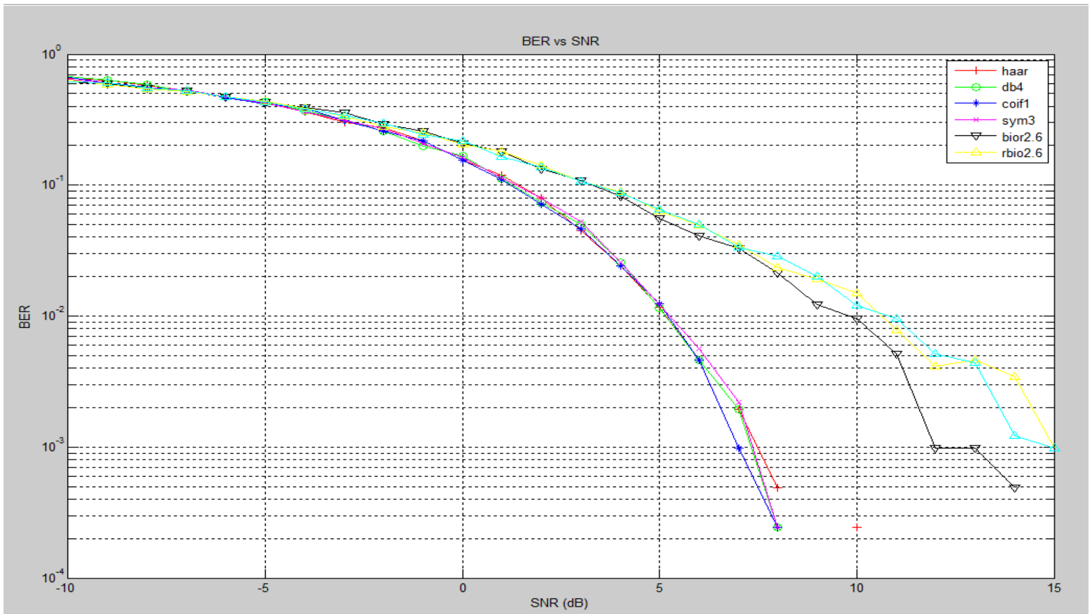

Figure 18: BER vs. SNR plot of different wavelet families for QPSK encoder WPM

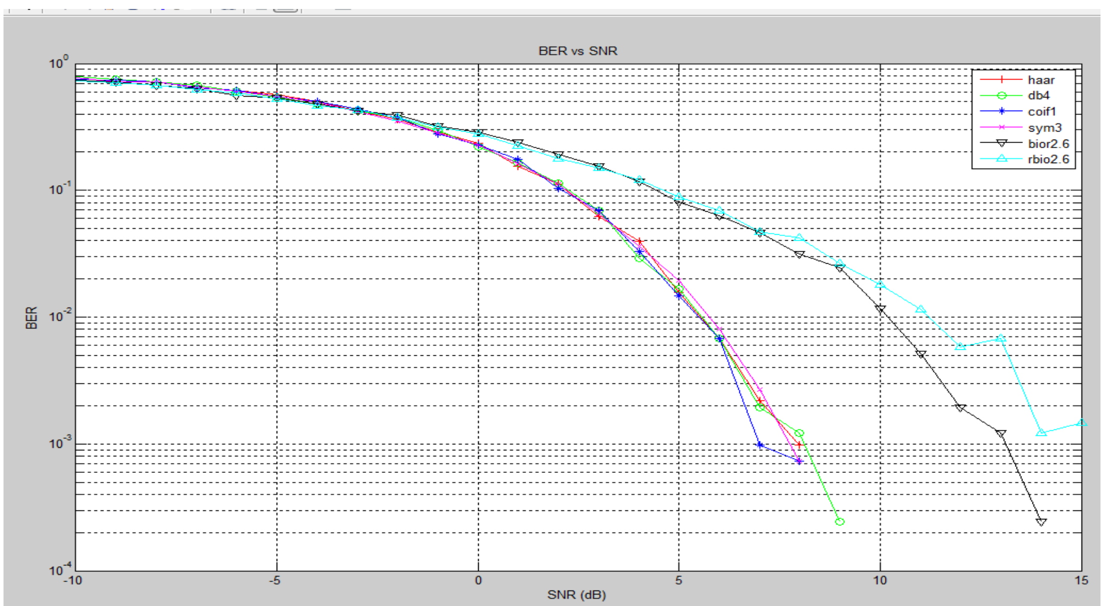

Figure 19: BER vs. SNR plot of different wavelet families for 64-QAM encoder WPM

Inference:

