Design and Simulation of an OFDM-Based Transceiver

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ABSTRACTThis project demonstrates the design and simulation of an Orthogonal Frequency Division Multiplexing (OFDM)-based image transmission system using MATLAB. To simulate real-world conditions, the transmitted signal is subjected to additive white Gaussian noise (AWGN) and multipath fading. Performance is evaluated in terms of Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR). The results demonstrate the robustness of OFDM in recovering data despite noise and channel effects, with reconstructed images closely resembling the original input. The project underscores the importance of FFT and IFFT in achieving efficient and reliable communication in OFDM systems.

INDEX TERMS OFDM,FFT, IFFT, Convolution,Modulation, BPSK

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is an important and widely used technology used in modern wireless communication systems. It is valued for its ability to efficiently use available bandwidth and reduce problems like signal interference. This project focuses on designing and simulating an OFDM-based system for transmitting images using MATLAB The core concepts like the Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) is seamlessly used to process the data between the frequency and time domains.

The main aim of this work is to modulate an image signal using OFDM and transmit it over a simulated channel that introduces noise and multipath fading effects. Various modulation schemes, such as Binary Phase Shift Keying (BPSK), is applied to encode the image data. By employing IFFT at the transmitter and FFT at the receiver, the system ensures the orthogonality of subcarriers and facilitates efficient signal recovery.

To mimic real-world scenarios, the transmitted signal is exposed to additive white Gaussian noise (AWGN) and multipath fading.In multipath fading, the core concept convolution is used. On the receiver side, methods like channel estimation and equalization are used to reconstruct the transmitted image. The system's effectiveness is measured using performance metrics, including Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR), demonstrating OFDM’s ability to maintain reliable data transmission under challenging conditions.

Through this project, the critical role of FFT and IFFT in OFDM systems is emphasized, showcasing the potential of this technology to deliver reliable and efficient communication solutions.

II. OVERVIEW OF OFDM

Orthogonal Frequency Division Multiplexing(OFDM), is a widely used technology in terms of modern wireless communication systems. It is an advanced multi-carrier modulation technique, where the multi-carrier are positioned orthogonally to each other.The OFDM also resolves the issues related to the intersymbol interference (ISI) by performing image multiplexing on the orthogonal property.Furthermore, OFDM is spectrally sufficient mechanism than the conventional signal carrier modulation technique.The OFDM also offers higher spectrum efficiency as well as robustness during the multi-channel propagation. The OFDM signal frequency spectrum is shown below in Figure.1.

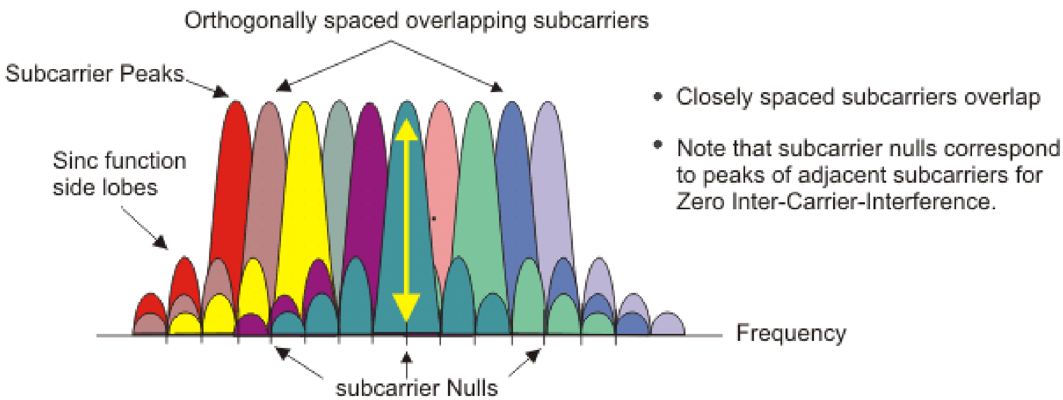

Figure.1: OFDM Frequency Spectrum

In the OFDM frequency domain spectrum it is visible that the subcarriers are overlapping, actually they are orthogonally positioned, so that the data inside the signal is not distorted. The orthogonality of the sub-carriers is achieved by placing them in such a manner that the peak of one sinusoid is at the null of others which are overlapping. This orthogonally placed sub-carriers are converted to time domain from frequency domain by Inverse Fast Fourier Transform, where the orthogonality is also maintained in time domain.

