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Design and Implementation of OFDM Trans-Receiver for IEEE 802.11(WLAN)

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ABSTRACT: *Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technique. OFDM provides high bandwidth efficiency because the carriers are orthogonal to each other's and multiple carriers share the data among themselves. The main advantage of this transmission technique is their robustness to channel fading in wireless communication environment. Orthogonally placed sub carriers are used to carry the data from the transmitter end to the receiver end. Presence of guard band in this system deals with the problem of ISI and noise is minimized by larger number of sub carriers. This paper present transmission of an OFDM System using the software tool MATLAB and have undertaken various methods to reduce the errors in the system so that this system can be used more commonly and effectively***.

Keywords: *FFT, IFFT, MATLAB*

I. INTRODUCTION

With the ever growing demand of this generation, need for high speed communication has become an utmost priority. Various multicarrier modulation techniques have evolved in order to meet these demands, few notable among them being Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiplexing (OFDM) [1]. Orthogonal Frequency Division Multiplexing is a frequency division multiplexing (FDM) scheme utilized as a digital multi carrier modulation method. A large number of closely spaced orthogonal sub carriers is used to carry data. The data is divided into several parallel streams of channels, one for each sub carriers. Each sub carrier is modulated with a conventional modulation scheme (such as BPSK) at a low symbol rate, maintaining total data rates similar to the conventional single carrier modulation schemes in the same bandwidth. OFDM is being used because of its capability to handle with multipath interference at the receiver. Due to multipath it faces the problem of inter symbol interference (ISI) and inter channel interference (ICI).Hence, the two main drawbacks of OFDM are the large dynamic range of the signals being transmitted and the sensitivity to frequency errors. Using a MATLAB simulation we can implement an OFDM transmission. Using this simulation we can see the amount of errors coming in the transmission by using different conventional modulation schemes. Then we can analyze the results of each transmission and see how these errors can be reduced.

II. OFDM DETAIL OVERVIEW

This section covers the details regarding the development of OFDM system and important terminologies.

A. Development of OFDM System

The development of OFDM systems can be divided into three parts. This comprises of Frequency Division Multiplexing, Multicarrier Communication and Orthogonal Frequency Division Multiplexing. Frequency Division Multiplexing is a form of signal multiplexing which involves assigning non overlapping frequency ranges or channels to different signals or to each user of a medium. A gap or guard band is left between each of these channels to ensure that the signal of one channel does not overlap with the signal from an adjacent one. Due to lack of digital filters it was difficult to filter closely packed adjacent channels [2]. As it is ineffective to transfer a high rate data stream through a channel, the signal is split to give a number of signals over that frequency range. Each of these signals are individually modulated and transmitted over the channel. At the receiver end, these signals are fed to a de-multiplexer where it is demodulated and recombined to obtain the original signal.

B. *OFDM Theory*

Orthogonal Frequency Division Multiplexing is a special form of multicarrier modulation which is particularly suited for transmission over a dispersive channel [2].

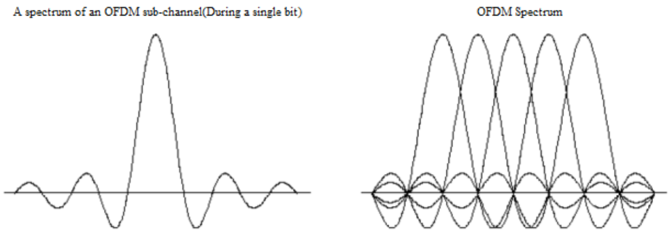

Figure 1. OFDM Spectrum

a) Orthogonality: Two periodic signals are orthogonal when the integral of their product over one period is equal to zero.

For The case of continuous time:

$$\int_0^T \cos(2\pi n f_0 t)\cos(2\pi m f_0 t)dt = 0,$$

For the case of Discrete Time:

$$\sum_{k=0}^{N-1} \cos\left(\frac{2\pi kn}{N}\right)\cos\left(\frac{2\pi km}{N}\right)dt = 0,$$

Where $m \neq n$ in both cases.

b) Sub-Carriers: Each sub-carrier in an OFDM system is a sinusoid with a frequency that is an integer multiple of a fundamental frequency. Each sub-carrier is like a Fourier series component of the composite signal, an OFDM symbol.

$$s(t) = \cos(2\pi f_c t + \theta_k)$$

$$= a_n \cos(2\pi n f_0 t) + b_n \sin(2\pi n f_0 t)$$

$$= \sqrt{a_n^2 + b_n^2}\cos(2\pi n f_0 t + \varphi_n),$$

The sum of the sub – carriers is then the baseband OFDM signal:

$$s_B(t) = \sum_{n=0}^{N-1}\{a_n \cos(2\pi n f_0 t) - b_n \sin(2\pi n f_0 t)\}$$

c) Inter Symbol Interference: Inter symbol interference (ISI) is a form of distortion of a signal in which one symbol interferes with subsequent symbols. This is an unwanted phenomenon as the previous symbols have similar effect as noise, thus making the communication less reliable. ISI is usually caused by multipath propagation or the inherent nonlinear frequency response of a channel causing successive symbols to blur together. The presence of ISI in the system introduces error in the decision device at the receiver output [3].

