DISCRETE WAVELET TRANSFORM BASED OFDM SYSTEM USING CONVOLUTIONAL ENCODING

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CERTIFICATE

I hereby declare that the thesis report entitled **"Discrete Wavelet Transform Based OFDM System Using Convolutional Encoding"** is an authentic record of my study carried out as requirement for the award of degree of M.E. (Wireless Communication Engineering) at Thapar University, Patiala, under the supervision of **Ankush Kansal**, Assistant Professor, Electronics and Communication Engineering Department.

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

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

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

Discrete Wavelet Transform (DWT) is broadly considered as an efficient approach to replace FFT in the conventional OFDM systems due to its better time-frequency localization, bit error rate improvement, interference minimization, improvement in bandwidth efficiency and many more advantages. Moreover, Convolutional codes are used in DWT based OFDM system which improves the bit error rate performance of the system. In communication systems, when the signal is transmitted over the channel, noise and unwanted interferences are introduced which leads to the distortion of transmitted signal. Hence, error control coding techniques are used to mitigate the effect of such channel distortions. The original data sequence is appended with redundant bits to increase the reliability of the system by adding cyclic prefix; which also answers the problem of ISI.

DWT is an effective tool to study the signals in time frequency joint domain as it is capable of providing simultaneous information about time and frequency, thus gives the time frequency representation of signal. Wavelet based OFDM is employed in order to remove the use of cyclic prefix which decreases the bandwidth wastage and the transmission power is also reduced. The BER performance of the OFDM system had been significantly improved by 4 dB at BER of $10^{-2.9}$ when DWT was used in place of conventional FFT method. Afterwards, all the wavelets were compared to find the optimum wavelet among all. The results achieved had shown that the wavelet 'bior5.5' outperformed all the other wavelets as

well as FFT-OFDM system because it makes use of two wavelets, one for decomposition and the other for reconstruction instead of the single one.

Finally, the performance of DWT OFDM system using Convolutional codes and without encoding is compared under AWGN as well as Rayleigh channel. The results show that there is an improvement of 2.5 dB at BER of $10^{-2.92}$ when AWGN channel is used. In case of Rayleigh channel, an improvement of 3.5 dB has been achieved at BER of $10^{-4.9}$. It is because the Convolutional encoding is very effective in removing the burst errors and distortions introduced by the channel. Moreover, the BER performance of a system is affected by the outage probability which occurs when the required data rate is not supported by the specific channel due to variable SNR. Convolutional encoding reduces the outage probability at higher SNR. Thus, DWT based OFDM with encoding performs significantly better at higher SNR.

CHAPTER 1
INTRODUCTION

1.1 OFDM

With the rapid growth in technology, the demand for flexible high data-rate services has also increased. The performance of high data rates communication systems is limited by frequency selective multipath fading which results in intersymbol interference (ISI). In the wireless channels, impairments such as fading, shadowing and interferences due to multiple user access highly degrade the system performance. Multicarrier modulation (MCM) is a solution that overcomes these problems in wireless channels. It is the technique of transmitting data that divides the serial high data rate streams into a large number of low data rate parallel data streams [1]. Orthogonal Frequency Division Multiplexing (OFDM) is a kind of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is then modulated by a low rate data stream at different carrier frequency. The conventional OFDM system makes use of IFFT and FFT for multiplexing the signals and reduces the complexity at both transmitter and receiver [2].

OFDM is comprised of a blend of modulation and multiplexing. The original data signal is split into many independent signals, each of which is modulated at a different frequency and then these independent signals are multiplexed to create an OFDM carrier. As all the subcarriers are orthogonal to each other, they can be transmitted simultaneously over the same bandwidth without any interference which is an important advantage of OFDM [3]. OFDM makes the high speed data streams robust against the radio channel impairments. OFDM is an efficient technique to handle large data rates in the multipath fading environment which causes ISI. With the help of OFDM, a large number of overlapping narrowband subcarriers, which are orthogonal to each other, are transmitted parallel within the available transmission bandwidth. Thus, in OFDM, the available spectrum is utilized efficiently.

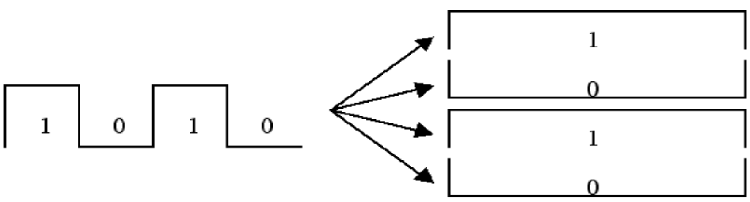

Fig. 1 Traditional vs. OFDM

1.1.1 Significance

With the rapidly growing technology, the demands for high speed data transmission are also increasing. OFDM is a multicarrier modulation technique which has the capability to fulfil this demand for large capacity. OFDM is reliable and economical to handle the processing power of digital signal processors. OFDM is used in many applications such as IEEE 802.11 wireless standard, Cellular radios, GSTN (General Switched Telephone Network), DAB (Digital Audio Broadcasting), DVB-T (Terrestrial Digital Video Broadcasting) [3], HDTV broadcasting, DSL [4] and ADSL modems and HIPERLAN type II (High Performance Local Area Network) [4].

1.1.2 Orthogonality

Orthogonality is the property when the signals are mutually independent of each other [5]. When the information signals are orthogonal, they can be transmitted simultaneously over the common channel without any interference. In case of loss of orthogonality, the performance of the communication system suffers degradation. The general multiplexing schemes are essentially orthogonal. In Time Division Multiplexing, multiple information signals are transmitted over the single channel but on unique time slots. Only one signal is transmitted during each slot to prevent any kind of interference among different information signals which makes the TDM system orthogonal in nature. Similarly, Frequency Division Multiplexing systems are orthogonal in frequency domain.

In OFDM signal, all the subcarriers are well spaced out in frequency to maintain orthogonality among them [6]. Orthogonality is achieved by allocating a different subcarrier to each information signal. All the subcarriers are made orthogonal to each other as the baseband frequency of each sub carrier is chosen in such a way that it is an integral multiple of inverse of the symbol period.

Orthogonal Frequency Division Multiplexing (OFDM) is a kind of multi-carrier modulation, which divides the available spectrum into a number of parallel subcarriers and each subcarrier is then modulated by a low rate data stream at different carrier frequency which is given in [7] as equation (1.1):

$$\int_{0}^{T} \cos(2\pi f_n t) \times \cos\left(2\pi f_m t\right) dt = \delta\left(n-m\right) \tag{1.1}$$

where $\delta\left(n-m\right)$ is the Dirac Delta function.

The subcarrier frequency f_n is defined as given in equation (1.2),

$$f_n = n\Delta f \tag{1.2}$$

$$\Delta f = \frac{f_s}{N} = \frac{1}{NT} \tag{1.3}$$

Here, f_s is the entire bandwidth and N is the number of subcarriers.

These subcarriers become orthogonal to each other when two different subcarrier waveforms are multiplied and integrated over symbol period results into zero.

1.1.3 Protection against ISI

Intersymbol interference is a very common problem found in the existing high speed communication systems. It occurs when the transmitted data interferes with itself and is not decoded correctly at the receiver. The transmitted signal gets reflected from many large objects; hence more than one copy of the signal reaches the receiver which is known as multipath. These copies of signal reach at the receiver after some delay and interfere with the original signal resulting into ISI [7]. Intersymbol interference can be classified into two types: interchannel ISI and intrachannel ISI. The non-ideal sub band filters leaks the signals from one channel to the adjacent channels which results into interchannel ISI, while intrachannel ISI results from channel dispersion [8].

Interchannel ISI is also known as adjacent channel interference or crosstalk. These two are defined as follows:

A. Intrachannel ISI

It is very easy to mathematically model intrachannel ISI. Consider a channel of length L [9],

$$y_n = \sum_{k=0}^{L-1} h_k x_{n-k} = h_0 x_n + \underbrace{\sum_{k=1}^{L-1} h_k x_{n-k}}_{ISIterm} \tag{1.4}$$

If the channel length is known, ISI can simply be eliminated by upsampling the signal by L before it is passed through the channel and on the receiver side, it is downsampled by L before modulation. But in this case, it is difficult to estimate the length of channel. Moreover, upsampling leads to high bit rate which increases transmission bandwidth requirements. Therefore, this technique is useful only for very short channels in which equalization is easier to implement. Thus, equalization comes out to be the only solution for removing intrachannel interference.

B. Interchannel IS1

Interchannel interference or the adjacent channel interference results from the non-ideal sub band filters. Thus, it can be reduced significantly by the use of filters having high spectral containment or simply high stop band attenuation. For this purpose, the long sub band filters are used which cause longer processing delays. Due to the presence of non-ideal sub band filters, every sub channel obtains a random unrelated contribution involving variable amplitudes from all other sub bands. AWGN model is used to approximate these contributions. If the channel is ideal, interchannel ISI does not have any effect due to orthogonality [9].

OFDM is very robust against ISI which makes it suitable for the high speed communication systems. When the data transfer speed is increased in the communication systems, the time duration for every single transmission gets shorter. But the delay time caused by multipath makes ISI a limitation in high data rate transmission. OFDM is the solution to this problem as it sends many low speed transmissions simultaneously. Adding a guard interval eliminates the effect of ISI but the guard period must be longer than the delay spread of channel. The remaining effects including amplitude scaling and phase rotation, resulting from ISI are corrected by the channel equalization.

1.1.4 Advantages

1. OFDM allows simultaneous transmission of subcarriers over a common channel thus making the efficient use of the available spectrum.
2. OFDM divides the frequency channel into many narrowband flat fading sub-channels which makes it more resistant to frequency selective fading.
3. OFDM makes use of cyclic prefix which helps in eliminating ISI and ICI.
4. If the symbols are lost due to frequency selectivity of channel, they can be recovered using appropriate channel coding and interleaving.
5. Channel equalization is potentially simpler as compared to the adaptive equalization techniques used in single carrier systems.
6. Maximum likelihood decoding can also be used in OFDM with less complexity.
7. OFDM is comparatively less sensitive to the timing offsets than single carrier systems.
8. FFT and IFFT are used in OFDM for modulation and demodulation in place of arrays of sinusoidal generators which makes it computationally efficient and cost effective.

9. It provides better protection against co-channel interference as well as impulsive parasitic noise.
10. OFDM randomizes the burst errors effectively which are caused due to fading and allows proper reconstruction even without forward error correction.

1.1.5 Disadvantages

1. The amplitude of OFDM signal has a very large dynamic range. Therefore, RF power amplifiers are required which possess high peak to average power ratio (PAPR).
2. OFDM systems are more sensitive to the carrier frequency offset and drift as compared to the single carrier systems.

1.2 CONVENTIONAL OFDM SYSTEM USING FFT

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation technique in which the spectrum of the subcarriers overlap on each other. The frequency spacing among them is selected in such a way that orthogonality is achieved among the subcarriers. The block diagram of a basic OFDM system is shown in Fig. 2.

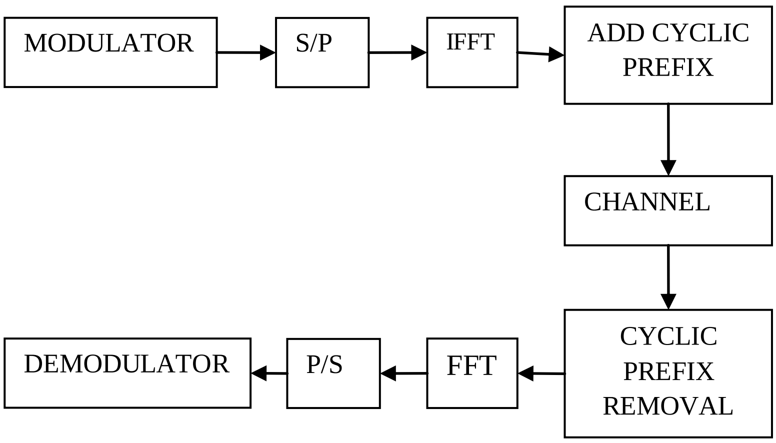

Figure 1.2: OFDM trans-receiver

The inverse transform block can be implemented using either IDFT or IFFT, and forward transform using DFT or FFT. The data generator first generates a serial random data bits stream [10]. This serial data stream carrying information is grouped into bits/word according to the modulation scheme used and then each word is converted into parallel bit stream. Each bit stream is used to modulate one of the N orthogonal subcarriers [10]. The data is processed using modulator to map the input data into symbols based on the modulation technique used. These symbols are now passed through IFFT block to perform IFFT operation to generate N parallel data streams. Its output in discrete time domain is given by equation (1.5),

$$X_k(n) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X_m(i) e^{\frac{j2\pi ni}{N}} \tag{1.5}$$

Then the cyclic prefix is added to this transformed data in order to alleviate the ISI effect. Cyclic prefix is usually the last 25% part of the original symbol. The next step is to pass this data through a channel. The channel model can be AWGN, Rayleigh or any other channel. To generate an OFDM symbol, the channel encoding of serial data stream is done followed by modulating the symbol using any modulation scheme. Before modulating the signal using IFFT, these serial data symbols are converted into N parallel data constellation points where N is number of IFFT points. After processing the data through IFFT block, the time domain OFDM modulated symbol is converted back to a serial stream and cyclic prefix which acts as guard interval is added to each OFDM symbol. The basic rectangular pulse shape for the symbols is considered as they have large bandwidth due to its sinc shaped spectrum. Thus, windowing is essential to reduce the out of band energy of the side lobes. Then the symbol stream is converted to analog form for pass-band processing and transmission. The receiver performs the exact opposite of the transmitter [11].

To successfully generate OFDM, the relationship among all the carriers must be controlled carefully to sustain the orthogonality of the carriers. Due to this, OFDM symbol is generated choosing the spectrum required firstly, based on the input data, and modulation scheme used. Some data is assigned to each carrier to be produced to transmit. The required amplitude and phase of the carrier is then calculated based on the modulation scheme which is typically differential BPSK, QPSK, or QAM.

