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Exploring Time-Domain OFDM Signal Generation: Performance Analysis in Communication Systems

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Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is a method used to send multiple signals over a communications link where it can transmit subchannel frequencies closely spaced without overlapping. Furthermore, OFDM is a multicarrier modulation commonly used in telecommunication, especially in wireless communication systems such as the 4th Generation (4G) and Long-Term Evolution (LTE) due to its capability of providing some advantages in terms of data transmission. In a conventional OFDM system, the OFDM signal generation is made using complex input data represented in the frequency domain before being transformed into the time domain for transmission. This paper intends to explore the viability of generating the OFDM signal using a time-domain approach. This study then further assesses the processing performance of OFDM signal simulated as a communication system, in the frequency domain and the time domain by analyzing the Bit-Error-Rate (BER). In this study, Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shift Keying (QPSK) were applied. The findings indicate that, the generated OFDM signal using the time domain method shows similar characteristics in terms of amplitude to those generated conventionally, specifically at $t = 0.49\ s$, $A = 120.4\ V$ and $121.0\ V$ for the time and frequency domain, respectively, when QAM is utilized. Meanwhile, using QPSK, at $t = 0.5\ s$, the amplitude for the frequency and time domain are $33.9\ V$ and $32\ V$, respectively. The error obtained between frequency and time domain are relatively small, $0.014\ V$ and $0.012\ V$ for QAM and QPSK, respectively. Besides, the BER value using QAM, at $SNR = 5\ dB$, is about 1×10^{-1} for both time domain and frequency domain, which closely mirrors the theoretical BER. Similarly, for QPSK, at $SNR = 6\ dB$, BER is 0.0023, 0.0030, 0.0035 for the theoretical, time domain, and frequency domain, respectively. Based on the findings, the time-domain approach can be used in generating the OFDM signals and less complexity rather than the conventional, and the choice of domain does not introduce significant variances in the performance of the OFDM signal in communication system.

1. Introduction

Wireless communication is widely used in this modern world and is part of our daily communication routine. Wireless communication, such as Wi-Fi, 4th Generation (4G), and the most recent Li-Fi, is thought to be the fastest growing in the communication field [1-3]. With this rapid growth in wireless communication comes a higher demand for data transmission. Thus, Orthogonal Frequency Division Multiplexing (OFDM) was introduced to overcome the issues due to its capability of achieving high data rates and spectral efficiency. When it comes to OFDM, Digital Signal Processing (DSP) is involved, since both are closely related concepts in the realm of signal processing and modern communication systems. DSP is a technology which involves transforming the analog signal into a digital signal for processing. It deals with various types of signals, such as audio, video, speech, and data.

Real-world phenomena are naturally continuous, consisting of the constantly fluctuating energy levels of physical processes including heat, light, sound, electricity, and magnetism. A significant transformation is needed in order to fully utilise these continuous phenomena in the context of an analog signal. These continuous energy levels are transformed into controllable electrical voltage and current signals by transducers. These signals, which are still analog in nature, need to go through a significant alteration, whereby the highlights of DSP. The connection between the analog and digital domains has given DSP its role in sampling and transforming these analog signals into a digital version that can be processed [4], [5]. Modern communication networks are constructed on top of this mechanism including OFDM.

Presenting OFDM, a multicarrier digital modulation technique that demonstrates how DSP can impact communication in the future. By transferring massive volumes of data using tightly spaced modulated carriers, it surpasses the limitations of traditional frequency division multiplexing (FDM). Since the subcarrier frequencies are orthogonal to one another, there is no need for an inter-carrier guard band, as in traditional frequency division multiplexing (FDM) [6], [7]. The orthogonality of the subcarrier frequencies leads to the elimination of crosstalk between the subchannels. As a result, no separate filter is required for each subchannel. Furthermore, in OFDM, multiple modulated carriers are squeezed tightly together at a reduced bandwidth, making it resistant to frequency selective fading or narrowband interference [8], [9]. Due to its ability to withstand frequency selective fading, OFDM excels in the elimination of inter-symbol interference (ISI), increasing its robustness to multipath fading [7], [9], [10]. Besides, OFDM is also appealing in optical fibre communications due to its immunity to ISI and inter-carrier interference (ICI) [6], [10-12]. In addition, OFDM is also widely used in optical communication specifically in visible light communication (VLC), as highlighted by Afgani M *et al.* that OFDM is a perfect solution in terms of multipath effects to prevent shadowing effects [13], [14].

However, despite its remarkable capabilities, generating the OFDM signal in practice presents inherent complexities. In conventional, the basic operation of the OFDM system using either Quadrature Amplitude Modulation (QAM) or Quadrature Phase Shift Keying (QPSK) modulation scheme consists of frequency domain and time domain processing techniques [15]. This process can be considered complex as it involves domain transformation for transmission. Interestingly, based on references [16], and [17] in the industrial field, stated that the fundamental principle of generating an OFDM signal is by combining all subcarriers to form an array of parallel signals. These subcarriers are modulated and have the capability to either carry distinct baseband signals independently or, more commonly, to be grouped together to maximize the data throughput for a single data stream. This suggests that the need for domain transformation is not required as in the conventional approach. Therefore, in this study, a method for generating the OFDM signal in the time domain, eliminating the need for domain transformation has been explored. This alternative approach is then compared with the conventional OFDM signal generation method, which involves the transformation technique. The comparison is made by calculating the Mean squared Error (MSE) of both the conventional signal (frequency domain) and the time domain-based OFDM signal. The purpose of this study is to provide insights into the effectiveness and possible benefits of the time domain-based OFDM signal-generating technique in real-world applications.

