Application of QPSK-OFDM for Improved Underwater Wireless Communication System

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***Abstract*— The problems of signal loss and poor channel estimation are inherent in underwater communication. In this work, underwater communication system has been improved using Orthogonal Frequency Division Multiplexing (OFDM) system with quadrature phase shift keying (QPSK) based on modulation scheme. The modern choice of underwater communication system, where the available bandwidth was divided into many overlapping sub-channels, such that the symbol duration was compared to the multipath spread of the channel; thus, eliminating inter symbol interference as well as improving bandwidth availability. Matlab tool was used to develop and implement series of simulations of the underwater acoustic communication system model. The proposed OFDM-QPSK underwater wireless acoustic technique achieved a BER of 2.44 × 10^{-4}, approximately equivalent to 1.8%, and a SNR of 42.82 dB, at a transmission bit rate of 67.93 bit/s. The work showed a positive improvement and a novel achievement as compared to many literatures. Comparing the results of existing literature and the results obtained from this work, it can be logically summarized that a better performance OFDM system is achieved by utilizing the QPSK modulation scheme as presented in this work. The results showed an improved channel characterization, low noise level and suitable modelling for the underwater acoustic applications.**

***Index Terms*—OFDM, Acoustic, Underwater, Channel, Gaussian Noise, Communication.**

I. INTRODUCTION

The introduction of underwater sensor network, submarine communications, military surveillance and remotely operated vehicles (ROV) has opened a completely new area of research and development, although most of the applied concepts have been adopted from radio frequency (RF) applications. The major challenge has been on how to apply those successful concepts to the underwater channel, particularly at the physical layer [1]. Electromagnetic waves are useful for long distance wireless communications. However, when water is used as the medium of propagation, the limited application of these waves has led to the usage of sound waves as the transmission medium [2]. At present, underwater communication systems involve the transmission of information in the form of acoustic (sound), electromagnetic, or optical waves.

Electromagnetic and optical waves propagate poorly in seawater, leaving the acoustic signaling as the only viable option for long range underwater communication [3]. Acoustic communication is the most versatile and widely used technique in underwater environments due to the low attenuation of sound in water [1]. During the past two decades, significant advancements have been made in the development of underwater acoustic communication systems in terms of their operational range and data developments [2], [4]-[14].

OFDM is a telecommunication method of encoding digital data on multiple carrier frequencies [5]. To overcome errors in mobile communication channels resulting in multipath propagation and Doppler effects, the term coded orthogonal frequency-division multiplexing (COFDM) was introduced by Alard in 1986, which applies a forward error correction (convolutional coding) and time/frequency interleaving to the signal being transmitted [3], [15], [18], [19].

This study focuses on Orthogonal Frequency Division Multiplexing (OFDM) technique as it applies to underwater acoustic communication network protocol. In Frequency Shift Keying (FSK) modulation, information bits are used to select the carrier frequencies of the transmitted signal and the receiver compares the measured power at different frequencies to infer the transmitted bits. This method does not require channel estimation, although guard bands are required to avoid interference from frequency spreading [6], [16]. The transmitted FSK signal can be represented as [7]:

$$\tilde{x}(t) = 2\Re \sum_{i=-\infty}^{\infty} e^{j2\pi f(i,s|i|)(t-iT)}\, g(t-iT) \qquad (1)$$

where T is the time duration of each tone spaced by 1/T, f(I, s[i]) is a function that determines the tone of the ith symbol, s[i] is the data symbol, and g(t) is the pulse shaping function. In Direct Sequence Spread Spectrum (DSSS) modulation, a narrowband waveform of bandwidth W is spread to a large bandwidth before transmission. Each symbol is multiplied by a spreading code of length N= B/W chips. The baseband signal is represented as [7]:

$$\sum_{i=-\infty}^{\infty} s|i| \sum_{n=0}^{N-1} c[i,n]\, g(t-(iN+n)Tc) \qquad (2)$$

where c[i,n] is the chip sequence for the ith symbol, and Tc is the chip duration. The passband signal can be represented as [8]:

$$\tilde{x}(t) = 2\Re\{x(t)e^{j2\pi fct}\} \qquad (3)$$

II. MATERIALS AND METHOD

A. *OFDM Model Development*

In modeling the OFDM aspects, both physical and mathematical relations are utilized in demonstrating the OFDM system. The derived mathematical models form the basis for the software simulation and analysis using Matlab. The models are, thereafter, related to the underwater scenario.