The multiple orthogonal subcarriers generated, which are overlapped in spectrum mathematically resemble to N-point IDFT of the transmitted symbols. In practice, DFT and IDFT processes are useful for implementing these orthogonal signals. So to generate an OFDM symbol IDFT of modulated signal is computed. Fast Fourier transform and inverse Fast Fourier transform can be used to implement DFT and IDFT, respectively [12]. To generate orthogonal sub-carriers, N-point IFFT is applied to the transmitted symbols to generate the sum of N orthogonal subcarrier signals. Thus an OFDM symbol is generated by computing the IDFT of the complex modulation symbols to be conveyed in each sub-channel. The transformed output is now added with a cyclic prefix before transmission which acts as a guard interval and it is added in order to alleviate ISI effect. It is usually last 25% part of the original OFDM symbol. This symbol is passed through AWGN channel. At the receiver, the exact reverse operation is carried out to obtain the original data back. The Cyclic prefix is eliminated and the data is processed in the FFT block. Finally, it is passed through the demodulator to recover original data. The output of the FFT in frequency domain is given by,

$$U_m(i) = \sum_{n=0}^{N-1} U_k(n) e^{-\frac{j2\pi ni}{N}} \tag{1.6}$$

The receiver receives the data after passing through channel which gets corrupted by additive noise. Then, the N-point FFT of the received symbols is taken to obtain the noisy version of transmitted symbols at the receiver. Since all the subcarriers are having finite duration, the spectrum of OFDM signal can also be represented as the summation of the frequency shifted sinc functions taken in the frequency domain.

1.2.1 Mathematical Analysis of FFT-OFDM

Consider the transmission system as shown in Figure 1.3. The shape of transmitted spectra is selected so that ICI does not occur; i.e., the spectra of all the individual subchannels are zero at the reamaining subcarrier frequencies. The N subcarrier frequencies are modulated by N serial data elements which are spaced by $\Delta t = \frac{1}{f}$, where f_s is the symbol rate, and are then frequency division multiplexed. To make the system less vulnerable to delay spread impairments, the signalling interval T is increased to $N\Delta t$. Moreover, the subcarrier frequencies are chosen such that they are separated by multiples of *1/T* which results into zero signal distortion in transmission. If the coherent detection of a signal element is carried out in any one subchannel of the parallel system, it does not give any output for a received element in any other subchannel.

The data symbols $d(n)$ can, be represented as $a(n) + jb(n)$ where $a(n)$ and $b(n)$ are real sequences which represent the in-phase and quadrature components respectively and the transmitted waveform can be represented as [5]

$$D(t) = \sum_{n=0}^{N-1} \left\{ a(n) \cos\cos(\omega_n t) + b(n) \sin\sin(\omega_n t) \right\} \tag{1.7}$$

where $f_n = f_0 + n\Delta f$ and $\Delta f = 1/N\Delta t$. The pulse shaping can also be included in place of basic rectangular shape to extend the above expression.

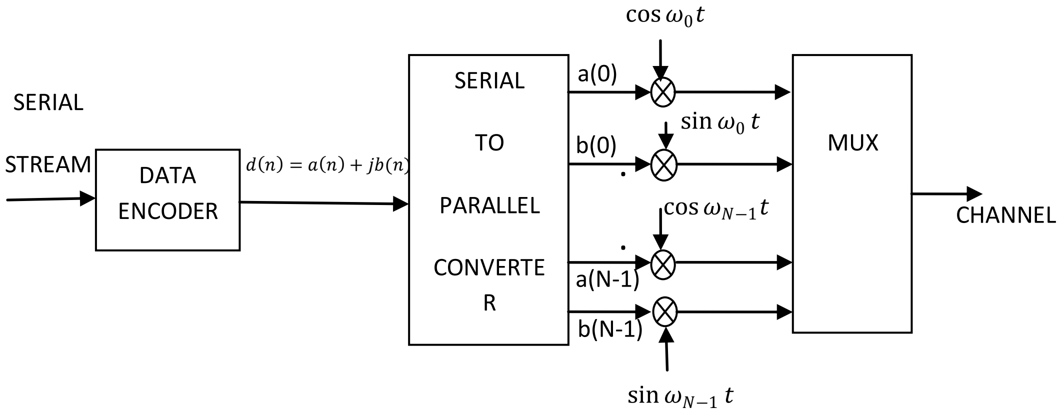

Fig. 1.3 OFDM Transmitter [5]

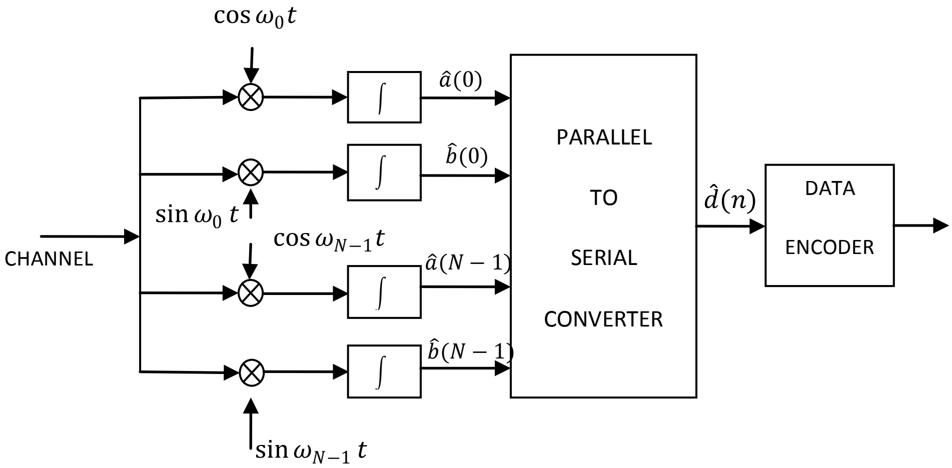

Figure 1.4: OFDM receiver [5]

Theoretically, bandwidth efficiency can be achieved by using M-ary digital modulation schemes in OFDM which is defined as bit rate per unit bandwidth, of $\log_2 M$ bits/s/Hz. If the symbol rate of the serial data stream is given to be $1/\Delta t$**,** the bit rate for a corresponding M-ary system is $\log_2 M/\Delta t$**.** However, every subchannel transmits at a much lower rate, $\log_2 M/(N\Delta t)$.

The total bandwidth of the OFDM system is [5]:

$$B = f_{N-1} - f_0 + 2\delta \tag{1.8}$$

where f_n is the n^{th} subcarrier and δ is the one-sided bandwidth of the sub channel. The subcarriers are uniformly spaced so that $f_{N-1} - f_0 = (N-1)\Delta f$. Since $\Delta f = 1/N\Delta t$, due to the orthogonality constraint, $f_{N-1} - f_0 = (1 - \left(\frac{1}{N}\right)\left(\frac{1}{\Delta t}\right)$.

Therefore, the bandwidth efficiency β becomes [5]:

$$\beta = \frac{\log_2 M}{\left(1-\frac{1}{N}\right)+2\delta\Delta t} \tag{1.9}$$

For strictly band-limited spectra having bandwidth Δf and orthogonal frequency spacing with $\delta = \frac{1}{2}\Delta f = 1/2N\Delta t$, $\beta = \log_2 M$ bits/s/Hz. But the spectra overflow the minimum bandwidth by the factor α so that $\delta = (1+\alpha)(1/2N\Delta t)$ and the efficiency given by equation (1.9) becomes [5]:

$$\beta = \frac{\log_2 M}{1+\frac{\alpha}{N}} < \log_2 M \tag{1.10}$$

To attain the highest bandwidth efficiency in an OFDM system, N must be large and α must be small.

1.2.2 Implementation of OFDM system using DFT

The main drawbacks of using the parallel systems are the hardware complexity required for implementation of the system, and chances of severe mutual interference among the subchannels when the transmission channel distorts the signal. The hardware complexity including filters, modulators, etc. can be minimized by removing any pulse shaping, and by using the DFT to implement the modulation processes [13]. The multitone data signal can be effectively implemented by taking the FFT of the original data stream and IFFT can be used to replace the bank of coherent demodulators. The equation (1.7) can be rewritten as:

$$D(t) = \mathrm{Re}\left[\sum_{n=0}^{N-1} d(n)e^{-j\omega_n t}\right] \tag{1.11}$$

Assuming $t = m\Delta t$, the resultant sampled sequence $D(m)$ can also be considered as the real part of the discrete Fourier transform of the data sequence $d(n)$. When the signal is truncated to the interval $(0, N\Delta t)$, a frequency response of $sin\, x/x$ is achieved on each sub channel having zeros at multiples of $1/T$. However, such spectral shape leads to large side lobes and gives rise to significant interchannel interference in the presence of multipath. The complexity can further be reduced by using the FFT algorithm to implement the DFT if N is large.

If the transmission channel is distortion less, the transmitted signals will be received at the receiver without any error due to the orthogonality of the subcarriers. Consider the transmission system in Fig. 1.4. The data to be transmitted is represented by the sequence of

N complex numbers $\{d(0), d(1), \ldots, d(N-1)\}$. The data encoder generates these complex numbers from a binary data sequence. Then, DFT is performed on the block of data sequence which generates the transmitted symbols [14]

$$D(m) = DFT\{d(n)\} = \sum_{n=0}^{N-1} d(n) e^{-j(2\pi/N)nm} \tag{1.12}$$

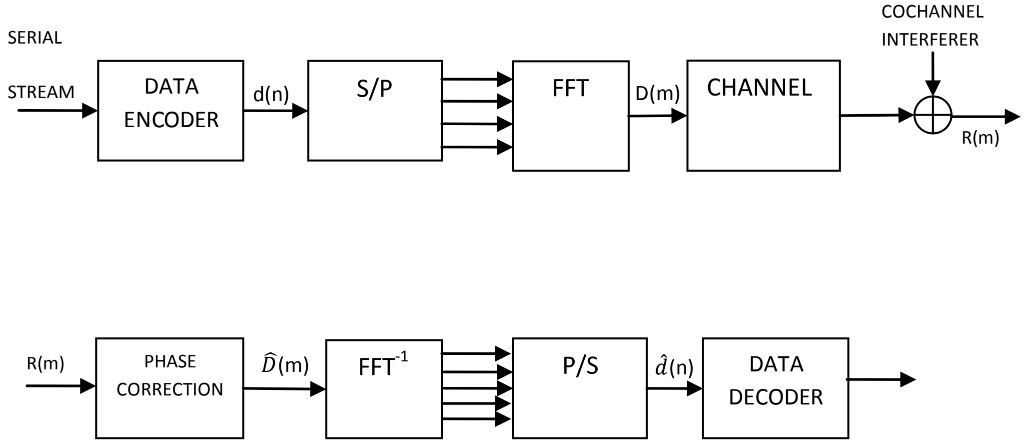

Figure 1.5: OFDM implemented using FFT [5]

As a distortionless channel has been assumed, the data sequence received at the output of the IDFT is exactly same as the transmitted data sequence because of the orthogonality among the subcarrier exponentials. The distortions caused due to the transmission medium lead to the impairments in orthogonality. In a non frequency selective flat Rayleigh fading environment, the Rayleigh channel effects can be characterized as the transmitted signal processed multiplicative noise process. This multiplicative process can be represented by a complex fading envelope having samples $Z(m) = A(m)e^{j\theta(m)}$ where $A(m)$ are the Rayleigh distribution samples and the $\theta(m)$ are uniform distribution samples. The sequence of equation (1.12) is multiplied by these samples to get equation (1.13),

$$R(m) = Z(m)D(m) \tag{1.13}$$

The output data sequence denoted by $\hat{d}(k)$ is the IDFT of equation (1.13),

$$\hat{d}(k) = \frac{1}{N}\sum_{m=0}^{N-1} Z(m)D(m)e^{j(2\pi/N)km}$$

$$= \sum_{n=0}^{N-1} d(n)\left[\frac{1}{N}\sum_{m=0}^{N-1} Z(m)e^{j\left(\frac{2\pi}{N}\right)m(k-n)}\right]$$

$$= \sum_{n=0}^{N-1} d(n) z(k-n) \tag{1.14}$$

where $z(n)$ is the IDFT of $Z(m)$. Clearly seen from equation (1.14), $\hat{d}(k)$ is represented as the complex-weighted average of the samples of a complex fading envelope. In the distortion less channel, if $Z(m) = 1$ for all m, $z(k-n)$ is the Kronecker delta function given by δ_{kn} and $\hat{d}(k) = d(k)$. In the presence of fading, $z(k-n) \neq \delta_{kn}$ and

$$\hat{d}(k) = d(k) z(0) + \sum_{\substack{n=0 \\ n \neq k}}^{N-1} d(n) z(k-n) \tag{1.15}$$

The second term $\sum_{\substack{n=0 \\ n \neq k}}^{N-1} d(n) z(k-n)$ represents the intersymbol interference caused due to the loss of orthogonality among subcarriers. If the fading is not corrected, the output sequence gets corrupted by ISI even in the absence of any co-channel interferer. The solution is to use pilot based correction which provides amplitude and phase reference and it also neutralizes the unwanted effects due to multipath propagation.

By definition, in a fading environment coherent detection requires a phase reference but gain correction is also required in an OFDM system to mitigate the intersymbol interference. If the phase correction and gain correction is used in the absence of co-channel interference, in equation (1.15), it can be easily shown that $\hat{d}(k) = d(k)$

In a cellular mobile system, if the other users are using same carrier frequency, it leads to the dominant transmission impairment assuming the desired signal and undesired co-channel interferer from single user is received simultaneously. It is also assumed that both the signals are modulated by different data sequences having the same signalling rates and are subjected under mutually independent Rayleigh fading [14].

Due to the need of enhancing the energy of the cochannel interferer during deep fading of the desired signal, it is not beneficial to use unlimited gain correction in the absence of a cochannel interferer in the received signal. If the unlimited gain correction is done in the presence of a cochannel interferer, it leads to the detrimental effects shown as follows. Let the desired transmitted signal sequence be $D(m)$ and $I(m)$ be the cochannel interferer sequence. With the desired fading sequences and interferer complex fading sequences as $Z_d(m) = A_d(m) e^{j\theta_d(m)}$ and $Z_i(m) = A_i(m) e^{j\theta_i(m)}$ respectively, the received sequence can be represented as

$$R(m) = Z_d(m)D(m) + \sqrt{\gamma} Z_i(m) I(m) \tag{1.16}$$

where γ is the interference-to-signal power ratio (SIR^{-1}). *R(m)* is corrected by a complex correction sequence $Z_c(m) = Z_p(m)$ the complex pilot fading envelope giving

$$\tilde{D}(m) = \frac{R(m)}{Z_c(m)} = \frac{Z_d(m)}{Z_p(m)} D(m) + \sqrt{\gamma} \frac{Z_i(m)}{Z_p(m)} I(m) \tag{1.17}$$

Taking the IDFT of equation (1.18), the received data sequence becomes

$$\hat{d}(k) = \sum_{n=0}^{N-1} d(n) z(k-n) + \sqrt{\gamma} \frac{Z_i(m)}{Z_p(m)} I(m) e^{j(2\pi/N)km} \tag{1.18}$$

where

$$z(k-n) = \frac{1}{N} \sum_{m=0}^{N-1} \frac{Z_d(m)}{Z_p(m)} e^{j\left(\frac{2\pi}{N}\right)m(k-n)}$$

If the unlimited gain correction and phase correction is done, i.e., $Z_p(m) = Z_d(m)$, $z(k-n) = \delta_{kn}$, there is no ISI, and equation (1.18) becomes

$$\hat{d}(k) = d(k) + \sqrt{\gamma} \frac{1}{N} \sum_{m=0}^{N-1} I(m) \frac{Z_i(m)}{Z_d(m)} e^{j(2\pi/N)km} \tag{1.19}$$

Here, the cochannel interferer is the only reason for distortion. As $Z_i(m)$ and $Z_d(m)$ are statistically independent, the average energy of the interferer may get boosted than the desired signal by unlimited gain correction if the desired signal is under fade but the interferer is not [15].