d) Inter Carrier Interference: Presence of Doppler shifts and frequency and phase offsets in an OFDM system causes loss in orthogonality of the sub carriers. As a result, interference is observed between sub-carriers. This phenomenon is known as inter carrier interference (ICI).

e) Cyclic Prefix: The Cyclic Prefix or Guard Interval is a periodic extension of the last part of an OFDM symbol that is added to the front of the symbol in the transmitter, and is removed at the receiver before demodulation. The cyclic prefix has important benefits that, the cyclic prefix acts as a guard interval. It eliminates the inter symbol interference from the previous symbol.

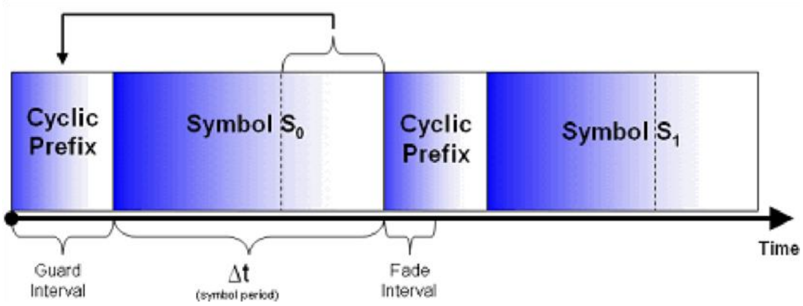

Figure 2. Cyclic Prefix

f) Modulation: Modulation is the technique by which the signal wave is transformed in order to send it over the communication channel in order to minimize the effect of noise. This is done in order to ensure that the received data can be demodulated to give back the original data. In an OFDM system, the high data rate information is divided into small packets of data which are placed orthogonal to each other. This is achieved by modulating the data by a desirable modulation technique (QPSK). After this, IFFT is performed on the modulated signal which is further processed by passing through a parallel to serial converter. In order to avoid ISI we provide a cyclic prefix to the signal.
g) Communication Channel: This is the channel through which the data is transferred. Presence of noise in this medium affects the signal and causes distortion in its data content.
h) Demodulation: Demodulation is the technique by which the original data (or a part of it) is recovered from the modulated signal which is received at the receiver end. In this case, the received data is first made to pass through a low pass filter and the cyclic prefix is removed. FFT of the signal is done after it is made to pass through a serial to parallel converter. A demodulator is used, to get back the original signal.

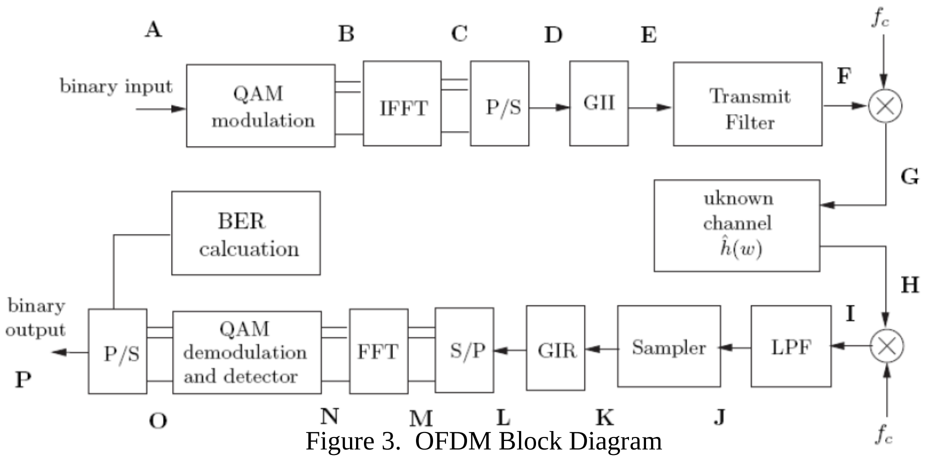

Figure 3. OFDM Block Diagram

III. DESIGN AND IMPLEMENTATION

A. Overview

Figure 3 shows a block diagram of an OFDM system. ADC, DAC, and RF front-ends (Amplification, RF up conversion/down conversion, etc.) are not simulated in this project. This MATLAB simulation program consists of six files. The MATLAB code used in this paper was developed by Paul Guanming Lin [4]. This implementation is used to transmit a computer file in binary data form modulated by OFDM [5].

OFDM_SIM.m shall be run while other m-files will be invoked accordingly. Source data for this simulation is taken from an 8-bit bitmap image file based on the user's choice. The image data will then be converted to the symbol size (bits/symbol) determined by the choice of MPSK from four variations provided by this simulation. The converted data will then be separated into multiple frames by the OFDM transmitter. The OFDM modulator modulates the data frame by frame.