B. OFDM Signal Transmission and Modulation

The constituent elements of the OFDM signal transmitter are shown in Figure 1. The serial random source data represents the message bits or information signal to be transmitted. The OFDM transmitter maps the information signal bits into a sequence of PSK or QPSK/QAM symbols, which are subsequently converted into N-parallel streams. Each of the N symbols from the serial-to-parallel (S/P) conversion is carried out by the different sub-carriers after the digital modulation through the Inverse Fast Fourier Transforms (IFFT) method.

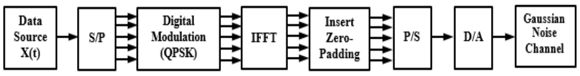

Figure 1: OFDM Signal Transmission Flow Physical Model

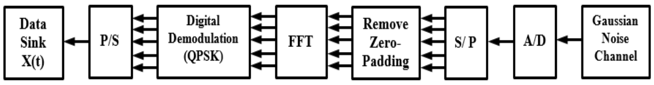

Figure 2: OFDM Signal Reception Flow Physical Model

In the multichannel system, the S/P conversion process causes an extension of the transmission time duration for N symbols to NTs, which forms a single OFDM symbol with a time duration given by T=[NT]s. Let Ψ(l,k)(t) denote the lth OFDM signal at the kth Subcarrier, which is given as equation (4).

$$\Psi_{i,k}(t) = \begin{cases} e^{j2\pi f_k(t-iT)}, & 0 < t \le T \\ 0, & Elsewhere \end{cases} \tag{4}$$

Then, the analogue modulation of the baseband and passband (information) OFDM signals respectively, can be modelled in the continuous-time domain as equation (5) and (6).

$$\mathrm{x}_l(t) = Re\left\{\frac{1}{T}\sum_{l=0}^{\infty}\left\{\sum_{k=0}^{N-1} X_i[k]\Psi_{l,k}(t)\right\}\right\} \tag{5}$$

and

$$\mathrm{x}_l(t) = \sum_{l=0}^{\infty}\sum_{k=0}^{N-1} X_l[k]e^{j2\pi f_k(t-lT)} \tag{6}$$

Equation (5) and (6) represent the analogue modulated OFDM signal in a continuous-time baseband form, where $\Psi l, k$ and $Xl[k]$ are the Subcarrier and information signals respectively.

However, the modulation of the OFDM signal is usually in discrete form through IFFT [5], and to achieve this, the analogue form of the modulated message or information signal is first subjected to sampling. Thus, equation (6) is sampled at $t = lT + nT_s$ with $T_s = T/N$ and $f_k = k/T$, to yield the corresponding discrete-time OFDM symbol, where T and T_s are the OFDM signal symbol period and sampling rate respectively. Thus, the resulting OFDM signal from the sampling process is expressed as equation (7).

$$x_l[n] = \sum_{k=0}^{N-1} X_l[k]e^{j2\pi kn/N} \text{ for } n = 0, 1, 2, \ldots\ldots, N-1 \tag{7}$$

Equation (7) thus represents the N-point of Inverse Discrete Fourier Transform (IDFT) of OFDM QPSK (PSK or QAM) data symbols $\{X_l[k]\}_{k=0}^{N-1}$ and can be computed efficiently using the IFFT algorithm. The IDFT is defined as follows [6]:

$$f(k\Delta t) = \frac{1}{N}\sum_{k=0}^{N-1} F(n\Delta f)e^{j2\pi kn/N} \tag{8}$$

For an OFDM discrete signal of magnitude $X_l[n]$, the IFFT satisfying the discrete equality is given as:

$$\Delta f = \frac{1}{N\Delta t} \tag{9}$$

By substituting this discrete equality equation (9) into the general IDFT equation (8), the modulated discrete OFDM signal at the transmitter is generated as stated in equation (7).