Referring back to DSP, a method that manipulates the analog signal into a digital signal to enable a wide range of applications. A DSP system consists of an analog-to-digital (ADC) converter, a DSP processor and a digital-to-analog (DAC) converter. Each of the components has its role to complete the processing of a signal. In order to perform the processing digitally, ADC converts the analog signal into a digital signal that is appropriate as an input to the DSP processor. Whereby, a DAC converts the digital signal into an analog signal to give the information to the user. In some applications, the DAC is not necessitated, such as digital radar signal processing, the extracted information can be conveyed in a digital format without the need for a DAC [4]. Hence, this study then further delves into the intricacies of OFDM signal processing, where these signals can be simulated as a communication system in either the frequency domain or the time domain by assessing its performance in terms of the Bit Error Rate (BER) under varying Signal-to-Noise Ratio (SNR) conditions.

The evaluation of the performance of OFDM systems is important, and one crucial aspect of this evaluation is the Bit Error Rate (BER). BER is a key metric that quantifies the accuracy of data transmission in a communication system. It measures the ratio of incorrectly received bits to the total number of transmitted bits, providing valuable insights into the system's robustness and reliability. In this work, the operation of generating the OFDM signal is executed using MATLAB software.

This paper is organized as follows: The first section covers the OFDM system, which includes the operation of the OFDM and modulation technique. Followed by, the method used for generating the OFDM signals and Mean Squared Error (MSE) calculation for the generated OFDM signal which is explained in the third section. The performance evaluation and comparison of the OFDM communication system are elaborated in the fourth section. The results and discussion are then described in the fifth section, and the last section is the conclusion of this study.

2. Orthogonal Frequency Division Multiplexing (OFDM) System

Orthogonal Frequency Division Multiplexing (OFDM) is a signal multiplexing technique used in digital communication systems. It is based on dividing the available frequency spectrum into multiple narrow subcarriers, each of which can carry its own data stream. Using a large number of subcarriers allows OFDM to transmit high-speed data over a wireless channel while minimizing the effects of interference and signal fading [7]. OFDM is a form of multicarrier modulation, which means that it uses multiple carriers to transmit information. In OFDM, the carriers are closely spaced and orthogonal to each other, which means that they do not interfere with each other [8]. Each subcarrier is modulated using a digital modulation scheme such as QAM or QPSK [2], [9], [18].

The operation of an OFDM system simulated in a wireless communication system consists of three main elements; the transmitter, the channel and the receiver. The process of generating an OFDM signal involves transforming the input data from the frequency domain to the time domain using the Inverse Fast Fourier Transform (IFFT) [6], [9], [19-21]. The resulting signal is then divided into subcarriers, each of which is modulated with the input data. The modulated subcarriers are then combined into a single OFDM signal transmitted over the wireless channel. The block diagram depicting the OFDM transmitter system is shown in Fig. 1.

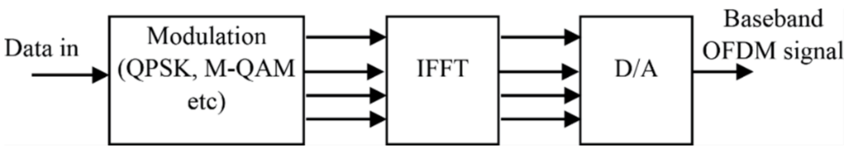

Fig. 1 *Block diagram of the OFDM transmitter system [22][23]*

At the receiver, the OFDM signal is demodulated by reversing the process. The received signal is divided into subcarriers, and each subcarrier is demodulated to recover the transmitted data. The demodulated subcarriers are then combined using the Fast Fourier transform (FFT) to recover the original frequency-domain signal [19-21]. The block diagram representing the OFDM receiver system is shown in Fig. 2.

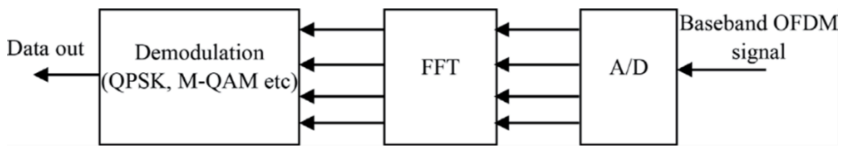

Fig. 2 *Block diagram of the OFDM receiver system [19]*

As mentioned above, the process of generating the OFDM signal requires a modulation technique such as QAM or QPSK. The modulation is an exercise of diverging either the amplitude or angle of a periodic waveform, known as the carrier signal using a modulating signal that in general encompasses information to be transmitted [18]. Generally, there are three basic methods to perform the modulation which are amplitude, frequency and phase [24]. In analogue modulation, the signals are mathematically described as the basic equation of a cosine wave [22-24]:

$$V(t) = A(t)\cos[2\pi f_c t + \theta(t)] \tag{1}$$

where V is carrier wave, A is amplitude, f_c is carrier frequency and θ is phase. In equation (1), three parameters can be varied: amplitude, frequency and phase. Based on the variation of the above three parameters of carrier signals, there exists a large number of digital modulation techniques [24].