Before the exit of the transmitter, the modulated frames of time signal are cascaded together along with frame guards inserted in between as well as a pair of identical headers added to the beginning and end of the data stream. The communication channel is modeled by adding Gaussian white noise and amplitude clipping effect.

The receiver detects the start and end of each frame in the received signal by an envelope detector. Each detected frame of time signal is then demodulated into useful data. The modulated data is then converted back to 8-bit word size data used for generating an output image file of the simulation. Error calculations are performed at the end of the program. Representative plots are shown throughout the execution of this simulation

B. System Configuration and Parameters

At the beginning of this simulation MATLAB program, a script file ofdm_parameters.m is invoked, which initializes all required OFDM parameters and program variables to start the simulation. Some variables are entered by the user [4].The rest are either fixed or derived from the user-input and fixed variables. The user input variables include:

1) Input file:an 8-bit grayscale (256 gray levels) bitmap file
2) IFFT size: an integer of a power of two;
3) Number of carriers: not greater than [(IFFT size)/2 – 2];
4) Digital modulation method: BPSK, QPSK, 16-PSK
5) Signal peak power clipping in dB
6) Signal-to-Noise Ratio in dB

All user-inputs are checked for validity and the program will request the user to correct any incorrect fields with brief guidelines provided. An example is shown in Figure 4. This script also determines how the carriers and conjugate carriers are allocated into the IFFT bins, based on the IFFT size and number of carriers defined by the user. Figure 5 shows an example of 120 carriers and 120 conjugate carriers spreading out on 256 IFFT bins.

```
###########################################
#*********** OFDM Simulation ************#
###########################################

source data filename: abc
"abc" does not exist in current directory.
source data filename: cat.bmp
Output file will be: cat_OFDM.bmp
IFFT size: 1200
IFFT size must be at least 8 and power of 2.
IFFT size: 1024
Number of carriers: 1000
Must NOT be greater than ("IFFT size"/2-2)
Number of carriers: 500
Modulation(1=BPSK, 2=QPSK, 4=16PSK, 8=256PSK): 3
Only 1, 2, 4, or 8 can be choosen
Modulation(1=BPSK, 2=QPSK, 4=16PSK, 8=256PSK): 4
Amplitude clipping introduced by communication channel (in dB): 6
```

Figure 4. User Input Panel

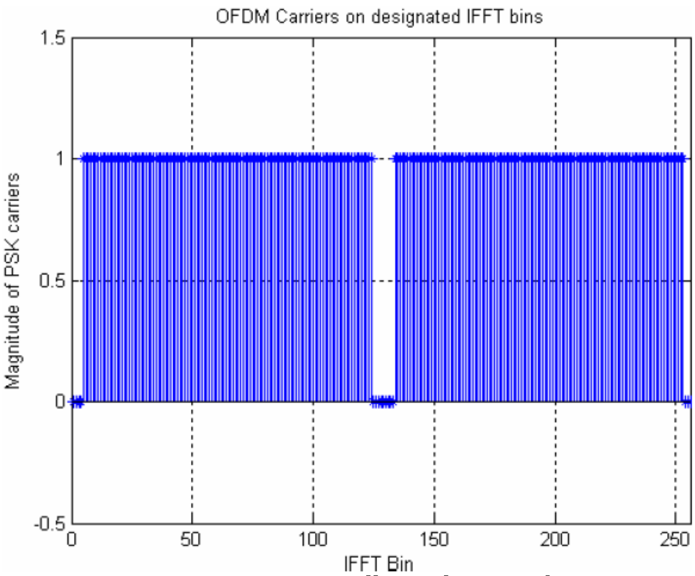

Figure 5. OFDM carriers allocated to IFFT bins

C. OFDM Transmitter

Frame Guards:

The core of the OFDM transmitter is the modulator, which modulates the input data stream frame by frame. Data is divided into frames based on the variable symb_per_frame, which refers to the number of symbols per frame per carrier. It is defined by: symb_per_frame = ceil (2^13/carrier_count). This limits the total number of symbols per frame (symb_per_frame * carrier_count) within the interval of [2^13, 2*(2^13-1)], or [8192, 16382]. However, the number of carriers typically would not be much greater than 1000 in this simulation, thus the total 14 number of symbols per frame would typically be under10, 000. This is an experimentally reasonable number of symbols that one frame should keep under for this MATLAB program to run efficiently; thereby symb_per_frame is defined by the equation shown above. As shown in Figure 6, even if the data stream is not sufficiently long to be divided into multiple frames, two frame guards with all zero values and in a length of one symbol period are still added to both ends of the modulated time signal. This is to assist the receiver to locate the beginning of the substantial portion of the time signal.