C. OFDM Signal Reception and Demodulation

At the receiver, where the digital message bits are retrieved and reconstructed from the multipath noisy channel, the reverse of the transmission process is carried out as shown in Figure 2 above. Channel noise was eliminated, zero-padding was removed, and the OFDM signal was demodulated to discrete message bits. The encoded digitalized channel signals were first converted into an equivalent, parallel analogue signals. Thereafter, the channel guard zero-padding was removed to allow for analogue reconstruction of the message bits by the process of Fast Fourier Transform (FFT), which efficiently reverse the processes of IDFT and IFFT to extract the required digital message signal.

Now, let the received baseband OFDM symbol transmitted via the wireless channel be given as:

$$y_l(t) = \sum_{k=0}^{N-1} X_l\,[k]e^{j2\pi f_k(t-lT)}, lTt \le lT + nT_s \tag{10}$$

The transmitted information signal $X_l[k]$, can be reconstructed in analogue form and then digitized by applying the orthogonality condition among the Subcarriers as stated in [19]. Thus, the discrete time domain representation of equation (10) is given as follows:

$$\begin{aligned} X_l[k] = Y_l[k] &= \sum_{n=0}^{N-1} y_l[n]\, e^{-j2\pi kn/N} \\ &= \sum_{n=0}^{N-1}\left\{\frac{1}{N}\sum_{i=0}^{N-1} X_l[i]e^{j2\pi in/N}\right\}e^{-j2\pi kn/N} \\ &= \sum_{n=0}^{N-1}\sum_{i=0}^{N-1} X_l[i]\, e^{j2\pi(i-k)n/N} \end{aligned} \tag{11}$$

Equation (11) therefore, represents the original message bits at the instance of transmission but now recovered by the demodulation process with negligible amount of data loss which can be lumped to the sampling effects.

D. Model for Deep Water Environment

For a deep-water wireless communication system, where the guard time is expected to be less than the delay spread, there will be an inter block interference which may degrade the overall performance of the communication system [17]. Hence, the OFDM was modelled such that the guard time is greater than the delay spread. Figure 3 shows the illustration of a deep-water communication channel.

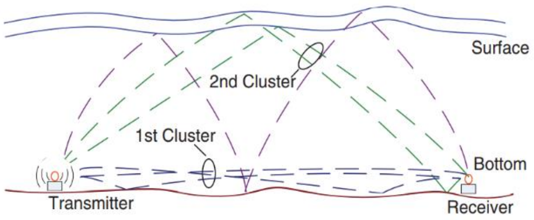

Figure 3: Illustration of Deep-Water Acoustic Communication Channels [18]

The model used at the transmitter side consists of a typical OFDM system with K sub-channels, which was designed considering the effects of underwater channel. The transmitter system model is shown, where S/P denotes serial-to-parallel conversion. In the transmitter model when data streams that contain information bits are received, they are converted into K-parallel streams which contains Ni information bits in each. Ni is defined based on the mapping used in the transmitter. Based on these analysis, matlab coding of equation (11) was used to simulate and hence, show the behaviour of the system. For each step, signal sampling was carried out.

III. RESULTS AND DISCUSSION

A. *OFDM Signal Transmission*

Figure 4 shows the frequency response of the OFDM sub-carriers required for the implementation of the IFFT modulation, as well as the power spectral density (PSD) of the subcarrier signal at the OFDM transmitter. The main task is to centralize the OFDM spectrum on the carrier frequency. The mapping and digital encoding facilitated the serial-to-parallel conversion of the input data, and at the transmitter output, the frequency response was converted into time response, and then from parallel-to-serial.

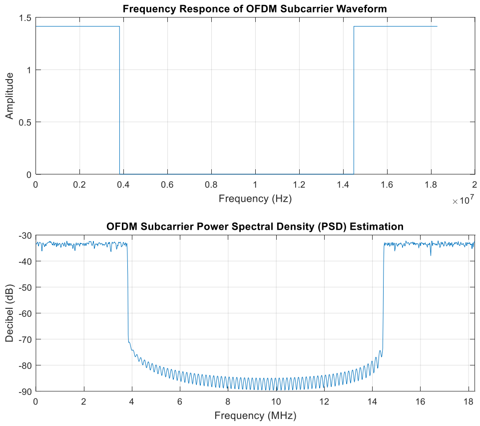

Figure 4: Frequency and PSD Responses of OFDM Signal Carrier.