Among all the wavelets, Daubechies family gives the best performance because of its high power and biorthogonal and reverses biorthogonal wavelets gives average performance.

5.2.5 BER for WPM and OFDM

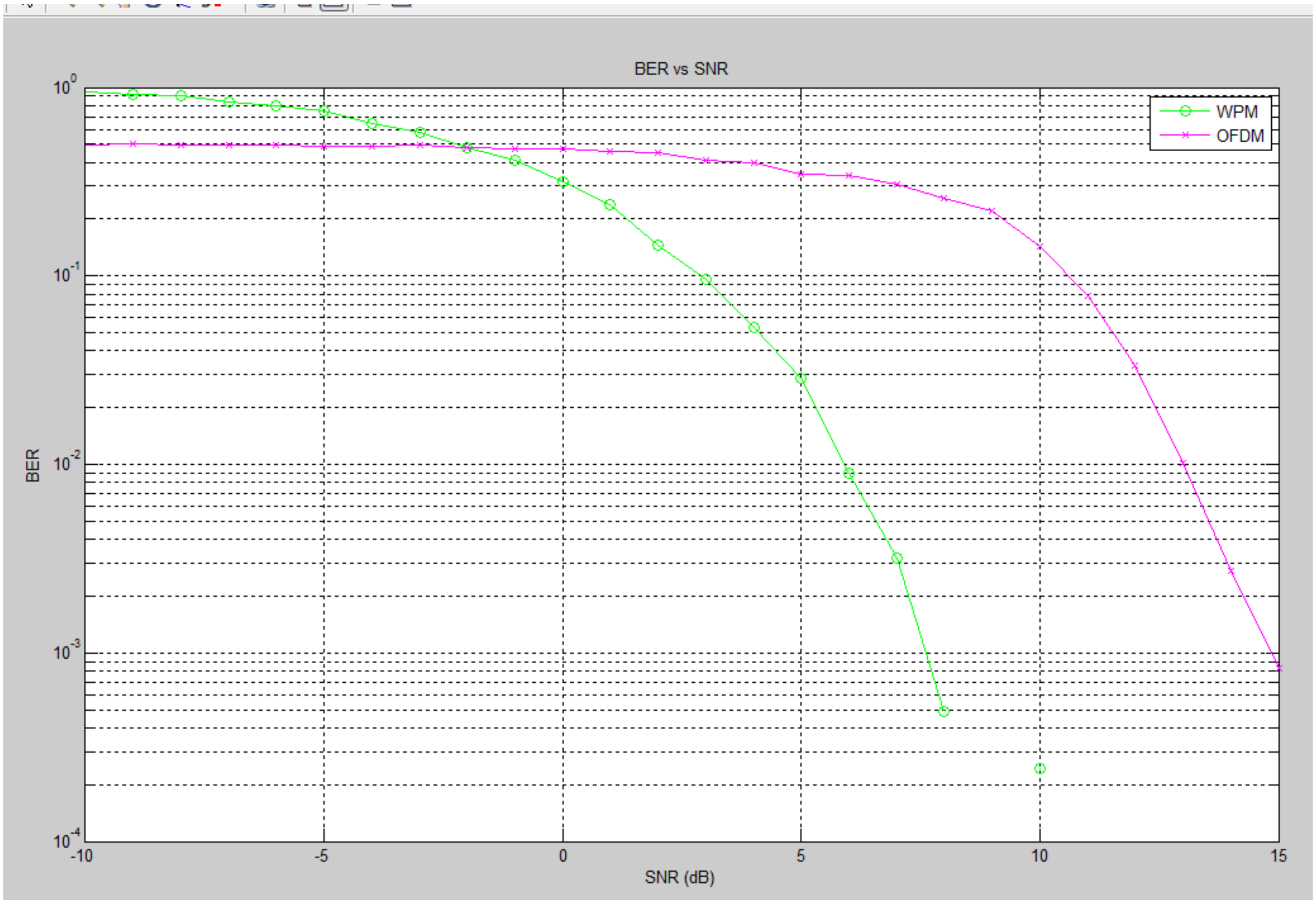

Figure 20: BER vs. SNR plot for comparison of performance of OFDM and WPM

Inference

The above snapshot of output shows the bit error rate vs. signal to noise ratio of WPM (Daubechies) and OFDM for 64-subcarriers and QPSK encoding.

We can infer that at low SNR where the noise power is greater than signal power, OFDM gives better performance than WPM but as the signal power exceeds noise power WPM provides far better performance in communication systems.

