Performance Evaluation of DWT based OFDM System With DAPSK Modulation

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ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation scheme that has high performance over multipath environments and is used in many wireless applications. In OFDM the data is transmitted using several narrow-band orthogonal sub-carriers. Conventionally OFDM is implemented using Discrete Fourier transform (DFT) and usually adopts either binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM) as the modulation scheme.

In this dissertation a Matlab simulation of a discrete wavelet transform (DWT) based OFDM system adopting differential amplitude phase shift keying (DAPSK) as its modulation scheme is presented. The main aim of the simulation is to evaluate the performance of such system in terms of bit error rate (BER) and peak average power ratio (PAPR). The performance of the system was evaluated in the presence of Additive white Gaussian noise (AWGN) and multipath fading as channel impairments. The results show the superiority of the DWT based OFDM system when compared to a DFT based system with 64-DAPSK modulation.

ACKNOWLEDGMENTS

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Nomenclature

ADSL	Asymmetric Digital Subscriber Line
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
DAB	Digital Audio Broadcasting
DAPSK	Differential Amplitude Phase Shift Keying
DCT	Discrete Cosine Transform
DFT	Discrete Fourier Transform
DPSK	Differential Phase Shift Keying
DSP	Digital Signal Processing
DVB	Digital Video Broadcasting
DWT	Discrete Wavelet Transform
FDM	Frequency Division Multiplexing
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
HF	High Frequency
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
LTE	Long Term Evolution
OFDM	Orthogonal Frequency Division Multiplexing

PAPR	Peak to Average Power Ratio
QAM	Quadrature Amplitude Modulation
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SNR	Signal to Noise Ratio
VDSL	Very high bit rate Digital Subscriber Line
WIMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Networks
WOFDM	Wavelet based OFDM

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) as a concept was first introduced for military applications in 1957 as a parallel transmission system [7]. In 1971, S. B. Weinstein and P. M. Ebert made a huge contribution in OFDM history when they introduced multiplexing using discrete Fourier transform (DFT) to improve the implementation complexity [8]. Since then OFDM became the interest of many research institutes as they became focused on developing OFDM based systems. But still the use of OFDM in commercial communication systems was limited due to the high costs associated with the requirements for implementation. The use of OFDM has experienced a breakthrough in the 1990s with advancements in digital signal processing (DSP) hardware.

OFDM is a frequency division multiplexing (FDM) based multicarrier modulation technique. Multicarrier modulation was introduced to replace and overcome the drawbacks of the single carrier modulation techniques. Basically OFDM spreads the data over a number of orthogonal narrow-band sub-carriers to carry the data stream. In OFDM the sub-carriers are orthogonal, hence an overlap between the sub-carriers can occur unlike in the FDM where all the sub-carriers must be completely separated. Conventionally fast Fourier transform (FFT) algorithm is used to practically implement the orthogonal sub-carriers. The main advantages of the OFDM systems are the high bandwidth and power efficiency due to the narrow-band orthogonal sub-carriers, it is robust against inter symbol interference (ISI) and frequency selective fading caused by multipath and sever channel conditions. That is why OFDM is widely used in many digital communication applications such as digital audio broadcasting (DAB), digital video broadcasting (DVB), wireless local area networks (WLAN), worldwide interoperability for microwave access (WIMAX), 4G long term evolution (LTE), asymmetric digital subscriber line (ADSL) and very high bit rate digital subscriber line (VDSL).

1.1. Motivation

OFDM as every thing else also has some drawbacks. The main drawbacks of the conventional DFT based OFDM are high peak to average power ratio (PAPR), the need of cyclic prefix or guard intervals reducing the bandwidth efficiency and the need of channel estimation and equalization at the receiver. Continuous Research is being done to try to overcome these drawbacks and improve the performance of OFDM systems as it is now being adopted by almost all the new wireless technologies.

The main motivation behind this work is to improve the OFDM performance by dealing with some of the drawbacks, such as the need of cyclic prefix, the high PAPR and the need of channel estimation.

1.2. Aim of the project

Figure 1.1 shows a block diagram of a basic digital communication system, this dissertation focuses only on the blocks featured in the highlighted area in figure 1.1. Since OFDM is considered as a modulation and multiplexing technique, therefore only the modulator, demodulator and the channel blocks are considered in this dissertation. The information source in this dissertation is assumed to be a stream of random bits as this system is not implemented for a specific application, for digital wireless communication systems the input data are in bits.

In conventional OFDM DFT is used to implement the orthogonal sub-carriers, and usually adopts either binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM) as the modulation scheme for the system.

The main aim of this project is to simulate and evaluate the performance of a discrete wavelet transform (DWT) based OFDM system adopting differential amplitude phase shift keying (DAPSK) as the modulation technique for wireless communication. As there were no extensive work done on such systems. Replacing DFT with DWT for generating the orthogonal sub-carriers and adopting DAPSK instead of the conventional modulation schemes is expected to improve the performance of the OFDM system.

The objectives for meeting the proposed aim are as follows:

- Implement a 64-DAPSK modulation scheme.
- Implement a DWT based OFDM system.
- implement a DFT based OFDM system for the sake of comparison.
- Evaluate the performance of both systems.

The systems were evaluated in the presence of Additive white Gaussian noise (AWGN) and over multipath fading channel. The Performance of both systems are evaluated in terms of bit error rate (BER) and PAPR.

1.3. Outline

The rest of this dissertation is organized as follows:

- Chapter 2: Literature review to sum up and review the content of the most relevant materials discussed in previous work is presented.

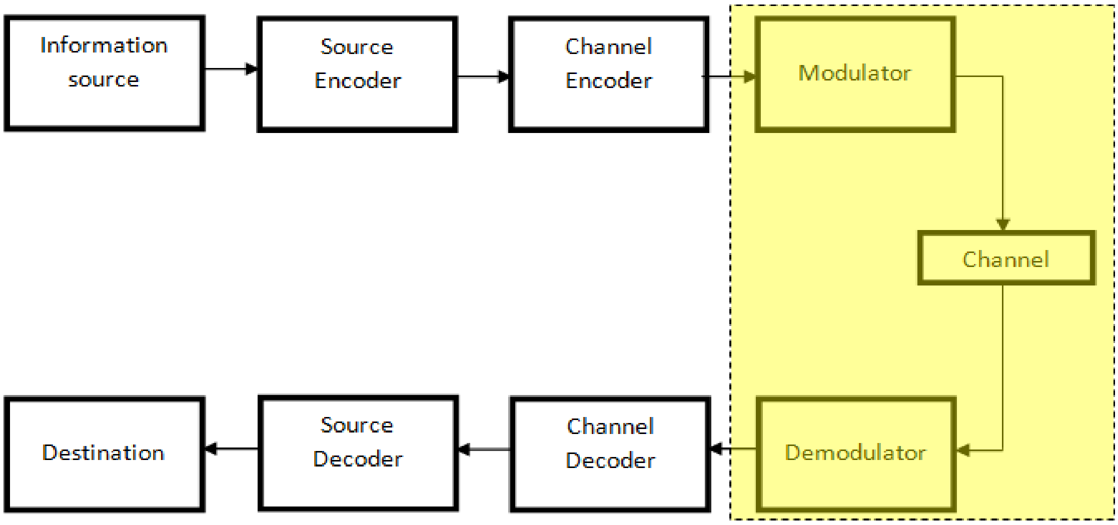

Figure 1.1.: Block diagram of a basic digital communication system.

- Chapter 3: Theoretical background information on conventional OFDM, DWT-OFDM and DAPSK is provided.
- Chapter 4: The simulation tool and the simulation environment is introduced, as well as presenting the simulation results.
- Chapter 5: The discussion of the simulation results.
- Chapter 6: The conclusion of the dissertation and future work proposals.

2. LITERATURE REVIEW

A literature review of existing material that is related to the topic of interest is presented in this chapter. This chapter is divided into two sections, the first is the methodology in which the strategy adopted in searching for the related materials is explained and the second section is the discussion where the chosen material is reviewed.

2.1. Methodology

Finding materials that dealt with the research topic was an essential step for conducting this dissertation. These materials would help in defining the research topic, in addition to providing an overview and basics needed to conduct this dissertation. The first step in finding the relevant material is identifying keywords that define the topic of interest, the keywords used in this search process were “OFDM”, “DWT”, “WOFDM” and “DAPSK”. The next step is to decide where to search for the relevant material as it is very important for efficient searching; the databases used in this report are the university’s library, IEEE Xplore [9] and science direct [10]. The search included books, journals and papers. The next step in the search process is selecting the relevant papers and discarding the irrelevant ones. The process of choosing the relevant papers was done based on the following criteria:

- Recent publication date was preferred although not a must.
- At least one technique used in the paper must be common with the topic of interest in terms of the modulation scheme or the technique used to generate the orthogonal sub-carriers.
- Similar parameters used for testing the performance.
- Results evaluated in practical channel conditions.

After finishing the searching process and choosing the relevant papers it was obvious that there were no extensive research on DWT-OFDM with DAPSK as the modulation technique which confirms the motivation behind this dissertation.

2.2. Relevant work

In this section the chosen papers are presented and reviewed. The papers are sorted topically which means that the papers are divided according to the relevant topic it represents, since no papers were found during the search process adopting the same modulation scheme and the same sub-carrier generation technique as the topic of interest. The topics represented by the papers and according to which they were divided are OFDM, wavelet based OFDM (WOFDM) and DAPSK.

2.2.1. Conventional OFDM

OFDM was introduced long ago, hence most of the important contributions to the conventional OFDM were published years ago. Since some papers presented in this part of the literature review goes back to the 1960's, this subsection can be considered as the history and development of the conventional OFDM.

Chang in 1966 introduced the characteristics of the pulses that can be used in OFDM, the pulses were characterized as being band-limited overlapping spectra. An example of such pulse was the full cosine-roll off [11]. Saltzberg than introduced OFDM-OQAM system to reduce ISI and inter carrier interference (ICI); Saltzberg also proved that the sub-carriers should be separated by $^1/_{2T}$ for orthogonality [12]. Hirosaki then improved the OFDM-OQAM system by introducing DFT for DSP implementation [13].

Another fundamental contribution was introduced in 1967 by Zimmerman and Kirsch when they designed and implemented an OFDM transceiver using DFT for the sub-carrier generation [14]. The high complexity of the transceiver intrigued Paul Ebert, Jack Salz, and B. Weinstein to find a solution, that was using FFT algorithm to implement the DFT which decreases the complexity from N^2 to NlogN [8]. Another major contribution was the cyclic prefix proposed by Peled and Ruiz to get rid of ISI that was one of the main challenges facing OFDM systems [15]. Another major challenge was the high PAPR a number of solution was discussed in [16] and [17] to overcome this challenge such as clipping, coding, tone reservation or injection, dynamic constellation extension, signal phasing and various signal formation techniques such as mapping and interleaving.

OFDM systems were not used in practical commercial applications until the advancement of DSP. The first major application was the ADSL that achieves fast data transmission over copper wires [18]. Another major application was the DVB which also uses OFDM for video broadcasting; two versions of DVB exists the first is the DVB-T [19] and the DVB-H [20] which is more mobile friendly version. OFDM is also used in wireless applications such as WIFI, WIMAX and many other application [21].

2.2.2. WOFDM

M.A. Tzannes, M.C. Tzannes and H.L. Resnikoff discovered that the orthogonal sub-carriers can be generated using transforms other than the DFT to over come its flaws, and introduced DWT as one of these transforms [22] which is the transform used in this dissertation. The following papers are the most relevant papers to the topic of interest that used DWT to generate the sub-carriers.

[23]compared three trans-multiplexing techniques for OFDM systems these techniques were DFT based OFDM, DWT based OFDM and wavelet packet transformation (WPT) based OFDM. The properties of the three transformation techniques were explained and their expected performance in terms of computational complexity was compared analytically. In this paper no simulation was done to practically test the three systems, the comparison was done theoretically. Unlike in [24] were the performance of the same three techniques were compared using simulated results, the comparison was done in terms of BER at different signal to noise ratio (SNR), The authors concluded after comparing the results that the DWT based OFDM system is better than the other two techniques, but the authors of the paper didn't mention the type of modulation or signal mapping they used and also didn't mention the channel conditions they tested the system in. In [25] the authors compared the performance of a discrete cosine transform (DCT) based OFDM with DWT based OFDM and conventional OFDM in the presence of AWGN and over Saleh-Valenzuela (SV) channel model at 60 GHz. The BER at different SNR was calculated for the systems and for several wavelet families. the results showed that the conventional OFDM is superior over the SV channel model at 60Hz.

[26], [27] and [28] focused their work on testing wavelet OFDM system over a multipath frequency selective channel and compare it to the performance of the conventional OFDM over the same channel conditions. [27] evaluated the performance of a WPT based OFDM and conventional OFDM adopting QPSK as the modulation scheme, the performance of the system was evaluated over a Rayleigh fading channel and in the presence of AWGN. The BER of the two systems was simulated at different SNR with various Doppler shifts. [28] evaluates the performance of a DWT based OFDM over two different frequency selective channels. similarly [26] evaluated the performance of a WOFDM using WPT over an eight path frequency selective channel using different models such as outdoor and indoor models. The results of the three papers were diverse in terms of the value of BER, but all agreed that a wavelet based OFDM system either using DWT or WPT have better performance when compared to the conventional OFDM system over fading channels.

As the high PAPR is one of the major disadvantages of conventional OFDM, [29], [30] and [31] presented WOFDM systems as a solution for the PAPR problem. [29] and [31] both used WPT to reduce the PAPR and compare it with the conventional OFDM. [30] used DWT based OFDM system and compared the results with the conventional OFDM, also the PAPR was calculated for different wavelet families. All the three authors concluded that the PAPR in the Wavelet based OFDM (WOFDM) systems is significantly less than in the conventional OFDM systems and that the Haar wavelet family results in the least PAPR.