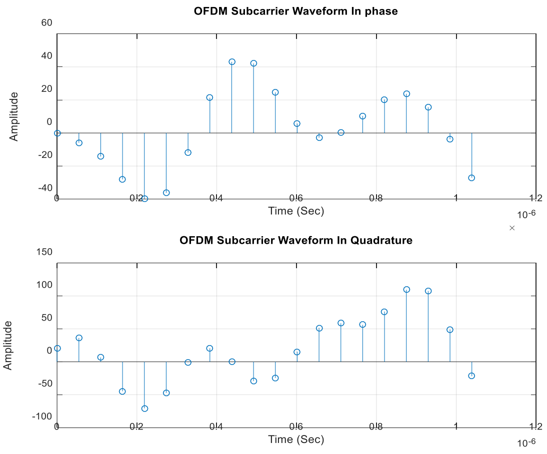

Figure 5: Time Response of OFDM Signal Carrier

Figure 5 shows the time domain expression of Figure 4. It shows the power spectral density as well as the carrier signal for the OFDM. To confirm the orthogonality condition, both the time and the frequency response graphs show orthogonality in terms of phase differences. Thus, the carrier signals are orthogonal and therefore, enhances the implementation of the OFDM process. Figure 6 gives the frequency response of the message signal available at the transmitter input. The signal, which was originally analogue was discretized and then, converted into parallel package, frequency response signals for QPSK modulation.

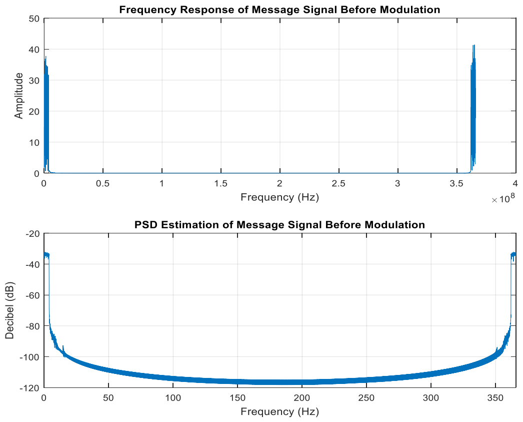

Figure 6: Frequency and PSD Responses of Message Signal.

Figure 7 represents the information signal to be modulated and transmitted. The message signal was also transmitted in two channels with different amplitudes which represents a non-single channel transmission, and for modulation in both the In-phase and Quadrature aspects of the QPSK modulation scheme. The IFFT modulated the discrete subcarriers with the message signal and generated a frequency response modulated signal, as shown in Figure 8.

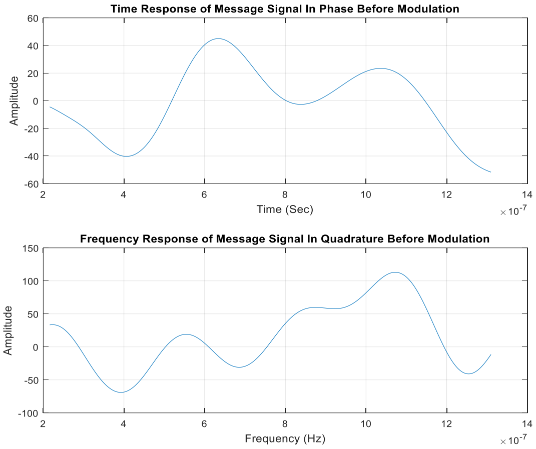

Figure 7: Time Response of OFDM Message Signal (Source Data)