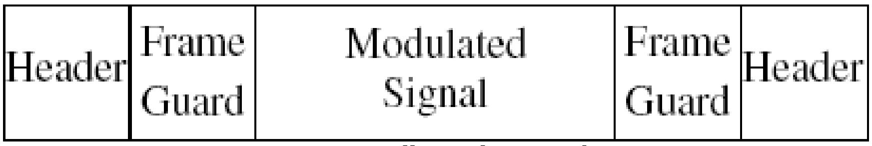

Figure 6. OFDM carriers allocated to IFFT bins

OFDM Modulator:

It is normal that the total number of transmitting data is not a multiple of the number of carriers. To convert the input data stream from serial to parallel, the modulator must pad a number of zeros to the end of the data stream in order for the data stream to fit into a 2-D matrix. Suppose a frame of data with 11,530 symbols is being transmitted by 400 carriers with a capacity of 30 symbols/carrier. 470 zeros are padded at the end in order for the data stream to form a 30-by-400 matrix, as shown in Figure 7.

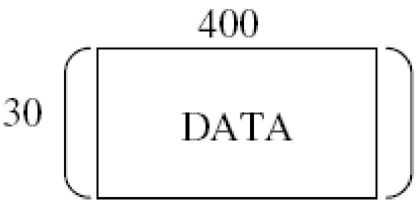

Figure 7. Data_tx_matrix

Differential Phase Shift Keying (DPSK) Modulation:

Before differential encoding can be operated on each carrier (column of the matrix), an extra row of reference data must be added on top of the matrix. Figure 8 shows a 31-by-400 resulted matrix. For each column, starting from the second row (the first actual data symbol), the value is changed to the remainder of the sum of its previous row and itself over the symbol size (power 2 of the PSK order).

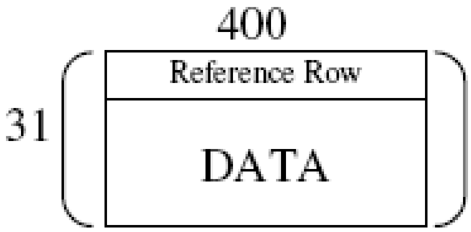

Figure 8. Differential Matrix

IFFT: Spectral Space to Time Signal

Figure 9 shows that the matrix is widened to IFFT size (for example: IFFT size = 1024) and becomes a 31-by-1024 IFFT matrix. Since each column of the DPSK matrix represents a carrier, their values are stored to the columns of the IFFT matrix at the locations where their corresponding carriers should reside. To obtain the transmitting time signal matrix, Inverse Fast Fourier Transform (IFFT) of this matrix is taken. Only the real part of the IFFT result is useful, so the imaginary part is discarded.

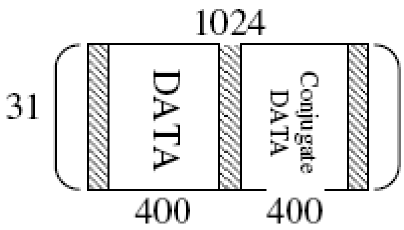

Figure 9. Pre-IIFT Matrix

Periodic Time Guard Insertion:

An exact copy of the last 25% portion of each symbol period (row of the matrix) is inserted to the beginning.

As shown in Figure 10, the matrix is further widened to a width of 1280. This is the periodic time guard that helps the receiver to synchronize when demodulating each symbol period of the received signal. The matrix now becomes a modulated matrix. By converting it to a serial form, a modulated time signal for one frame of data is generated.

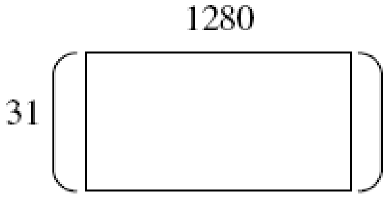

Figure 10. Modulated Matrixes

D. Communication Channel

A variable clipping in this MATLAB program is set by programmer. Peak power clipping is basically setting any data points with values over clipping below peak power to clipping below peak power. The peak-to- RMS ratios of the transmitted signal before and after the channel are shown for a comparison regarding this peak power clipping effect. An example is shown in Figure 11.

```
Summary of the OFDM transmission and channel modeling:
Peak to RMS power ratio at entrance of channel is: 14.893027 dB
Peak to RMS power ratio at exit of channel is: 11.502826 dB
#******** OFDM data transmitted in 5.277037 seconds ********#
```

$$\sigma \text{ of AWGN} = \sqrt{\frac{\text{variance of the modulated signal}}{\text{linear SNR}}}$$

Figure 11. OFDM Transmission Summary

Channel noise is modeled by adding a white Gaussian noise (AWGN) defined by:

E. OFDM Receiver

Frame Detector:

A trunk of received signal in a selective length is processed by the frame detector (ofdm_frame_detect.m) in order to determine the start of the signal frame. The selected portion of received signal is sampled to a shorter discrete signal with a sampling rate defined by the system.

A moving sum is taken over this sampled signal. The index of the minimum of the sampled signal is approximately the start of the frame guard while one symbol period further from this index is the approximate location for the start of the useful signal frame. The frame detector will then collect a moving sum of the input signal from about 10% of one symbol period earlier than the approximate start of the frame guard to about one third of symbol period further than the approximate start of the useful signal frame.

