

Performance Enhancement Of Underwater Acoustic Communication Using Adaptive OFDM Techniques

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Abstract

Underwater Acoustic channels present unique challenges for communication due to their time-varying multipath characteristics, which result in severe signal degradation. Attain high data rates, low latency, and high throughput in such environments remains a complex task. In our work, we representing a robust Orthogonal Frequency Division Multiplexing (OFDM) transceiver system specifically tailored for UWA communication. The design aims to enhance data rate performance while operating within the limited bandwidth typically available in underwater channels. To achieve this, we implemented efficient adaptive modulation techniques, advanced channel estimation methods, and channel equalization schemes to address the adverse effects of UWA channel conditions. The proposed system adapts modulation schemes—such as Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM), and 64-QAM—based on the signal-to-noise ratio (SNR) of the Rayleigh fading channel. This adaptive modulation dynamically adjusts the system parameters to optimize data throughput under varying channel conditions. Our work also includes the use of the Kalman filter for channel estimation. The Kalman filter minimizes the mean squared error, providing an accurate channel estimation even in the presence of noise and severe fading. This precise channel estimation is critical for the subsequent equalization process, ensuring effective compensation for multipath effects and improving overall system performance. Simulation results validate the effectiveness of the proposed methods. The OFDM with adaptive modulation performs the system without adaptive modulation, demonstrating significant improvements in data rate and throughput. Furthermore, the integration of the Kalman filter enhances the reliability of channel estimation, which directly contributes to the superior performance of the receiver.

Keywords—UWA, OFDM, Adaptive modulation, Kalman filter, Rayleigh channel model, Channel equalization.

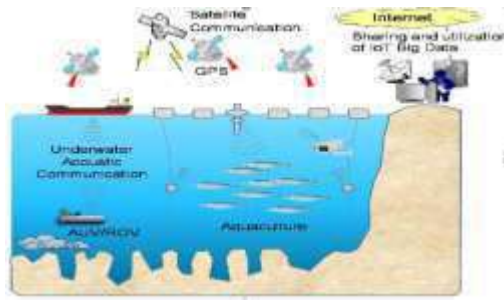
The increasing need for high data rate in digital

1. Introduction

In wireless communication, Underwater Acoustic channels are known as some of the most challenging communication media. Compare to the electromagnetic wave channel and optical wave channel the UWA channel is considered by large transmission loss and delay, multi-path effect and Doppler Effect. Such parameters highly affect the performance of UWA communication and limit the channel capacity. In such a communication channel attaining high data rate, a low latency and a high throughput which often is a very challenging task.

communications offer the Orthogonal Frequency-Division Multiplexing (OFDM) for achieving better performance in high-rate data transmission[1]. OFDM is also a multicarrier modulation technique and considered as a best technique to combat frequency-selective fading channels in wireless communication systems [2, 3].

OFDM is used in many applications like Digital Audio Broadcasting, Digital television(terrestrial).



2. Related Work

Orthogonal Frequency Division Multiplexing has recently gained prominence as a robust multicarrier modulation technique for underwater acoustic communication. This is due to its effectiveness in managing frequency-selective channels, a common challenge in underwater environments. Many studies have explored ways to optimize the performance of OFDM in these challenging conditions, characterized by issues such as multipath propagation, Doppler effects, and high ambient noise. One primary area of focus has been improving the efficiency of OFDM systems through adaptive modulation techniques. In these approaches, modulation schemes like Quadrature Amplitude Modulation (QAM) and Phase-Shift Keying (PSK) are dynamically adjusted based on the prevailing channel conditions, enabling a balance between data rate and error resilience.

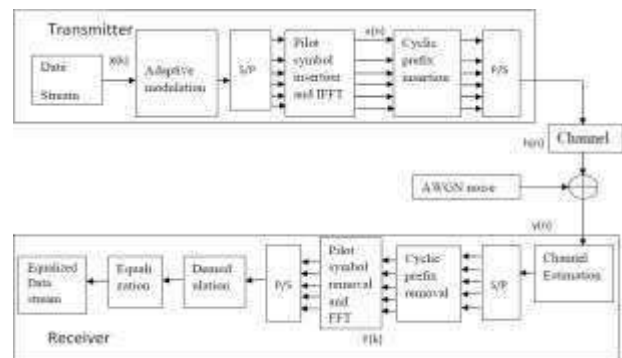
Channel estimation is another critical factor influencing the performance of underwater OFDM systems. Various methods have been thoroughly investigated, including pilot-assisted techniques, Least Squares (LS), and Minimum Mean Square Error (MMSE) methods. State-of-the-art advancements now include Doppler-resilient channel estimation techniques and machine learning-based models, which are likely to provide the most effective ways for addressing the channel's variability. Additionally, researchers have explored joint optimization frameworks that integrate adaptive modulation with advanced channel estimation methods. These frameworks demonstrate substantial improvements in key performance metrics, such as bit error rate, throughput, system reliability, and energy efficiency, making them highly suitable for underwater communication systems.