[32] simulated a DVB-T system but instead of using the conventional OFDM as the

modulator WOFDM was used. The BER was calculated in the presence of AWGN at different SNR and for different wavelet families. The results showed a better performance in term of BER for the WOFDM based DVB-T system and that the haar wavelet family gives the best performance. The results were obtained in the presence of AWGN only which is not enough as it is impractical. the system has to be evaluated over a fading channel.

2.2.3. DAPSK

DAPSK as a concept for OFDM systems was introduced in [5] for DVB-T application, the detailed description of DAPSK is presented in chapter 3. The paper explains the modulation technique and then simulate a conventional OFDM system adopting 64-DAPSK as the modulation technique in the presence of AWGN and Rayleigh channel. The results were compared with similar OFDM systems but adopting 64-QAM and 64-DPSK as the modulation technique over the exact same channel for fair comparison. The results showed that the BER in case of the 64-DAPSK system is better than the 64-DPSK but worse than 64-QAM, but this comparison is incomplete as the 64-DAPSK might be better in terms of implementation complexity as it doesn't need channel estimation or equalization. [33] introduce a two dimensional demodulation algorithm for differential modulation in general, and applied it on DAPSK and DPSK to evaluate and compare the performance of the new algorithm. the authors concluded that the new algorithm offers better computational complexity that can reach up to 85% less. Extensive work on DAPSK as an OFDM modulation technique is presented in [6], the error probability is evaluated and the optimum ring ratio and detection thresholds are determined. In addition to a comparison between 64-QAM and 64-DAPSK OFDM systems over different high frequency (HF) channels. Both Systems gave approximately the same BER results over different channels.

3. BACKGROUND

3.1. Conventional OFDM

The basic concept of OFDM is based on FDM which is simply an early form of OFDM. FDM divide the stream of data into N smaller streams and then modulates them onto N narrow-band sub-carriers, instead of using the whole frequency band like in the case of single carrier modulation. The sub-carriers almost experience flat fading in a frequency selective channel as they are narrow band. The sub-carriers are separated by guard intervals so the carriers don't interfere with each other as shown in figure (3.1a), data can be recovered at the receiver using filters. The guard intervals consumes a part of the frequency band affecting the bandwidth efficiency.

OFDM improves the bandwidth efficiency and removes the guard intervals between sub-carriers. Sub-carriers in OFDM overlap but don't interfere with one another as they are orthogonal as shown in figure (3.1b). Two signals are said to be orthogonal over the period T if:

$$< u, v >= \int_0^T u(t).v(t) \quad dt = \begin{cases} 0 & if\ u \neq v \\ C & if\ u = v \end{cases}$$

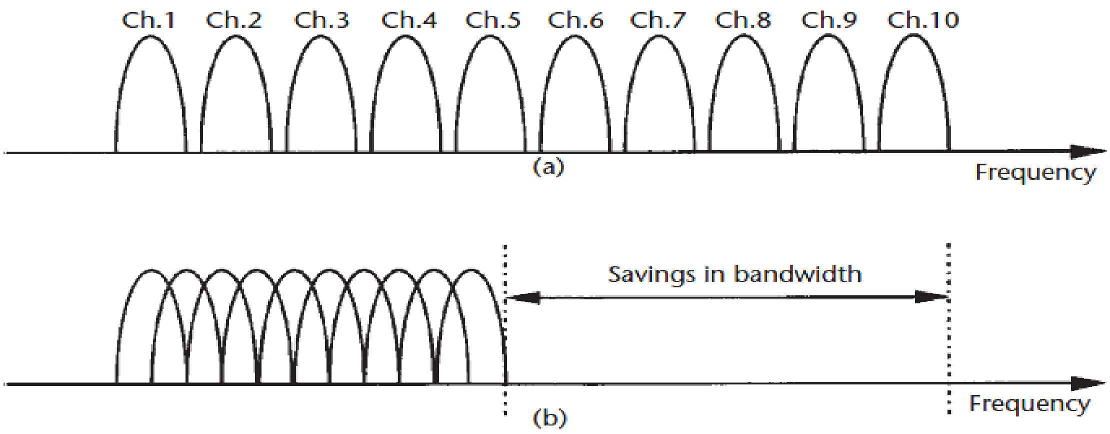

Figure 3.1.: Concept of the OFDM signal: (a) FDM and (b) OFDM [1]

Equation (3.1) represents the mathematical equivalence of an OFDM signal

$$v(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi k \Delta f}, \qquad 0 > t > T \tag{3.1}$$

where N is the number of sub-carriers, X_k is the data symbol transmitted on the k^{th} sub-carrier and Δf is the spacing between the sub-carriers. For orthogonality Δf must be equal to $\frac{1}{2T}$.

DFT and IDFT are used to generate the orthogonal sub-carriers instead of IQ modulators as suggested in [8] to make it more practical. DFT is an invertible transform and it form orthogonal basis. DFT and IDFT formulas are shown in equations 3.2 and 3.3 respectively. The similarities between equations (3.1) and (3.3) indicates that the IDFT can be used in transmitter to generate the orthogonal sub-carriers and the DFT can be used in the receiver as it is the inverse process. DFT and IDFT are practically implemented using the hardware efficient FFT and IFFT algorithms respectively.

$$X_k = \sum_{n=0}^{N-1} x_n \, e^{-j2\pi n f_0} \tag{3.2}$$

$$x_n = \frac{1}{N} \sum_{n=0}^{N-1} X_k \, e^{j2\pi n f_0} \tag{3.3}$$

The path between the transmitter and the receiver or the channel distorts the transmitted OFDM symbols causing ISI and ICI which effects the sub-carriers orthogonality, hence cannot be correctly demodulated at the receiver. Figure (3.2) shows the effect of the channel on one OFDM symbol and figure (3.3) shows the effect of the channel distortion on adjacent symbols and how they can interfere with one another. Guard intervals where no information is sent are inserted between symbols

Figure 3.2.: Effect of channel on OFDM symbol [2].

to overcome ISI caused by the channel distortion as shown in figure (3.4). Still the ICI problems exists after adding the guard time. To get rid of ICI cyclic prefix is used instead of the guard intervals. For cyclic prefix the guard interval is replaced by a number of samples from the end of the OFDM symbol, this part added makes

Figure 3.3.: Effect of channel on OFDM signal [2].

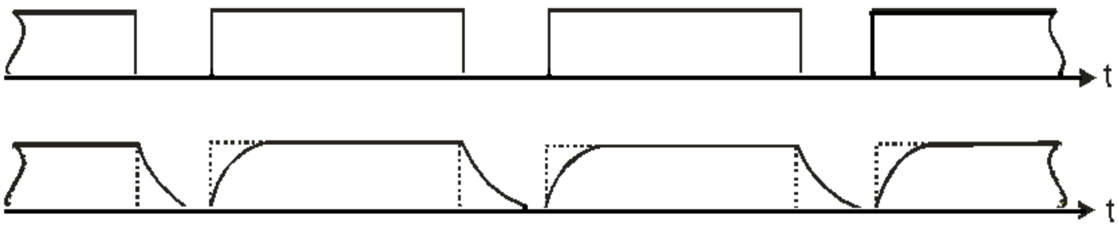

Figure 3.4.: OFDM signal with guard intervals [2].

the signal periodic and thus eliminates ICI. The cyclic prefix contains unnecessary information and so it is ignored at the receiver. An OFDM signal with cyclic prefix is shown in figure (3.5).

The basic model of an OFDM's transmitter and receiver are shown in figures (3.6) and (3.7) respectively. The first block is the serial to parallel converter that takes the stream of bits as it's input and divide those bits into N blocks where N is the number of sub-carriers required. The bits then enter the constellation mapping block, in constellation mapping the input bits are converted to a given constellation. Usually BPSK, QPSK or M-QAM constellations are used in conventional OFDM systems. The type of constellation is chosen according to the communication channel used. The output data from this block is in complex form (a+jb). The complex data then enters the IFFT block where they are converted from the frequency domain to the time domain and modulated to the orthogonal sub-carriers. The sub-carriers have a sinc waveform in the frequency domain and each sub-carrier has a null at the center frequency of the other sub-carriers as shown in figure (3.8). After the data is transformed the cyclic prefix is added and the data is converted back from parallel to series.

The transmitted data reaches the receiver distorted due to the channel effects. The receiver basically inverts each process performed in the transmitter. First the received data are converted from series to parallel and the cyclic prefix is eliminated. As the received data is still in time domain FFT is applied to convert it back to frequency domain. Finally the data are mapped back to the original bits if possible, some bits are not mapped correctly due to the effect of the channel.

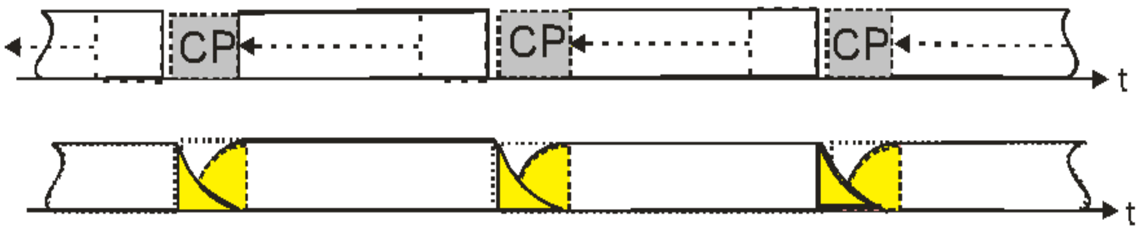

Figure 3.5.: OFDM signal with cyclic prefix [2].

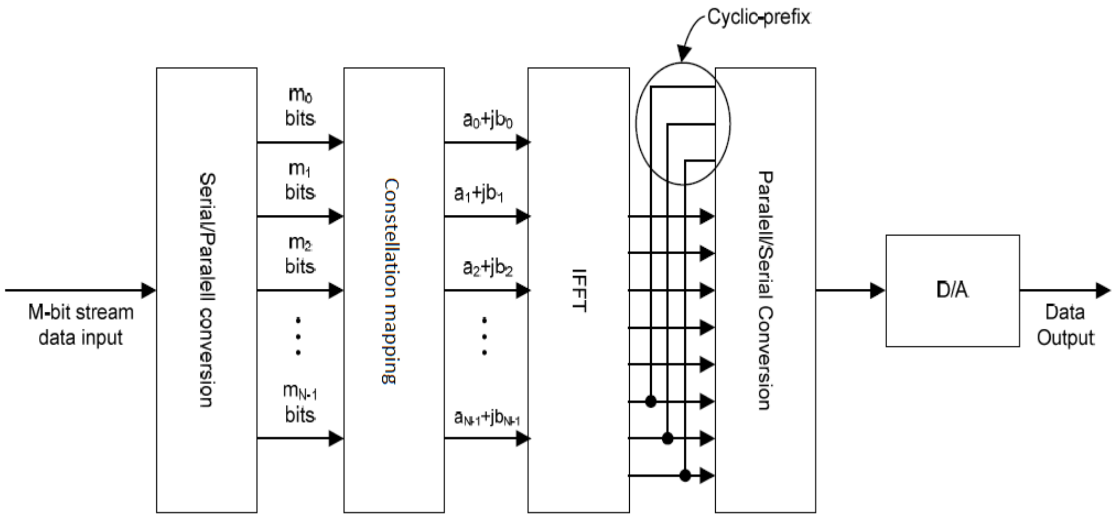

Figure 3.6.: Block diagram of an OFDM basic transmitter [3].

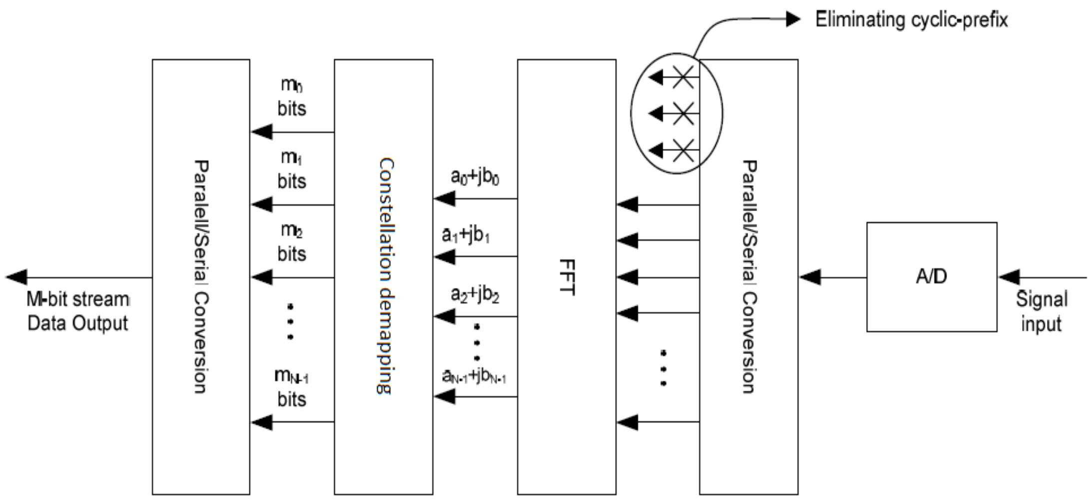

Figure 3.7.: Block diagram of an OFDM basic receiver [3].