Demodulation Status Indicator:

As mentioned, received OFDM signal is typically demodulated frame by frame. The OFDM receiver shows the progress of frames being demodulated. It is a neat idea to keep the number of displays for this progress within a reasonable range, so that the MATLAB command screen is not overwhelmed by these status messages. To achieve this, the first and last frames are designed to show for sure, the rest would have to meet a condition: rem (k,max (floor(num_frame/10),1))==0 where k is the variable to indicate the k-th frame being modulated, and num_frame is the total number of frames. It means that for a total number of frames being 20 or more, it only displays the n-th frame when n is an integer multiple of the round-down integer of a tenth of the total number of frames; and for a total number of frames being 19 or less, it shows every frame that is being modulated.

This would keep the total number of displays within the range from 11 to 19, provided that the total number of frames is more than 10; otherwise, it simply shows as many messages as the total number of frames.

OFDM Demodulator:

Like any typical modulation/demodulation, OFDM demodulation is basically a reverse process of OFDM modulation. And like its modulator, the OFDM demodulator demodulates the received data frame by frame unless the transmitted data has length less than the designed total number of symbols per frame.

a) Periodic Time Guard Removal: The previous example used in section “OFDM Modulator” shall continue to be used for illustration. Figure 12 shows that after converting a frame of discrete time signal from serial to parallel, a length of 25% of a symbol period is discarded from all rows. Thus the remaining is then a number of discrete signals with the length of one symbol period lined up in parallel.

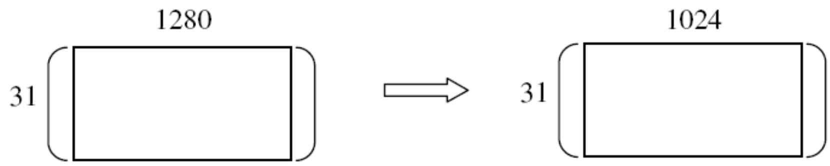

Figure 12. Time Guard Removal

b) FFT Time Signal to Spectral Space: Fast Fourier Transform (FFT) of the received time signal is taken. This results the spectrum of the received signal. As shown in Figure 13, the columns in the locations of carriers are extracted to retrieve the complex matrix of the received data.

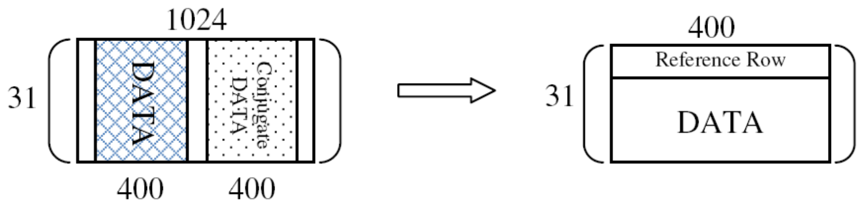

Figure 13. Received Data Extracted from FFT bins

c) Differential Phase Shift Keying (DPSK) Demodulation: The phase of every element in the complex matrix is converted into 0-360 degrees range and translated to one of the values within the symbol size. The differential operation is performed in parallel on this new matrix to retrieve the demodulated data. This differential operation is basically calculating the difference between every two consecutive symbols in a column of the matrix. As shown in Figure 14.

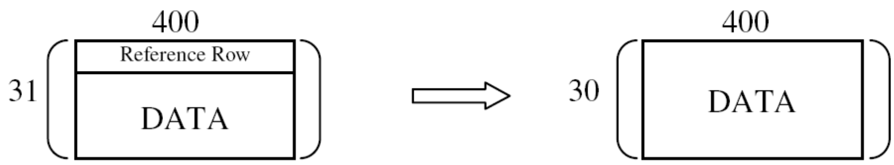

Figure 14. Differential Demodulation

The reference row is removed during this operation. Finally, a parallel to serial operation is performed and the demodulated data stream for this frame is obtained.

E. Error Calculations

Bit Error Rate (BER):

Demodulated data is compared to the original baseband data to find the total number of errors. Dividing the total number of errors by total number of demodulated symbols, the bit-error-rate (BER) is found.

Phase Error:

During the OFDM demodulation, before being translated into symbol values the received phase matrix is archived for calculating the average phase error, which is defined by the difference between the received phase and the translated phase for the corresponding symbol before transmission.

Percent Error of Pixels in the Received Image:

All afore mentioned error calculations are based on the OFDM symbols. What is more meaningful for the end-user of the OFDM communication system is the actual percent error of pixels in the received image. This is done by comparing the received image and original image pixel by pixel.