3. Methodology of the OFDM Signal Generation

In this study, the method used to generate the OFDM signals through two approaches. The first approach is the conventional: the frequency domain, while the second approach is the time domain approach. By completing the generation of the OFDM signal, two modulation techniques are used: Quadrature Amplitude Modulation (QAM) and Quadrature Phase Shift Keying (QPSK). Fig. 3 presents the block diagram depicting the key stages of OFDM signal generation using the frequency domain and the time domain approach.

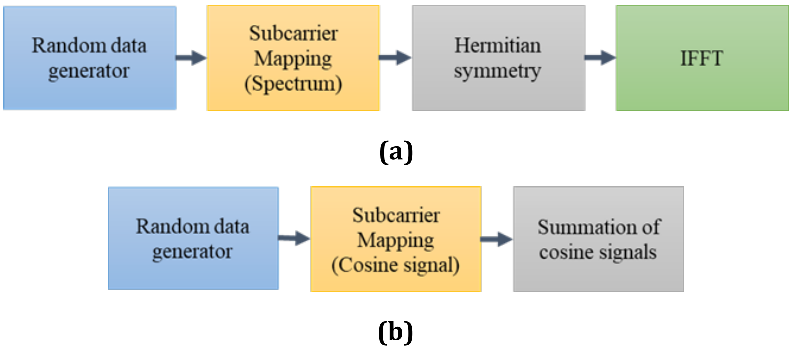

Fig. 3 *Block diagram of the OFDM signal generation using (a) The frequency domain; (b) The time domain method*

3.1 The OFDM Signal Generation using The Frequency Domain Method

The frequency domain method for generating the OFDM signal is the conventional method where the transformation of the domain is required using the IFFT to convert the signal from the frequency domain to the time domain. Fig. 3 illustrates the process for generating the OFDM signal which consists of several steps.

The process begins with the declaration of samples, N, representing the number of subcarriers. Following, random data representing the user data is generated and modulated using the modulation techniques. Then, the modulated signal of user data is combined to construct a complete OFDM spectrum by applying the concept of Hermitian symmetry which then be mathematically expressed as in equation (2):

$$Y_{OFDM}(k) = \sum_{u=1}^{\frac{N}{2}-1} X_u(k) \quad (2)$$

where $Y_{OFDM}(k)$ represents the frequency domain OFDM signal, $X_u(k)$ represents the user's spectrum. Following that, the OFDM signal is generated by performing the IFFT to the OFDM spectrum, as shown in equation (3):

$$y_{OFDM}(n) = \frac{1}{N} \sum_{k=0}^{N-1} Y_{OFDM}(k) e^{j2\pi nk/N} \quad (3)$$

where $y_{OFDM}(n)$ represents the time domain OFDM signal, N denotes the number of subcarriers in the OFDM system, n is the sample index of the OFDM signal, and $Y_{OFDM}(k)$ defines the frequency domain OFDM signal. The IFFT operation converts the frequency-domain OFDM spectrum into the time-domain OFDM signal.

3.2 The OFDM Signal Generation using The Time Domain Method

This approach generates the OFDM signal using the time domain method with several steps. The process of generating the OFDM signal using the time domain method starts with declaring the sample index, n and the sampling time, t_s where the time, t is the relationship between n and t_s as defined in equation (4):

$$t = n \times t_s \quad (4)$$

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Following that, the data generated is random data simulating the user data. The data is then modulated to generate the modulation symbol which is then converted into the time domain by extracting the value of magnitude and phase. Subsequently, the cosine signals indicate the user's assigned signals are generated. These signals are then converted from analog to discrete form using equation (5):

$$x_u(n) = A_u \cos(2\pi f_u n t_s + \theta_u) \quad (5)$$

where A_u is the amplitude, θ_u is the phase of the user data, and f_u in equation (5) is the user's orthogonal frequency assigned. Finally, all user's signals are summed together to form the complete OFDM signal and denoted as x_{OFDM} as expressed in equation (6):

$$x_{OFDM}(n) = \sum_{u=1}^{\frac{N}{2}-1} x_u(n) \quad (6)$$

In equation (6), N indicates the total number of subcarriers, and the summation is executed for all user signals to generate the OFDM signal.

3.3 Mean Squared Error (MSE) Calculation of the Generated OFDM Signal

This section explains the methodology applied to determine the accuracy of the generated OFDM signals using the time and frequency domain approach, by calculating the Mean Squared Error (*MSE*).

According to the flowchart depicted in Fig. 4, the first step is generating the time domain-based OFDM signal with several steps as explained earlier. Following that, the frequency domain-based OFDM signal (conventional OFDM) is generated. Then, the error between frequency domain-based OFDM and time domain-based OFDM is calculated. The Mean Squared Error (MSE) of the signals is calculated after the error calculation. A predetermined *MSE* threshold of 0.1 is used in this study.

The selection of this threshold is based on the findings from previous research investigating the optimization techniques of MSE in OFDM systems. The referenced studies did not specify a threshold value, however, their collective findings on MSE provided insightful information that assisted this study choose a suitable threshold value. Morosi *et al.* and Rosati *et al.* focused on MSE optimization in channel estimation, with MSE values obtained are 0 and 10^{-3}, respectively [25], [26]. Morosi *et al.* emphasised the importance of MSE analysis in pilot-aided systems, while Rosati *et al.* introduced a method for selecting the most significant samples of the Channel Impulse Response (CIR) and deriving an optimal threshold to minimize MSE. Origanti *et al.* demonstrated the efficacy of minimum mean square error detection with MSE values around 10^{-4}, and Anuraj *et al.* compared Spatial Modulation and OFDM, with an obtained MSE value of around 0.05 for OFDM [27], [28].