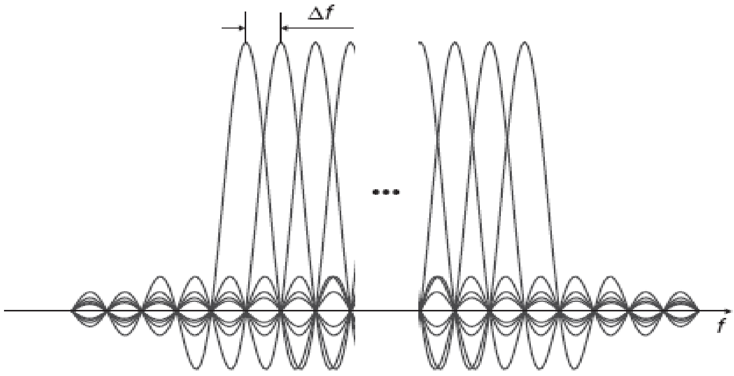

Figure 3.8.: OFDM sub-carriers

3.2. DWT-OFDM

Wavelet refers to a small wave with limited duration. wavelets form the basis of DWT. Unlike sine waves which form the basis of the Fourier transform, the wavelets are irregular, asymmetric and have limited durations. Wavelet transform provides variations in time-frequency resolutions due to the variation in it basis function in terms of frequency and scale as shown in figure (3.9) which is a major advantage over Fourier transform. The wavelet basis function divides the data into different frequency components and chooses the component that relates to its scale. It is clear from figure (3.9) that the wavelet basis function is divided into windows with variable sizes at different frequencies which causes the variation in time-frequency resolution, unlike the Fourier basis function that is divided into square windows of fixed sizes which doesn't provide variation in time-frequency resolution as shown in figure (3.10). The variation in time-frequency resolution provides an infinite

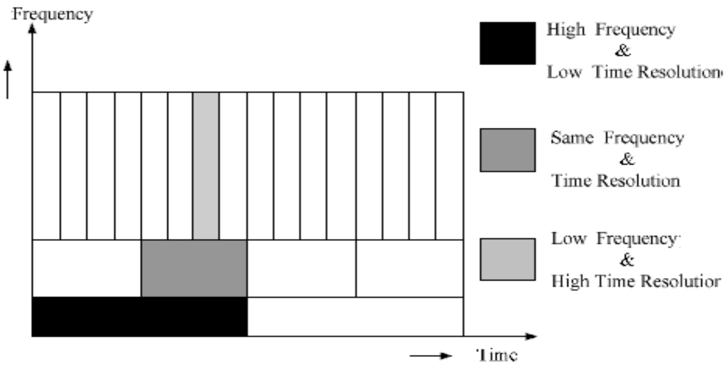

Figure 3.9.: Wavelet basis function [4].

number of basis functions for wavelet transform but only one basis function for Fourier transform.

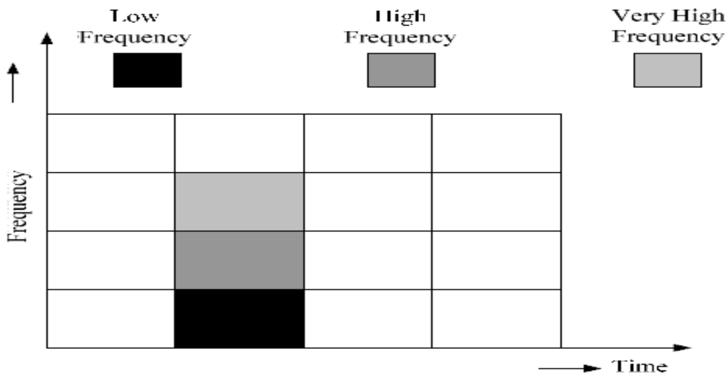

Figure 3.10.: Fourier basis function [4].

The mathematical representation of DWT and IDWT formulas are shown in equations (3.4) and (3.5) respectively.

$$D_k = \sum_{k=0}^{N-1} d(k)\psi(2k-n) \tag{3.4}$$

$$d(k) = \sum_{m=o}^{\infty}\sum_{n=0}^{\infty} D_k\psi(2k-n) \tag{3.5}$$

Where ψ is the wavelet kernel and is selected according to the mother wavelet chosen. To practically implement DWT only two filter banks are required, a low pass filter and a high pass filter; which makes the implementation simple in terms of complexity. The description of the DWT implementation is provided in chapter four. The only difference in the block diagram between DFT-OFDM and DWT-OFDM is that the IDFT and DFT blocks in figures (3.6) and (3.7) respectively are replaced by IDWT and DWT as shown in figures (3.11) and (3.12) respectively. It is also clear that there is no cyclic prefix used in DWT-OFDM systems due to the overlapping properties of DWT; as well as that the side lobes in case of DWT contains very low data and that most of the data is carried in the main lobe, hence the amount of interference is very low [23].

3.3. DAPSK

In this section the mapping scheme or the modulation scheme that is used in this dissertation is explained. DAPSK is a multilevel modulation technique. DAPSK is chosen as the modulation scheme as it doesn't require any channel estimation nor equalization at the receiver, which improves the complexity of the receiver compared

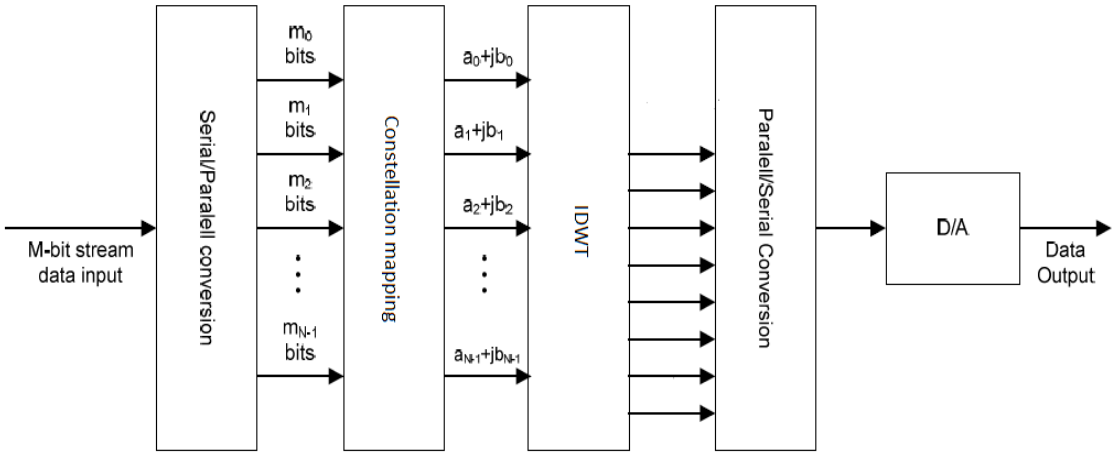

Figure 3.11.: Block diagram of DWT-OFDM transmitter.

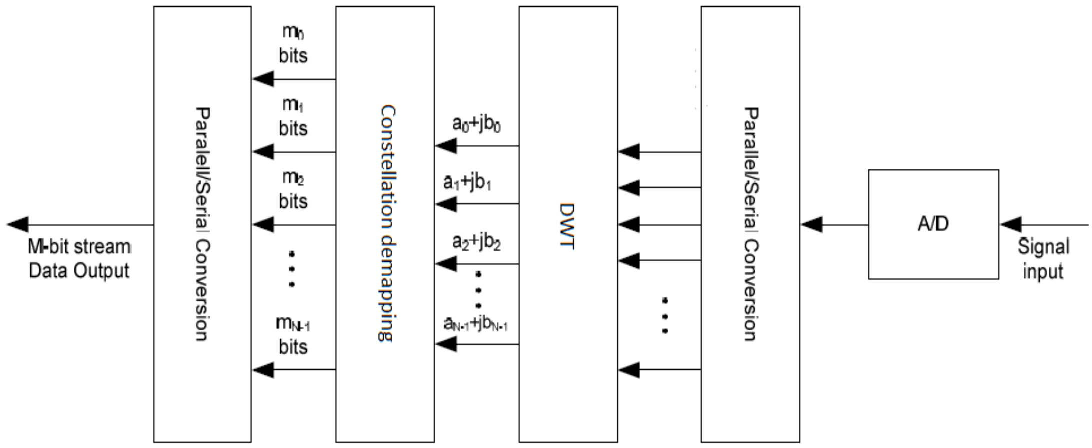

Figure 3.12.: Block diagram of DWT-OFDM receiver.

to other modulation schemes. As any differential modulation technique DAPSK can be represented as follows:

$$S_{i,k} = B_{i,k}.S_{i-1,k} \tag{3.6}$$

where $S_{i,k}$ is the complex symbol, $B_{i,k}$ is the bit sequence to be modulated and $S_{i-1,k}$ is the previous modulated complex symbol. In this dissertation 64-DAPSK was employed. DAPSK uses both amplitude and phase for modulation. For 64-DAPSK the number of bits per modulated symbol or in other words the number of bits used to get $B_{i,k}$ in equation (3.6) is six. Those six bits are going to be referred to as b_0, b_1, b_2, b_3, b_4 and b_6. The first four bits are responsible for the phase modulation while the last two bits will be responsible for the amplitude part along with the previous modulated symbol as shown in equation (3.6). $B_{i,k}$ in equation (3.6) can be represented as shown in equation (3.7) for 64-DAPSK.

$$B_{i,k} = a^q \;.\; e^{j\pi\Delta\varphi} \tag{3.7}$$

$$q = 0, ...3$$

$$n = 0, ...15$$

$$\Delta\varphi = 22.5$$

where a^q represents the four possible amplitude levels and $e^{j\pi\Delta\varphi}$ represents the sixteen possible phase states as shown from the constellation diagram presented in figure (3.13). The four bits (b_0,.....b_3) that are responsible for the phase transition is applied to a normal 16-DPSK to satisfy the phase transitions shown in figure (3.13). To achieve the four amplitude circles as shown in the constellation diagram, bits b_4 and b_5 are used along with the amplitude of the previous modulated symbol$|S_{i-1,k}|$. Table (3.1) illustrates the value of the amplitude given the two input bits and the amplitude of the previous symbol.

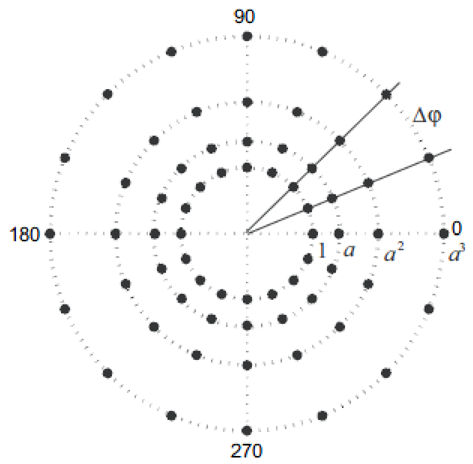

Figure 3.13.: 64-DAPSK constellation diagram [5].

Table 3.1.: Amplitude value for 64-DAPSK [6].

$\lvert B_{i,k}\rvert = a^q$		Amplitude bits (b_4,b_5)			
		00	01	11	10
$\lvert S_{i-1,k}\rvert$	1	1	a	a^2	a^3
	a	a	a^2	a^3	1
	a^2	a^2	a^3	1	a
	a^3	a^3	1	a	a^2

For demodulation again for the first four bits ordinary 16-DPSK demodulation is carried out. As for the bits representing the amplitude table (3.2) demonstrates the hard decision parameters according to certain thresholds, where $R_{i,k}$ is the received symbol and $R_{i-1,k}$ is the previously received symbol. The threshold values are half the distance between any two adjacent amplitudes.

Table 3.2.: Amplitude value for 64-DAPSK demodulation [6].

$\frac{\lvert R_{i,k}\rvert}{\lvert R_{i-1,k}\rvert}$	$\leq a^{-2.5}$	$[a^{-2.5}, a^{-1.5}]$	$[a^{-1.5}, a^{-0.5}]$	$[a^{-0.5}, a^{0.5}]$	$[a^{0.5}, a^{1.5}]$	$[a^{1.5}, a^{2.5}]$	$>a^{2.5}$
b_4, b_5	01	11	10	00	01	11	10

4. SIMULATION AND RESULTS

This chapter consists of two sections, computer simulations and results. In the computer simulations section a description of the simulation code and the simulation tool is presented. In the second section all the obtained results from the simulation is presented.

4.1. Computer simulations

MATLAB is used for all the simulations presented in this dissertation. MATLAB is a widely used simulation tool in the engineering community, MATLAB allows matrix manipulations and data plotting and used for signal processing, communications, control design, test and measurement, modeling and analysis [34].

The implemented OFDM system consists of three sections, namely the transmitter, the channel and the receiver; and each section consists of a number of blocks. Each block is implemented in a separate M-file and then the blocks are called in the main M-file which is responsible for the simulation of the whole OFDM system and plotting all the required graphs. The MATLAB code used for the simulation is presented in the Appendix.

In the following subsections the implementation of each major block in the OFDM system is described.

4.1.1. Signal generation

A random sequence of bits is generated. The number of bits is determined according to the number of sub-carriers required, number of bits per symbol and number of OFDM symbols used in the simulation. For this simulation the number of sub-carriers used was 64, 6 bits per symbol for 64-DAPSK and 15 OFDM Symbols, by a simple calculation the number of generated bits were 6000, which yielded a total amount of about 1000 sample for all the OFDM symbols which is sufficient to test the performance of the system.

4.1.2. 64-DAPSK modulation

Before the bits are modulated they were divided into groups of six and put into a matrix form. The matrix consists of N rows which is the number of sub-carriers and S columns which is the number of OFDM symbols. The previous steps convert the signal from serial to parallel, each column in the matrix represents an OFDM symbol.

Now the modulation process starts as explained in section (3.3). The first four bits of every symbol were modulated using ordinary 16-DPSK and the last two bits were used for the amplitude demodulation according to table (3.1). The value of the amplitude parameter a found in table (3.1) was set to 1.4 as it was found by [6] that 1.4 is the optimum value for perfect demodulation. Figure (4.1) shows the constellation diagram simulated for a sequence of randomly generated bits.