A. *KEY COMPONENTS OF OFDM*

The key components to obtain an OFDM signal are sub-carriers, modulation, Inverse Fast Fourier Transform and lastly the cyclic prefix. In order to transmit a signal through OFDM signal, the data is modulated with multiple sub-carriers using suitable modulation schemes(BPSK, QAM etc). After the modulation of the signal the subcarriers go through the inverse FFT to achieve the time domain signal. Basically, this time domain signal is transmission ready. But before transmission a cyclic prefix to the time domain signal to mitigate the inter-symbol interference(ISI).

B. *ROLE OF IFFT AND FFT IN OFDM SYSTEM*

Inverse FFT and FFT are two most important mathematical transforms that play a crucial role in generation and processing of an OFDM signal. IFFT is used in the transmitter and the FFT is used in the receiver side. The reason behind using the IFFT in the transmitter is to convert the signal to time domain and preserving the subcarriers orthogonally.The orthogonality of an OFDM transmit signal consists of N adjacent and orthogonal sub-carriers by the frequency distance Δf on the frequency axis[1]. All sub-carrier signals are mutually orthogonal within the symbol duration of length $T_s = \frac{1}{\Delta f}$. For OFDM based systems, the symbol duration T_s is much larger compared to the maximum multipath delay[1]. A complex symbol block is formed through symbol modulation.Normally, when subcarrier spectra overlap, subcarrier interference results, except at orthogonally spaced frequencies. The complex form of the transmitted signal through OFDM can be considered as:

$$x(t) = \frac{1}{N}\sum_{n=0}^{N-1} Sn \times e^{j2\pi fnt} \tag{1}$$

In the above equation, the data symbol is represented as S_n, number of sub-carriers as N and frequency at the nth subcarrier can be indicated as f_n [2]. In this project N = 64 subcarriers are used for the simulation, which is likely an appropriate value for performing IFFT in the simulations.

Similarly, a reverse process is performed in the receiver unit to get back the transmitted data.In the receiver unit a Fast Fourier Transform is performed to get the accurate separation of the sub-carriers.

In this project, an image is modulated with the modulation scheme BPSK. Then the images are divided into *N=64* sub-carriers. Then the IFFT is performed as per Eq.(1). The MATLAB built-in function “ifft()” is used to efficiently generate the time domain signal. Similarly, to demodulate the data FFT is performed in the receiver end with built-in function “fft()”.

III. SYSTEM DESIGN OVERVIEW

In this project, a transceiver is designed in MATLAB which can efficiently transmit an image and receive the image. At first the image is converted to binary streams, which is later converted to parallel binary data streams. Then the binary data is divided into N numbers of sub-carriers, and to a modulation scheme(BPSK). After the modulation of the data IFFT is performed to get the time domain signal and ensure the orthogonality, after that a cyclic prefix is added as guard between the OFDM symbols. Then the signal is transmitted.

To simulate the real world scenario Additive White Gaussian Noise (AWGN) and Multipath Channel fading is added to the transmitted data.

In the receiver end, the data is first converted to a parallel stream from the serial streams of data. Fast Fourier Transform (FFT) is performed to convert the data back into frequency domain. A channel estimation is also performed to estimate the channel properly. After all these processes the data is demodulated according to its modulation scheme. After the demodulation of the data the image is recovered. The overall system is shown in the block diagram Figure. 2.