3. Materials and Methods

The design methodology for an (UWA) of OFDM system with adaptive modulation and channel

estimation involves several crucial steps. First, a comprehensive analysis of the underwater acoustic channel (UWA) is conducted to understand its unique characteristics, such as multipath propagation, Doppler effects, and temporal fluctuations. Based on this analysis, key OFDM system parameters, including subcarrier spacing, cyclic prefix length, and pilot allocation, are optimized to minimize inter-symbol interference (ISI) and inter-carrier interference (ICI). Adaptive modulation is achieved through an algorithm that dynamically evaluates the real-time quality of the channel. This algorithm assigns modulation schemes to subcarriers—such as transitioning from Quadrature Phase-Shift Keying (QPSK) to 16-Quadrature Amplitude Modulation (16-QAM)—to achieve the best balance between data rate and reliability.

Channel estimation, a critical component of the system, is performed using pilot-based techniques. To account for the time-varying nature of the underwater channel, advanced estimation methods like Least Squares (LS) and Minimum Mean Square Error are employed, ensuring robust and reliable communication in challenging underwater environments.



The frequency offset compensation algorithms, in turn, help in consistent performance of the system. In addition, the system is simulated on a MATLAB/Python platform for evaluation of metrics such as BER, spectral efficiency, and throughput under various channel conditions of underwater. The results that are generated from simulations are presented to prove the efficacy of the proposed system in mitigating the challenges in underwater communication. Performance metrics are benchmarked against representative channel models or an experimental setup. The OFDM system first exploits orthogonal subcarriers in order to efficiently

execute data transmission. Binary streams can be modulated; for example, QPSK, DPSK, and 16-QAM can be modulated depending on the channel signal-to-noise ratio for the respective channels. After insertion of pilot symbols, control and equalization are enabled, which is made efficient by the employment of FFT/IFFT for modulation and demodulation. The simulated results confirm to be robust and adaptable regarding an underwater environment.

$$X_0(k) = FFT[X_0(n)] = \sum_{n=0}^{N-1} x_0(n)e^{j2\pi kn} \quad (1)$$

$$x_0(n) = IFFT[X_0(k)] = \frac{1}{N} \sum_{k=0}^{N-1} X_0(k)e^{j2\pi kn} \quad (2)$$

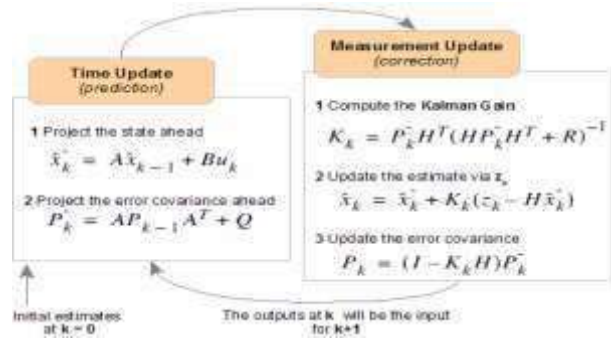
Cyclic prefix is the parameter that enables the OFDM signal to operate dependently and it is used to defend the OFDM signals from inter symbol interference. In this experiment we used acyclic prefix of length 16 to limit the OFDM signals from inter symbol interference [12]. The received signal can be given by,

$$y_k(n) = h_k(n) * x_k(n) + z(n)$$

Here, we used the Rayleigh fading channel as the medium for communication, which plays a critical role in underwater acoustic (UWA) communications. Several factors, including Doppler spread, noise, high path loss, multipath effects, and variable propagation delay, significantly impact the reliability and performance of UWA communication systems. These combined effects cause the UWA channel to exhibit temporal and spatial variability, limiting the available bandwidth and making it highly dependent on both range and frequency. Key parameters influencing UWA communication include transmission loss, acoustic noise, and attenuation. Transmission loss occurs due to two primary factors: attenuation and geometric spreading loss. Acoustic noise is mainly due to the shipping activities and machinery, while attenuation arises primarily from absorption, which converts the energy of the propagating acoustic wave into heat. The signal-to-noise ratio for the channel can be determined based on the energy per bit to noise power spectral density ratio (E_b/N_0). These factors collectively challenge the efficiency of UWA communication, requiring careful consideration in system design.