A substitute to the unlimited gain correction and phase correction is by having a limited gain correction but the desired signal into deep fades is not followed. However, if the correction of the desired signal is not done perfectly, it leads to increased intersymbol interference.

The correction signal in such situation is given in the form of equation (1.20) [15],

$$Z_c(m) = \begin{cases} A_d(m) e^{j\theta_d(m)} & when\ A_d(m) > \epsilon \\ \epsilon e^{j\theta_d(m)} & when\ A_d(m) \le \epsilon \end{cases} \tag{1.20}$$

where ϵ is the gain limit. The gain limit is defined in terms of the average value of local field strength. Therefore, if $z(k-n) \neq \delta_{kn}$ in equation (1.19), it results in intersymbol interference

(ISI). As a result, there is a trade-off between the intersymbol interference and energy of the cochannel interference.

Moreover, an optimum gain correction factor can be developed as another alternative which considers both distortion effects. The optimum gain correction factor given by $F(m)$ can be derived by minimizing the mean square distortion between $D(m)$ and $\widehat{D}(m)$. The correction sequence in equation (1.20) becomes,

$$Z_c(m) = Z_p(m)F(m)$$
$$= Z_d(m)\left[1+\gamma\left(\frac{A_i(m)}{A_d(m)}\right)^2\right] \tag{1.21}$$

It would be more difficult to realize the correction procedure as compared to the gain limiting procedure. The frequency selective fading can also be present in addition to the distortions caused by ISI and cochannel interference. This makes the received signal envelopes decorrelated at different frequencies which reduce the effectiveness of the pilot correction procedure as there is possibility that a data point which is being corrected may be decorrelated from the corresponding pilot complex fading envelope.

Eventually, OFDM technique has a major advantage of averaging the impairments which makes the bursty Rayleigh channel less bursty [14]. The correlation among the samples of the complex fading envelope decides the extent to which the averaging process approaches a Gaussian channel. Also, more the value of *N*, more the independent fades are averaged which enables the randomization of the burst errors thus helps in bit error correction. The simulation results make this property more evident which indicate that the curves for the BER fall between the exponential Gaussian channel curves and the linear Rayleigh channel curves. If the value of *N* is very large, the BER curve approaches that for a Gaussian channel [15].

1.3 PROBLEM DEFINITION

Wavelet based OFDM is found to be an efficient method to replace FFT based OFDM systems as wavelets has many advantages as compared to FFT-OFDM. DWT based OFDM has the potential to decrease the hardware complexity because Cyclic Prefix is not required in this case and proposed system gives nearly perfect reconstruction.

DWT is an effective tool to study the signals in time frequency joint domain as it has the ability to provide simultaneous information about time and frequency, thereby gives the time frequency representation of the signal. It has been found that wavelets have compact localization in both time domain and frequency domain and have better orthogonality. DWT based OFDM has the ability to combat the narrowband interference as the wavelets possess high spectral containment properties; making the system more robust against inter-carrier interference as compared to FFT realization. As cyclic prefix is not used in DWT OFDM, the data rates are better than that of FFT OFDM systems [16].

Wavelet based OFDM is employed in order to remove the use of cyclic prefix which decreases the bandwidth wastage and the transmission power is also reduced by the use of wavelet transform. The spectral containment of the channels in DWT-OFDM is also better than the FFT-OFDM. Discrete wavelet transform is a type of wavelet transform which is found to be an alternative approach to replace IFFT and FFT in OFDM systems. In Wavelet transform, the desired signal is decomposed into set of basis waveforms, known as wavelets, which provide the way for analyzing the signals by investigating the coefficients of wavelets. DWT is used in several applications and has become very popular among engineers, technologists and mathematicians. The basis functions of wavelet transform are localized both in time and frequency and possess different resolutions in both domains which makes the wavelet transforms a powerful tool in various applications.

Different resolutions correspond to analyze the behaviour of the process and the power of the transform. Due to these properties, the wavelets and wavelet transform find their applications in various fields such as data compression, image compression, radar, computer graphics and animation, astronomy, human vision, nuclear engineering, acoustics, biomedical engineering, music, seismology, turbulence, magnetic resonance imaging, fractals and pure mathematics.

Since wavelet transform has many advantages such as flexibility, lesser sensitivity against channel distortion and interference as well as better utilization of spectrum, it has been proposed to design the sophisticated wireless communication systems [16]. Wavelets are beneficial in various aspects such as channel modelling, data representation, transceiver design, and source and channel coding, data compression, interference minimization, energy efficient networking and signal de-noising in wireless communication systems.

A low pass filter and high pass filter is employed to operate as QMF and satisfies perfect reconstruction and ortho-normal properties. In wavelet based OFDM, the modulated signal is transmitted using zero padding and vector transposing. DWT is known as a flexible and highly efficient method for decomposition of signals.

1.4 WAVELETS

A wavelet is a small waveform that has effectively limited duration having an average value of zero. Wavelets have limited duration and tend to be asymmetric and irregular. The wavelet analysis consists of breaking up a signal into scaled and shifted versions of the original signal or mother wavelet. Wavelets are a class of functions used to localize a given function in both space and scaling. A family of wavelets can be constructed from a function $\psi(x)$, sometimes known as a "mother wavelet," which is confined in a finite interval [17]. Daughter wavelets $\psi^{a,b}(x)$, are then formed by translation (b) and contraction (a). Wavelets are especially useful for compressing image data, since a wavelet transform has properties which are in some ways superior to a conventional Fourier transform.

An individual wavelet can be defined by [17],

$$\psi^{a,b}(x) = |a|^{-1/2}\,\psi\left(\frac{x-b}{a}\right) \tag{1.22}$$

Then,

$$W_{\psi}(f)(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\,\psi\left(\frac{t-b}{a}\right)dt \tag{1.23}$$

where a is the scaling factor and b is the translation factor.

1.4.1 Orthonormal Wavelets

The orthonormal wavelets can be given in terms of convolution equation as follows [18]:

$$h_k(n) = h\left(\frac{n}{2^k}\right) * g\left(\frac{n}{2^{(k-1)}}\right) * \ldots\ldots * g\left(\frac{n}{2^{(k-j)}}\right) * \ldots\ldots * g(n)$$

$$h_{M-1}(n) = g\left(\frac{n}{2^{(M-2)}}\right) * g\left(\frac{n}{2^{(M-1)}}\right) * \ldots\ldots * g\left(\frac{n}{2^{(k-j)}}\right) * \ldots\ldots * g(n) \tag{1.24}$$

where $k-j$ is a non-negative integer for $k, j \in \{0,1,\ldots\ldots,\mathrm{M}-2\}$ and M is the number of subcarriers. The sequences $g(n)$ and $h(n)$ correspond to the discrete impulse responses of the low pass and high pass filters of a Quadrature Mirror Filter bank with perfect reconstruction. They are used to construct the orthonormal wavelets, $h_k(n)$**,** from the tree-structured QMF bank. The high pass filter can be found from the low pass filter by the relationship $h(n) = (-1)^n g(L-1-n)$, where L is the length of the sequence. The orthonormality among the wavelets is given as: $h_k(n), h_j\left(n-2^{n_j}m\right) = \delta(k-j)\,\delta(m)$

where $\langle . \rangle$ denotes the inner product, δ is the Kronecker delta function and n_j is a positive integer.

1.4.2 Quadrature Mirror Filters

An important feature of the discrete wavelet transform is the relationship between the impulse responses of the high pass (analysis) and low pass (scale) filters. The relationship is stated below [19]:

$$h[n] = (-1)^n g[L-1-n], \tag{1.25}$$

where $g[n]$ and $h[n]$ are the impulse responses of the high pass and low pass filters, and L is the filter length. Filters satisfying this condition are commonly used in signal processing, and they are known as the Quadrature Mirror Filters (QMF). The two filtering and sub-sampling operations can be expressed by the expressions given in (1.26),

$$y_{high}[k] = \sum_n x[n] g[2k-n],$$

$$y_{low}[k] = \sum_n x[n] h[2k-n] \tag{1.26}$$

The reconstruction in this case is easy since the half-band filters form orthonormal bases. The above procedure is followed in a reverse order for the reconstruction. The signals at every level are upsampled by two, passed through the synthesis filters $g'[n]$, and $h'[n]$ (highpass and lowpass, respectively), and then added up. A nice feature to note here is that the impulse responses of the analysis and synthesis filters are conjugate time reversed versions of one another i.e.

$$h'[n] = g^*[-n] \text{ and } g'[n] = h^*[-n]$$

Therefore, the reconstruction formula for each layer is given as:

$$x[n] = \sum_{k=-\infty}^{\infty} \left(y_{high}[k] g[2k-n] + y_{low}[k] h[2k-n] \right) \tag{1.27}$$

1.4.3 Properties of Wavelets

The most important properties of wavelets are the admissibility and the regularity conditions and these are the properties which gave wavelets their name. The square integrable function $\Psi(\mathrm{t})$ satisfying the admissibility condition,

$$\int \frac{|\Psi(\omega)|^2}{|\omega|} d\omega < +\infty \tag{1.28}$$

can be used to first analyze and then reconstruct the signal without loss of information. In the above equation $\Psi(\omega)$ is the Fourier Transform of $\Psi(t)$.The admissibility condition implies that the Fourier Transform of $\Psi(t)$ vanishes at zero frequency, i.e.

$$|\Psi(\omega)|^2 |_{\omega=0} = 0 \tag{1.29}$$

This means that wavelets must have a band-pass like spectrum. A zero at the zero frequency also means that the average value of the wavelet in time domain must be zero,

i.e., $\int \Psi(t) dt = 0$

Therefore it must be oscillatory. That is $\Psi(t)$must be a wave.

A. Regularity

The wavelet transform of a one-dimensional function is two-dimensional. The time-bandwidth product of the wavelet transform is the square of the input signal and for most practical applications this is not a desirable property. Therefore, one imposes some additional conditions on the wavelet functions in order to make the wavelet transform decrease quickly with decreasing scale s. These are the regularity conditions and they state that the wavelet function should have some smoothness and concentration in both time and frequency domains [20].

B. Vanishing moments

If we expand the wavelet transform into the Taylor series at $t = 0$ until order n (let $\tau = 0$ for simplicity) we get

$$X(s,0) = \frac{1}{\sqrt{s}} \left[\sum_{p=0}^{N} x^{(p)}(0) \frac{t^p}{p!} \psi\left(\frac{t}{s}\right) dt + R(n+1) \right] \tag{1.30}$$

Here $x^{(p)}$ stands for the p^{th} derivative of x and $R(n + 1)$ means the rest of the expression. Now if we define the moments of the wavelet by

$$N_p = \int t^p \Psi(t) dt \tag{1.31}$$

Then we can write the equation (31) into the finite development

$$X(s,0)=\frac{1}{\sqrt{s}}\left[x(0)N_0 s+\frac{x^{(1)}(0)}{1!}N_1 s^2+\frac{x^{(2)}(0)}{2!}N_2 s^3+\ldots+\frac{x^{(n)}}{n!}N_n s^{n+1}+R\left(s^{n+2}\right)\right] \quad (1.32)$$

From the admissibility condition we already have that the 0^{th} moment $N_0 = 0$ so that the first term in the right hand side of above equation is zero. If we now manage to make the other moments up zero, then the wavelet transform coefficients $x(s,\tau)$ will decay as fast as s^{n+2} for a smooth signal $x(t)$. This is known in as the vanishing moments or approximation order. If a wavelet has N vanishing moments, then the approximation order of the wavelet transform is also N**.** For large classes of Wavelets, more regularity implies more vanishing moments and with increasing number of vanishing moments the wavelet becomes smoother or more regular [20]. Summarizing, the admissibility condition gave us the wave, regularity and vanishing moments gave us the fast decay and put together they give us the wavelet.

C. Compact Support

Compactly supported wavelets that is, be zero off for some finite intervals were first developed by Daubechies. The scaling function is compactly supported if and only if the filter constructed by the wavelet has a finite support and their supports are the same. Once a scaling function is found that constitutes a valid MRA, an appropriate analyzing wavelet is readily determined [20].

D. Symmetry

Symmetric scaling functions and wavelet functions are important because they are used to build basis of regular wavelets over an interval.

E. Wavelet Filter Length

The waveforms length can be derived from a detailed analysis of the tree algorithm. Explicitly, the wavelet filter of length L_0 generates M waveforms of length:

$$L=(M-1)(L_0-1)+1 \quad (1.33)$$

In Daubechies wavelet family for instance, the length L_0 is equal to twice the wavelet vanishing order N. For the order 2 Daubechies wavelet, L is equal to 4, and thus a 32 subcarrier wavelet transform is composed of waveforms of length 94. Daubechies has proved to generate an orthogonal wavelet with N vanishing moment a filter with minimum length $2N$ had to be used. Daubechies filters, which generate Daubechies wavelets, have a length of $2N$.