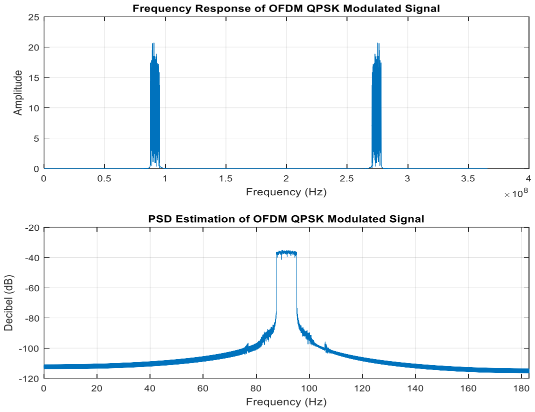

Figure 8: OFDM Modulated Discrete Signal

Figure 8 is the actual response of the IFFT action in the QPSK modulation scheme. The QPSK sends two binary bits at a time as against one bit sent if a binary phase shift keying (BPSK) is chosen. This makes QPSK robust and flexible with an acceptable bit-error-rate (BER) within a very long signal transmission. In this work, the receiver was assumed to be stationary to minimize the effect of wide Doppler shifts. With this assumption, QPSK modulation scheme performed better than BPSK in terms of BER. The modulated discrete signal was then subjected to zero-padding (ZP) to further fortify it against intercarrier interference (ICI).

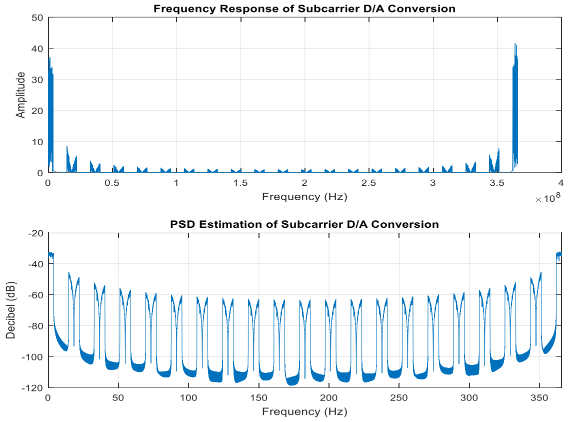

Figure 9: Frequency Response of Digital-to-Analogue Conversion of Modulated Discrete OFDM Signal.

Also, since the receiver was assumed to be stationary, fast fading and frequency selectivity resulting in intersymbol interference (ISI) were mitigated to the suppressed ISI. The ZP modulated discrete signal was then subjected to upwards conversion into analogue. A digital-to-analogue converter (DAC) converted the ZP modulated discrete signal into the corresponding analogue signal, as shown in Figure 9 and 10.

Figure 10 shows the In-phase (real) response and Quadrature (imaginary) response of the QPSK modulation effect. It is the final stage of the modulation process before transmission into the underwater channel. The time response is analogue and sinusoidal in nature, but the output of the D/A converter does not represent a pure sinusoid. To achieve this, the resulting analogue signal was filtered by a D/A low-pass filter whose response is shown in Figure 11 and then converted from parallel into serial by the P/S converter at the transmitter antenna section.

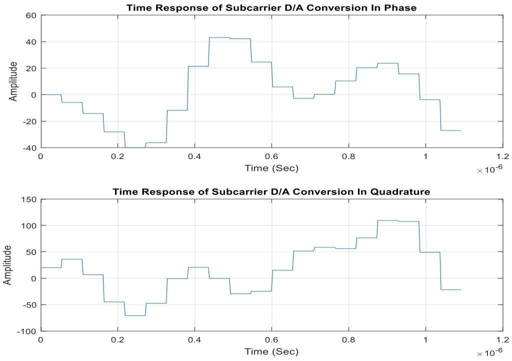

Figure 10: Time Response of Digital-to-Analogue Conversion of Modulated Discrete OFDM Signal.

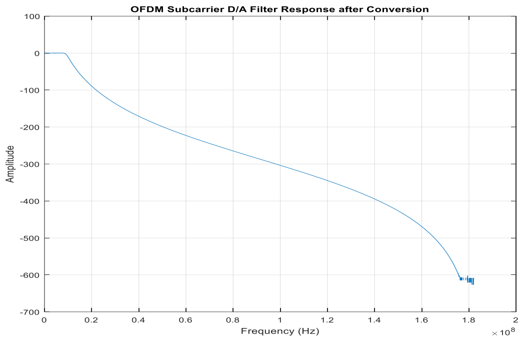

Figure 11: Digital-to-Analogue Conversion Low-Pass Filter Response.