Program Display:

A summary showing the above error calculations is displayed at the end of the program. In an example shown in figure 15, an 800-by-600 image is transmitted by 400 carriers using an IFFT size of 1024, through a channel with 5 dB peak power clipping and 30 dB SNR white Gaussian noise.

```
#**************** Summary of Errors ****************#
Data loss in this communication = 0.125000% (1200 out of 960000)
Total number of errors = 1174 (out of 958800)
Bit Error Rate (BER) = 0.122445%
Average Phase Error = 1.877366 (degree)
Percent error of pixels of the received image = 0.257708%
```

Figure 15. Error Calculations

IV. SIMULATION RESULTS

Parameters	*Values*
Source Image Size	800x600
IFFT Size	512
Number of Carrier	250
Modulation Method	QPSK
Peak Power Clipping	5dB
Signal to Noise Ratio	30dB

Table 01. User Input Values

Using above parameters we got BER of 0.028661% while the percent error in the output image pixels is 0.111227%. This is expected when the OFDM symbol size is not the same as word size of the source data i.e. modulation method is not 256-PSK. The reason is that a set of four QPSK symbols is mapped to one 8-bit word, and when one or more of the QPSK symbols in a set is decoded incorrectly, the whole 8-bit word is mistranslated, therefore, it counts as all 4 QPSK symbols are errors when considering the pixels percent error [7].

However, in BER calculation, the interest is in the accuracy of the Tx and Rx, thus it only counts the QPSK symbols that are decoded incorrectly. Average phase error of 2.059264 degree means that there's still a certain distance from the tolerance of 45 degree.With 0.111227% pixel percent error, the noise on the output image is easily observable, but the information content received is highly usable. This is due to the use of QPSK, in which received phases have 45 degree of tolerance. A sign of successful. By dropping the number of carriers and IFFT size to about half while all other parameters remain the same, the simulation runtime for both the transmitter and receiver don't seem to vary much. This is because the simulation program monitors the total number of symbols to form one frame of data, thus total number of frames did not vary much.

The runtime measured depends on the number of computer operations, which directly depends on the number of frames of data needed to be modulated and demodulated for a fixed number of symbols per frame [7].

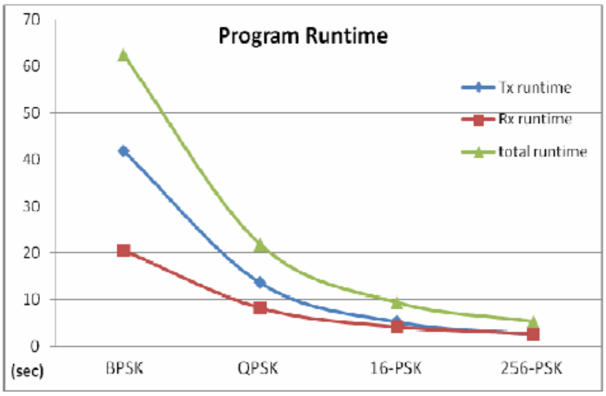

Figure 16. Program runtime

Conclusively, this runtime measurement does not reflect the variance of the efficiency based on varied numbers of carriers. However, it's meaningful to use this measurement in understanding the variance of efficiency based on varied orders of PSK. The runtimes tripled for a simulation with BPSK while other parameters remain the same

A plot shows that using 16-PSK and 256-PSK also verifies this theory. However, as shown in Figure BER increased massively by raising the PSK order, as a trade-off for decreasing runtime. SNR is inversely proportional to error rates. Figure 17 shows the relationship between the two for all four M-PSK methods. As expected, higher order PSK requires a larger SNR to minimize BER.

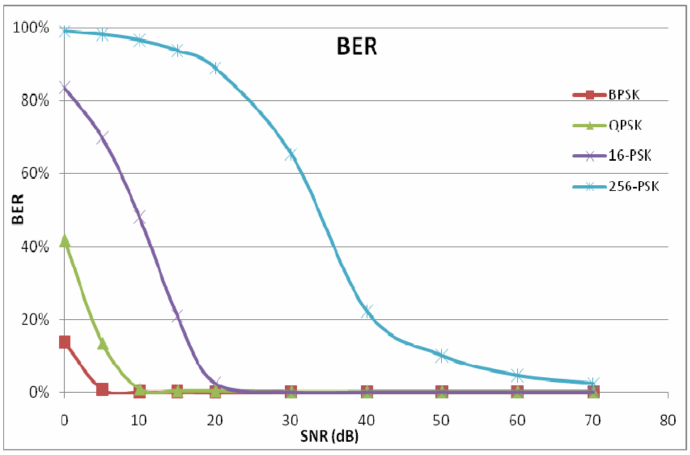

Figure 17. BER Vs SNR

Similarly, as shown in Figure 18, 256- PSK and 16-PSK require a relatively large SNR to transmit data with an acceptable percent error.

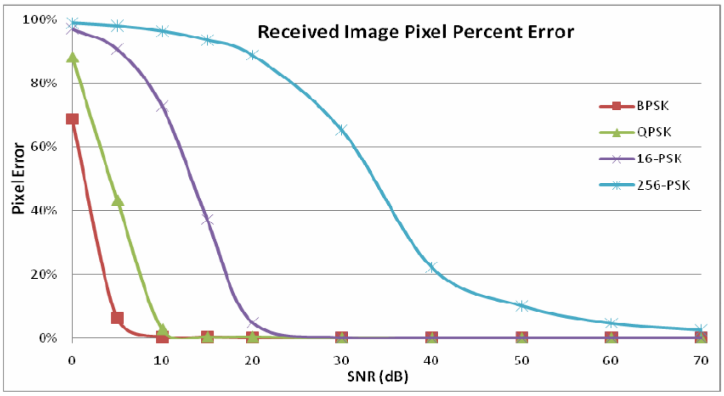

Figure 18. Pixel Error Vs SNR

Below shown the original image and received images for different orders of PSK with varied SNR.