Table 1.1 Summary of Wavelet families' characteristics and their associated wavelet filter lengths [15]

Wavelet Family	Abbreviated Name	Vanishing Order	Filter Length L_0
Haar	haar	1	2
Daubechies	dbN	N	2N
Symlets	symN	N	2N
Coiflets	coifN	N	6N
Discrete Meyer	dmey	-	62

1.5 ZERO FORCING EQUALIZATION

Zero forcing equalization can be applied to time domain DWT OFDM system which equalizes the received signal by applying the inverse of the channel frequency response to it. It is done to compensate the effect of channel from the signal in order to remove intersymbol interference from it [21]. If H is the channel response, x is the transmitted signal and n is additive white Gaussian noise, the received signal y be represented by equation (1.34),

$$Y = Hx + n \tag{1.34}$$

Then the received signal will be equalized bin time domain by multiplying it with inverse of channel response i.e.

$$Y_{equ} = Y.\left(H^{-1}\right) \tag{1.35}$$

1.6 CONVOLUTIONAL ENCODING

Convolutional codes are the promising solution to the increasing demands of high data rate applications of wireless communication. Convolutional codes form the powerful and most widely used class of error-correcting codes. Viterbi decoding, in conjunction with improved version of sequential decoding made the use of Convolutional codes possible in satellite as well as deep space communications. These codes also find their applications in various wireless standards (Wi-Fi 802.11, Wi-MAX), GSM, and voice-band modems. Convolutional codes also play a vital role in low latency applications such as constituent codes in Turbo codes and in speech transmission [22].

Convolutional codes as inner codes are used with block codes for correcting burst errors and as outer codes to form concatenated codes. When the Convolutional codes are decoded using Viterbi-like algorithms, the wrong path chosen in trellis leads to the errors occurring in bursts. Such burst error patterns that occur in the decoding of inner code are recovered using the burst error correcting capabilities of the outer code. Convolutional codes add redundant bits i.e., parity bits to the message bits to protect the useful information. Thus the parity bits are transmitted along with the message bits. There are many ways to understand the Convolutional codes and maximum likelihood decoding algorithm is used to recover the original message by selecting the most likely message from the set of all transmitted messages [23].

Convolutional codes are somewhat considered as an identical form of block codes, but they are entirely different in terms of their description, properties, their decoding techniques as well as applications.

The Convolutional codes differ from block codes in the following manners:

- Block codes transforms the words into codewords block by block, but Convolutional encoder performs the Convolutional of information bits with the generator coefficients and transforms the whole sequence into encoded bits.
- In Convolutional codes, a block of n bits generated by the encoder depends on the block of k message bits as well as on the preceding (N-1) blocks of message bits.
- Convolutional codes are very efficient in processing the soft-decision input and computing the soft-decision output.
- Block codes are constructed using analytical methods, but Convolutional codes are constructed by trial and error methods.
- Unlike block codes, Convolutional codes do not require any block synchronization.

1.6.1 Convolutional Encoder

A Convolutional encoder is known to be linear having finite number of states. It consists of shift registers and algebraic function generators [23]. Usually the binary data is considered which is shifted along the shift registers by one bit at a time. Convolutional codes are generally defined in terms of three parameters: (n, k, m). Here, n is the number of output encoded bits, k is the number of input message bits and K is the number of memory registers.

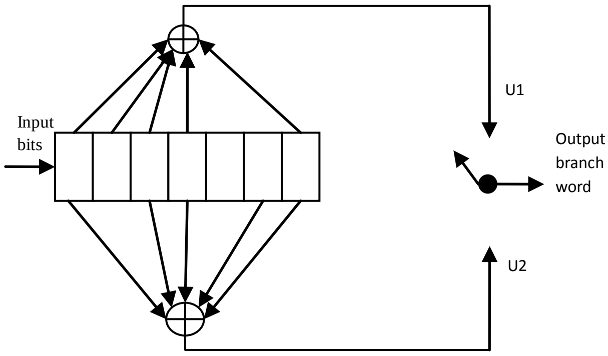

Fig. 1.6 Convolutional Encoder [25]

Also, k/n is the code rate $(n \geq k)$. The value of these n and k parameters ranges between 1 to 8, m from 2 to 10 and code rate can take value between 1/8 to 7/8 expect in deep space communication where its value is taken 1/100 or even longer. The manufacturers always specify the code parameters (n, k, L) on the Convolutional code chips where L is known as constraint length. It is given by: $L = k(m-1)$

Each message bit remains in the encoder memory for m+1 time units and it is likely to affect any of the n outputs. Thus, the constraint length can be represented as the maximum number of encoder outputs that can be affected by the number of information bits in the encoder memory. The encoder for generator polynomial (171,133) with code rate ½ is shown in figure 1.5.

1.7 BIT INTERLEAVING

In order to maximize the diversity in a fading channel, the error correction coding coupled with interleaver is used. It separates the adjacent coded symbols farther than the coherence time of fading process by creating large Euclidean distance between the code words of a convolution code. The burst errors occurring in the channel or caused by the detector on the receiver side are dispersed by a de-interleaver at the receiver. A random interleaver is used in this system and a pseudo-random permutation is selected, which is assumed to be known both at the transmitter and the receiver and is used to reorder the coded symbols [24].

1.8 CHANNEL MODELS

1.8.1 AWGN

The Additive White Gaussian Noise Channel is the simplest mathematical model for channel realization when the thermal noise is assumed to be the only source of disturbance at the receiver side. The AWGN channel simply adds the white Gaussian noise to the signal which is transmitted through it [25]. Thus, the received signal $r(t)$ is represented as the sum of transmitted signal $s(t)$ through AWGN channel and the white Gaussian noise $n(t)$ added to it, i.e.

$$r(t) = s(t) + n(t) \tag{1.36}$$

Also, the noise sample follows the Gaussian distribution and its probability density function with variance σ^2 is given by equation (1.37) [17],

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-m)^2}{2\sigma^2}} \tag{1.37}$$

1.8.2 Rayleigh Channel

Fading occurs as a result of multipath components present in a channel. When the signal is transmitted through a wireless propagation channel in the absence of even single direct link between transmitter and receiver, the transmitted signal experiences multiple reflections, diffractions, refractions and scattering which results in the time spreading of the signal and causes fluctuations in the amplitude, phase and the angle of arrival of the received signal, giving rise to the name 'multipath fading'. If both the transmitter and receiver or one of them is moving, then these moments leads to Doppler shifts in the received signal resulting in intercarrier interference [25].

When a signal is transmitted through a Rayleigh channel, its power is assumed to vary randomly according to the Rayleigh distribution. The Rayleigh distribution is represented by the radial component of the sum of two Gaussian random variables which are uncorrelated. The Rayleigh fading channel is considered to model the effect of propagation environment on the radio signals such as in wireless devices. Rayleigh fading model is mostly used when the line of sight is not present between the transmitter and the receiver. The time dispersion in a multipath environment causes the signal to undergo either flat with Rayleigh distribution or frequency selective fading. Small-scale fading is also known as Rayleigh fading due to the fact that if there are large number of multiple reflective paths but there is not even a single line-of-sight signal component, the received signal's envelope is statistically described by a Rayleigh probability density function given as [26]:

$$p(x) = \begin{cases} (x/\sigma^2)e^{\left(-\frac{x^2}{2\sigma^2}\right)} & 0 \le x < \infty \\ 0 & otherwise \end{cases} \tag{1.38}$$

where x is amplitude of the received signal, and $2\sigma^2$ is the mean power of the multipath signal envelop.

1.9 OUTLINES OF THE THESIS

Chapter 1 concentrates on the brief overview of OFDM, its characteristics and advantages and an introduction to wavelets and Convolutional encoding and their analysis. **Chapter 2** provides an insight into literature review related to the DWT based OFDM systems and its comparison with conventional FFT based OFDM system. The gaps and drawbacks of the existing system are discussed in **Chapter 3**. Later, the objectives are defined for the thesis work carried out. The proposed DWT based OFDM system with encoding and its mathematical analysis is presented in **Chapter 4**. In **Chapter 5,** simulation results carried out using MATLAB are discussed for the comparison of DWT-OFDM and FFT-OFDM and then comparison of the different wavelet families among themselves. Also, the proposed encoded DWT-OFDM is compared with DWT-OFDM without encoding in terms of bit error rate. Finally, **Chapter 6** concludes the work carried out in this thesis with the future scope.

CHAPTER 2
LITERATURE REVIEW

This chapter concentrates on the literature review including OFDM systems, DWT based OFDM systems, and comparison of FFT based OFDM system with DWT based OFDM systems and Convolutional encoding. By studying the data through many sources, we work for improving the performance of DWT based OFDM system by simulation method.

2.1 EVOLUTION OF FFT BASED OFDM SYSTEMS

Robert W. Chang et al. [9] introduced an orthogonal multiplexing technique to simultaneously transmit large number of data messages with maximum data rate through a transmission medium which is band-limited but without nay ISI and ICI. Adaptive correlation is used for data processing as the orthogonality is sustained among the received signal without any effect of phase distortions. This proposed system provides strong protection against channel noises as well as intersymbol interferences.

L. J. Cimini [5] analyzed a modulation technique which combats the effects of cochannel interferences and multipath propagation in a digital mobile channel. DFT is used to multiplex the signals in frequency orthogonally and Rayleigh fading effect is significantly reduced when used with pilot based correction with an improvement of 6 dB. The proposed technique also provides protection against delay spread.

S. B. Weinstein et al. [7] proposed a data communication system by using DFT and IDFT for the modulation and demodulation processes. The system requires banks of subcarrier oscillators and coherent demodulators. In order to eliminate the complexity, Fast Fourier system can be used for digital implementation. The effects of linear channel distortions are studied and differential phase modulation scheme is used.

R. Kumar et al. [10] compared the performance of time domain equalization with frequency domain equalization technique by using a window function in time domain equalization and correlative polynomial in frequency domain equalization. It is shown that windowing scheme performs better to suppress ICI than correlative coding. Moreover, the CIR is improved and BER is reduced in case of time domain windowing technique.

2.2 PERFORMANCE OF DWT BASED OFDM SYSTEMS

Wornell et al. [21] introduced the design of transmitter and receiver for wavelet modulation. The performance of wavelet modulation in an additive white Gaussian noise (AWGN) channel had also been also evaluated. Moreover, the bit error rate (BER) performance of wavelet modulation has been discussed as a function of Signal to Noise Ratio (SNR) in the channel. Also, the estimate of the received signal becomes more accurate when the number of noisy observations used to calculate it is increased.

Dereje Hailemariam et al. [28] investigated the performance of Wavelets based MC-CDMA in three transmission scenarios and in his direction to future work he predicts designing of wavelet filters which are better suited to OFDM left as an area to be explored.

Antony Jamin et al. [24] concluded the performance results of the new modulation scheme named wavelet packet modulation as an alternative to the conventional OFDM and they stressed to study the best method to be used in order to select suitable wavelets. The selection of orthogonal wavelet bases, which can match the corresponding channel characteristics and other parameters for wireless communication, was left for future investigation.

Rohit Bohde et al. [33] adopted Discrete wavelet transforms (DWT) in place of FFT for frequency translation by using different modulation schemes i.e. 16-QAM, 32-QAM, 64-QAM and 128-QAM for both DWT and FFT based OFDM system model to achieve better performance in terms Bit Error Rate for AWGN channel. It was found that all the wavelets perform better as compared to the IFFT-FFT implementation. Moreover, Haar and bior1.1 mother wavelets were proved to be the best choice for implementation of DWT-OFDM. He further proposed to design and implement an OFDM transmitter and receiver on FPGA hardware. His work also included the designing of mapping module, serial to parallel converter and parallel to serial converter module. For FPGA implementation, Haar wavelet was recommended.

Md. Mahmudul Hasan et al. [23] presented that PAPR can be greatly reduced in DWT based OFDM systems if the traditional sinusoid carriers of the FFT based OFDM are replaced with suitable wavelets. Also, the PAPR performances of wavelet based OFDM system and classical FFT based OFDM system are examined. The simulation results showed that the Complementary Cumulative Distribution Function of PAPR for the DWT based OFDM signal achieved about 7dB improvement in PAPR than the traditional OFDM signals at 10-3 of CCDF. OFDM is considered as an attractive signalling technique for communications due to its channel robustness and spectrum efficiency but the drawback of very high peak power of the composite transmit signal. The simulation results showed that PAPR could be reduced up to 7dB using different wavelet functions.

El-Khamy et al. [36] proposed the use of discrete wavelet transform (DWT) in OFDM systems to mitigate the degrading effect of inter symbol interference successfully without using any cyclic prefix (CP). Therefore, bandwidth is conserved and the spectral efficiency is also improved. In this paper, least mean square (LMS) adaptive beamformer is utilized in a DWT based OFDM system is considered. The use of the DWT helps in reducing the signal space dimension which reduces the complexity along with the data denoising. Time saving can be achieved in signal beamforming processing by taking different decomposition level in the wavelet transform, with acceptable accuracy. It is demonstrated through the theoretical analysis and computer simulations that the suggested scheme achieves better beamforming performance with faster convergence, when different wavelet families and different decomposition levels are used, as compared to conventional adaptive beamforming.

Govinda Raju et al. [39] showed that the Haar and Daubechies based orthonormal wavelets have the capability of reconstructing the transmitted signal at the receiver and the effect of noise is minimized using wavelet denoising for different values of SNR on AWGN channel. The transmitted symbols and reconstructed symbols are compared after wavelet denoising for an analysis. The scatter plot analysis is also presented for different values of SNR. The elapsed simulation time is less for DWT-OFDM as compared to FFT-OFDM. The DWT based OFDM has the potential to reduce hardware complexity since it does not need a cyclic prefix.

Marius Oltean **et al.** [42] examined the BER performance of a DWT based multicarrier modulation scheme. The frequency-selective as well as time-variant channel is considered. The time-frequency localization of the wavelet carriers significantly influences the BER performance at certain transmission scales. The BER performance of a Wavelets based OFDM transmission through a two-ray FSF channel has been investigated. Under these conditions, the good frequency localized wavelets provide the best results as compared to the wavelets localized in time which leads to the poor performance. By balancing the ISI with the time variability of the channel, those wavelets achieving a convenient time-frequency trade-off can also adapt better to the conditions of the channel and lead to superior performance.

Anfal Ali Alansari [44] introduced the Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) system which offered new improvement performance results which have not been exist in either individual MIMO or OFDM. In order to confirm the issues such as high peak to average power ratio and synchronization error, the performance results of the individual OFDM, MIMO and MIMO-OFDM systems are discussed with the implementation of these systems using Discrete Wavelet Transform (DWT) and a comparison between these systems using MATLAB software is done. OFDM, MIMO and MIMO-OFDM systems were analyzed and a comparison between them were held in terms of BER and SNR and as a result for this work it was concluded that using wavelet transform enhances the performance of the wireless system; there is an improvement in the BER when wavelet transform was used.

Andre Ken Lee et al. [45] investigated the significant effect of presence of noise on the performance of the OFDM receiver in the wireless channel. Then a receiver based on DWT based FFT algorithm is proposed that has inbuilt denoising capacity coupled with little additional computation. MATLAB simulations are carried out to verify the feasibility of the proposed denoising algorithm on OFDM signals. The result shows the suppression of noise thus supporting the claim.