5.2.6 BER of WPM in multipath fading channels

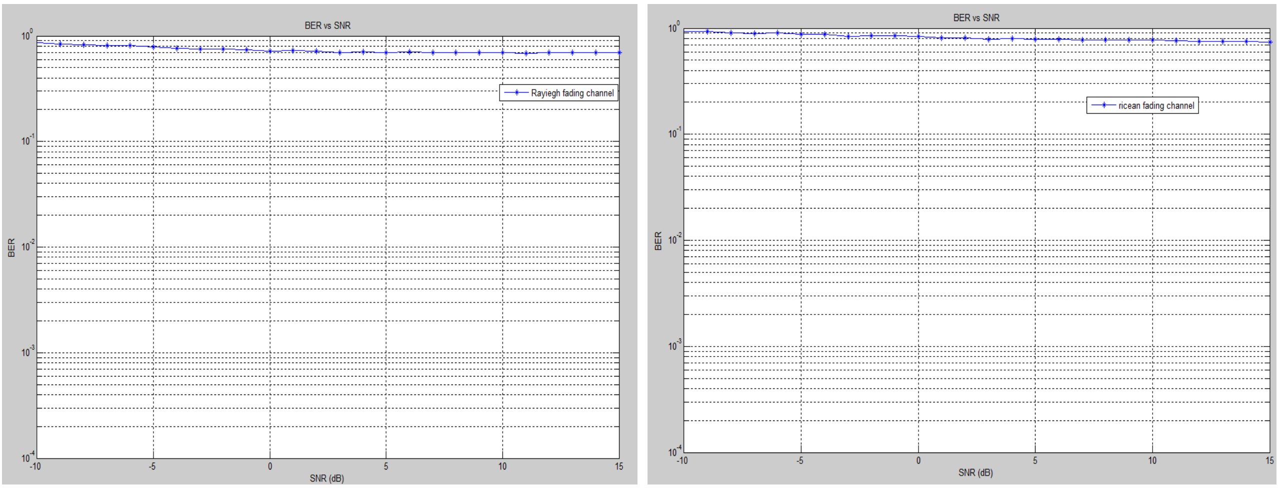

Figure 21: BER VS SNR of WPM in Rayleigh and Rician multipath fading channel

Inference

The above figures are results of WPM simulated in rayleigh and ricean multipath fading channel with doppler shift of 5Hz and a 2 path channel with 3db decrease in average power for every 10microseconds of path delay.

We can infer that increase in signal to noise ratio doesn't change the bit error rate. This is because ISI and ICI which should be reduced using equalization.