KALMAN FILTER BASED CHANNEL ESTIMATION

Channel estimation is a scheme, in which the channel



state information is retrieved by using the channel impulse response. Kalman filtering is an efficient technique to remove impurities in linear systems [8]. The Kalman filter is a recursive filter that is with the help of state space methods and recursive algorithms [12]. The Kalman filter algorithm includes two steps; a) Prediction b) Correction

This process is repeated for each state with value from previous state as initial value. Therefore, Kalman filter is called a recursive filter and it is represented in state-space model and the state-space model consists of two equations:

$$x_k = Ax_{k-1} + w_{k-1} \quad (4)$$

$$y_k = Cx_k + v_k \quad (5)$$

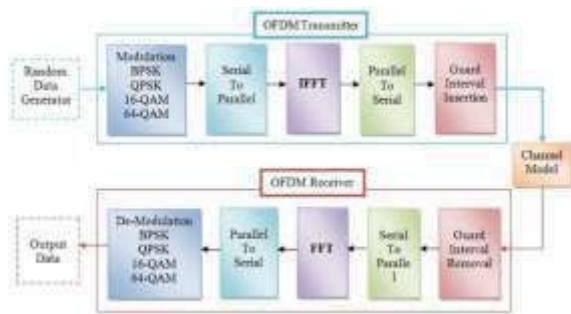
x_k is the N-dimensional state vector at $k=1,2,3,\dots,n$. Process noise „w“ is the N-dimensional uncorrelated input vector of state equation. y_k is the M-dimensional noisy observation vector and the measurement noise v_k is a zero mean white Gaussian noise. A is the state transition matrix which can be obtained using the Yule-Walker equations (AR process) and „C“ is the output matrix which are given by

$$A = \begin{bmatrix} -A_1 & -A_2 & \dots & -A_p \\ 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \end{bmatrix}$$

and $C = [I, 0, \dots, 0]$. Where I is the N x N identity matrix and $A_1, A_2, \dots, A(p)$ are the AR model coefficients. At the k-1th iteration, the state vector is considered as zero vectors and the state transition matrix is

calculated using the Yule Walker AR process. The Kalman filter is then applied to measure the unknown state of the system. Received signal $y_k(n)$ at each instant is given as input observation to Kalman filter algorithm[13].

SOFTWARE STIMULATION



Software Simulation of OFDM System Design Using Adaptive Modulation and Channel Estimation for Underwater Acoustic Communication. Our work involves the software simulation of an Orthogonal Frequency Division Multiplexing system with adaptive modulation and channel estimation tailored for UWA communication. Our work utilizes Google Colab as the development platform, taking advantage of its cloud-based capabilities and robust Python libraries such as NumPy, SciPy, and Matplotlib. These tools are employed to model and evaluate the performance of an underwater acoustic (UWA) communication system. The simulation is designed to address the unique challenges of UWA channels, including multipath propagation, time-varying characteristics, and Doppler effects. A key feature of the system is adaptive modulation, which dynamically adjusts the modulation scheme—such as QPSK or 16-QAM—for each subcarrier based on real-time channel conditions. This approach optimizes the trade-off between data rate and reliability. Additionally, channel estimation techniques like least squares (LS) and minimum mean square error (MMSE) estimators are implemented to counteract channel impairments and enhance system performance. The simulation evaluates crucial performance metrics, including bit error rate (BER), spectral efficiency, and resilience to channel variations. By leveraging Google Colab, the project benefits from a collaborative environment, access to high computational power, and seamless integration with Python-based tools. This setup provides a practical and efficient solution for studying and refining OFDM system designs in the challenging context of underwater acoustic communication.

No of subcarriers	512
Cyclic prefix length	16
Sampling period of channel	1e-3
Max Doppler frequency shift	0
Distance	15 m
No of OFDM symbols	1000
FFT size	256
Carrier frequency	8KHz
Receiver noise bandwidth	2KHz
2KHz No of pilot symbols	4
Modulation schemes	QPSK, DPSK, 16-QAM, 64-QAM

Algorithm Overview for OFDM System

The overall algorithm for OFDM system works as follows:

1. Determine the variables and matrices.
2. Generate the random input serial data stream.
3. Modulate the data using efficient modulation techniques.
4. Convert the serial data into parallel data then apply IFFT algorithm.
5. Insert the cyclic prefix symbols to avoid Inter symbol interference.
6. Convert the parallel data into serial data and pass through the Rayleigh fading channel with AWGN noise.
7. Convert the serial data into parallel data and remove the cyclic prefix symbols.
8. Channel estimation using Kalman filter.
9. Apply FFT algorithm and remove the pilot symbols.
10. Convert the parallel data into serial data and demodulate the data.
11. Equalize the modulated data using equalizer.
12. Calculate the SNR, BER and plot the results.
13. Based on the SNR the modulation techniques will be selected.