Matthieu Gautier et al. [41] proposed that it is possible to build a multicarrier modulation based on the good time-frequency localization of the pulse shaping that reduces both narrowband interferences and multipath channel interferences. The Wavelet theory is a solution to this scheme. The wavelet packet based OFDM is introduced and compared to the conventional Orthogonal Frequency Domain Multiplexing (OFDM) modulation in a wireless environment in presence of narrowband interferences and multipath channel interferences. MATLAB simulations proved that the wavelets are more robust against the narrowband interferences as compared to the OFDM modulation. Moreover, simulations showed that the use of complex wavelet outperforms the use of real wavelets for multipath transmission and outperforms the OFDM modulation without using the cyclic prefix technique.

2.3 COMPARISON OF FFT-OFDM WITH DWT-OFDM SYSTEMS

Haixia Zhang et al. [27] examined that performance of DWT-OFDM is much better than DFT-OFDM but there is a drawback of an error floor in DWT- OFDM systems which comes as a result of the Haar wavelet base as the different wavelet base have different characteristics. Therefore, other wavelet bases are proposed to be employed to improve the bit error performance of DWT- OFDM.

W. Saad et al. [29] proposed an efficient technique to implement the OFDM system using wavelet transform because of the drawbacks of OFDM-FFT based system such as the high peak-to-average ratio (PAR) and synchronization. The performance of proposed system is superior as compared to traditional OFDM-FFT system in Additive White Gaussian Noise (AWGN) channel. The system performance in terms of Bit Error Rate as a function of SNR and the peak-to-average ratio (PAR) is described. In addition, the proposed system offers nearly perfect reconstruction for the input signal in presence of the Gaussian noise. Moreover, it had lesser PAR value and the frame size had no effect on the proposed system performance.

Swati Sharma et al. [32] evaluated the performance results of an OFDM system by using FFT and DWT in terms of bit error rate probability (BER) for different channels scenarios. From the performed simulations in the AWGN channel, the DWT based OFDM system was found to have better performance than the FFT-OFDM for both types of the modulation techniques used viz. BPSK and DBPSK. Moreover, DWT-OFDM system outperformed the FFT-OFDM system in other channels i.e. Rayleigh and Rician fading channels as well and the BER of Wavelet based system was found to be lesser as compared to the Fourier transform based system. They also stressed on implementing and finding the transform that performs better in the multipath wireless channels.

Mrs. M.B. Veena et al. [35] proposed an DWT-IDWT based OFDM transmitter and receiver that achieve better performance in terms of SNR and BER for AWGN channel using different modulation schemes. The OFDM model is developed using Simulink and various test cases have been considered to verify the performance. The DWT OFDM using Lifting Scheme architecture is implemented on FPGA optimizing hardware, speed and cost. The wavelet filter used for this is Daubechies (9, 7) with N=2. The RTL code is written in Verilog-HDL and simulated in Modelsim. The design is then synthesized in Xilinx and implemented on Virtex5 FPGA board and the results were validated using ChipScope. It is seen that Haar outperformed FFT-OFDM system by nearly 1.5db for 16-QAM modulation scheme for the same BER of 0.001. Simulation is done using modelsim and results are analyzed. Then the design is implemented on FPGA and results are validated using ChipScope.

Lalchandra Patidar et al. [38] compared the BER performance of FFT-based Orthogonal Frequency Division Multiplexing system with DCT-Based OFDM using modulation technique BPSK over the AWGN environment and Multipath Rayleigh Fading environment. It is clear from the results that the BER shift in DCT- OFDM system is less than the FFT-OFDM system. Moreover, the BER performance of FFT-OFDM is compared with DCT-OFDM over AWGN environment and Multipath Rayleigh Fading environment. It has been observed that BER performance of FFT based and DCT based OFDM over AWGN is better as compared to Multipath Rayleigh Fading environment. FFT-Based OFDM is faster in terms of processing time as compared to DCT-Based OFDM on individual channel. The total processing time taken under AWGN channel is comparatively less as taken in case of Multipath Rayleigh Fading channel.

Achala Deshmukh et al. [34] compared the BER performance of conventional FFT-OFDM system with DWT-OFDM system and DCT-OFDM system in an AWGN channel environment and Saleh-Valenzuela (SV) channel model at 60 GHz using several wavelets such as Haar, Daubechies, Symlet, biorthogonal. The BER is calculated for signaling format BPSK and the performance is analyzed at 60 GHz. Simulation results show that DCT based scheme yields the lowest average bit error rate. While out of all wavelet mother used Haar and Daubechies wavelet based scheme yields lower BER than FFT-OFDM for an AWGN channel. Whereas SV channel model working at 60 GHz FFT-OFDM performs best amongst the three.

Rohit bohde et al. [37] presented a comparative study on BER performance of DWT based OFDM and FFT based OFDM systems using different wavelet families for AWGN channel. The results showed that the DWT-OFDM system operates at its optimum performance with different wavelets and DWT-OFDM is superior to FFT-OFDM in terms of bit error rate (BER). For DWT-OFDM, Haar and bior1.1 wavelets were found to be the best choice for implementation. For FPGA implementation, Haar wavelet is recommended.

G. Gowri et al. [31] analyzed the performance of OFDM using FFT as well as DWT using various parameters such as Bit Error Rate, eye diagram and constellation diagram. BER is calculated using different wavelets and different modulation schemes. The results proved that DWT-OFDM has a very great advantage over the FFT-OFDM. Especially, the HAAR wavelet under the BPSK modulation provides a very good platform for the wireless communication with the minimum BER, less Inter Symbol Interference (ISI), and generally with the less PAPR. The Daubechies 4 has been used at the receiver to take the forward transform and the minimum BER is obtained when the Haar wavelet is used at the transmitter at an SNR of 10 db.

Rama Kanti et al. [43] analyzed a technique called Orthogonal Wavelet Division Multiplex (OWDM) to replace FFT in the conventional OFDM to measure the respective performances of the wavelets. The proposed system used IDWT in of place of IFFT to generate the output. The computational complexity is comparatively lower and it increases flexibility as well as the spectral efficiency and decrease the BER. From the simulation results, it is recommended that the Haar wavelet is the most suited for OWDM, while the Symlet wavelet is the least suited. Moreover, in case of OWDM, the resilience to noise owing has been improved due to the lack of orthogonality between the sub-bands and the effective bandwidth of each sub-band has increased. The results showed when different OWDM schemes were used, many of them outperformed than OFDM in terms of BER and the best BER performance is achieved by Haar wavelet as compared to other wavelets and OFDM as well. It is also clear from these results that when the multi-path interference and AWGN channel are considered, there is a direct similarity between OFDM and OWDM.

Shivaji Sinha et al. [40] presented a comparative study on DWT-OFDM and FFT-OFDM systems in terms of bit error rate probability using different modulation schemes and wavelets. Results also show that the BER performance of DWT-OFDM is superior as to FFT-OFDM, especially when it uses bior 5.5 or rbior 3.3 wavelet families for AWGN channel for all 4 types of the modulations used viz. 16-QAM, 4-QAM, DPSK and 4-PSK. Moreover, DWT-OFDM outperformed FFT-OFDM for both type of wavelets.

2.4 CONVOLUTIONAL CODES AND THEIR UTILITY IN OFDM SYSTEMS

S. Vikrama Narasimha Reddy et al. [26] presented the use of Convolutional codes for low error probabilities and high data rates used in applications regarding wireless communication systems. These codes are basically designed based on code rate and constraint length. To reduce the constraint length and to achieve high data rates and feasibility, the parallel implementation is used. The design of recursive and non recursive codes is decided according to the single or multiple inputs which are considered at a time. Moreover, the applications of these codes are discussed.

Enis Akay [18] analyzed Bit Interleaved Coded Modulation Beam forming (BICMB) in 2007. BICMB makes use of the channel state information at the transmitter and the receiver. By using CSI BICMB achieves full spatial multiplexing and maintains full spatial diversity of NM over N transmit and M receive antennas. The considerable performance gains may be limited with channel estimation errors and limited feedback whose but still significantly more gains than conventional systems.

Frederik Simoens et.al [20] investigated linear precoding for bit-interleaved coded modulation (BICM) using additive white Gaussian noise (AWGN) channels. Linear precoder is concatenated with outer convolutional encoder which produces a powerful code with a limited decoding complexity. For a binary phase-shift keying (BPSK) signal set, the optimal precoders that result from these rules are also derived. Numerical results confirm the analytical findings and simulations illustrate the effectiveness of the approach. They showed that a precoder is suboptimal for BPSK when non iterative receiver is used.

CHAPTER 3

GAPS AND OBJECTIVES

3.1 GAPS

- The BER of an OFDM is only ideal in a fading environment but it does not behave well in a non-linear channels.
- Another problem emerging in conventional OFDM system is Peak to average Power ratio (PAPR). When the output of IFFT possess non-uniform power spectrum, the transmission energy is allocated to few subcarriers rather than majority. This problem is termed as PAPR which is undesirable as it results in out of band distortion power.
- The cyclic prefix is added to OFDM symbols to mitigate the interference between symbols but it reduces the bandwidth efficiency and increases the system complexity.
- Another drawback in OFDM system is the need of tight synchronization. Pilot tones have to be used to achieve phase synchronization and channel equalization.
- Coding is required in order to mitigate the effect of burst error distortions introduced by the channel.

3.2 OBJECTIVES:

- To compare the Bit Error Rate Performance of DWT based OFDM system with FFT based OFDM system.
- To analyze different wavelet families by comparing their Bit Error Rates
- To apply Convolutional Codes to Wavelet based OFDM and study its BER performance in AWGN and Rayleigh channel.

3.3 METHODOLOGY

The conventional OFDM system makes use of IFFT and FFT in the transmitter and receiver respectively but it has some drawbacks. OFDM provides an efficient means to reduce the intersymbol interference with the use of cyclic prefix but CP has the drawback of reducing the spectral containment of the channels. To overcome these drawbacks, DWT-OFDM is used as an alternative method. Cyclic prefix is not required in DWT-OFDM systems as wavelets possess orthonormal nature, thus satisfy the perfect reconstruction property.

Moreover, the Convolutional encoding is used with DWT OFDM system. Convolutional codes are very effective in removing the burst errors and distortions caused by the channel. Moreover, the BER performance of the system is affected by the outage probability. Outage probability is the probability when the required data rate is not supported by the specific channel due to variable SNR. The Convolutional encoding coupled with bit interleaving reduces the outage probability at higher SNR. Thus, the DWT-OFDM system with encoding outperforms significantly at higher values of SNR.

CHAPTER 4

DWT BASED OFDM SYSTEM

4.1 INTRODUCTION

DWT based OFDM is an efficient approach to replace FFT in conventional OFDM systems. DWT is employed in order to remove the use of cyclic prefix which decreases the bandwidth wastage and the transmission power is also reduced by the use of wavelet transform. The spectral containment of the channels in DWT-OFDM is better than FFT-OFDM. In Wavelet transform, the signal of interest is decomposed into set of basis waveforms, known as wavelets, which provide the way for analyzing the signals by investigating the coefficients of wavelets. DWT is used in several applications and has become very popular among engineers, technologists and mathematicians. The basis functions of wavelet transform are localized both in time and frequency and possess different resolutions in both domains which makes the wavelet transforms a powerful tool in various applications. Different resolutions correspond to analyze the behaviour of the process and the power of the transform.

Due to these properties, the wavelets and wavelet transform find their applications in various fields such as data compression, image compression, radar, computer graphics and animation, astronomy, human vision, nuclear engineering, acoustics, biomedical engineering, music, seismology, turbulence, magnetic resonance imaging, fractals and pure mathematics. Since wavelet transform has many advantages such as flexibility, lesser sensitivity against channel distortion and interference as well as better utilization of spectrum, it has been proposed to design the sophisticated wireless communication systems [25]. Wavelets are beneficial in various aspects such as channel modelling, data representation, transceiver design, and source and channel coding, data compression, interference minimization, energy efficient networking and signal de-noising in wireless communication systems.

A low pass filter and high pass filter is employed to operate as QMF and satisfies perfect reconstruction and orthonormal properties. In wavelet based OFDM, the modulated signal is transmitted using zero padding and vector transposing. DWT is known as a flexible and highly efficient method for decomposition of signals.

The block diagram of wavelets based OFDM is shown in figure 4.1.

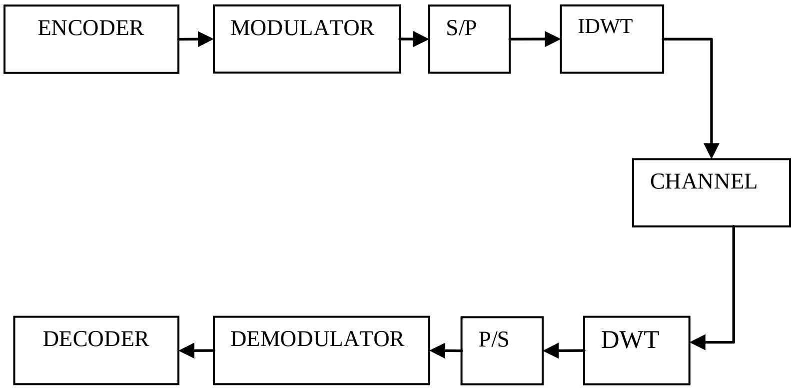

Fig. 4.1 Block diagram of encoded DWT-OFDM

The data generator first generates a serial random data bits stream. This data stream is passed through the encoder which consists of Convolutional encoder followed by the bit interleaver. The bits are first interleaved with help of convolution encoder and interleaver and then the data is processed using modulator to map the input data into symbols based on the modulation technique used. The DWT-OFDM symbol $s(t)$ can be represented as equation (4.1) [21],

$$s(t) = \sum_{j \leq J} \sum_{k} w_{j,k}(t)\psi_{j,k}(t) + \sum_{k} a_{J,k}\varphi_{J,k} \tag{4.1}$$

The orthogonality of these carriers relies on time location *(k)* and scale index *(j)*. This symbol is clearly the weighted sum of wavelet and scale carriers which is similar to the Inverse Wavelet Transform (IDWT). In DWT-OFDM, the input data is processed same as in FFT-OFDM but the advantage in this case is that the cyclic prefix is not required because of the overlapping nature of wavelet properties. The data is processed in the IDWT block, whose output can be given as equation (4.2),

$$d(k) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} D_m^n 2^{\frac{m}{2}} \psi(2_k^m - n) \tag{4.2}$$

where k is the number of subcarriers ($0 \leq k \leq N - 1$), D_m^n are the wavelet coefficients which represents the signal in scale and position on time-axis and $\psi(t)$ is the wavelet function with compressed factor m times and shifted n times for each subcarrier [27]. At the receiver side, the process is reversed. The output of discrete wavelet transform (DWT) is represented by equation (4.3),

$$D_m^n = \sum_{k=0}^{N-1} d(k) 2^{\frac{m}{2}} \psi(2_k^m - n) \tag{4.3}$$

The Discrete Wavelet Transform is used in a variety of signal processing applications, such as Internet communications compression video compression, object recognition and numerical analysis. The main advantage of wavelet transform over Fourier transform is that it is discrete both in time as well as scale. The transform is implemented by the use of filters. One filter of the analysis pair is a low pass filter (LPF), while the other one is a high pass filter (HPF). Each filter consists of a down-sampler to make the transform efficient. In Wavelet based OFDM (DWT-OFDM), the time-windowed complex exponentials are replaced by wavelet "carriers", at different scales *(j)* and positions on the time axis *(k)*. These functions are generated by the translation and dilation of a unique function, called "wavelets mother" [28] and denoted by $\psi(t)$.