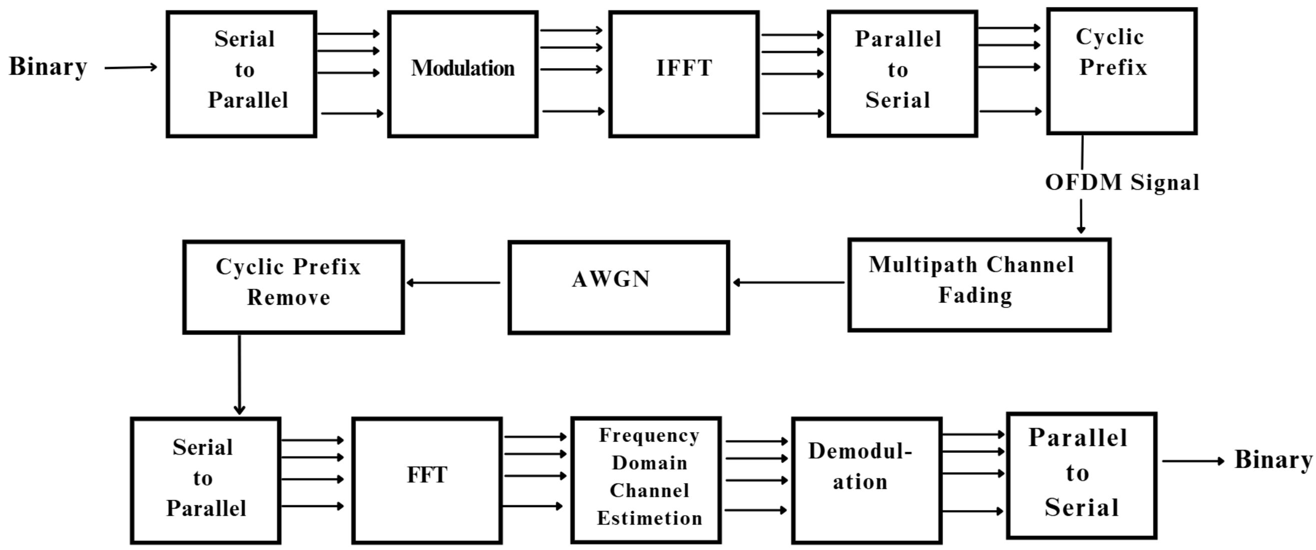

Figure 2: Block diagram

IV. SYSTEM DESIGN IMPLEMENTATION

A transceiver is simulated in the MATLAB script, the transmitter first preprocesses the data to prepare the data for modulation, after the modulation of the data a cyclic prefix is added to finally make the transmission ready. After adding the Additive White Gaussian Noise(AWGN) and multipath channel effect, the data is given to the receiver, where the receiver decodes the information and recovers the image.The whole project is simulation based. The code is written in MATLAB script which is provided in section VII. .In MATLAB, to simulate the overall system some preliminary parameters are set, the simulation parameters are shown below in Table I.

TABLE I: Simulation Parameters

Modulation Method	BPSK
FFT/IFFT size	64
Cyclic Prefix Extension	16
Channel Taps	8
Channel Estimation	LS (Least Squares)
SNR(Signal to noise ratio)	10,20,30 dB

A. DATA PRE-PROCESSING

The data preprocessing stage prepares the input image for modulation and transmission by converting it into a suitable binary format. Initially, the image is read into MATLAB and transformed into its binary representation, where each pixel value, typically stored as an 8-bit integer, is broken down into a sequence of binary digits. This binary stream serves as the raw data to be transmitted. Since the modulation process requires data to be grouped into symbols of specific sizes, determined by the modulation order, the binary stream is padded to ensure its total length is a multiple of the modulation order. Padding ensures compatibility with the modulation scheme and prevents incomplete symbol groups. Once padded, the binary data is segmented into chunks of size equal to the modulation order, which represent individual symbols to be mapped onto a constellation diagram during the modulation phase. In the MATLAB implementation, the variable mod_order plays a crucial role in defining the number of bits per symbol, ensuring proper grouping and formatting of the binary stream to meet the requirements of the selected modulation scheme. This structured preparation enables efficient data transmission in the subsequent stages of the system.

B. *DATA MODULATION*

For data modulation, Binary Phase Shift Keying (BPSK) is selected as the modulation scheme due to its simplicity and robustness in noisy environments. In this stage, the binary data stream obtained during preprocessing is directly mapped to symbols in the BPSK constellation diagram. In this scheme, each binary bit is represented as a complex-valued symbol, where 0 is mapped to -1 and 1 is mapped to +1. To achieve this, the modulation order, defined by the variable mod_order, determines the number of bits per symbol. For BPSK, mod_order is set to 1, indicating that each symbol represents a single bit.

The code starts by calculating mod_ind, which represents the number of distinct symbols in the modulation scheme. For BPSK, mod_ind is 2. The next step defines the points on the unit circle for the modulation. The symbols are represented on the complex plane with real and imaginary components. In the code, the in-phase component is defined as in_phase = cos(n) and the quadrature component is quadrature = sin(n). These points are then combined to form complex-valued symbols, stored in the symbol_book variable. The BPSK constellation consists of two points, mapped as +1 and -1 along the real axis, corresponding to binary values 1 and 0, respectively.

The resulting symbol_book contains the mapping of binary data to complex symbols, and this symbol mapping is used to modulate the binary data stream in preparation for transmission.

C. *CYCLIC PREFIX*

The cyclic prefix (CP) is a crucial component in OFDM systems, added to mitigate inter-symbol interference (ISI) caused by multipath propagation. It is a repetition of the last portion of an OFDM symbol, prepended to the symbol itself before transmission. The length of the cyclic prefix (L_{cp}) is chosen to exceed the maximum delay spread of the channel.