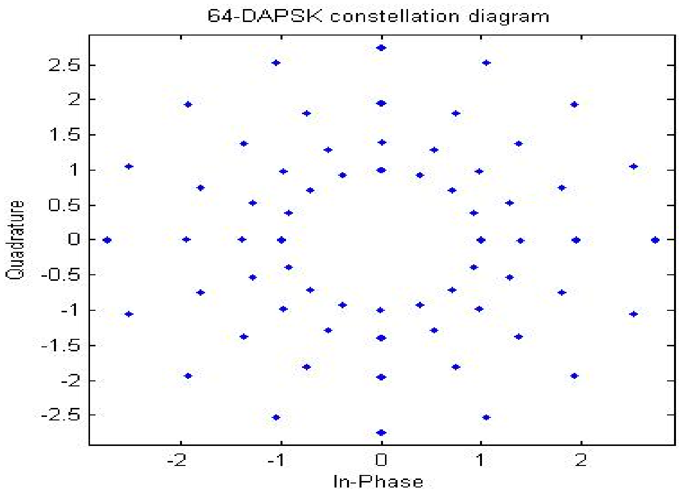

Figure 4.1.: Simulated 64-DAPSK constellation diagram.

4.1.3. Inverse transformation

The main focus of this dissertation is to evaluate the performance of a DWT based OFDM system adopting 64-DAPSK as the modulation scheme. To correctly evaluate the performance of the DWT based system, A DFT based system and a DCT based system both adopting a 64-DAPSK modulation scheme were also implemented to compare the results with the DWT based system.

In this subsection the IDWT, IDFT and IDCT blocks of the transmitter are described, but mainly focusing on the IDWT since it is the topic of interest.

4.1.3.1. IDWT

The IDWT block is the inverse process of the DWT block. To implement the IDWT only two filters are required, a low-pass and a high-pass filter. Figure (4.2) shows the

IDWT implementation, where D_K is the K^{th} OFDM symbol after being modulated and O_k is a vector of zeros having the same number of elements as the OFDM symbol. It is clear that the modulated signalD_k is upsampled and then filtered using the low-pass filter (L[n]), as for O_k it is also upsampled and filtered but using the high-pass filter (H[n]). Then the filter outputs are added together. The IDWT process is iterative which means that the same procedure can be repeated as many times as required. Both filters coefficients are determined according to which wavelet family is used, in this dissertation the haar wavelets are used. Figures (4.3), (4.4) and (4.5) shows the simulated D_k, O_k and $d(k)$ signals respectively.

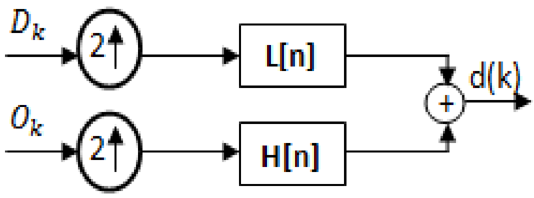

Figure 4.2.: IDWT filter implementation.

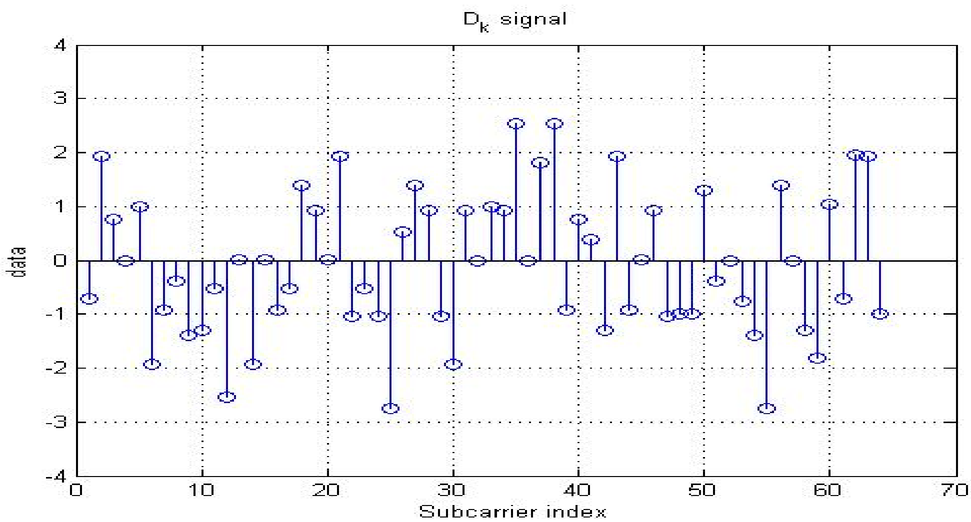

Figure 4.3.: IDWT simulated D_k signal.

4.1.3.2. IDFT and IDCT

For implementing the IDFT and the IDCT an embedded function in the MATLAB is used for the transformation process. As for the addition of the cyclic prefix, after the transformation the last N_g samples of each OFDM symbol is copied and added at the beginning of the OFDM symbol. In this dissertation N_g is set to $1/4$ of the

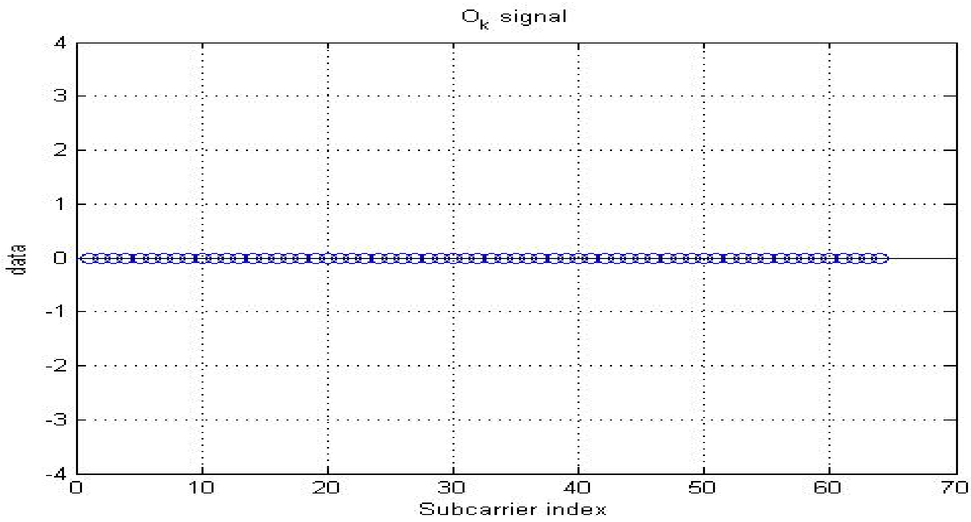

Figure 4.4.: IDWT simulated O_k signal.

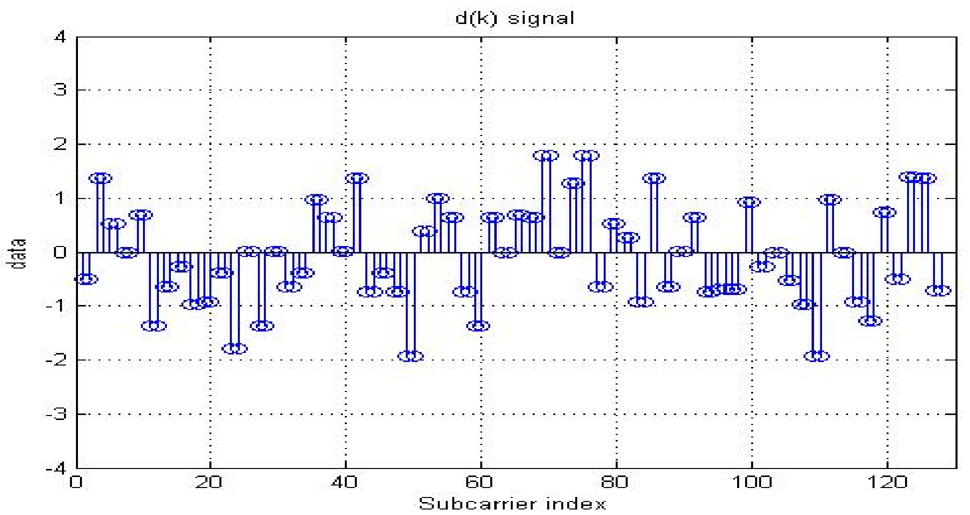

Figure 4.5.: IDWT simulated d(k) signal.

number of sub-carriers. Both the transformation and the addition of the cyclic prefix are implemented in the same M-file and called by the main file for execution.

4.1.4. Channel

In wireless communication the channel is always unpredictable. The signal traveling from the transmitter to the receiver suffers from very harsh conditions, such as fading, noise and Doppler spread.

The first channel impairment is the noise in the channel which causes the signal to attenuate. Noise in the channel is modeled as an additive white Gaussian noise (AWGN). AWGN is a result of several independent noise sources and is added to the signal.

The main channel impairment is fading, fading occurs due to multipath reflections. The transmitted signal experience several reflections from objects between the transmitter and the receiver, resulting in simultaneous reception of the signal from different paths. The fading in this dissertation is modeled as Rayleigh fading, where the magnitude of the signals arriving at the receiver have a Rayleigh distribution. In Rayleigh fading there is no line of sight component and the receiver only depends on the reflected components. Rayleigh fading can be either flat or frequency selective, frequency selective fading occurs when the signal's bandwidth is larger than the coherence bandwidth of the channel and flat fading occurs when the signal's bandwidth is smaller than the coherence bandwidth of the channel. When the transmitter or the receiver are in motion this causes a Doppler effect which also affects the transmitted signal. the Doppler effect is relative to the speed of motion, the higher the speed the higher the effect an vice versa. The received signal after passing through the channel can be represented as follows:

$$r(n) = x(n) * h(n) + w(n)$$

where r(n) is the received signal, x(n) is the transmitted signal, h(n) is the channel response and w(n) represents the added noise.

The performance of the DWT-OFDM system is evaluated over flat fading, frequency selective fading and in the presence of AWGN and with a maximum Doppler shift of 120 Hz . The multipath channel model parameters are summarized in table (4.1). The effect of flat fading channel in the presence of noise at SNR of 25dB on a DWT-

Table 4.1.: Channel model parameters.

Path	Power [dB]	Delay [μs]
1	-3	0
2	0	0.2
3	-2	0.5
4	-6	1.6
5	-8	2.3
6	-10	5

OFDM, DFT-OFDM and DCT-OFDM signals are shown in figures (4.6), (4.7) and (4.8) respectively.

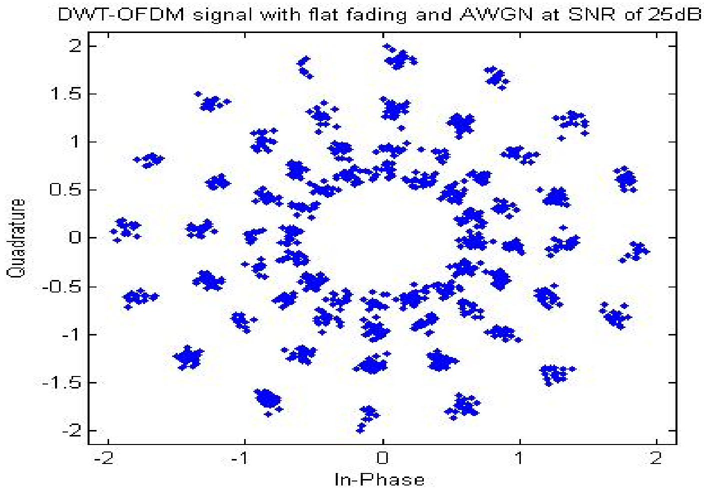

Figure 4.6.: Scatter plot for DWT-OFDM signal over a flat fading channel and in presence of AWGN.

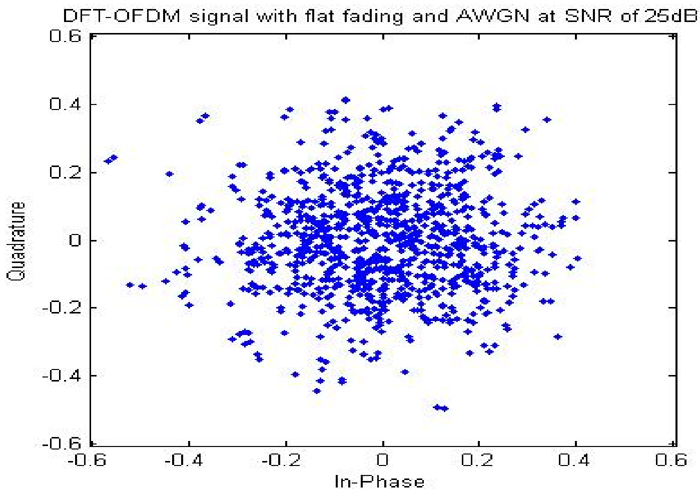

Figure 4.7.: Scatter plot for DFT-OFDM signal over a flat fading channel and in presence of AWGN.

4.1.5. Transformation

The DWT, DFT and DCT blocks are simply the inverse of the processes explained for the IDWT, IDFT and IDCT blocks respectively.