Figure 12 represents the OFDM transmitted signal after it has been modulated and converted by IDFT or IFFT respectively, into analogue form. The carrier signals appeared to be impregnated in the envelope signal, while the amplitude was similar to the message signal. It can be concluded that multipath OFDM modulation has been successfully carried out. The transmitted signal shows both the real (In-phase) and imaginary (Quadrature) of the QPSK modulator as can be seen from the two lateral divisions along the time axis, with amplitudes spreading into the positive half (In-phase) above and negative half (Quadrature) beneath. Thus, the carrier message signals are amplitude modulated in a multipath OFDM QPSK scheme and transmitted through underwater channel wirelessly.

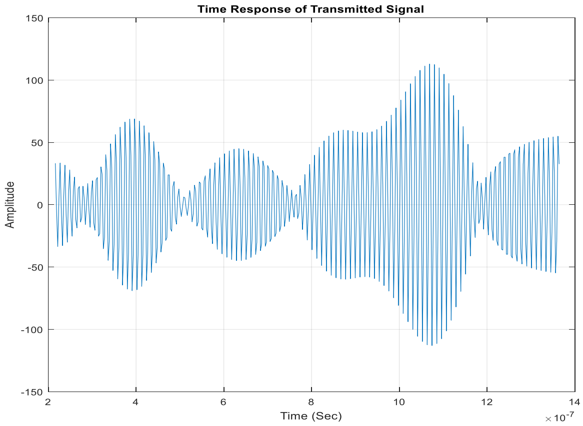

Figure 12: Time Response of OFDM Modulated Signal by IFFT.

B. OFDM Underwater Channel Estimation

Figure 13 shows the impulse response of the additive white noise (AWGN) as a typical example of the actual underwater challenges to transmission of signals. It is full of slowly travelling acoustic waves and spiky spectral space [6]. The transmitted OFDM QPSK signal was expected to travel in this noisy channel to the receiving antenna. With this undulating waveform, the receiving antenna will find it difficult to maintain a stationary position and this results in angular deviations from the transmit signal, known as Doppler shift [6]. The normalized power delay profile for the underwater channel is shown in Figure 14. Figure 13 and 14 were obtained using Simulink to determine the response of AWGN using QPSK technique.

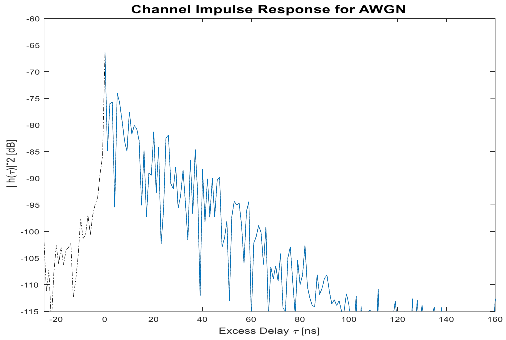

Figure 13: OFDM Additive Gaussian White Noise (AWGN) For Underwater Channel.

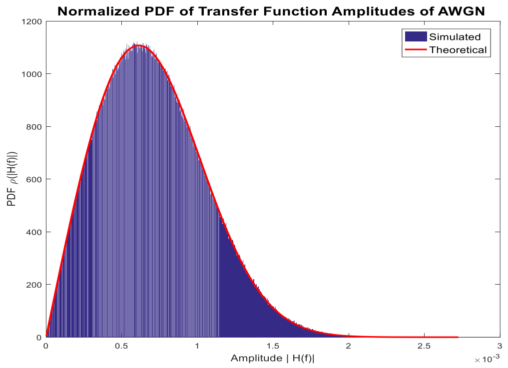

Figure 14: OFDM Normalized PDF (AWGN) for Underwater Channel Model.

C. OFDM Signal Reception

Figure 15 represents the received OFDM signal with additive channel noise just before it is subjected to FFT process. Comparing the transmitted signal (before being compromised by AWGN) with the received signal over the noisy channel, the difference could be attributed to the presence of noise in the channel, and mixed in some proportions with the received signal. Thus, time response is converted into frequency response at the receiver antenna region and the resulting frequency response is shown in Figure 16.