Purpose:

1. To prevent ISI by allowing the receiver to capture the signal without interference from preceding symbols.
2. To simplify equalization by converting the linear convolution of the channel into circular convolution, facilitating efficient frequency domain processing.

D. *NOISE AND MULTIPATH CHANNEL FADING*

In real-world wireless communication, transmitted signals are subjected to noise and fading due to multipath propagation. Noise is typically modeled as additive white Gaussian noise (AWGN). An additive white Gaussian noise (AWGN) channel model is a simple model that represents the noise that affects a transmitted signal as it passes through a channel.[3]

The received noisy signal is:

$$x_s^{noise} = x_s + n \tag{2}$$

Multipath channel fading is a phenomenon that occurs when a signal travels from the transmitter to the receiver through multiple paths. These paths can be due to reflections, diffractions, and scattering caused by obstacles like buildings, trees, or other objects in the environment.[4]

The faded signal (x_s^{faded}) is obtained by convolving the noisy signal (x_s^{noise}) with the channel impulse response (g):

$$x_s^{faded} = x_s^{noise} * g \tag{3}$$

where, g is the channel impulse response and $g[i] = \frac{e^{-i}}{||g||}$

E. *FFT FOR FREQUENCY DOMAIN CONVERSION*

In OFDM, FFT (Fast Fourier Transform) is used to modulate and demodulate symbols in the frequency domain. At the transmitter, IFFT maps data symbols to subcarriers in the time domain. At the receiver, FFT converts the received signal back to the frequency domain for symbol demodulation. At the receiver, the Fast Fourier Transform (FFT) is used to process the received time-domain signal and convert it back into the frequency domain. OFDM is particularly effective in handling multipath fading. Using the FFT helps separate these paths in the frequency domain, making it easier to correct for these effects.

FFT (Frequency Domain): $X[k] = \sum_{n=0}^{N-1} x[n]e^{\frac{-j2\pi kn}{N}}$ (4)

F. CHANNEL ESTIMATION

Channel estimation is a process used in communication systems to measure and compensate for the effects of the transmission channel. The channel can alter the signal due to various factors like multipath fading, noise, and interference, which can degrade the quality of the signal and the information it carries.

The goal of channel estimation is to figure out how much the signal has been changed while traveling from the transmitter to the receiver, so the receiver can correct these changes and recover the original signal as accurately as possible.

The Least Squares (LS) method is commonly used, which estimates the channel response by dividing the received pilot symbols by the known transmitted symbols.

Mathematical Representation (LS Estimation):

$$\widehat{H}[k] = \frac{Y[K]}{X[K]}, \quad (5)$$

here:

Y[k]: Received pilot symbol.

X[k]: Transmitted pilot symbol.

V. RESULTS AND EVALUATION

The transmission and simulations are done for three different modulation schemes and different Signal to Noise Ratio(SNR). Performance of the system is also evaluated as per the Bit Error Rate(BER).SNR is the ratio of signal power and the noise power, which is calculated in dB scale as per,

$$\left(\frac{S}{N}\right)dB = 10log\left(\frac{Power(Sig)}{Power(Noise)}\right) \quad (6)$$

The Bit Error Rate (BER) measures the fraction of bits received incorrectly compared to the total number of transmitted bits. It is an important performance metric in digital communication systems as it quantifies the impact of noise, fading, and other distortions on the transmitted data. Mathematically, BER is calculated as:

$$BER = \frac{Number\ of\ Error\ Bits}{Total\ Number\ of\ Transmitted\ Bits} \quad (7)$$

In the simulation, BER is computed by comparing the original binary data stream with the recovered binary data stream at the receiver. Higher SNR values generally lead to lower BER, indicating better system performance. The results from the simulation include constellation diagrams of transmitted and received signals, recovered images, and BER analysis for the selected BPSK modulation at varying

SNR levels. These results demonstrate how higher-order modulation schemes, while offering increased data rates, are more sensitive to noise and channel imperfections, leading to a higher BER compared to lower-order schemes like BPSK. For different SNR values different for each modulation the results are shown in Table III.

TABLE III:Simulation Results

Modulation	SNR(dB)	BER	Observation
BPSK	10	0.019	Low-order modulation, high robustness to noise, low BER even at lower SNR.
	20	0.0034	Significant reduction in BER with increased SNR.
	30	0.0026	A bit higher performance with increased SNR, thus a good quality image is transmitted.

The constellation diagram and the transmitted and received image for BPSK modulation is shown below in the Figure. 3 and Figure. 4.