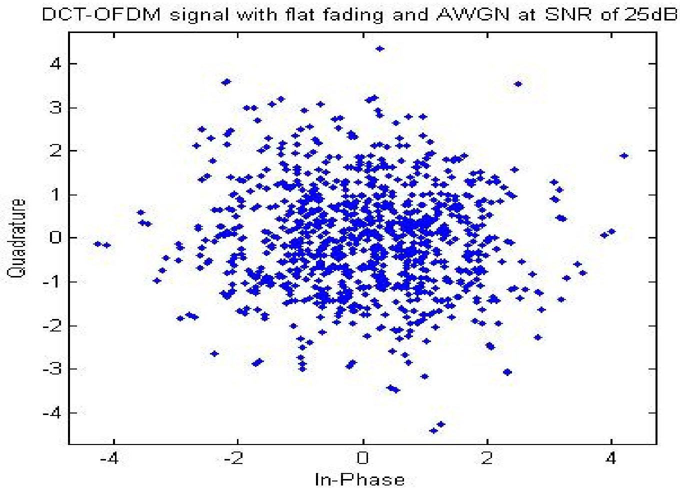

Figure 4.8.: Scatter plot for DCT-OFDM signal over a flat fading channel and in presence of AWGN.

4.1.5.1. DWT

To implement DWT the same two filters used for IDWT must be used. As shown in figure (4.9) the received signal is filtered twice once with the low pass filter and once with the high pass filter. This process splits the signal into two equal halves for the analysis of low and high frequency components. the output of the two filters is then downsampled. The output of the high-pass filter contains a small amount of information and is ignored. This process is also iterative. The number of iterations this time depends on the number of iterations used in the IDWT block. The output of the low-pass filter is always used as the input signal for the next iteration and finally the output of the low-pass filter after the final iteration is passed to the next block. Figures (4.10), (4.11) and (4.12) shows the d(k), D_k and O_k signals respectively.

4.1.5.2. DFT and DCT

First of all the cyclic prefix of each OFDM symbol is detected and removed. The removed cyclic prefix is then ignored as it is of no use. Now the signal is without the cyclic prefix and ready for the transformation. For the DFT and the DCT transformation an embedded MATLAB function is used. After the transformation the signal is passed to the next block.

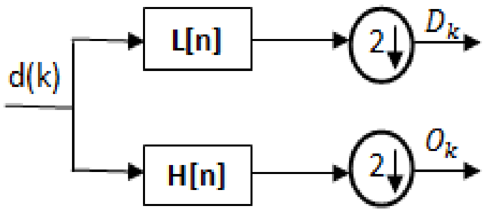

Figure 4.9.: DWT filter implementation.

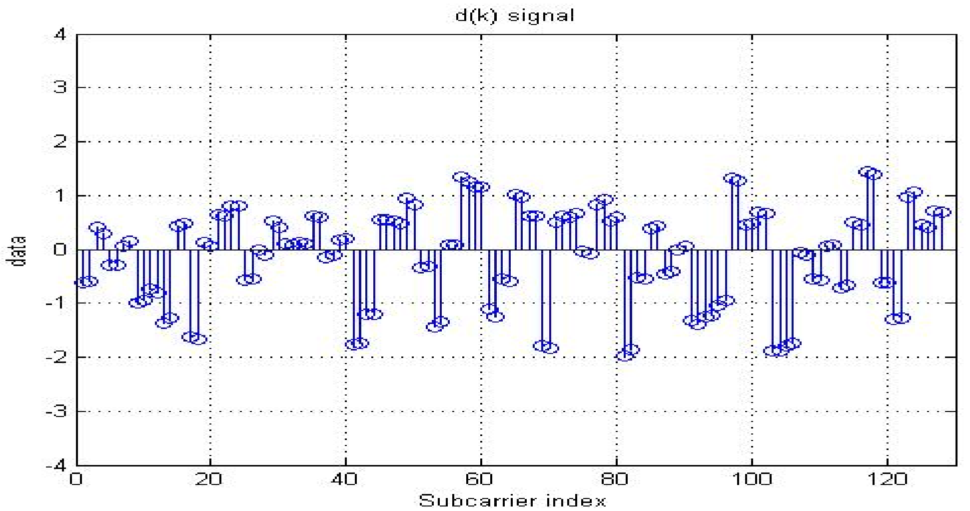

Figure 4.10.: DWT simulated d(k) signal.

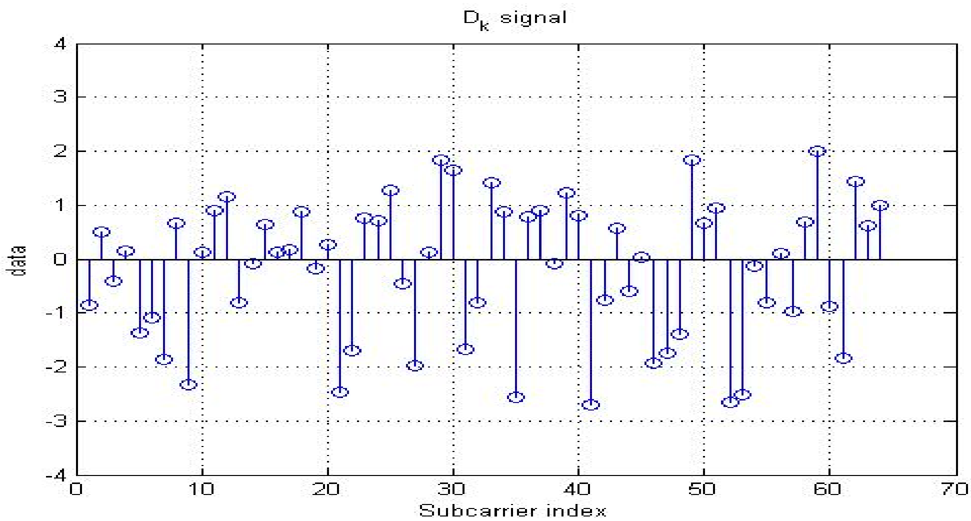

Figure 4.11.: DWT simulated D_k signal.

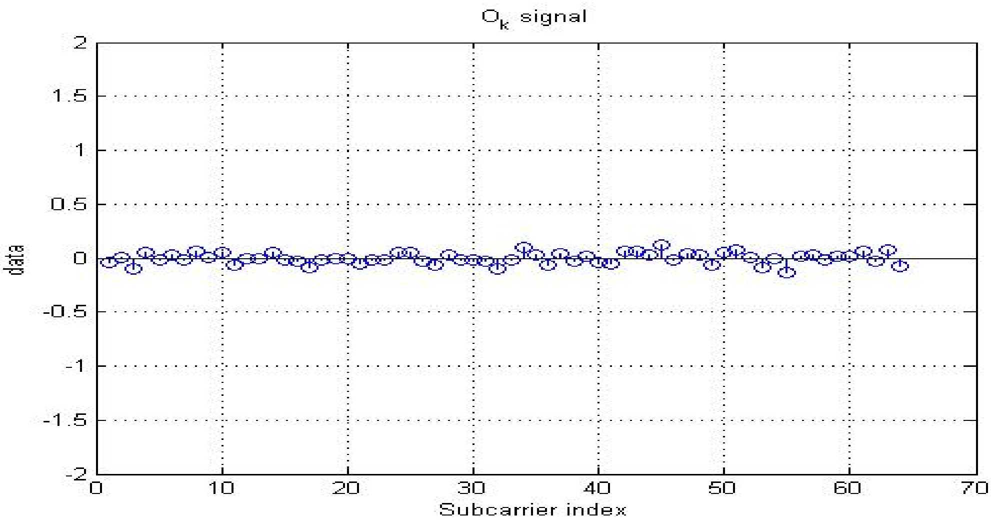

Figure 4.12.: DWT simulated O_k signal.

4.1.6. 64-DAPSK demodulation

This block is responsible for the 64-DAPSK demodulation. The demodulation process is performed as explained in section (3.3). The first four bits are determined by the phase of the received symbols by performing an ordinary 16-DPSK demodulation. The last two bits are determined by the amplitude of the received symbols according to certain thresholds as shown in table (3.2).

4.1.7. BER and PAPR calculation

To evaluate the performance of the 64-DAPSK DWT-OFDM system and compare it to DFT-OFDM and DCT-OFDM systems, Two evaluation parameters were used.

The first parameter is the bit error rate (BER), BER refers to the number of bits in error in the received signal compared to the transmitted signal. BER is measured at different SNRs, it is used to investigate the robustness of the signal to the channel impairments. The measured BER is then plotted against the SNR that it was calculated at to show the relationship between them. The BER is calculated by comparing the received signal with the transmitted signal and then dividing the number of bits in error by the number of total bits in the signal.

The second parameter is the peak to average power ratio (PAPR), PAPR is a measurement of the variations in the signal's envelope. PAPR is calculated as follows:

$$PAPR_{dB} = 10Log10\left[\frac{max|S(t)|^2}{E[|S(t)|^2}\right]$$

where S(t) is the signal of interest. The PAPR is calculated for the transmitted and the received signal. The complementary cumulative distribution function (CCDF) was used to investigate the performance in terms of PAPR, the CCDF of PAPR can be defined as follows:

$$P(PAPR(dB) \ > \ PAPR_{th}(dB))$$

where $PAPR_{th}$ is the threshold value in dB.

4.2. Results

In this section all the simulation results are presented.

4.2.1. BER

To evaluate the performance of the DWT-OFDM system over different channel conditions, the results of the BER calculation is presented.

Figure (4.13) shows the BER at different SNRs for DWT-OFDM, DFT-OFDM and DCT-OFDM systems in the presence of AWGN only for the sake of comparison. It is clear that in case of the presence of AWGN only the DWT-OFDM system outperforms the DFT-OFDM and DCT-OFDM systems by 5 dB at BER of 0.0001. The figure also demonstrates that both DFT-OFDM and DCT-OFDM systems have similar performance.

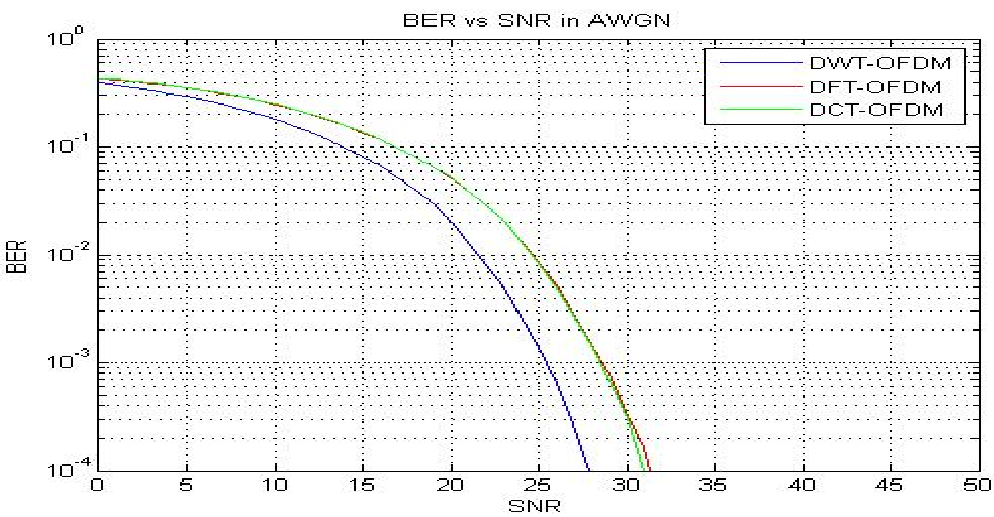

Figure 4.13.: Performance of BER in the presence of AWGN at different SNR.

The BER was also observed over a Rayleigh flat fading channel in the presence of AWGN in figure (4.14). The DWT-OFDM outperforms both the DFT-OFDM and the DCT-OFDM systems by about for 4 dB at BER of 0.001. Again DFT-OFDM and DCT-OFDM shows similar performance as each other. The performance over a Rayleigh multipath frequency selective channel in the presence of AWGN was also simulated. Figure (4.15) shows the performance curves in terms of BER for the DWT-OFDM, DFT-OFDM and DCT-OFDM systems over the frequency selective channel. It is observed that the DWT-OFDM systems again outperforms both the DFT-OFDM and the DCT-OFDM systems by 3dB at BER of 0.001. The performance curves of the DFT-OFDM and DCT-OFDM systems were almost the same at different SNRs.

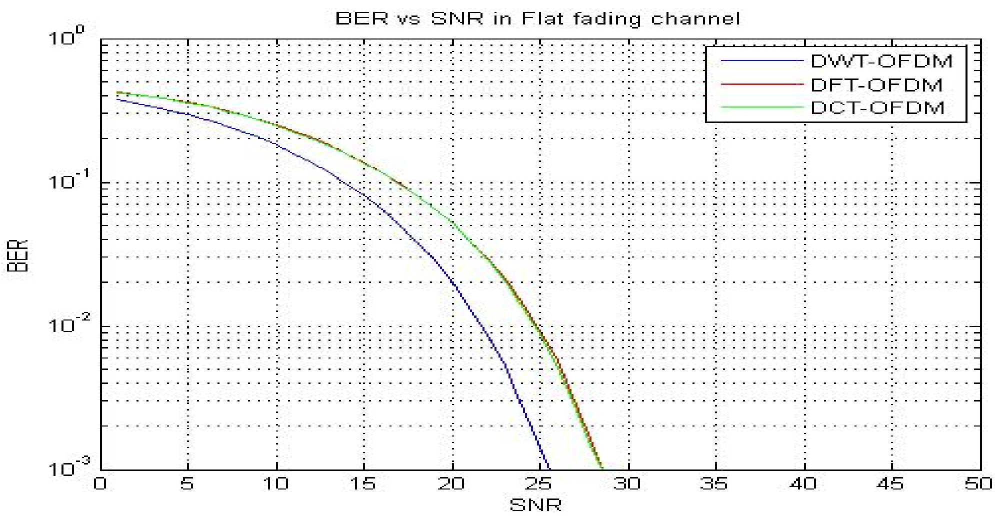

Figure 4.14.: Performance of BER over Rayleigh flat fading channel in the presence of AWGN.