5.2.7 Comparison of WPT and FFT in terms of computational complexity

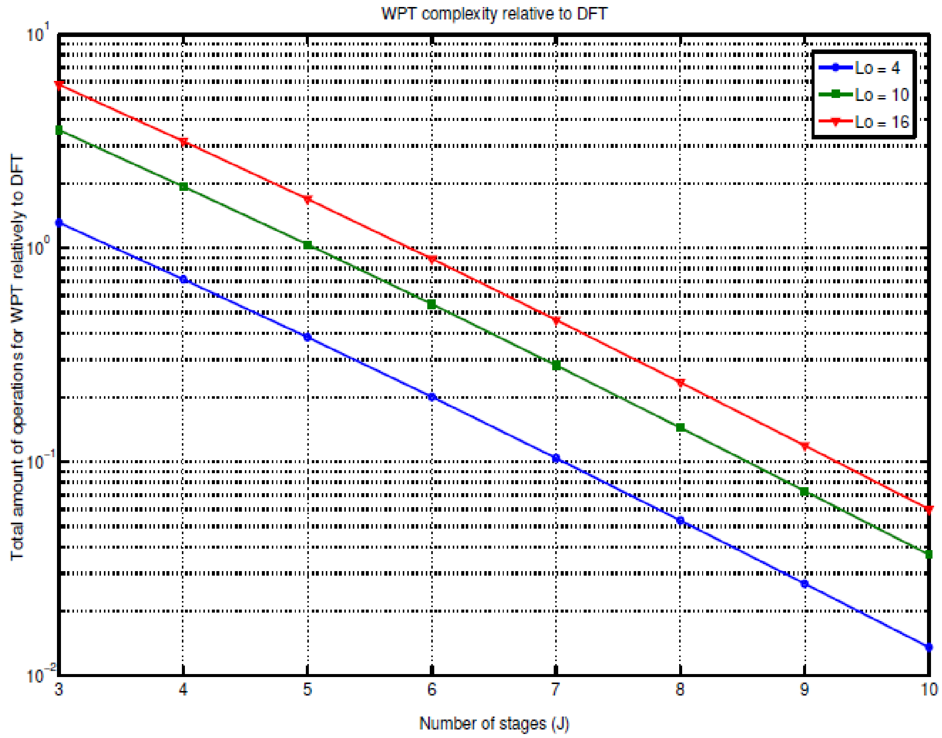

Figure 22: WPT complexity relative to that of the DFT as a function of the transform size [2]

Inference

The above figure shows the Ratio of total no. operations of WPT and FFT vs. number of stages $J = 2^M$ for different filter lengths of generating wavelet (L_o =4, 10, 16).

We can depict from the snapshot that for L_o=4, WPT has less no. of operations for J>3, but as the filter length increases, number of operation of FFT is low for small J but WPT is effective large no of stages.

Chapter 6

CONCLUSION

Conclusion

In this project the advantages of using WPM for multicarrier communication systems and comparison between this new scheme and OFDM has been evaluated. Overall, the performance results of WPM lead us to conclude that this new modulation scheme is a viable alternative to OFDM to be considered for today's communication systems. OFDM remains nevertheless a strong competitor because of its capability to cope with multipath effects efficiently. WPM is slightly more sensitive than OFDM to commonly encountered types of distortion due to non-ideal elements of the system.

The major interest of WPM nevertheless resides in its ability to fulfil the wide range of requirements of tomorrow's ubiquitous wireless communications. The overlapping of wpm symbols causes a significant amount of interference that requires an dedicated equalization scheme to be studied. A study on synchronization of the WPM signals in both time and frequency domains would most probably lead to efficient algorithms, due to the multi-resolution nature of the multiplexed signal.

Future Scope

The performance of wavelet packet modulation in Rayleigh and Rician fading channels is poor because multipath delay and Doppler shift incudes ISI and ICI into the signal. To compensate these effects Equalization has to be done either using LMS or MLSE algorithms for Adaptive equalization technique. These eliminate both frequency selective fading and fading due to Doppler spread. This can be considered as future work that can be carried out on this project.

Finally, it is important to underline that wavelet theory is still developing. Wavelet based communication systems have already shown a number of advantages over conventional systems. It is expected that more is still to be pointed out as the knowledge of this recently proposed scheme gains more interest within both the wireless communication industry and research community.

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