4. Results and Discussion

The simulation output of the BER performance of DPSK, QPSK, 16-QAM modulation techniques are shown in figure to figure respectively and the BER

performance of the OFDM system with adaptive modulation is shown in figure(6). The simulation of the comparison of the real states and the estimated states is shown in the figure and the results for signal tracking using Kalman filter in Rayleigh channel are shown in figure to figure respectively. It shows the BER performance without Adaptive modulation schemes for the E_b/N_0 ratio of 1-30 dB:

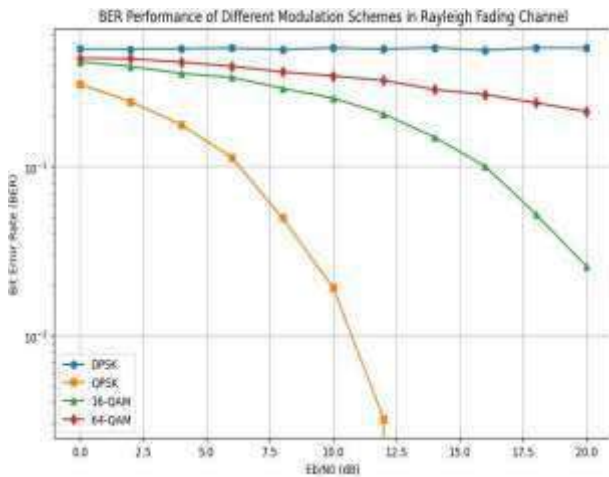


Figure: BER Performance in Rayleigh Channel for DPSK.

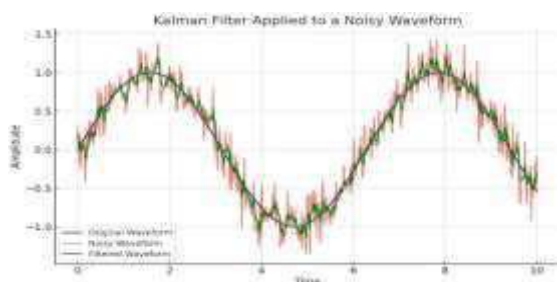


Figure : Kalman Filter Applied to noisy waveform

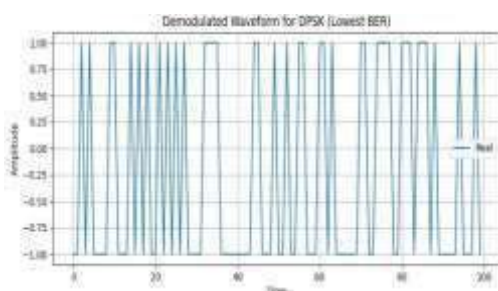


Figure: OFDM-System Design Using Adaptive Modulation and Demodulation(with BER for OFDM)

BER for OFDM: 0.475

5. Conclusion

Underwater Acoustic (UWA) Communication is some of the challenging and interesting area of research in

nowadays. Since UWA is highly limited in bandwidth achieving high data rate, low latency and high throughput is a very challenging task. To achieve these objectives, we have used many techniques that include efficient Adaptive modulation scheme, Channel estimation using Kalman filter and channel equalization schemes with OFDM multicarrier modulation technique. From the simulation results we found that some modulation schemes like DPSK, QPSK and 16-QAM are the best adaptive modulation schemes for underwater communication for highly limited bandwidth even in the presence of channel noise. The simulation output proves that the performance of the OFDM system with the use of Adaptive modulation is better when compared to the OFDM system without Adaptive modulation schemes. The Kalman filter is used for channel estimation and the signal tracking is achieved efficiently by using the Kalman filter. Thus by using the adaptive modulation schemes based on the SNR of the Rayleigh channel, channel estimation techniques like Kalman filter and channel equalization techniques like LMS, MMSE, we designed OFDM receiver which has high data rate for underwater communication. In future we can design the MIMO design which will have high data rate in the receiver by using other ways such as use of channel coding techniques and adaptive channel estimation schemes, etc. We can design the receiver and verify the performance using numerical simulation and Mathematical model.

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