The orthogonality of these carriers relies on time location *(k)* and scale index *(j)*. Wavelet carriers exhibit better time-frequency localization than complex exponentials [18] while DWT-OFDM implementation complexity is comparable to that of FFT- OFDM. These functions have orthonormal basis of, if infinite number of scales are considered. To obtain finite number of scales, scaling function is used. DWT-OFDM symbol now can be considered as weighted sum of wavelet and scale carriers which is close to the Inverse Wavelet Transform (IDWT).

The data symbols are seen by IDWT modulator as sequence of wavelet and approximation coefficients. At the output of the filter discrete version of DWT-OFDM symbol is obtained, with impulse response of filters (low-pass and high-pass) decided by the wavelet mother $\psi(t)$ [28].

$$\Psi_{J,K}(t) = 2^{-\frac{j}{2}}\Psi\left(2^{-j}t - k\right) \tag{4.4}$$

The decomposition of signal is done simultaneously using a high pass filter. The output gives the detail coefficients from the output of high-pass filter and the approximation coefficients from the output of low pass filter. The two filters are associated with each other and are known as a Quadrature Mirror Filters (QMF). However, as half of the frequencies of signal have been removed, so half of the samples can be discarded according to the Nyquist's rule. The outputs of the filter are then sub sampled by two. The time resolution has been halved due to the decomposition since the signal is characterized by only half of each filter output. However, the frequency resolution has been doubled since each output contains half the frequency band of the input [29]. The block diagram for the implementation of one level wavelet transform is shown in figure 4.2. Hence only one pair of filters i.e., an HPF and an LPF is used. Each sub stream of data is then sub-sampled by two.

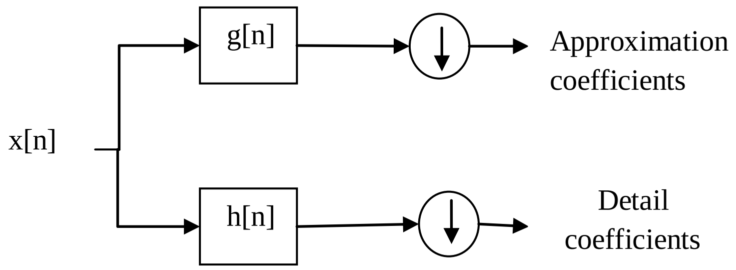

Figure 4.2: Wavelet Decomposition [29]

The description of DWT-OFDM transmitter and receiver is given in the following section:

4.1.1 DWT-OFDM transmitter

On the transmitter side, the digital modulator maps the serial data bits into OFDM symbols X_m in the similar way as in FFT-OFDM within the parallel N data streams represented by $X_m\ (i)$ where $(0 \le i \le N-1)$. Each data stream $X_m\ (i)$ is passed through serial to parallel converter to create a vector. Then the transpose of this vector is taken to obtain the approximation coefficients which are also known as scaling coefficients.

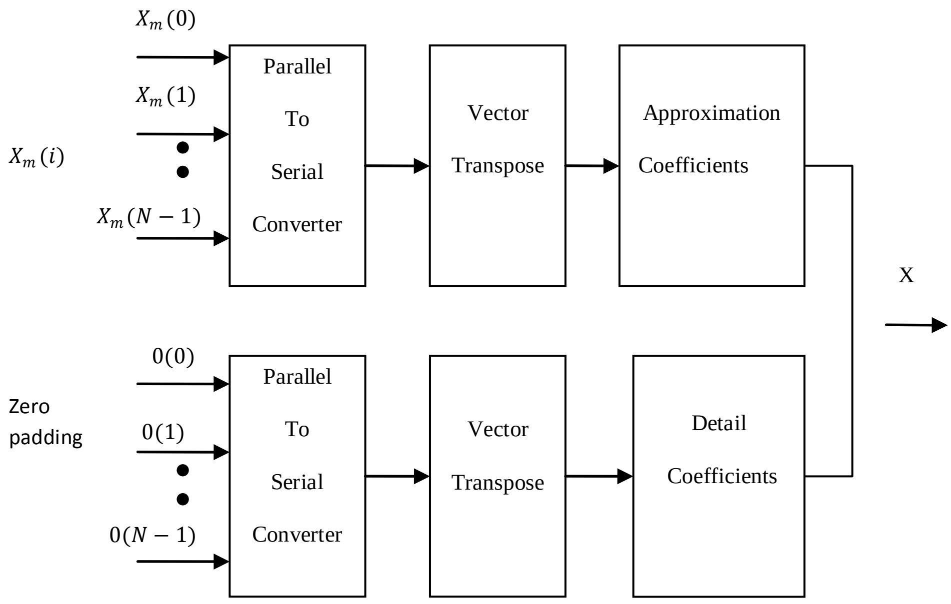

Fig. 4.3 DWT-OFDM transmitter

Thus the signal is upsampled and low-pass filtered to achieve the low frequency signals. In the similar way, the vector generated from the zeroes padding signal is convolved with the high-pass filter which contains the detailed coefficients or wavelet coefficients. The values of these approximation and detailed coefficients depend on the wavelet family which is used.

The MATLAB command $[X] = idwt(cA, cD, 'wname')$ is used to simulate the signal on the transmitter side where $'wname'$ represents the wavelet family used in simulation.

4.1.2 DWT-OFDM receiver

The DWT-OFDM receiver is shown in Fig. 4.4. It performs the exact reverse process of the transmitter. MATLAB command $[cA; cD] = dwt(Y; 'wname')$ is used to simulate the received signal where $wname$ represents the wavelet family used in simulation. The received data Y is decomposed into two parts and then sent to the low-pass and high-pass filters to obtain the approximation and detailed coefficients respectively. Only the output cA of the LPF is passed through the demodulator and the output cD of the HPF is discarded. Before demodulation, the transpose of data is taken and then passed through a serial to parallel converter. cD is discarded because it contains only zeroes elements and does not carry any useful information. The original data is recovered at the output of the demodulator [30].

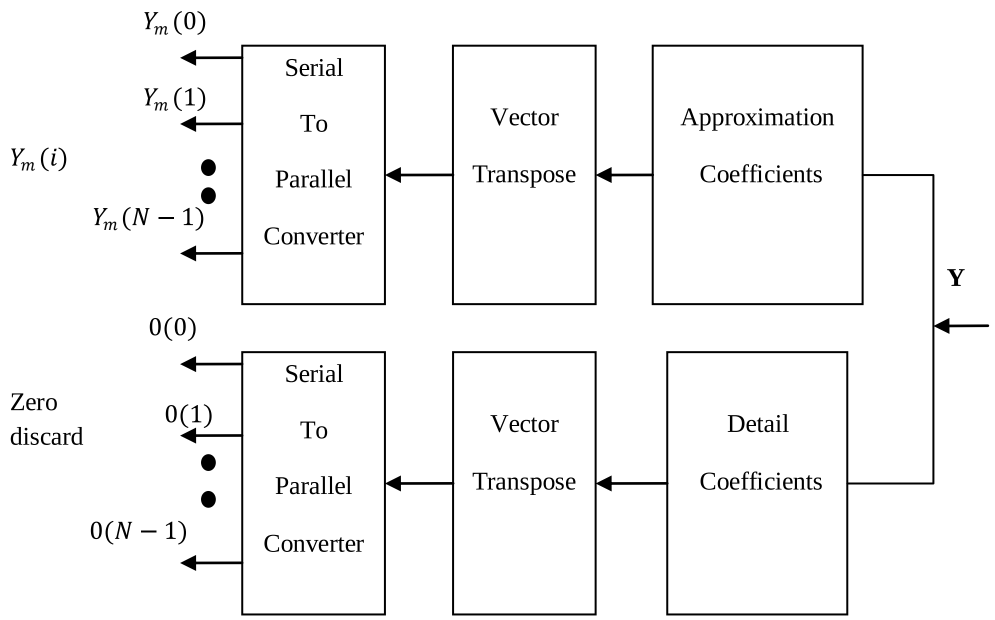

Fig. 4.4 DWT-OFDM receiver

4.2 MATHEMATICAL ANALYSIS OF DWT-OFDM SYSTEM

DWT-OFDM uses wavelet carriers at different scales (j) and positions on the time-axis (k). These functions are generated by the translation and dilation of a unique function, known as the 'wavelet mother' denoted by $\psi(t)$ and is given by equation (4.1) [29],

$$\psi_{j,k}(t) = 2^{-\frac{j}{2}}\psi(2^{-j}t - k) \qquad (4.1)$$

The scale index (j) and time location index (k) affects the orthogonality of the subcarriers and exhibits better time- frequency localization as compared to the complex exponentials used in FFT based OFDM systems [31]. The orthogonality is achieved if it satisfies the following condition, according to equation (4.5),

$$\langle \psi_{j,k}(t), \psi_{m,n}(t) \rangle = \begin{cases} 1 & if\ j = m, k = n \\ 0 & otherwise \end{cases} \tag{4.5}$$

The scaling function $\varphi(t)$ is used to obtain a finite number of scales and is generated using equation (4.6) [32],

$$\varphi_{j,k}(t) = 2^{\frac{j}{2}} \varphi(2^j t - k) \tag{4.6}$$

Higher the value of j, higher is the resolution. The lower resolution function, denoted by $\varphi(t)$can be represented as the weighted sum of shifted versions of some scaling functions at next higher resolution i.e. $\varphi(2t)$, given by equation (4.7),

$$\varphi(t) = \sum_k h(k)\sqrt{2}\, \varphi(2t - k) \tag{4.7}$$

To better describe the important features of a signal, another set of functions given by $\psi_{j,k}(t)$ is defined which is also represented in terms of the scaling function, given by equation (4.8) as follows,

$$\psi(t) = \sum_k g(k)\sqrt{2}\, \varphi(2t - k) \tag{4.8}$$

The set of $g(k)$ coefficients are known as the wavelet function coefficients. The wavelet basis function $\psi_{s\tau}(t)$ is defined in terms of the mother wavelet function as [32]:

$$\psi_{s\tau}(t) = \frac{1}{\sqrt{|s|}} \psi\left(\frac{t-\tau}{s}\right) \tag{4.9}$$

and is sometimes called baby wavelet. The transformed signal is a function of two variables: “s” called the scale, which scales a function by compressing or stretching it and “τ”, the translation parameter along the time-axis. The scale parameter “s”**,** is defined as $|1/\text{frequency}|$ and corresponds to frequency information of the signal. The translation parameter “τ”, relates to the location of the wavelet as it is shifted through the signal and it corresponds to the time information of the signal in the wavelet transform. The factor $\frac{1}{\sqrt{|s|}}$ is for energy normalization across the different scales.

Wavelets are the waveforms having localization both in time and frequency. They also possess the property of orthogonality across scale and translation. The discrete wavelet transform (DWT) provides a means of decomposing sequences of real numbers in a basis of compactly supported orthonormal sequences each of which is related by being a scaled and shifted version of a single function. As such it provides the possibility of efficiently representing those features of a class of sequences localized in both position and scale and possess the property of orthogonality across scale and translation. In equation (4.9), both (s,τ) are continuous variables and there is a redundancy in the CWT representation of $x(t)$. To overcome this problem, s and τ can be restricted to take discrete values.

That is

$$\begin{aligned} s &= 2^{-m}, m \in Z \\ \tau &= k2^{-m}, k \in Z \end{aligned} \tag{4.10}$$

where Z is the set of integers in $(-\infty,\infty)$. The DWT of a signal $x(t)$ is the set of coefficients $X_{DWT}(m,k)$ for m and k obtained as the inner product of the signal $x(t)$ and the wavelet function, $\psi_{m,k}$.The discrete wavelet and inverse discrete representation of a signal $x(t)$ is given by equation (4.11) and equation (4.12) respectively [33].

$$X_{DWT_k^m} = \int_{-\infty}^{\infty} x(t) 2^{\frac{m}{2}} \psi(2^m t - k) dt \tag{4.11}$$

$$X_{IDWT}(t) = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} X_k^m \, 2^{\frac{m}{2}} \psi(2^m t - k) \tag{4.12}$$

Where $\psi_{m,k}$ is the wavelet function [34]. Mallat's fast wavelet transform (FWT) provides a computationally efficient, practical, discrete time algorithm for computing the DWT.

4.2.1 Filter Banks, DWT and IDWT

Multi-resolution analysis (MRA) approach is used to explain Mallat's FWT [27, 30]. Let A_{m+1} be the projection operator which approximates the signal $x(t)$ at 2^{m+1} and $\Phi_k^{m+1} = \{2^{m+1}\Phi(2^{m+1}t - k); k \in Z\}$ is an orthonormal basis for V_{m+1}. The resolution limited approximation of the signal $x(t)$ is given by [35]:

$$A_{m+1}x(t) = \sum_k a_{m+1,k} \Phi_{m+1,k}(t) \tag{4.13}$$

where $a_{m+1,k}$ are approximation coefficients obtained by projections of $x(t)$ on to basis functions.

$$a_{m+1,k} = \int_{-\infty}^{\infty} x(t)\Phi_{m+1,k}\, dt \quad (4.14)$$

The approximation coefficients and wavelet coefficients at any coarser scale can be computed by

$$a_k^m = \sum_p h(p-2k)a_{m+1,k} \quad (4.15)$$

$$w_k^m = \sum_p g(p-2k)w_{m+1,k} \quad (4.16)$$

where $h(-k)$ and $g(-k)$ are the low pass and the high pass filters in the associated filter bank structure corresponding to DWT. Equations (4.15) and (4.16) represent the FWT to compute the DWT in equation (4.11).Conversely, it is possible to construct the approximation coefficients using

$$a_{m+1,k} = \sum_p h(2p-k)a_{m,p} + g(2p-k)w_{m,p} \quad (4.17)$$

This is the IFWT for computing the IDWT in equation (4.12). In the figure 4.2, $h(k)$ and $g(k)$ are the low pass and the high pass filters. These discrete time algorithms with filter bank implementations are used in wavelet modulation.