Collectively, these studies highlight the significance of MSE in assessing the performance of OFDM systems. This helps to provide significant context for choosing a threshold that ensures sufficient signal fidelity and alignment between signal representations in this study. This threshold serves as the foundation for the subsequent decision-making process, which ends if the computed *MSE* value is less than the threshold. On the other hand, if the *MSE* value is higher than the cutoff, the procedure repeats itself and returns to the signal generation phase.

MSE is a widely used metric for quantifying the difference between the desired signal and the received or reconstructed signal in signal processing and communication systems. Moreover, *MSE* is computed by taking the squared difference between corresponding elements of y and x, summing these squared errors, and then dividing the sum by the total number of elements to obtain the average squared error. The formula applied in this study for calculating *MSE* is expressed as:

$$MSE = \frac{1}{n}\sum (y - x)^2 \quad (7)$$

Here, n is the total number of samples in the signal, y is the value of the signal in the frequency domain, and x is the corresponding value in the time domain. A quantitative evaluation of the overall precision and fidelity of the OFDM signal transformation process is given by the obtained *MSE* value, with lower *MSE* values representing a closer match between the two domains. The flowchart of the overall process to calculate the *MSE* is illustrated in Fig. 4.

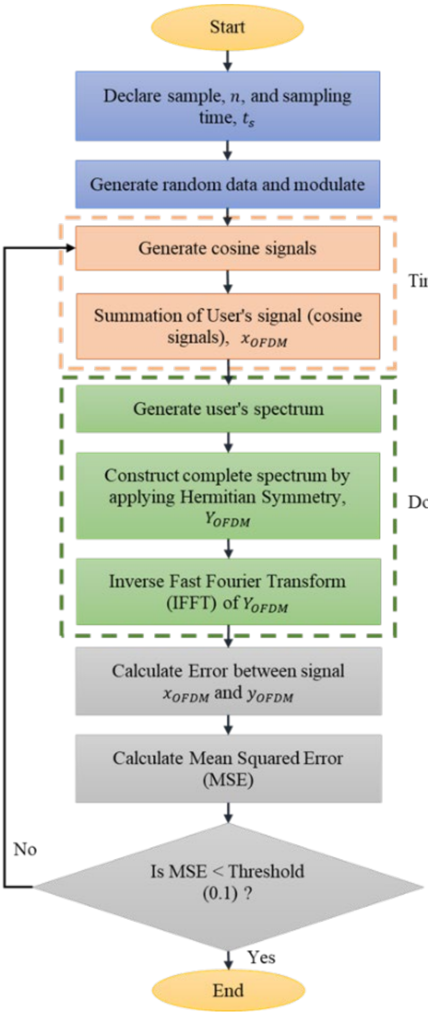


Fig. 4 *The flowchart of the overall process to evaluate the mean squared error (MSE) of the generated OFDM signal*

4. Performance Evaluation and Comparison of the OFDM Communication System

As part of this study, in the simulation-based OFDM communication system, the input signals are generated and the performance of the system is observed according to the channel model. This approach helps in obtaining a comprehensive understanding of the behaviour of the OFDM system in a simulated environment, which is useful for real-world applications. In this section, the performance of the simulated OFDM communication system in both the frequency and time domains is assessed. The evaluation involves a simulation designed to analyze the performance of the system in terms of the Bit Error Rate (*BER*) concerning the Signal-to-Noise Ratio (*SNR*). The overall process of the performance evaluation and comparison of the OFDM communication system is illustrated in Fig. 5. The block diagram depicted in Fig. 5 demonstrates the *BER* calculation process for the OFDM communication system simulated in the frequency domain and the time domain. Fig. 5(a) illustrates the simulation of the OFDM communication system in the frequency domain, while Fig. 5(b) illustrates the simulation in the time domain.

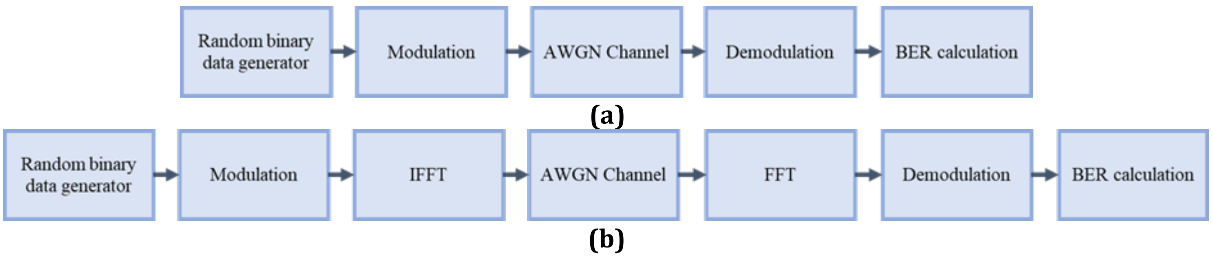


Fig. 5 *Block diagram illustrating the BER calculation process for the OFDM Signal in a communication system simulated in (a) The frequency domain; (b) The time domain*

According to both simulations, at the transmitter side, the simulation process begins with generating random binary data and performing modulation. Following that, the modulated signal passes through the channel for the frequency domain simulation. Conversely, for the time-domain simulation, the modulated signal is converted into a time-domain signal using the IFFT before it passes through the channel. On the receiver side, in the frequency domain simulation, the received signal is demodulated to recover its original binary bits data for BER calculation. In contrast, for the simulation in the time domain, the received signal is converted into the frequency domain using FFT before the demodulation process at the demodulator. After the demodulation process, the BER is calculated.