For the sake of comparison figure (4.16) shows the BER curves for the DWT-OFDM system over the flat fading and the frequency selective fading in the presence of AWGN. The performance seems to be similar in both cases, so to illustrate the difference between the two cases figure (4.17) shows the bar plot in both cases and the calculated BER values at different SNR is presented in table (4.2). It is clear from figure (4.16) that the DWT-OFDM over flat fading channel slightly outperforms the DWT-OFDM system over the frequency selective channel, table (4.2) shows that in case of flat fading the BER reaches the target of 0.001 at a SNR of 26 dB and at SNR of 28 dB in case of the frequency selective channel. This demonstrates the superiority of the DWT-OFDM system over flat fading channel when compared to frequency selective channel by approximately 2 dB.

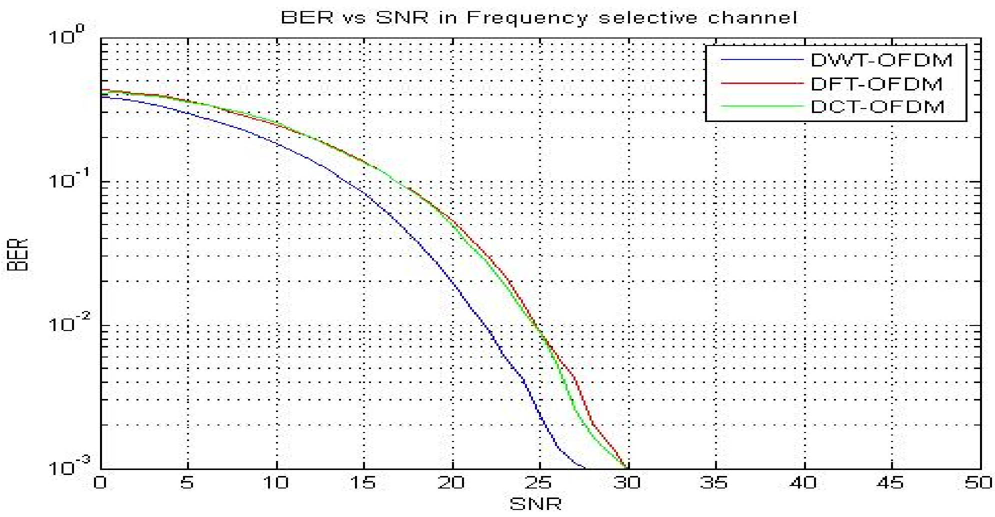

Figure 4.15.: Performance of BER over a frequency selective channel in the presence of AWGN.

Table 4.2.: Performance analysis over frequency selective and flat fading channels.

SNR [dB]	Flat fading channel BER	Frequency selective channel BER
5	0.291	0.296
10	0.198	0.204
15	0.084	0.082
20	0.018	0.020
26	0.001	0.004
28	0.001	0.001

4.2.2. PAPR

PAPR analysis for the the DWT-OFDM system is done by comparing the PAPR of the transmitted signal and the received signal for DWT-OFDM, DFT-OFDM and DCT-OFDM systems. In addition to demonstrating the effect of channel impairments at different SNR on the PAPR of the received signal. Figure (4.18) shows the CCDF of the PAPR for the DWT-OFDM, DFT-OFDM and DCT-OFDM transmitted signal. Figure (4.19) shows the CCDF of the PAPR for the DWT-OFDM, DFT-OFDM and DCT-OFDM received signal. Figure (4.20) shows the CCDF of the PAPR for the DWT-OFDM received signal at different SNRs to examine the effect of the channel on the received signal. For the transmitted signal the PAPR of the DWT-OFDM system is 5 dB lesser than in the DFT-OFDM system and 6 dB lesser that in the DCT-OFDM system. As for the received signal the PAPR of the DWT-OFDM system is 3 dB lesser than in the DFT-OFDM system and 3.5 dB lesser that in the DCT-OFDM system at a SNR of 10 dB. It is also clear from figure (4.20) that as the SNR decreases the PAPR increases.

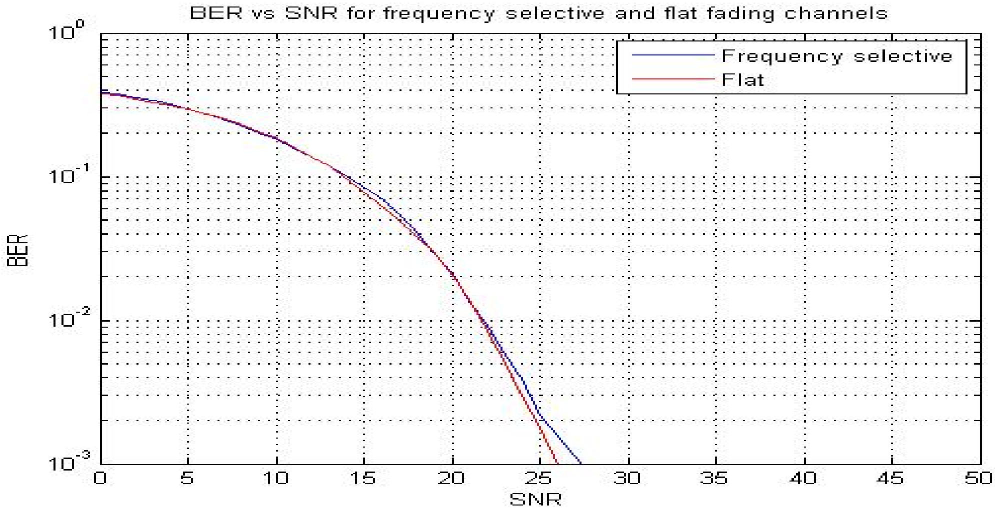

Figure 4.16.: ‘Performance of BER over frequency selective channel vs flat fading channel in the presence of AWGN.

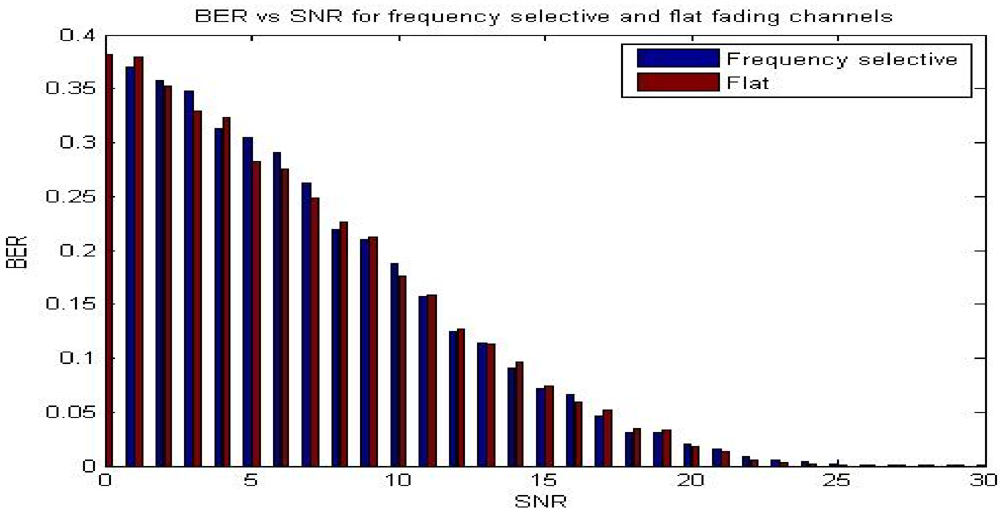

Figure 4.17.: Bar plot of BER over frequency selective channel vs flat fading channel in the presence of AWGN.

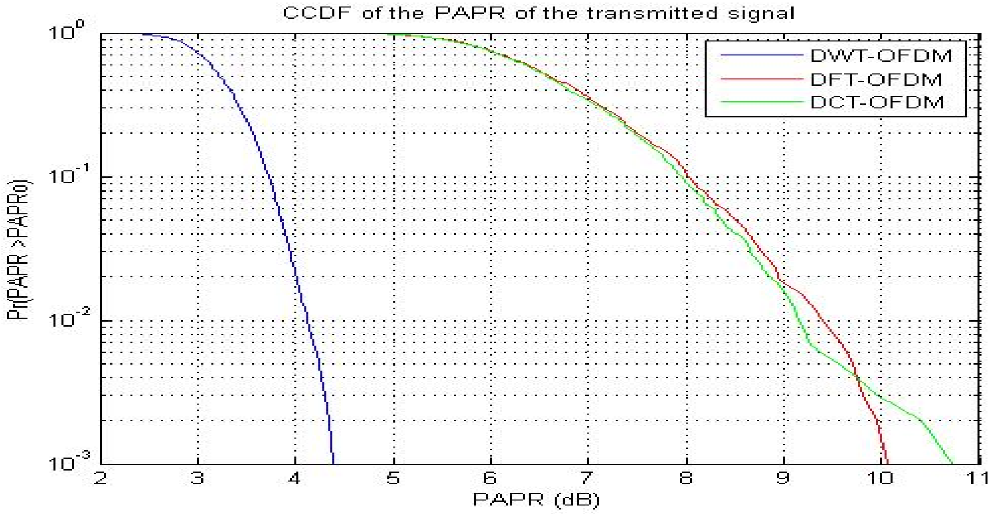

Figure 4.18.: Comparison of PAPR for the DWT-OFDM, DFT-OFDM and DCT-OFDM transmitted signal.

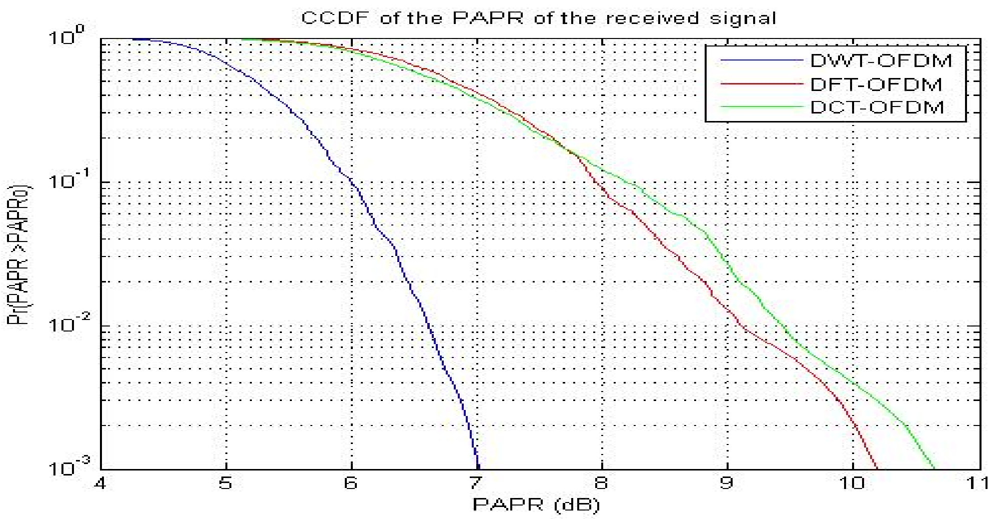

Figure 4.19.: Comparison of PAPR for the DWT-OFDM, DFT-OFDM and DCT-OFDM received signal at SNR of 10 dB.

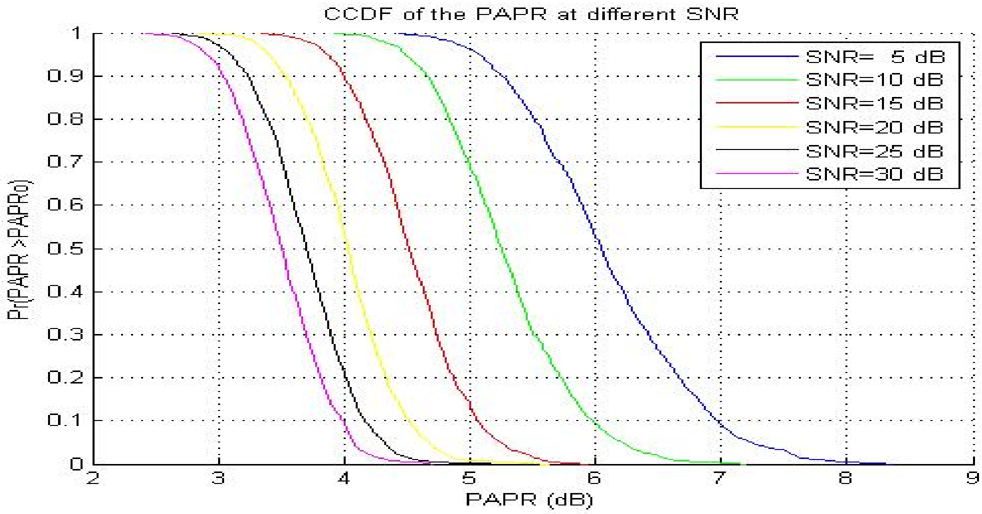

Figure 4.20.: CCDF of the PAPR of DWT-OFDM system at different SNRs.

5. DISCUSSION

The performance of the DWT-OFDM system adopting 64-DAPSK as the modulation scheme was evaluated using BER and PAPR. The results for both parameters were presented in chapter four.