A. Analysis

The analysis (Finer to Coarser Scales) of a signal $x(t)$ using DWT involves obtaining the scaling coefficients and wavelet coefficients at the desired coarsest scale and at higher scales. For the orthogonal wavelet system, the scaling coefficients at scale m are obtained as:

$$a_{m,k} = \int x(t)\Phi_{m,k}\, dt$$

$$= \int x(t)2^{\frac{m}{2}}\Phi(2^m t - k)\, dt$$

$$= 2^{\frac{-1}{2}} \int x(t)2^{\frac{(m+1)}{2}}\Phi(2^m t - k)\, dt \quad (4.18)$$

From equation (4.18) we see that

$$\Phi(2^m t - k) = \sum_u h(u)\sqrt{2}\Phi(2^{m+1}t - 2k - u) \quad (4.19)$$

Substituting equation (4.19) expression for $\Phi(2^m t - k)$ in (4.18) and rearranging,

$$a_{m,k} = \sum_u h(u) \int x(t) 2^{\frac{(m+1)}{2}} \Phi(2^{m+1}t - 2k - u) dt$$
$$= \sum_u h(u-2k) \int x(t) 2^{\frac{(m+1)}{2}} \Phi(2^{m+1} - u) dt$$
$$= \sum_p h(p-2k)\, a_{m+1,p} \quad (4.20)$$

Similarly, the wavelet coefficients at scale m also obtained as

$$w_{m,k} = \sum_p g(p-2k)\, w_{m+1,p} \quad (4.21)$$

B. Synthesis

The synthesis (Coarser to Finer Scales**)** involves reconstructing the original signal $x(t)$ from the scaling coefficients at the coarsest scale and the wavelet coefficients at higher scales. It has been shown that the scaling coefficients at finer scale are recursively computed using [30].

$$a_{m+1,k} = \sum_p a_{m,p} h(k-2p) + \sum_p w_{m,p}\, g(k-2p) \quad (4.22)$$

4.3 CONVOLUTIONAL ENCODING

For Convolutional codes, the information symbols denoted by u and the encoded symbols a are generally binary and the modulo-2 arithmetic operations are performed. Further, the sequences of message bits and output bits are split into small blocks of length k and n respectively, which are represented as:

$$u_r = (u_{r,1}, u_{r,2}, \dots \dots, u_{r,k}),$$
$$a_r = (a_{r,1}, a_{r,2}, \dots \dots, a_{r,k}) \quad (4.23)$$

The n encoded bits assigned to the k message bits are unique, reversible and time invariant but not memory less. In Convolutional codes, the current block not only depends on the present information block, but also on the m preceding information blocks. The encoder is a K-stage linear shift register which creates the encoded bits by linear combinations of the message bits. The convolution of information bit sequences and the set of generator coefficients is carried out.

$$a_{r,v} = \sum_{\mu=0}^{m} \sum_{\kappa=1}^{k} g_{\kappa,v,\mu} u_{r-\mu,\kappa} \quad (4.24)$$

Where $g_{\kappa,v,\mu}$ is set of generator coefficients with $1 \le \kappa \le k, 1 \le v \le n$ and $0 \le \mu \le m$ and m is the memory length. This parameter m affects the code rate and performance of the code as well as influences the complexity of decoding process. Block codes are a special case of Convolutional codes with memory length $m = 0$. Unlike block codes, which use large values of k and n, the practical Convolutional codes mostly use $k = 1$ and $n = 2$ or $n = 3$. The Convolutional encoder is implemented by a linear shift register which contains $u_r, u_{r-1}, \dots \dots, u_{r-m}$. a_r is formed by computing the n linear combinations of $k(m + 1)$ bits. u_{r+1} is inserted into the encoder and u_{r-m} is taken out. Initially, at $r = 0,$ zeroes are loaded to the shift register i.e. $u_{-1} = u_{-2} = \cdots = u_{-m} = 0$.

4.3.1 Generator Polynomial Representation

The generator coefficients $g_{v,\mu}$ can be represented in terms of generator polynomials, as given [25]:

$$g_v(x) = \sum_{\mu=0}^{m} g_{v,\mu} x^{\mu} \tag{4.25}$$

The sequences of information bits and encoded bits are characterized using power series and the vector of power series, respectively:

$$u(x) = \sum_{r=0}^{\infty} u_r x^r \ a(x) = (a_1(x), \dots, a_n(x)), \qquad a_v(x) = \sum_{r=0}^{\infty} a_{r,v} x^r \tag{4.26}$$

The Convolutional code is the polynomial multiplication of information symbol and generator polynomial,

$$\underbrace{(a_1(x), \dots, a_n(x))}_{=a(x)} = u(x) \cdot \underbrace{(g_1(x), \dots, g_n(x))}_{=G(x)} \tag{4.27}$$

i.e.,

$$a_v(x) = u(x) g_v(x) \qquad \text{for } v = 1, \dots, n.$$

The matrix $G(x) = (g_1(x), \dots, g_n(x))$ is known as the generator matrix. Hence, the set of coded data is expressed as

$$c = \left\{ u(x)G(x) \ \middle|\ u(x) = \sum_{r=0}^{\infty} u_r x^r,\ u_r \in \{0,1\} \right\} \tag{4.28}$$

The memory length for given Generator matrix is given by:

$$m = \max_{1 \le v \le n} \deg g_v(x) \tag{4.29}$$

4.4 ADVANTAGES OF USING WAVELETS IN WIRELESS COMMUNICATION

There are many desirable features of wavelets and wavelet packets which make their use advantageous for wireless communication systems which are described below [38]:

4.4.1 Semi-Arbitrary Division of The Signal Space and Multirate Systems

Wavelet transform can create subcarriers of different bandwidth and symbol length. Since each subcarrier has the same time-frequency plane area, an increase (or decrease) of bandwidth is bound to a decrease (or increase) of subcarrier symbol length. Such characteristics of the wavelets can be exploited to create a multirate system. From a communication perspective, such a feature is favourable for systems that must support multiple data streams with different transport delay requirements.

4.4.2 Flexibility with Time-Frequency Tiling

Another advantage of wavelets lies in their ability to arrange the time-frequency tiling in a manner that minimizes the channel disturbances. By flexibly aligning the time-frequency tiling, the effect of noise and interference on the signal can be minimized. Wavelet based systems are capable of overcoming known channel disturbances at the transmitter, rather than waiting to deal with them at the receiver. Thus, they can enhance the quality of service (QoS) of wireless systems.

4.4.3 Signal or Waveform Diversity

Wavelets give a new dimension – “Waveform diversity”, to the physical diversities currently exploited, namely, space, frequency and time-diversity. Signal diversity which is similar to spread spectrum systems, could be exploited in a cellular communication system, where adjacent cells can be designated different wavelets in order to minimize inter-cell interference. Another example is the Ultra Wideband (UWB) communication system where a very large band with reduced interference can be shared by users by clever use of transmitting pulse wave shapes.

4.4.4 Sensitivity to Channel Effects

The performance of a modulation scheme depends on the set of waveforms that the carriers use. The wavelet scheme therefore holds the promise of reducing the sensitivity of the system to harmful channel effects like Inter-symbol interference (ISI) and Inter-carrier interference (ICI).

4.4.5 Flexibility with Sub-Carriers

The derivation of wavelets is directly related to the iterative nature of the wavelet transform. The wavelet transform allows for a configurable transform size and hence a configurable number of carriers. This facility can be used, for instance, to reconfigure a transceiver according to a given communication protocol; the transform size could be selected according to the channel impulse response characteristics, computational complexity or link quality.

4.4.6 Power Conservation

Wavelet-based algorithms have long been used for data compression. In the context of mobile wireless devices, which are mostly energy starved, this has an added significance. By compressing the data, a reduced volume of data is transmitted so that the communication power needed for transmission is reduced.

CHAPTER 5

RESULTS AND DISCUSSION

In this thesis work, the conventional FFT based OFDM system using 16 QAM modulation technique under AWGN and Rayleigh channel has been considered to evaluate the performance of the proposed DWT based OFDM system and also using Convolutional codes [5]. The BER performance of conventional FFT based OFDM system and DWT based OFDM over AWGN channel is examined. MATLAB simulation has been carried out to compare the performance of FFT OFDM with DWT OFDM system and also to compare different wavelet families based OFDM system. Then, the DWT OFDM system is studied with and without Convolutional encoding over AWGN and Rayleigh channel. The simulation results are presented as follows:

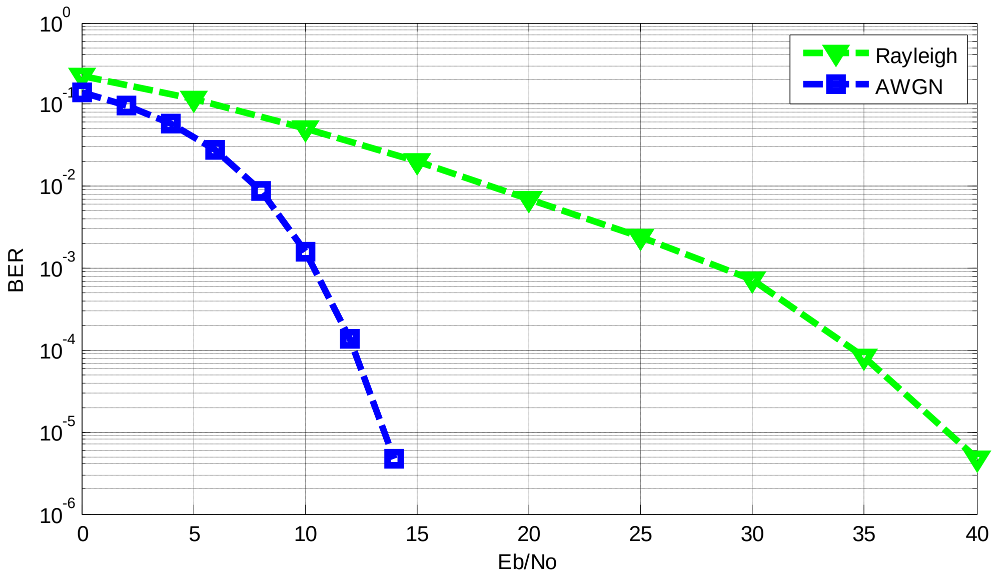

Fig. 5.1 Performance of OFDM system under AWGN and Rayleigh channel

Fig. 5.1 shows the performance of OFDM system under AWGN channel and Rayleigh channel. The BER equals to $10^{-2.9}$ is obtained at SNR of 10 dB when the system is observed under AWGN channel; whereas same BER is achieved at 25 dB when Rayleigh channel is considered. The same results were achieved in [5], so this system has been considered as the benchmark to examine the performances of proposed DWT OFDM system.

5.1 COMPARISON OF FFT OFDM WITH DWT OFDM

Simulation is carried out for both FFT-OFDM and DWT-OFDM system. The simulation parameters are given in table 5.1. The study and comparisons are based on simulation done using MATLAB. The BER performance as a function of SNR is examined for AWGN channel and the results are plotted as reported in Fig. 5.2.

Table 5.1 Simulation Parameters

Modulation Scheme	16 QAM
Number of subcarriers	64
Channel Model	AWGN
SNR range	0 to 30 dB
Number of samples	1000
Wavelet used	Bior 5.5

As shown in Fig 5.2, the BER of the OFDM system is significantly improved when FFT is replaced by DWT when BER is plotted as a function of SNR.

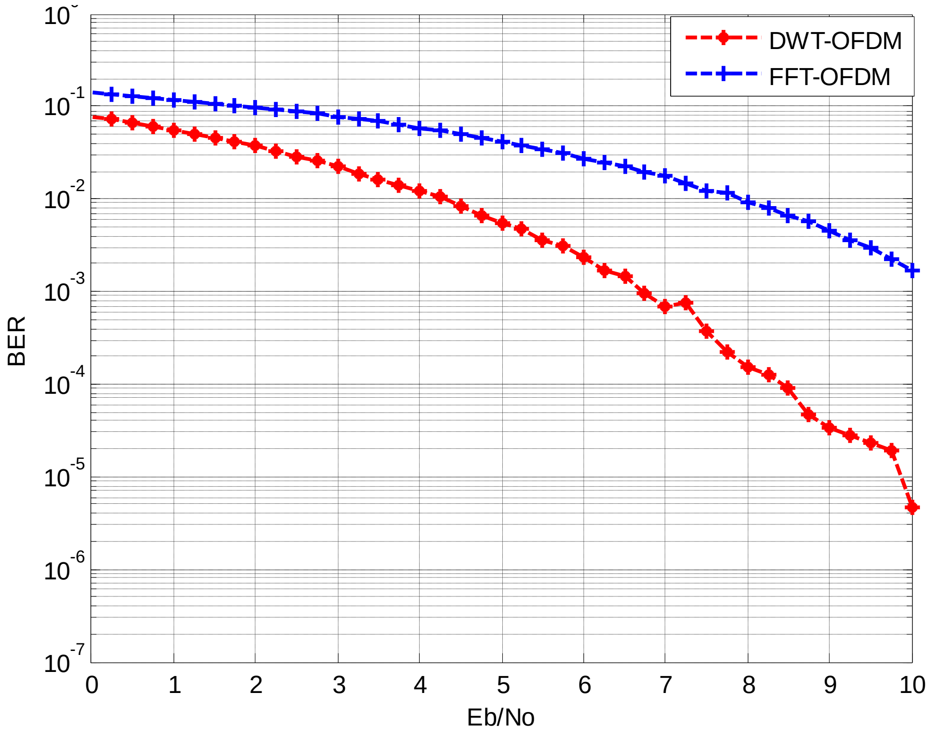

Fig. 5.2 BER comparison in AWGN channel

The improvement in BER performance can be examined by taking a particular value of BER and comparing the values of SNR at which it is obtained in FFT-OFDM system and DWT-OFDM system. In FFT based OFDM system, the BER of $10^{-2.9}$ has been obtained at SNR of

10 dB; whereas same BER is achieved at SNR of 6 dB by DWT based OFDM system. The BER is significantly improved by 4 dB by replacing FFT with DWT in OFDM system.