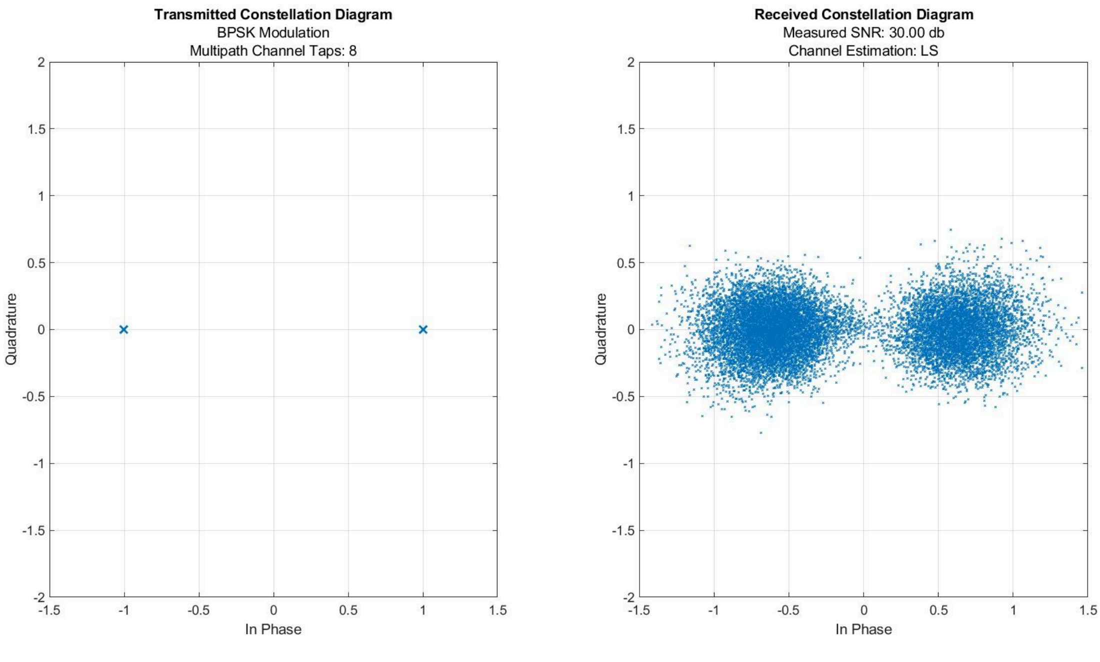

Figure 3: Constellation Diagram for BPSK Modulation at 30 dB SNR

Figure 4: Transmitted and Received Image

The system's performance using BPSK modulation shows reliable data transmission with low Bit Error Rate (BER) at higher SNR values, demonstrating the effectiveness of BPSK for robust communication in noisy environments.

VI. CONCLUSION

In this project, the BPSK modulation scheme was implemented for a simulated communication system, where data was transmitted through an OFDM-based transceiver. The system's performance was evaluated through Bit Error Rate (BER) analysis at various SNR levels, demonstrating the effectiveness of BPSK modulation for reliable data transmission in noisy environments. The successful recovery of the transmitted image further highlights the robustness of the system.

Throughout this project, the concepts of FFT (Fast Fourier Transform), IFFT (Inverse Fast Fourier Transform), and convolution were integral to understanding the system's design and operation. The FFT and IFFT allowed for efficient conversion between the time and frequency domains, which is essential in OFDM systems for modulating and demodulating signals. Convolution, on the other hand, played a key role in simulating the channel's effect on the transmitted signal, representing the impact of multipath fading. The learning outcomes from these concepts not only helped in the design and analysis of communication systems but also enhanced our understanding of signal processing techniques crucial for modern communication systems.

REFERENCES

[1] V. T. R. Kumar and K. V. Prasad, "Review on OFDM-Based Image Transmission System," **Int. J. Eng. Technol.**, vol. 7, no. 4, pp. 3962-3966, 2018.

[2] Hermann Rohling.*OFDM: Concepts for Future Communication Systems*(2011), Springer. pp [5-10]

[3] A. Ahmad, M. A. Sarijari, and M. F. Miswan, "Performance of AWGN and fading channels on wireless communication systems using several techniques," in Proc. 2018 IEEE Int. Conf. on Engineering

Technologies and Applied Sciences (ICETAS), Kuala Lumpur, Malaysia, 2018, pp. 1-5. doi: 10.1109/ICETAS.2018.8629185.

[4] M. D. Vishwakarma, S. S. Thakur, and P. P. Patil, "Analysis of multipath channel fading techniques in wireless communication systems," in Proc. 2018 IEEE International Conference on Emerging Trends and Innovations In Engineering And Technological Research (ICETIETR), 2018, pp. 1-4.