The BER results shows that the DWT-OFDM system outperforms both DFT-OFDM and DCT-OFDM systems over different channels. In the presence of AWGN the DWT-OFDM outperformed the DFT-OFDM system by 5 dB at BER of 0.0001. Over the flat fading channel and the frequency selective which are more practical than AWGN only the DWT-OFDM system also outperformed both DFT-OFDM and DCT-OFDM by 4 dB and 3dB at BER of 0.001 respectively. The reason for that is that the side lobes of the sub-carriers generated by DWT is much lower than those generated by DFT which makes it more immune to ISI. The BER curves also showed that over flat fading channel the DWT-OFDM system has a better performance than when compared to the frequency selective channel by 2 dB at BER of 0.001 dB. In addition to the improved performance the DWT-OFDM system is more bandwidth efficient as it does not need any cyclic prefix or guard intervals when compared to DFT-OFDM and the DCT-OFDM systems, Since the DWT sub-carriers overlap in both frequency and time domain. The BER results over the flat fading channel is very close to that in the frequency selective channel as the sub-carriers are narrow-band, so each sub-carrier in case of the frequency selective channel experience flat fading. the results proved that DWT-OFDM are more robust to channel impairment than DFT-OFDM and DCT-OFDM systems.

High PAPR is one of the main disadvantages of DFT-OFDM systems. The results show that DWT-OFDM systems has lower PAPR when compared to the DFT-OFDM and the DCT-OFDM systems. The PAPR of the transmitted signal was lower in the DWT-OFDM system by 5 dB and 6 dB than in the DFT-OFDM and DCT-OFDM systems respectively. As for the received signal at SNR of 10 dB and after passing through a flat fading channel the DWT-OFDM gives a PAPR lower than that of the DFT-OFDM and the DCT-OFDM systems by 3 dB and 3.5 dB respectively. DWT based OFDM system adopting 64-DAPSK modulation proved that it outperformed DFT based OFDM systems in terms of BER and PAPR and that it can be a viable option to be considered instead of the conventional OFDM systems.

Using the 64-DAPSK reduced the implementation complexity of the receiver, as it doesn't need channel estimation or equalization. DAPSK is a differential modulation and demodulation technique that compensates the channel effect on the signal without the need of any previous knowledge of the channel.

6. CONCLUSIONS AND FUTURE WORK

This chapter consists of two main sections. The first section is a brief summary of the work discussed previously in the dissertation, while the second section is some suggestions for future work that could be carried out.

6.1. Conclusions

The main aim of the dissertation was to evaluate the performance of a DWT based OFDM system adopting 64-DAPSK as the modulation scheme, given that no extensive work has been carried out on this specific topic. A literature review of existing material that is relevant to the topic of interest as well as a background overview on conventional OFDM, DWT-OFDM and DAPSK was presented.

A MATLAB simulation was carried out and different channel impairments were used. First the performance of the system was evaluated in the presence of AWGN only, then in the presence of AWGN and flat fading channel and finally in the presence of AWGN and frequency selective channel. The BER was calculated in every case and it's performance curve at different SNRs was presented. Another parameter used to evaluate the performance was the PAPR of the transmitted signal and the received signal over a flat fading channel and in the presence of AWGN at a SNR of 10 dB. A DFT based OFDM system with 64-DAPSK modulation was also simulated for the sake of comparison.

The BER results showed the superiority of the DWT-OFDM system over the DFT-OFDM system. In the presence of AWGN the DWT-OFDM outperformed the DFT-OFDM system by 5 dB at BER of 0.0001. Over the flat fading channel and the frequency selective which are more practical than AWGN only the DWT-OFDM system also outperformed the DFT-OFDM by 4 dB and 3 dB at BER of 0.001 respectively.

The results of the PAPR showed that DWT-OFDM systems has lower PAPR when compared to the DFT-OFDM system. The PAPR of the transmitted signal was lower in the DWT-OFDM system by 5 dB than in the DFT-OFDM system. As for the received signal at SNR of 10 dB and after passing through a flat fading channel the DWT-OFDM gives a PAPR lower than that of the DFT-OFDM system by 3 dB.

It was concluded that DWT-OFDM system with 64-DAPSK modulation is practical alternative to the DFT-OFDM system and can be considered in future wireless communication system.

6.2. Future work

In this dissertation a simple comparison between uncoded DWT-OFDM and DFT-OFDM was presented. There are number of ways in which this work can be carried forward. The work can be extended to include:

- A detailed comparison of the performance of the two systems when implemented in a practical application such as DVB-H or WIMAX.
- A comparison of the performance of the 64-DAPSK DWT-OFDM system with other DWT-OFDM systems adopting different modulation schemes such as M-QAM or M-PSK.
- Performance evaluation of a DWT-OFDM system with different channel coding techniques.
- Performance evaluation of a DWT-OFDM system with different interleaving techniques.
- Performance evaluation of a DWT-OFDM system with different synchronization techniques.
- Performance evaluation of a DWT-OFDM system with different channel equalization techniques.
- Performance evaluation of a DWT-OFDM system with different PAPR reduction techniques.

Finally, there is no practical application up to this date that uses wavelet based OFDM systems, which makes it a hot topic for researchers to explore.

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A. MATLAB code

The code of the main file

```
clear all
clc

M=64;
number_subcarriers=64;
msg_size=10;
Ng=number_subcarriers/4; %% number of cyclic perfix samples

msg=randint(number_subcarriers,msg_size,M); %% Data source
msg_vector=reshape(msg,1,number_subcarriers*msg_size);

modulated_signal=dapskmod(msg_vector); %% Modulation
modulated_matrix=reshape(modulated_signal,number_subcarriers,...
    msg_size);

%%%%%%%%%%%%%% inverse transform %%%%%%%%%%%%%%%%%%%%%
[after_idwt_matrix,after_idft_matrix,after_idct_matrix]=...
    itransform(modulated_matrix);

after_idwt_vector=reshape(after_idwt_matrix,1,...
    size(after_idwt_matrix,1)*msg_size);

after_idft_vector=reshape(after_idft_matrix,1,...
    size(after_idft_matrix,1)*msg_size);

after_idct_vector=reshape(after_idct_matrix,1,...
    size(after_idct_matrix,1)*msg_size);

%%%%%% Flat fading channel %%%%%%%%
after_flat_fading_dwt =flatfadingch(after_idwt_vector);

after_flat_fading_dft = flatfadingch(after_idft_vector);

after_flat_fading_dct = flatfadingch(after_idct_vector);

%%%%% Frequency selective Channel %%%%%%%%%%%

after_frequency_fading_dwt =multipathch(after_idwt_vector);

after_frequency_fading_dft = multipathch(after_idft_vector);
```

```
after_frequency_fading_dct = multipathch(after_idct_vector);



SNR=1:50;
for i=1:length(SNR)

    %%%%%%%%%%%%% adding AWGN for DWT-OFDM %%%%%%%%%%%%%%%%%
    after_noise_dwt=awgn(after_idwt_vector,SNR(i),'measured');
    after_noise_dwt_matrix=reshape(after_noise_dwt,...
        size(after_idwt_matrix,1),msg_size);

    after_noise_dwt_flat=awgn(after_flat_fading_dwt,SNR(i),...
        'measured');
    after_noise_dwt_flat_matrix=reshape(after_noise_dwt_flat,...
        size(after_idwt_matrix,1),msg_size);


    after_noise_dwt_frequency=awgn(after_frequency_fading_dwt,...
        SNR(i),'measured');
    after_noise_dwt_frequency_matrix=reshape(...
        after_noise_dwt_frequency,size(after_idwt_matrix,1),...
        msg_size);

    %%%%%%%%%%%%%%%%%%%%%% wavelet transform %%%%%%%%%%%%%%%
    after_dwt_matrix=dwavelet(after_noise_dwt_matrix, 'haar');
    after_dwt_vector=reshape(after_dwt_matrix,1,...
        number_subcarriers*msg_size);

    after_dwt_flat_matrix=dwavelet(...
        after_noise_dwt_flat_matrix, 'haar');
    after_dwt_flat_vector=reshape(after_dwt_flat_matrix,1,...
        number_subcarriers*msg_size);

    after_dwt_frequency_matrix=dwavelet(...
        after_noise_dwt_frequency_matrix, 'haar');
    after_dwt_frequency_vector=reshape(after_dwt_frequency_matrix...
        ,1,number_subcarriers*msg_size);

    %%%%%%%%%%%%% demodulation %%%%%%%%%%%%%%%%%%%%%%%%%%%
    demodulated_signal_dwt=dapskdemod(after_dwt_vector);

    demodulated_signal_dwt_flat=dapskdemod(...
        after_dwt_flat_vector);

    demodulated_signal_dwt_frequency=dapskdemod(...
        after_dwt_frequency_vector);

    %%%%%%%%%%%%%%% BER calculation %%%%%%%%%%%%%%%%%%%%%
    [number_dwt,ratio_dwt] = biterr(msg_vector,...
        demodulated_signal_dwt,6,'overall');
    BER_dwt(i)=ratio_dwt;
```

```
    [number_dwt_flat,ratio_dwt_flat] = biterr(...
        msg_vector,demodulated_signal_dwt_flat,6,'overall');
    BER_dwt_flat(i)=ratio_dwt_flat;

    [number_dwt_frequency,ratio_dwt_frequency] = ...
        biterr(msg_vector,demodulated_signal_dwt_frequency,...
        6,'overall');
    BER_dwt_frequency(i)=ratio_dwt_frequency;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %%%%%%%%%%%%% adding AWGN for DFT-OFDM %%%%%%%%%%%%%%%%
    after_noise_dft=awgn(after_idft_vector,SNR(i),'measured');
    after_noise_dft_matrix=reshape(after_noise_dft,...
        size(after_idft_matrix,1),msg_size);

    after_noise_dft_flat=awgn(after_flat_fading_dft,SNR(i),...
        'measured');
    after_noise_dft_flat_matrix=reshape(after_noise_dft_flat,...
        size(after_idft_matrix,1),msg_size);


    after_noise_dft_frequency=awgn(after_frequency_fading_dft,...
        SNR(i),'measured');
    after_noise_dft_frequency_matrix=reshape(...
        after_noise_dft_frequency,size(after_idft_matrix,1),...
        msg_size);

    %%%%% fourier transform and removing cyclic prefix %%
    after_dft_matrix=dfourierandcp(after_noise_dft_matrix,Ng);
    after_dft_vector=reshape(after_dft_matrix,1,...
        number_subcarriers*msg_size);

    after_dft_flat_matrix=dfourierandcp(...
        after_noise_dft_flat_matrix,Ng);
    after_dft_flat_vector=reshape(after_dft_flat_matrix,...
        1,number_subcarriers*msg_size);

    after_dft_frequency_matrix=dfourierandcp(...
        after_noise_dft_frequency_matrix,Ng);
    after_dft_frequency_vector=reshape(after_dft_frequency_matrix...
        ,1,number_subcarriers*msg_size);

    %%%%%%%%%%%%% demodulation %%%%%%%%%%%%%%%%%%%%%%%%%%%
    demodulated_signal_dft=dapskdemod(after_dft_vector);

    demodulated_signal_dft_flat=dapskdemod(after_dft_flat_vector);

    demodulated_signal_dft_frequency=dapskdemod(...
        after_dft_frequency_vector);
```

```
    %%%%%%%%%%%%%%% BER calculation %%%%%%%%%%%%%%%%%%%%%%%%%%
    [number_dft,ratio_dft] = biterr(msg_vector,...
        demodulated_signal_dft,6,'overall');
    BER_dft(i)=ratio_dft;

    [number_dft_flat,ratio_dft_flat] = biterr(msg_vector,...
        demodulated_signal_dft_flat,6,'overall');
    BER_dft_flat(i)=ratio_dft_flat;

    [number_dft_frequency,ratio_dft_frequency] = ...
        biterr(msg_vector,...
        demodulated_signal_dft_frequency,6,'overall');
    BER_dft_frequency(i)=ratio_dft_frequency;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %%%%%%%%%%%%% adding AWGN for DCT-OFDM %%%%%%%%%%%%%%%%
    after_noise_dct=awgn(after_idct_vector,SNR(i),'measured');
    after_noise_dct_matrix=reshape(after_noise_dct,...
        size(after_idct_matrix,1),msg_size);

    after_noise_dct_flat=awgn(after_flat_fading_dct,SNR(i),...
        'measured');
    after_noise_dct_flat_matrix=reshape(after_noise_dct_flat,...
        size(after_idct_matrix,1),msg_size);


    after_noise_dct_frequency=awgn(after_frequency_fading_dct,...
        SNR(i),'measured');
    after_noise_dct_frequency_matrix=reshape(...
        after_noise_dct_frequency,size(after_idct_matrix,1),...
        msg_size);

    %%%%%% cosine transform and removing cyclic prefix %%%%%%
    after_dct_matrix=dctandcp(after_noise_dct_matrix,Ng);
    after_dct_vector=reshape(after_dct_matrix,1,...
        number_subcarriers*msg_size);

    after_dct_flat_matrix=dctandcp(after_noise_dct_flat_matrix,Ng);
    after_dct_flat_vector=reshape(after_dct_flat_matrix,1,...
        number_subcarriers*msg_size);

    after_dct_frequency_matrix=dctandcp(...
        after_noise_dct_frequency_matrix,Ng);
    after_dct_frequency_vector=reshape(...
        after_dct_frequency_matrix,1,number_subcarriers*...
        msg_size);

    %%%%%%%%%%%%% demodulation %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    demodulated_signal_dct=dapskdemod(after_dct_vector);

    demodulated_signal_dct_flat=dapskdemod(after_dct_flat_vector);
```

```
    demodulated_signal_dct_frequency=dapskdemod(...
        after_dct_frequency_vector);

    %%%%%%%%%%%%%%% BER calculation %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    [number_dct,ratio_dct] = biterr(msg_vector,...
        demodulated_signal_dct,6,'overall');
    BER_dct(i)=ratio_dct;

    [number_dct_flat,ratio_dct_flat] = biterr(msg_vector,...
        demodulated_signal_dct_flat,6,'overall');
    BER_dct_flat(i)=ratio_dct_flat;

    [number_dct_frequency,ratio_dct_frequency] = ...
        biterr(msg_vector,...
        demodulated_signal_dct_frequency,6,'overall');
    BER_dct_frequency(i)=ratio_dct_frequency;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%% PAPR %%%%%%%%%%
[papr_dwt_transmitted,range_dwt_transmitted]=PAPR(after_idwt_matrix);
[papr_dft_transmitted,range_dft_transmitted]=PAPR(after_idft_matrix);
[papr_dct_transmitted,range_dct_transmitted]=PAPR(after_idct_matrix);

[papr_dwt_received,range_dwt_received]=PAPR(reshape(awgn(...
    after_flat_fading_dwt,10,'measured'),size(after_idwt_matrix,1)...
    ,msg_size));
[papr_dft_received,range_dft_received]=PAPR(reshape(awgn(...
    after_flat_fading_dft,10,'measured'),size(after_idft_matrix,1)...
    ,msg_size));
[papr_dct_received,range_dct_received]=PAPR(reshape(awgn(...
    after_flat_fading_dct,10,'measured'),size(after_idct_matrix,1)...
    ,msg_size));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%% PLOTTING BER %%%%%%%%%%%%%%%%%%

semilogy(SNR,BER_dwt)
grid on
hold on
semilogy(SNR,BER_dft,'r')
hold on
semilogy(SNR,BER_dct,'g')
hold on
title('BER vs SNR in AWGN channel')
xlabel('SNR')
ylabel('BER')
legend('DWT-OFDM','DFT-OFDM','DCT-OFDM')


figure()
```

```
semilogy(SNR,BER_dwt_flat)
grid on
hold on
semilogy(SNR,BER_dft_flat,'r')
hold on
semilogy(SNR,BER_dct_flat,'g')
hold on
title('BER vs SNR in Flat fading channel')
xlabel('SNR')
ylabel('BER')
legend('DWT—OFDM','DFT—OFDM','DCT—OFDM')


figure()
semilogy(SNR,BER_dwt_frequency)
grid on
hold on
semilogy(SNR,BER_dft_frequency,'r')
hold on
semilogy(SNR,BER_dct_frequency,'g')
hold on
title('BER vs SNR in Frequency selective channel')
xlabel('SNR')
ylabel('BER')
legend('DWT—OFDM','DFT—OFDM','DCT—OFDM')

%%%%%%%%%%%%%%%%%%%%%%% PLOTTING PAPR %%%%%%%%%%%%%%%%%%
figure()
semilogy(range_dwt_transmitted,papr_dwt_transmitted)
hold on
semilogy(range_dft_transmitted,papr_dft_transmitted,'r')
hold on
semilogy(range_dct_transmitted,papr_dct_transmitted,'g')
hold on
title('CCDF of the PAPR of the transmitted signal')
xlabel('PAPR (dB)')
ylabel('Pr(PAPR >PAPRo)')
grid on
legend('DWT—OFDM','DFT—OFDM','DCT—OFDM')

figure()
semilogy(range_dwt_received,papr_dwt_received)
hold on
semilogy(range_dft_received,papr_dft_received,'r')
hold on
semilogy(range_dct_received,papr_dct_received,'g')
hold on
title('CCDF of the PAPR of the received signal')
xlabel('PAPR (dB)')
ylabel('Pr(PAPR >PAPRo)')
grid on
legend('DWT—OFDM','DFT—OFDM','DCT—OFDM')
```