5.2 COMPARISON AMONG DIFFERENT WAVELET FAMILIES

The BER of different wavelet families is compared and plotted. The simulation parameters mentioned in table 5.1 are used. The Haar wavelet is the simplest but discontinuous wavelet which resembles a step function. The Daubechies family (dbN) consists of compactly supported wavelets with extreme phase and highest number of vanishing moments for a given support width. The bi-orthogonal family (biorNr.Nd) exhibits the property of linear phase which is required for reconstruction of the signal. Coiflets family consists of compactly supported wavelets with highest number of vanishing moments for both ψ and φ. Symlets wavelets are compactly supported wavelets which have least asymmetry. Comparison of these wavelet families is given in fig. 5.3.

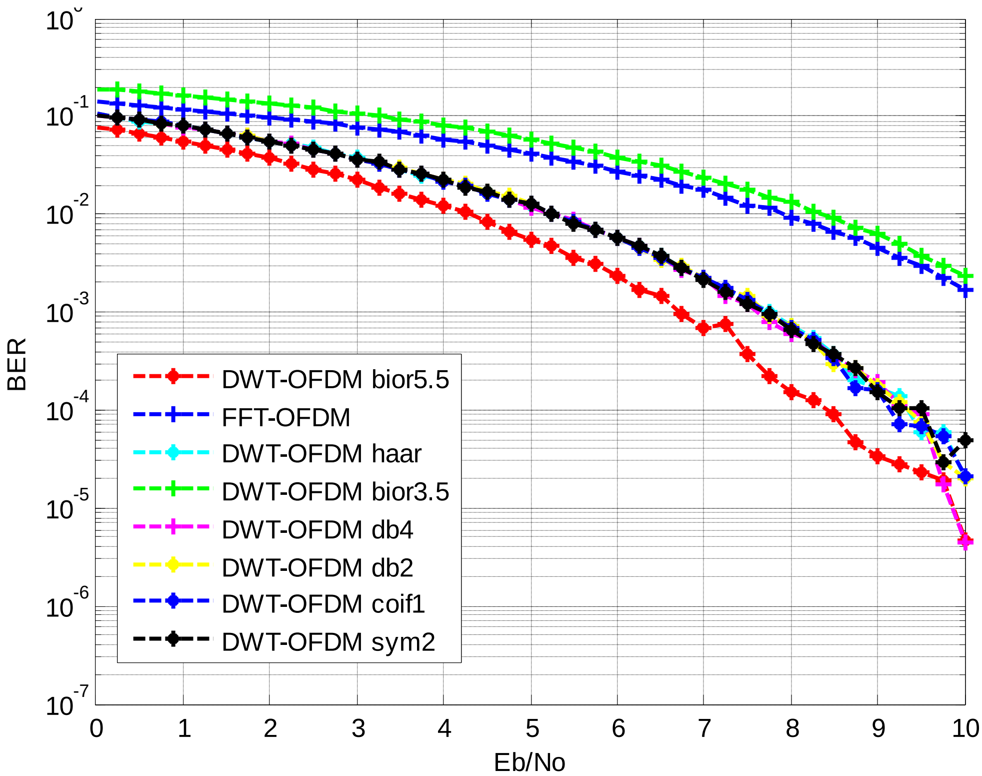

Fig. 5.3 BER comparison for different wavelet families

Clearly from the Fig. 5.3, seven wavelets have been considered for comparison in terms of BER and the value of BER of each wavelet family is mentioned in table 5.2 as given below.

Table 5.2 Comparison of different wavelets in terms of BER

Wavelet	BER at SNR = 8dB
Daubechies (db2)	7×10^{-4}
Daubechies (db4)	6×10^{-4}
Haar	6×10^{-4}
Bior3.5	2×10^{-2}
Bior5.5	1.5×10^{-4}
Coif1	8×10^{-4}
Sym2	7×10^{-4}

The bior5.5 wavelet outperforms all the other wavelets i.e. haar, db2, db4, coif1 and sym2 wavelets. Bior3.5 comes out to be the worst of all. The major improvement is seen among bior3.5 and bior5.5 by 4 dB at BER equals to $10^{-2.95}$.

5.3 COMPARISON BETWEEN DWT-OFDM SYSTEM WITH AND WITHOUT ENCODING IN AWGN CHANNEL

Simulation is carried out for DWT-OFDM system with and without encoding for AWGN channel by taking SNR in the range 0 to 40 dB and 4-QAM modulation technique is used. The number of samples is 1000 and the number of subcarriers i.e. N is 64. The BER comparison with DWT-OFDM with and without encoding in AWGN channel is represented by Fig. 5.4.

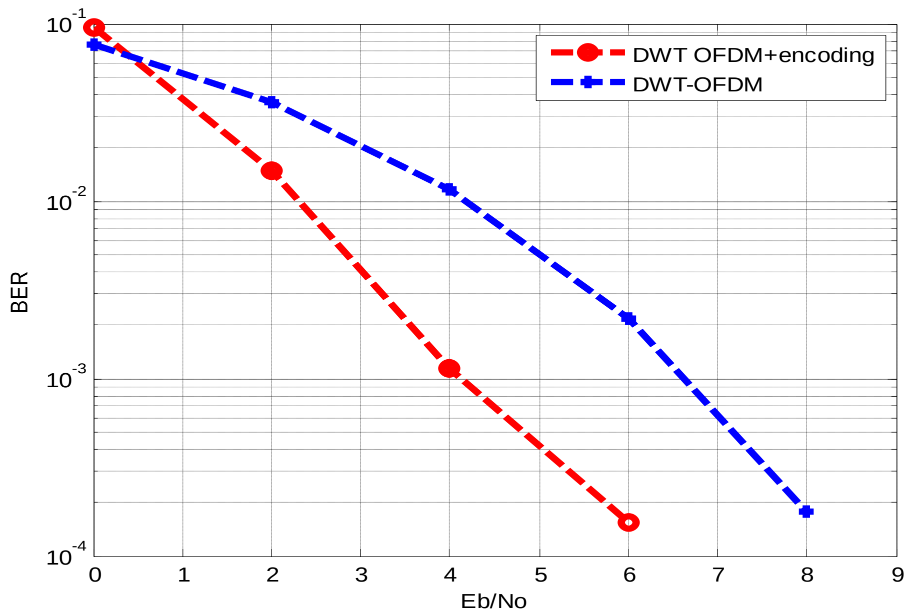

Fig. 5.4 BER comparison of DWT OFDM with and without encoding in AWGN

By taking the value of SNR of both the systems at a particular value of BER, the performance of DWT OFDM system with encoding as well as without encoding can be evaluated in AWGN channel. The BER of $10^{-2.9}$ is obtained at SNR of 3.5 dB by using DWT based OFDM with Convolutional codes whereas the same value of BER is achieved at 6 dB of DWT based OFDM system without encoding. Hence, there is a significant improvement of 2.5 dB in the performance of the system using Convolutional codes.

5.4 COMPARISON BETWEEN DWT-OFDM SYSTEM WITH AND WITHOUT ENCODING IN RAYLEIGH CHANNEL

Further, the BER for DWT OFDM system with encoding and without encoding is compared in Rayleigh channel. The simulation parameters are same as were used for comparison of both the systems in presence of AWGN channel. The BER of encoded DWT-OFDM system is significantly improved over the higher SNR range in Rayleigh channel. BER comparison for DWT-OFDM with and without Convolutional encoding in Rayleigh channel is given in fig. 5.5,

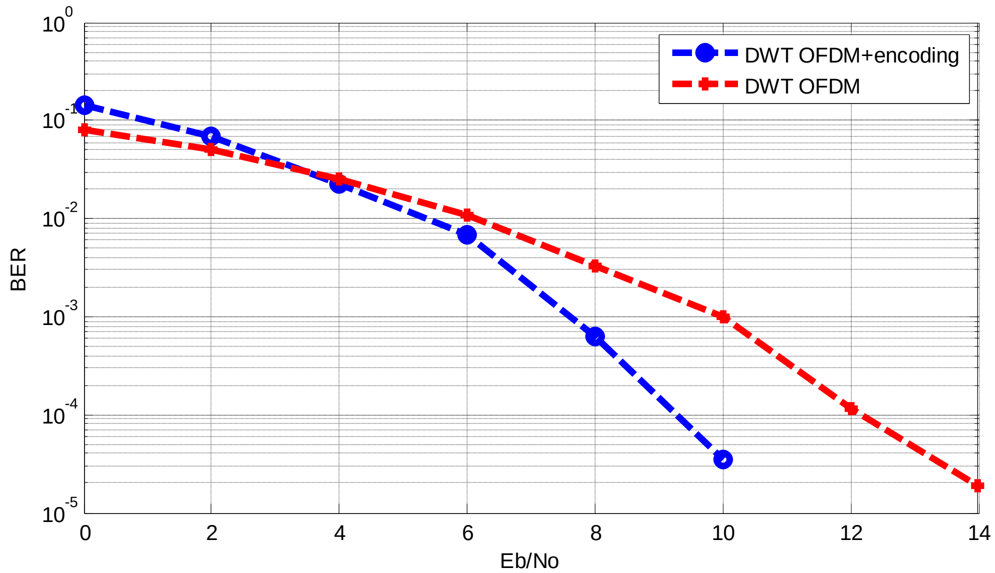

Fig. 5.5 BER comparison in Rayleigh channel

As clearly shown in the fig. 5.5, the BER of proposed system is significantly improved as compared to the DWT OFDM system without encoding. Using Convolutional codes in DWT based OFDM, the BER of $10^{-4.9}$ is obtained at SNR of 10 dB in Rayleigh channel whereas the same value of BER is achieved at 13.5 dB of DWT based OFDM system without encoding. Thus, an improvement of 3.5 dB has been achieved.

5.5 CONCLUSION

FFT based OFDM system using 16 QAM modulation technique under AWGN and Rayleigh channel has been considered as the benchmark and compared with the DWT OFDM system. An improvement of 4 dB has been achieved at $10^{-2.9}$. Afterwards, all the wavelets are compared to find the best wavelet among all. The wavelet 'bior5.5' outperforms all the other wavelets as well as FFT-OFDM system because it makes use of two wavelets, one for decomposition and the other for reconstruction instead of the single one. Finally, the performance of DWT OFDM system using Convolutional codes and without encoding is compared under AWGN as well as Rayleigh channel. The results show that there is an improvement of 2.5 dB at BER of $10^{-2.92}$ when AWGN channel is used. In case of Rayleigh channel, an improvement of 3.5 dB has been achieved at BER of $10^{-4.9}$.

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE

6.1 CONCLUSIONS

Initially the BER performance of FFT based OFDM system has been compared with DWT based system and the simulations have been carried out using MATLAB. The DWT-OFDM transmitter needs to transmit double the data as compared to FFT-OFDM as data contains the zero padding components. In FFT-OFDM, the cyclic prefix is employed in order to minimize the intersymbol interference. But its drawback is that it reduces the spectral containment of the channel, power efficiency and data throughput. To overcome these drawbacks, DWT-OFDM is used as an alternative method. Cyclic prefix is not required in DWT-OFDM systems as wavelets possess orthonormal nature, thus satisfy the perfect reconstruction property. It is found that the BER performance of DWT-OFDM surpasses FFT-OFDM in AWGN channel using 'bior5.5'. In FFT based OFDM system, the BER of $10^{-2.9}$ has been obtained at SNR of 10 dB; whereas same BER is achieved at SNR of 6 dB by DWT based OFDM system. The BER is significantly improved by 4 dB by replacing FFT with DWT in OFDM system.

Then, the performance comparison is done for different wavelet families in terms of BER. Haar wavelet is the simplest but discontinuous wavelet which resembles a step function. The Daubechies family (dbN) consists of compactly supported wavelets with extreme phase and highest number of vanishing moments for a given support width. The bi-orthogonal family (biorNr.Nd) exhibits the property of linear phase which is required for reconstruction of the signal. Coiflets family consists of compactly supported wavelets with highest number of vanishing moments for both ψ and φ. Symlets wavelets are compactly supported wavelets which have least asymmetry. The wavelet 'bior5.5' outperforms all the other wavelets as well as FFT-OFDM system because it makes use of two wavelets, one for decomposition and the other for reconstruction instead of the single one. The BER for all the wavelet families is mentioned in table 5.2.

Finally, MATLAB simulation for the DWT-OFDM system with and without Convolutional encoding is presented for both AWGN and Rayleigh channel. DWT has come up as an effective technique to be used in multicarrier modulation because of its good time-frequency localization properties, ICI and ISI suppression and flexibility. Moreover, the cyclic prefix is not used in DWT based OFDM system. The simulation results show that when the DWT-OFDM system is used with Convolutional encoding, the BER performance of the system is improved in AWGN as well as Rayleigh channel. The BER of $10^{-2.9}$ is obtained at SNR of 3.5 dB by using DWT based OFDM with Convolutional codes whereas the same value of BER is achieved at 6 dB of DWT based OFDM system without encoding. Hence, there is a significant improvement of 2.5 dB in the performance of the system using Convolutional codes.

Moreover, Using Convolutional codes in DWT based OFDM, the BER of $10^{-4.9}$ is obtained at SNR of 10 dB in Rayleigh channel whereas the same value of BER is achieved at 13.5 dB of DWT based OFDM system without encoding. Thus, an improvement of 3.5 dB has been achieved. This is because the Convolutional codes are very effective in removing the burst errors and distortions caused by the channel. Moreover, the BER performance of the system is affected by the outage probability. Outage probability is the probability when the required data rate is not supported by the specific channel due to variable SNR. The Convolutional encoding coupled with bit interleaving reduces the outage probability at higher SNR. Thus, the DWT-OFDM system with encoding outperforms significantly at higher values of SNR.

6.2 FUTURE SCOPE

Finally it is important to underline that wavelet theory is still developing .It is expected that more is still to be pointed out as the knowledge of this recently proposed scheme gains more interest .There are many possibilities for future work in this area, and are summarized as follows:

- *Diversity Scheme* on *Wavelet* based *OFDM*: improved transmission integrity may be achieved with aid of diversity. Space, time, frequency diversities are the most physical diversities to be exploited.
- *Equalization techniques*: equalization techniques and channel estimation on wavelet based realization could also be an area to be addressed.
- The initiative could be extended to address Orthogonal *Wavelet* based *Codes* for *Multiple access schemes.*

To sum up researches done in wavelets and their application for communication engineering is still at its infant stage and there are growing number of areas that upcoming researchers are invited to explore.

LIST OF PUBLICATIONS

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