Received Images using BPSK:

Figure 20. Received Image I Using BPSK

Parameters	*Values*
Source Image Size	800x600
IFFT Size	512
Number of Carrier	250
Modulation Method	BPSK
Peak Power Clipping	1dB
Signal to Noise Ratio	5dB

Table 02. User Input values for Image I

Errors	*Values*
Data loss in comm.	0.058594%
Total number of error	73369 (out of 3837750)
Bit Error Rate (BER)	1.911771%
Average Phase Error	27.571733 (degree)
Error in pixels	14.207708%

Table 03. Summa ry of Errors for Image I

Figure 21. Received Image II Using BPSK

Parameters	*Values*
Source Image Size	800x600
IFFT Size	512
Number of Carrier	250
Modulation Method	BPSK
Peak Power Clipping	1dB
Signal to Noise Ratio	30dB

Table 04. User Input values for Image II

Errors	*Values*
Data loss in comm.	0.058594%
Total number of error	0 (out of 3837750))
Bit Error Rate (BER)	0.000000%
Average Phase Error	1.407297 (degree)
Error in pixels	0.000000%

Table 05. Summary of Error for Image II

Received Images using QPSK:

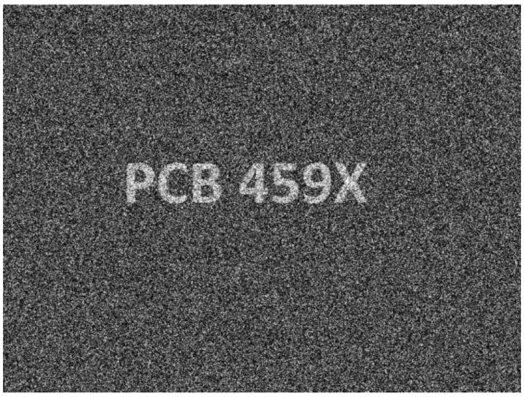

Figure 22. Received Image I Using QPSK

Parameters	*Values*
Source Image Size	800x600
IFFT Size	512
Number of Carrier	250
Modulation Method	QPSK
Peak Power Clipping	05dB
Signal to Noise Ratio	05dB

Table 06. User Input values for Image I

Errors	*Values*
Data loss in comm.	0.234375%
Total number of error	384902 (1915500)
Bit Error Rate (BER)	20.094075%
Average Phase Error	28.902475 (degree)
Error in pixels	59.086394%

Table 07. Summary of Error for Image I

Figure 23. Received Image II Using QPSK

Parameters	*Values*
Source Image Size	800x600
IFFT Size	512
Number of Carrier	250
Modulation Method	QPSK
Peak Power Clipping	05dB
Signal to Nois e Ratio	55dB

Table 08. User Input values for Image II

Errors	*Values*
Data loss in comm.	0.234375%
Total number of error	154 (out of 1915500)
Bit Error Rate (BER)	0.008040%
Average Phase Error	0.620729 (degree)
Error in pixels	0.031928%