In this simulation, the OFDM communication system in the frequency domain differs from the time domain due to the implementation of the FFT and IFFT block on the system. This implementation introduces variations to the transmitted signal through the channel, which creates a clear difference between the two simulated scenarios.

A significant factor in how accurately data is transmitted in the OFDM system is the *BER*. The probability of receiving an incorrect bit is quantified, revealing information on how robust the system is under various circumstances. The *BER* formula is expressed as:

$$BER = \frac{(Number\ of\ Bit\ Errors)}{(Total\ Number\ of\ Bits\ Transmitted)} \tag{8}$$

In this formula, the "Number of Bit Errors" represents the count of incorrectly received bits, and the "Total Number of Bits Transmitted" refers to the total number of bits in the transmitted signal.

Furthermore, the Signal-to-Noise Ratio (*SNR*), which is generally expressed in decibels (dB), evaluates the received signal's quality in the presence of noise. It provides a critical viewpoint on the system's ability to separate the signal from background noise. The *SNR* equation is described as:

$$SNR(dB) = 10\log_{10}(\frac{P_s}{P_n}) \tag{9}$$

Where, P_s denotes the signal power, while P_n represents the noise power. *SNR* quantifies the signal's strength relative to the noise level, and a higher *SNR* indicates better signal quality. These *BER* and *SNR* metrics serve as the foundation for the comparative analysis of the various processing techniques of the OFDM signal in this study. By assessing *BER* and *SNR* under different scenarios, insights into how the choice of domain affects the system's performance in terms of error tolerance and signal quality are gained. A higher *SNR* shows better signal quality, reflecting the system's ability to effectively distinguish the desired signal from noise interference.

In order to evaluate the system's performance, the simulation is designed with specific parameters outlined in Table 1. The table provides a detailed overview of the experimental setup, including the range of *SNR* values, modulation schemes, and other critical parameters that control the performance assessment of the OFDM systems under investigation. In this simulation, the modulation techniques used are 64-QAM, 16-QAM, and QPSK. The Signal-to-Noise Ratio (*SNR*) range was varied from 0 dB to 15 dB for QAM and from 0 dB to 7 dB for QPSK. The number of symbols per frame is set at 1000 symbols. The simulation employs the Additive White Gaussian Noise (AWGN) channel as the noise channel. A thorough comparison between the simulation results and the theoretical *BER* model was done in order to fully evaluate the system's performance. The MATLAB software's "berawgn" function, which is designed for the AWGN channel simulation, was used to create the theoretical model.

Table 1 *Simulation parameters*

Modulation scheme	**QAM**	**QPSK**
Modulation order (M)	64, 16	4
Number of bits per symbol (bit)	6, 4	2
Number of symbols per frame	1000	1000
SNR range (dB)	0-15	0-7
Noise channel	Additive White Gaussian Noise (AWGN)	Additive White Gaussian Noise (AWGN)

5. Simulation Results

In this section, the time domain method for generating the OFDM signals is compared to the frequency domain method, which is the conventional method for generating the OFDM signals. Different modulation techniques are used in this study in order to compare and analyse both methods. QAM and QPSK are the two modulation techniques used in this study, as the features of both modulation techniques are different.

According to the OFDM signal generation simulation, the results obtained are demonstrated in Fig. 6 and Fig. 7. There are 3 graphs for each figure; each graph represents the OFDM signal using the frequency domain method, the OFDM signal using the time domain method, and the error between the frequency and time domain-based OFDM. Fig. 6 describes the frequency and the time domain-based OFDM using QAM, while Fig. 7 illustrates the frequency and time domain-based OFDM using QPSK.

Based on a thorough visual inspection of the simulation results presented in Fig. 6, it becomes evident that both signals appear identical to one another. The error graph presented alongside provides quantitative evidence supporting this observation. Notably, at $t = 0.48\ s$, the discrepancy between the two signals is minimal, with a value of $A = 0.014\ V$ for the highest peak of the error graph and the MSE obtained is 6.4021×10^{-04}, which indicates less error occurred between signals.

Furthermore, based on the graphical representation of the OFDM signal for both domains, the amplitude shows identical characteristics. Specifically, at $t = 0.49\ s$, $A = 120.4\ V$ and $121.0\ V$ for both the time and frequency domain-based OFDM, respectively.

Consequently, these findings emphasize high similarity and consistency between the frequency and time domain-based OFDM signals. According to both visual and quantitative analyses support the conclusion that the two signals exhibit nearly identical characteristics, confirming the strength and precision of the simulation outcomes.