Modulation

```
function [modulated_signal] = dapskmod(signal)

modulation_parameter=1.4;
modulation_parameter2=modulation_parameter^2;
modulation_parameter3=modulation_parameter^3;
previous_modulation_parameter=1;
current_modulation_parameter=0;
amplitude_matrix=[];
phase_matrix=[];
dapsk_modulated=[];
counter=length(signal);

for i=1:counter
    %%% Separating the bits into a group of 4
    %%% and a group of two
        current_value=signal(i);
        binary_current_value=dec2bin(current_value,6);
        phase=binary_current_value(1:4);
        phase_matrix(i)=bin2dec(phase);
        amplitude=bin2dec(binary_current_value(5:6));
    %%% amplitude modulation
        if previous_modulation_parameter==1
           if  amplitude==bin2dec('00')
               current_modulation_parameter=1;
               previous_modulation_parameter=1;
           else
           if amplitude==bin2dec('01')
               current_modulation_parameter=modulation_parameter;
               previous_modulation_parameter=modulation_parameter;
           else
           if amplitude==bin2dec('11')
               current_modulation_parameter=modulation_parameter2;
               previous_modulation_parameter=modulation_parameter2;
           else
           if amplitude==bin2dec('10')
               current_modulation_parameter=modulation_parameter3;
               previous_modulation_parameter=modulation_parameter3;
           end
           end
           end
           end
        else
         if previous_modulation_parameter==modulation_parameter
           if  amplitude==bin2dec('00')
               current_modulation_parameter=modulation_parameter;
               previous_modulation_parameter=modulation_parameter;
           else
           if amplitude==bin2dec('01')
               current_modulation_parameter=modulation_parameter2;
               previous_modulation_parameter=modulation_parameter2;
```

```
        else
        if amplitude==bin2dec('11')
            current_modulation_parameter=modulation_parameter3;
            previous_modulation_parameter=modulation_parameter3;
        else
        if amplitude==bin2dec('10')
            current_modulation_parameter=1;
            previous_modulation_parameter=1;
        end
        end
        end
        end
        else
      if previous_modulation_parameter==modulation_parameter2
        if  amplitude==bin2dec('00')
            current_modulation_parameter=modulation_parameter2;
            previous_modulation_parameter=modulation_parameter2;
        else
        if amplitude==bin2dec('01')
            current_modulation_parameter=modulation_parameter3;
            previous_modulation_parameter=modulation_parameter3;
        else
        if amplitude==bin2dec('11')
            current_modulation_parameter=1;
            previous_modulation_parameter=1;
        else
        if amplitude==bin2dec('10')
            current_modulation_parameter=modulation_parameter;
            previous_modulation_parameter=modulation_parameter;
        end
        end
        end
        end
        else
      if previous_modulation_parameter==modulation_parameter3
        if  amplitude==bin2dec('00')
            current_modulation_parameter=modulation_parameter3;
            previous_modulation_parameter=modulation_parameter3;
        else
        if amplitude==bin2dec('01')
            current_modulation_parameter=1;
            previous_modulation_parameter=1;
        else
        if amplitude==bin2dec('11')
            current_modulation_parameter=modulation_parameter;
            previous_modulation_parameter=modulation_parameter;
        else
        if amplitude==bin2dec('10')
            current_modulation_parameter=modulation_parameter2;
            previous_modulation_parameter=modulation_parameter2;
        end
        end
```

```
            end
            end
          end
          end
          end
         end

         amplitude_matrix(i)=current_modulation_parameter;

end
%%% phase modulation
phase_modulated = (dpskmod(phase_matrix,16,pi/8,'gray'));

%%% combining amplitude and phase modulation
for i=1:counter

         current_angle=angle(phase_modulated(i));
         real=amplitude_matrix(i)*cos(current_angle);
         imaginary=amplitude_matrix(i)*sin(current_angle);
         dapsk_modulated(i)=complex(real,imaginary);
end

scatterplot(dapsk_modulated)
title('64-DAPSK constellation diagram')
figure()
modulated_signal=dapsk_modulated;
```

Inverse transforms

```
function [after_idwt_matrix,after_idft_matrix,...
    after_idct_matrix]=itransform(matrix)

number_subcarriers=size(matrix,1);
msg_size=size(matrix,2);
Ng=number_subcarriers/4;
%%%%%% inverse wavelet transform %%%%%%%%%%%%%%%
dwtmode('per')
for k = 1:msg_size
    ofdm_symbol = matrix(:,k);
    after_idwt_matrix(:,k) = idwt( (ofdm_symbol), ...
        zeros(number_subcarriers,1) , 'haar' );
end


%%%%%%%%%%%% inverse fourier transform %%%%%%%%%%%%%
idft_output=ifft(matrix);
%%%%%%%%%%%% adding cyclic prefix %%%%%%%%%%%%%%%%%
buffer=zeros(Ng,msg_size);
for p=1:msg_size
    counter=number_subcarriers-Ng+1;
    for o=1:Ng
```

```
        buffer(o,p)=idft_output(counter,p);
        counter=counter+1;
    end
end
after_idft_matrix=[buffer ; idft_output];


%%%%%%%%%%%% inverse cosine transform %%%%%%%%%%%%%%
idct_output=idct(matrix);
%%%%%%%%%%%% adding cyclic prefix %%%%%%%%%%%%%%%%%%
buffer=zeros(Ng,msg_size);
for p=1:msg_size
    counter=number_subcarriers-Ng+1;
    for o=1:Ng

        buffer(o,p)=idct_output(counter,p);
        counter=counter+1;
    end
end
after_idct_matrix=[buffer ; idct_output];
```

Channel

```
function after_fading = flatfadingch(signal)

Ts = 1/1e9;
Fdop = 120;
ch = rayleighchan(Ts, Fdop);
ch.ResetBeforeFiltering = 0;
after_fading = filter(ch,signal);
```

```
function after_fading = multipathch(signal)

Ts = 1/1e9;
Tau = [0 2 0.5 1.6 2.3 5]*1e-5;
PdpdB = [0 -15 -8 -30 -20 -3];
Fdop = 120;
ch = rayleighchan(Ts, Fdop, Tau, PdpdB );
ch.ResetBeforeFiltering = 0;
after_fading = filter(ch,signal);
```

PAPR calculation

```
function [ccdf,range]=PAPR(signal)
msg_size=size(signal,2);
for p=1:msg_size
 ofdm_symbol=signal(:,p);
 %%%%% PAPR (dB) calculation %%%%%%%%%%%%%%
```

```
paprdB(p)=10*log10(max(abs(ofdm_symbol).^2)/mean(abs(ofdm_symbol).^2));
end
%%%%% CCDF %%%%%%%%%%%%%
[f,x]=ecdf(paprdB);
ccdf=1-f;
ccdf=smooth(ccdf);
range=smooth(x);
```

Transform

```
function [transformed_matrix] = dwavelet(matrix,...
    required_mode)

msg_size=size(matrix,2);

dwtmode('per')
for k = 1:msg_size
    ofdm_symbol = matrix(:,k);
    [matrix_after_dwt(:,k),CD] = dwt((ofdm_symbol').'...
        ,required_mode);
end

transformed_matrix=matrix_after_dwt;
```

```
function [after_DFT] = dfourierandcp(matrix,Ng)

number_subcarriers=size(matrix,1)-Ng;
msg_size=size(matrix,2);
%%%% loop removes the cyclic prefix %%%%%
for q=1:msg_size
    counter=Ng+1;
    for w=1:number_subcarriers
        without_cyclic(w,q)=matrix(counter,q);
        counter=counter+1;
    end
end
%%%% fourier transform %%%%%%%%%%%%%%
after_DFT=fft(without_cyclic);
```

```
function [after_DCT] = dctandcp(matrix,Ng)
number_subcarriers=size(matrix,1)-Ng;
msg_size=size(matrix,2);
%%%% loop removes the cyclic prefix %%%%%
for q=1:msg_size
    counter=Ng+1;
    for w=1:number_subcarriers
        without_cyclic(w,q)=matrix(counter,q);
        counter=counter+1;
```

```
    end
end
%%%% cosine transform %%%%%%%%%%%%%%
after_DCT=dct(without_cyclic);
```

Demodulation

```
function [modulated_signal] = dapskdemod(signal)

modulation_parameter=1.4;
modulation_parameter2=modulation_parameter^2;
modulation_parameter3=modulation_parameter^3;
previous_modulation_parameter=1;
counter=length(signal);
for i=1:counter
    %%% amplitude demodulation
current_value=signal(i);
amplitude_ratio=abs(current_value)/abs(...
    previous_modulation_parameter);
previous_modulation_parameter=abs(current_value);

if amplitude_ratio<=(modulation_parameter^-2.5)
amplitude=1;
else
if (amplitude_ratio > (modulation_parameter^-2.5))...
        && (amplitude_ratio <= (modulation_parameter^-1.5))
amplitude=3;
else
if amplitude_ratio>(modulation_parameter^-1.5) ...
        && amplitude_ratio<=(modulation_parameter^-0.5)
amplitude=2;
else
if amplitude_ratio>(modulation_parameter^-0.5) ...
        && amplitude_ratio<=(modulation_parameter^0.5)
amplitude=0;
else
if amplitude_ratio>(modulation_parameter^0.5)...
        && amplitude_ratio<=(modulation_parameter^1.5)
amplitude=1;
else
if amplitude_ratio>(modulation_parameter^1.5) ...
        && amplitude_ratio<=(modulation_parameter^2.5)
amplitude=3;
else
amplitude=2;
end
end
end
end
end
end
```

```
receiver_amplitude_matrix(i)=amplitude;
ang=angle(current_value);
magn=1;
real=magn*cos(ang);
imaginary=magn*sin(ang);
phase=complex(real,imaginary);
receiver_phase_matrix(i)=phase;

end

%%% phase demodulation
demodulated_receiver_phase_matrix=...
    dpskdemod(receiver_phase_matrix,16,pi/8,'gray');
for i=1:counter
%%% demodulated bits
current_phase_value=demodulated_receiver_phase_matrix(i);
current_amplitude_value=receiver_amplitude_matrix(i);
binary_current_phase_value=dec2bin(current_phase_value,4);
binary_current_amplitude_value=dec2bin(...
    current_amplitude_value,2);
final_current_value(1:4)=binary_current_phase_value;
final_current_value(5:6)=binary_current_amplitude_value;
final_received_matrix(i)=bin2dec(final_current_value);

end
modulated_signal=final_received_matrix;
```