Table 09. Summary of Error for Image II

***Transmitter Plots** (Plots of BPSK SNR: 30 dB):*

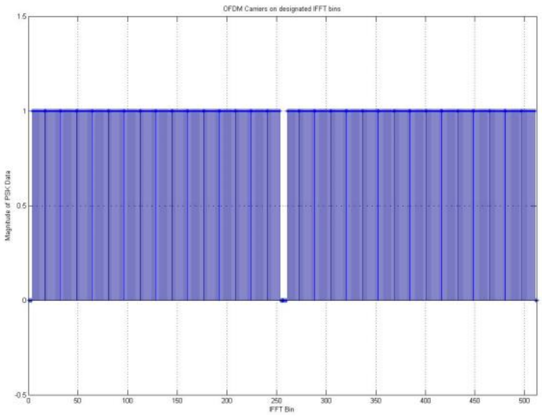

Figure 24. OFDM Carrier on Designated FFT Bins

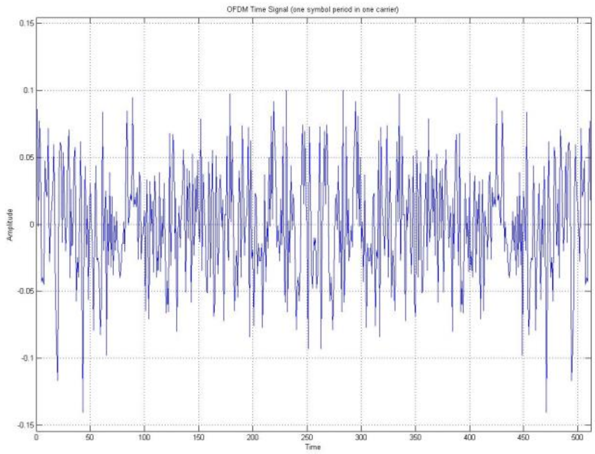

Figure 25. OFDM Time Signal

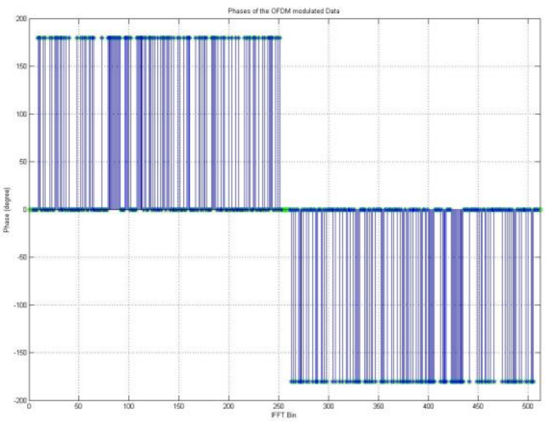

Figure 26. Phase of OFDM Modulated Data

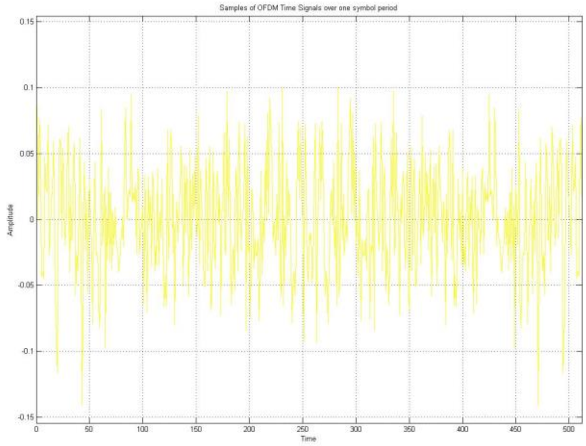

Figure 27. Sample of OFDM Time Signal

Receiver Plots *(Plots of BPSK SNR: 30 dB)*

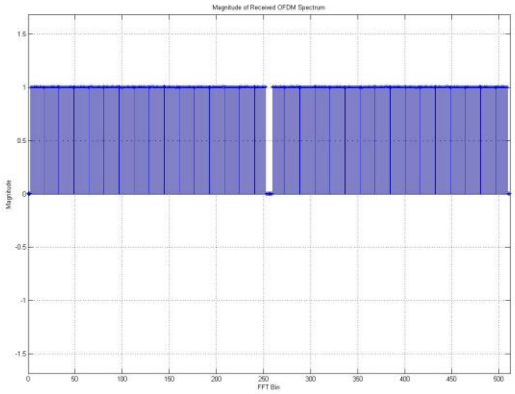

Figure 28. Magnitude of Received OFDM Spectrum

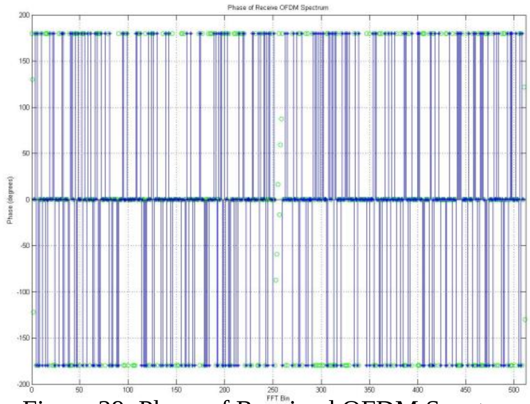

Figure 29. Phase of Received OFDM Spectrum

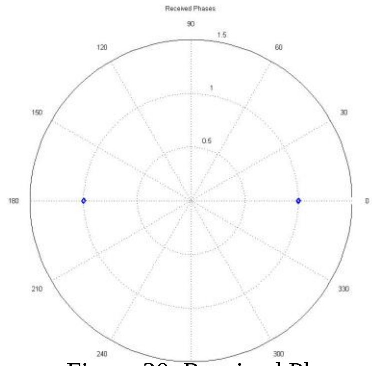

Figure 30. Received Phases

V. CONCLUSION

An OFDM trans-receiver is successfully simulated using MATLAB. All major components of an OFDM system are try to be covered. This has demonstrated the basic concept and feasibility of OFDM, which was thoroughly described and explained in this paper. It was noted that for some combinations of OFDM parameters, the simulation may fail for some trials but may succeed for repeated trails with the same parameters. It is because the random noise generated on every trial differs, and trouble may have been caused for the frame detector in the OFDM receiver due to certain random noise. Future work is required to debug this issue and make the frame detector free of error.

Other possible future works to enhance this simulation program include adding ability to accept input source data in a word size other than 8-bit, adding an option to use QAM (Quadrature amplitude modulation) instead of M-DPSK as the modulation method.

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