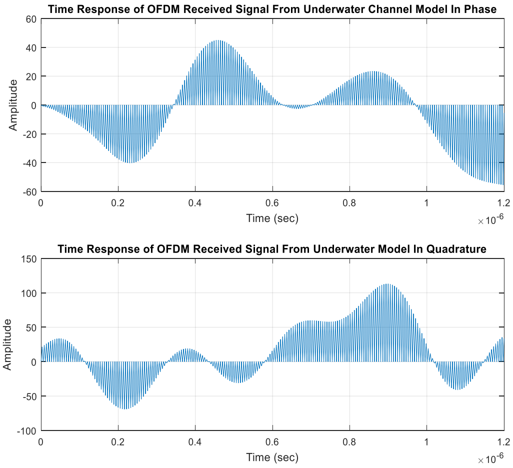

Figure 15: Time Response of OFDM Received Signal.

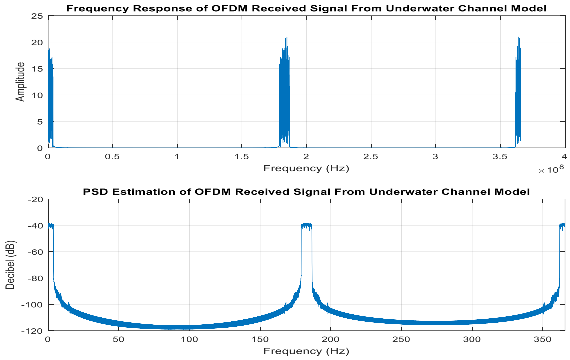

Figure 16: Frequency Response of OFDM Received Signal

Figure 17 shows the time response of the recovered message signal. Figure 18 is the frequency response of the original message signal. The time response of the recovered subcarrier signal is shown in Figure 19.

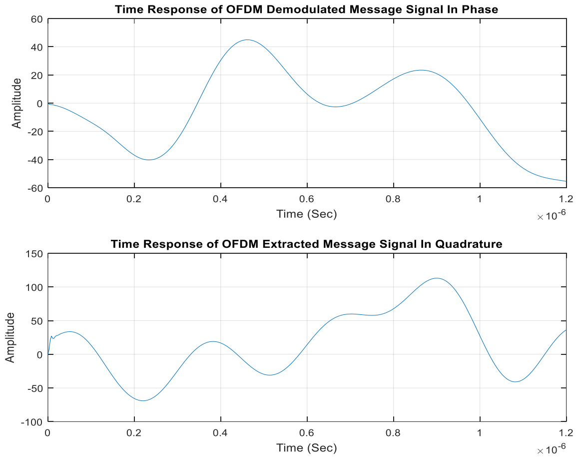

Figure 17: Time Response of OFDM FFT Demodulated Signal at Receiver.

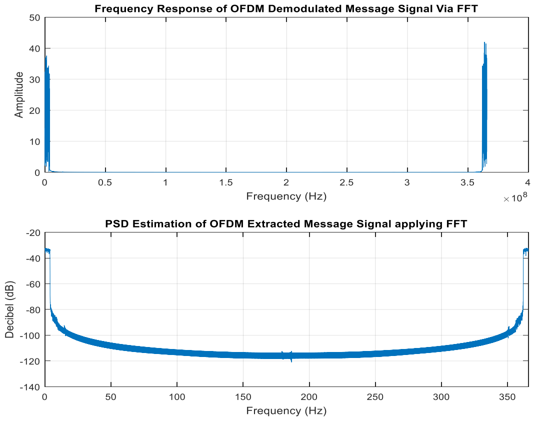

Figure 18: Frequency Response of OFDM FFT Demodulated Signal at the Receiver.