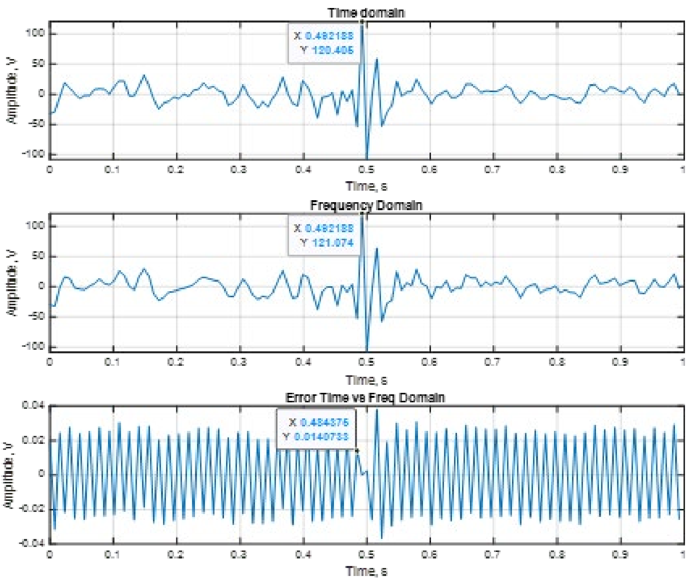


Fig. 6 *Frequency versus time domain-based OFDM using QAM and the error between the two signals*

Based on the simulation results presented in Fig. 7, it is noticeable that the OFDM signal exhibits similar characteristics when analyzed in both the frequency and time domains. The graph representing the frequency domain-based OFDM signal reveals that at $t = 0.5\ s$, the amplitude obtained is $A = 33.9\ V$. Similarly, in the graph representing the time domain-based OFDM signal, the amplitude at $t = 0.5\ s$ closely aligns, at $A = 32\ V$. The similarity of signal characteristics between the two domains is highlighted by these consistency of amplitude values.

The error graph presented in Fig. 7 further provides an explanation of the amplitude differences. Particularly, at $t = 0.49\ s$, the amplitude discrepancy $A = 0.012\ V$. This slight amplitude difference is indicative of the exceptional alignment between the time domain-based and frequency domain-based OFDM signal. Furthermore, according to the error graph, the value amplitude of the highest peak serves as another illustration of the small discrepancy between the two signal domains. Besides, the value of *MSE* obtained indicates less error occurred between signals which are 0.0010.

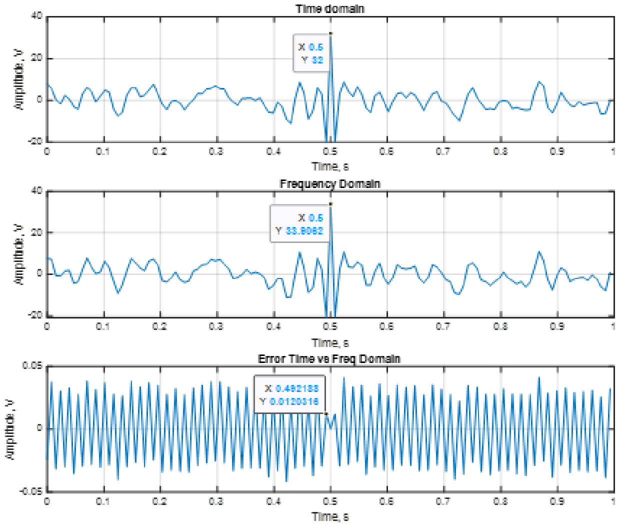


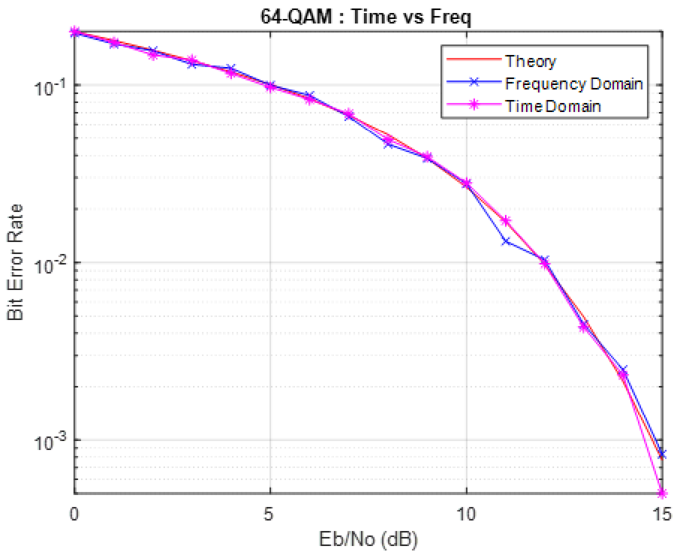
Fig. 7 *Frequency versus time domain-based OFDM using QPSK and the error between the two signals*

The results of MSE obtained in this study align well with the previous study that has investigated similar aspects of OFDM signal generation and MSE performance. In a study by Origanti *et al.*, the MSE performance of OFDM systems was investigated under various detection techniques in a Rician channel using 32-QAM modulation and found the MSE values were approximately 10^{-4} for Minimum Mean Square Error (MMSE) detection at SNR of 30 dB, and approximately 10^{-1} for Zero Forcing (ZF) and Maximum Likelihood (ML) detection methods [27]. A study investigated multiple data transmission modalities using OFDM signals generated using IFFT, focusing on modulation techniques including BPSK, 16-QAM, 32-QAM, and 64-QAM in an AWGN channel by Reddy *et al.* shows MSE values consistently below 0.05 for all modulation methods tested at SNR of 24 dB [29]. Furthermore, in a study conducted by Anuraj *et al.* on a comparative analysis of Spatial Modulation (SM) and OFDM systems with different QAM (M = 16, 32, 64, 128 and 256) symbol mapping schemes in a Rayleigh fading channel reported MSE performance below 0.05 for OFDM at SNR of 20 dB, for 16-QAM and gradually increase in MSE values with an increase in QAM orders [28].

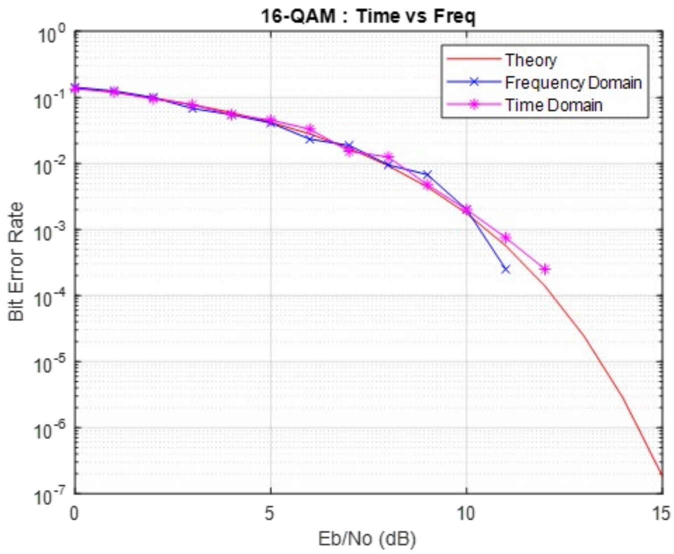
In general, this study's findings confirm the high degree of similarity between frequency and time domain-based OFDM signals in both QAM and QPSK modulation schemes. Both quantitative analysis and visual inspection repeatedly show the similarity of the signals to one another. The results show that the resemblance between frequency and time-domain-based OFDM signals is not particular to a specific modulation type. The amplitude and error peak variations are barely noticeable and well within tolerable variance limits. These differences are unlikely to have a substantial effect on the OFDM system's practical performance. The signals' high degree of similarity validates the dependability and efficiency of both signal-generation techniques for the OFDM communication systems and based on the value of *MSE* obtained are small.

The simulation results depicted in Fig. 8 is the plot of the Bit error rate (*BER*) against Signal-to-Noise-Ratio (*SNR*) for the simulated OFDM communication system in the frequency domain and time domain using 64-QAM and 16-QAM. Meanwhile, as illustrated in Fig. 9 is the plot of the Bit error rate (*BER*) against Signal-to-Noise-Ratio (*SNR*) for the simulated OFDM communication system in the frequency domain and time domain using QPSK.

According to the simulation results in Fig. 8, it can be seen that the *BER* values for the simulated OFDM communication system in the time domain and frequency domain closely align with the theoretical *BER* for both 64-QAM and 16-QAM, with slight differences. Specifically, at $SNR = 5\ dB$, the *BER* values are approximately 1×10^{-1} for both the time domain and frequency domain, which closely mirroring the theoretical *BER*, for 64-QAM. A similar pattern is observed for 16-QAM, with *BER* at 1×10^{-1} at $SNR = 5\ dB$. These findings imply that both time and frequency domain processing performance is noticeably similar to the theoretical *BER*, particularly for 64-QAM. The summary of the simulation results of *BER* against *SNR* of the frequency domain and time domain using 64-QAM and 16-QAM is provided in Table 2.



(a)



(b)

Fig. 8 *Comparison of the BER versus SNR performance for the frequency and time domain-based OFDM using (a) 64-QAM; (b) 16-QAM*

Table 2 *Summary of bit error rate (BER) simulation results for frequency and time domain-based OFDM systems for 64-QAM and 16-QAM*

	64-QAM			16-QAM		
SNR (dB)	Theoretical BER	BER (Frequency Domain)	BER (Time Domain)	Theoretical BER	BER (Frequency Domain)	BER (Time Domain)
0	0.199	0.196	0.200	0.140	0.138	0.143
3	0.137	0.103	0.138	0.077	0.067	0.079
6	0.083	0.087	0.083	0.027	0.026	0.028
9	0.038	0.038	0.039	0.004	0.004	0.004
12	0.009	0.010	0.009	0.0001	0.0002	0.0005
15	0.0007	0.0008	0.0005			

The comparison of *BER* against *SNR* between OFDM communication system simulated in the frequency domain and the time domain using QPSK modulation is depicted in Fig. 9. The simulation results indicate that the time domain closely aligns with the frequency domain, with the *BER* being noticeably lower and nearly aligning with the theoretical *BER*. Significantly, for an *SNR* of 6 dB, the theoretical *BER* is 0.0023, the time domain-based OFDM is 0.0030, and the frequency domain-based OFDM is 0.0035. The improved functionality of the time domain in the context of QPSK modulation is highlighted by this significant advantage in *BER*. Table 3 presents the summary of the simulation results of *BER* against *SNR* of the frequency domain and time domain using QPSK.