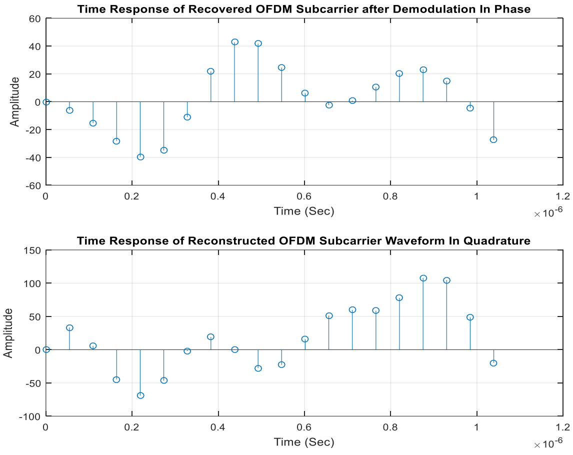

Figure 19: Time Response of OFDM Sub-Carrier Signal at Receiver.

Figure 20 shows the frequency response of the recovered OFDM symbol carrier signals and the corresponding PSD estimator. By comparing Figure 5 and 20, the similarities represent a validation of a successful application of the OFDM QPSK transceiver process. The slight differences account for the bit error associated with the channel. The degree of resemblance also accounts for the contributions and improvement for the underwater acoustic communication system using OFDM. Figure 21 is the OFDM receiver antenna orientation with respect to the transmitter.

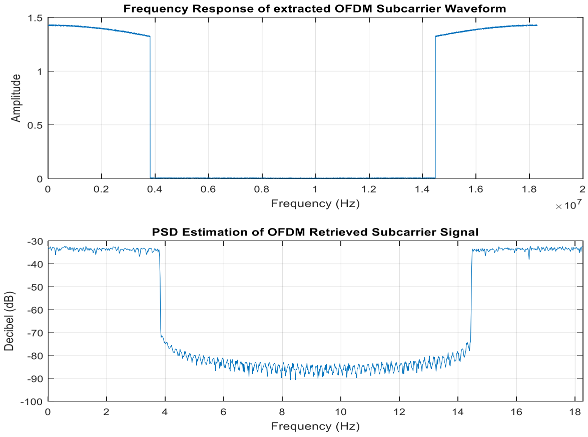

Figure 20: Frequency Response of OFDM Subcarrier Signal at Receiver

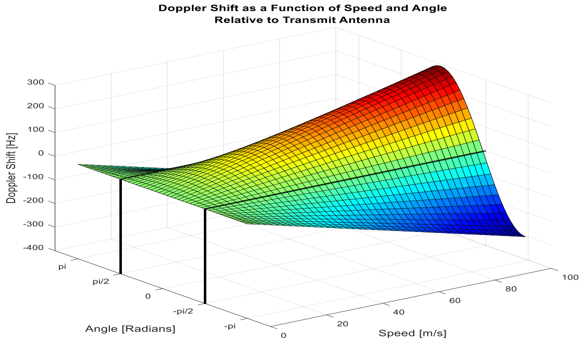

Figure 21: OFDM Receiver Antenna Orientation with Respect to Transmitter.

IV. CONCLUSION AND RECOMMENDATION

In this research, the underwater communication system was investigated and OFDM-QPSK modulation scheme was deployed as the preferred digital modulation because of its numerous advantages such as spectra efficiency, better bit-error-rate, and coding to reduce the BER. A model was developed, which was based on transmitter-channel-Receiver scheme, whereby the transmitter was made up of random signal generator after simulation. The analogue baseband signals were discretized and encoded before being modulated in the digital modulation scheme of the QPSK system. The IFFT converted the frequency domain output signal to time domain. This signal was transmitted via a noisy channel, which was modelled as Gaussian probability distribution function. The receiver blocks were modelled to demodulate the signal and retrieve the baseband signal with the blocks. Further, the process in the transmitter model was being repeated in reverse order. The results and the degree of similarities between the transmitter and the receiver accounted for the contributions and improvements of the underwater acoustic communication system using OFDM.

However, it is recommended that the channel noise be modelled as a non-Gaussian noise. Also, due to fast variation in underwater acoustic channel, there was an inter-subcarrier-interference as well as a loss of orthogonality among subcarriers in OFDM blocks, which accordingly caused distortion in the received signal. Carrier-frequency-offset (CFO) estimation and compensation techniques should be considered in the future work to bring the fast channel variation to a minimal level.

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