These findings are consistent with recent research investigating the performance of OFDM in terms of BER. Kapse *et al.* and Chen *et al.* both delve into the effects of different modulation techniques on OFDM systems' BER [30], [9]. Kapse *et al.* study focuses on the influence of design factors and finds promising results with BPSK exhibiting a lower *BER* of 0.04 at $-5\ dB$. Chen *et al.* research compares QPSK and 16-QAM modulation. Both studies underscore the importance of selecting the appropriate modulation scheme to achieve a low BER. Farzamnia *et al.* corroborate these findings, demonstrating that M-QAM modulation outperforms M-PSK in data transmission rates and communication reliability [31]. They observe better BER performance with M-QAM across all analysed channel types, with the lowest *BER* below 10^{-4} in the AWGN channel. Additionally, Vincent *et al.* address the issue of high Peak-to-Average Power Ratio (PAPR) in OFDM systems, which can be alleviated to enhance BER performance. For 16 QAM, optimal BER performance is achieved with the utilization of $db1$ with the Partial Transmit Sequence (PTS) technique, yielding a *BER* around 10^{-7}. Meanwhile, for 64 QAM, the best combination is the conventional usage of $db3$, resulting in a *BER* value of 10^{-3} [20].

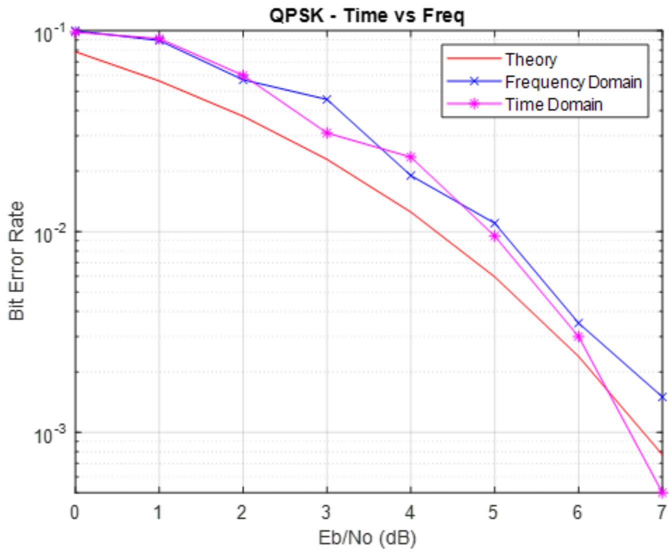


Fig. 9 *Comparison of the BER versus SNR performance for the frequency and time domain-based OFDM using QPSK*

Table 3 *Summary of bit error Rate (BER) simulation results for frequency and time domain-based OFDM systems for QPSK*

SNR (dB)	QPSK		
	Theoretical BER	BER (Frequency Domain)	BER (Time Domain)
0	0.0786	0.100	0.0985
1	0.0562	0.0895	0.0915
2	0.0375	0.0570	0.0600
3	0.0228	0.0455	0.0310
4	0.0125	0.0190	0.0235
5	0.0059	0.0095	0.0110
6	0.0023	0.0035	0.0030
7	0.0007	0.0015	0.0005

Regarding the simulation results obtained, it can be concluded that the processing performance of OFDM signal simulated in both time and frequency domain, nearly resembles the theoretical *BER* across different modulation schemes. Particularly, the time domain performs better in terms of *BER* for QPSK modulation than the frequency domain. These findings demonstrate the adaptability and effectiveness of the time domain in real-world communication systems, especially when QPSK modulation is used.

6. Conclusion

In this study, a time domain-based to generate the OFDM signals is studied, simulated and analyzed. There are two modulation techniques used for generating the OFDM signal: QAM and QPSK. According to the results, the signal generated using the time domain approach exhibits similarities with the output of the frequency domain method in terms of amplitude value. Although minor amplitude differences were observed between the two signal domains, these discrepancies are well within acceptable variance limits. Meanwhile, the simulation of the OFDM communication system was performed to evaluate the processing performance of the signal that is simulated in both domains in terms of *BER* against *SNR* and the results show that both the time domain and the frequency domain closely align with the theoretical *BER* values. However, the time domain surpasses the frequency domain in achieving lower *BER* values, especially when QPSK modulation is employed. These results demonstrate the significance of considering the modulation technique when selecting the appropriate domain for OFDM signal transmission. Moreover, from a simulation perspective, the processes carried out in the frequency domain are more concise compared to those in the time domain. This suggests that, in terms of processing, the frequency domain offers advantages due to its simplicity compared to the time domain. As a result, this study indicates that time domain-based OFDM is particularly effective in generating the OFDM signal and as for the performance processing of the OFDM signal, the choice of domain for simulating the signal does not have any effect on the system's performance. This suggests that time-domain-based OFDM may be a preferred choice for real-world communication systems when specific modulation types are considered. For future research, the main focus will be on the application of the time domain-based OFDM signal in a Visible Light Communication (VLC) system. The goal of this endeavour is to examine the signal's performance across the entire VLC system, which will provide significant insight into its efficiency and practical use.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Ariffuddin Joret, Ismail Musirin, M. F. L. Abdullah, Asmarashid Ponniran, Zahriladha Zakaria;* ***data collection:*** *Najwanisa Tusin, Ariffuddin Joret;* ***analysis and interpretation of results:*** *Najwanisa Tusin, Ariffuddin Joret;* ***draft manuscript preparation:*** *Najwanisa Tusin, Suhaimi Sulong, Sharifah Saon. All authors reviewed the results and approved the final version of the manuscript.*

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