

A Novel Beam-Domain OFDM Framework For Robust Underwater Acoustic Communication With Realistic Noise And Multipath Modelling

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Abstract

Underwater acoustic communication is hindered by multipath propagation, ambient noise, and bandwidth constraints. This study introduces a novel beam-domain OFDM framework that enhances communication reliability in realistic underwater environments. The proposed model integrates beam space transformation with OFDM modulation to achieve improved spatial selectivity and interference mitigation. Realistic channel and noise modeling, including multipath delay spread and colored oceanic noise, are incorporated to emulate practical conditions. Key performance indicators such as BER, throughput, energy efficiency, and outage probability are analyzed. Simulation results reveal that beam-domain processing provides superior robustness and efficiency compared to conventional OFDM systems, making this framework a strong candidate for next-generation underwater acoustic communication design. Unlike conventional OFDM systems, the proposed design incorporates beam-space processing and realistic channel-noise modeling to enhance robustness, spatial selectivity, and energy efficiency under complex oceanic conditions.

Keywords: UWA, OFDM, BER

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I. Introduction

Underwater acoustic communication is essential for applications such as ocean monitoring and autonomous underwater operations, yet it faces significant challenges due to severe multipath propagation, Doppler effects, and frequency-dependent ambient noise. Although orthogonal frequency division multiplexing is widely used for its ability to handle frequency-selective channels efficiently, its performance degrades in harsh underwater environments with strong interference and limited bandwidth. However, many existing studies rely on simplified assumptions and do not fully consider realistic channel behavior or comprehensive performance evaluation. To overcome these limitations, a beam-domain OFDM framework is developed that incorporates practical channel characteristics, including delay spread, coherence bandwidth, and colored noise based on established underwater noise models and this approach provides a more realistic and flexible platform for analyzing and improving underwater communication systems.

II. Literature Study

Underwater acoustic OFDM systems are hindered by multipath, Doppler spread, and impulsive noise, leading to the adoption of advanced techniques for performance improvement. Beamforming methods enhance spatial signal quality [1], while message passing strategies improve resilience to impulsive noise through joint estimation [2]. Deep learning approaches have shown effectiveness in receiver design and channel estimation under complex conditions [3] and sparse Bayesian learning techniques further refine estimation by exploiting channel sparsity with improved efficiency [4], [5], [8]. Hybrid learning methods enhance adaptability across varying environments [6]. Additionally, improved waveform designs such as Z-OFDM increase robustness to Doppler effects [7], and efficient Doppler compensation techniques help reduce computational complexity. These developments collectively advance system reliability.

III. Proposed Framework

The proposed framework considers a beam-domain orthogonal frequency division multiplexing (OFDM) system designed for underwater acoustic communication (UAC) employing a uniform linear array (ULA) of hydrophones at the receiver. The model captures the essential aspects of acoustic propagation, including multipath effects, ambient noise shaping, and spatial beamforming, to emulate realistic oceanic conditions.

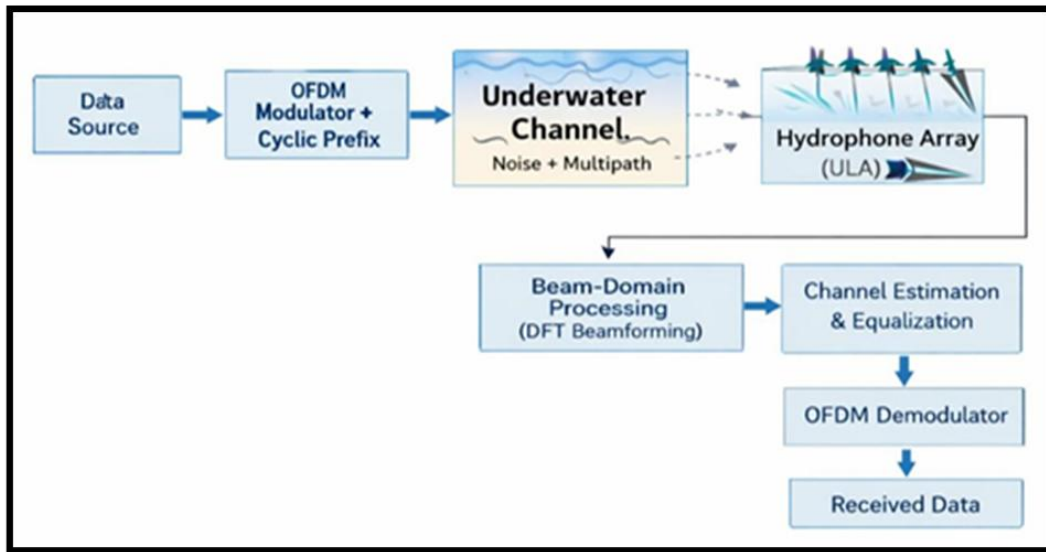


Figure 1: Block Diagram of Beam Domain UWA Model

Algorithm/ Pseudo Code

Step 1: Generate Modulated Symbols

Map input bits to 16-QAM symbols: $X(k), k=0,1,\dots,N_{FFT}-1$

Step 2: Pilot Insertion

Reserve one OFDM symbol for pilot transmission; remaining symbols carry data.

Step 3: OFDM Modulation (IFFT)

Convert frequency-domain symbols to time domain: $x(n)=IFFT\{X(k)\}$

Step 4: Cyclic Prefix Addition

Append CP of length N_{CP} : $x_{cp}(n)=[x(N-N_{CP}),\dots,x(N-1),x(0),\dots,x(N-1)]$

Step 5: Transmit Beamforming

Apply steering vector $a_t(\theta)$ to direct signal: $x_t(n)=a_t(\theta)x_{cp}(n)$

Step 6: Multipath Channel Representation: $H(f) = \sum_{l=1}^L \alpha_l e^{-j2\pi f \tau_l}$.

Step 7: Compute power delay profile (PDP), RMS delay spread and coherence bandwidth.

Step 8: Mathematical Noise Model (Urick):

The total noise power spectral density (PSD) : $N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$

Step 9: Doppler Compensation Model: $f_d = \frac{v}{c} f_c$

Step 10: Received Signal with Doppler: $y(n) = \sum_{i=1}^L a_i x(n - \tau_i) \cdot e^{j2\pi f_d n} + w(n)$

Step 11: Doppler Compensation: $y_{comp}(n) = y(n) \cdot e^{-j2\pi f_d n}$

Step 12: Signal after Compensation: $y_{comp}(n) = \sum_{i=1}^L a_i x(n - \tau_i) + w(n)$

Step 13 FFT at Receiver: $Y(k) = FFT\{y_{comp}(n)\}$

Step 14: Compute Performance Metrics

IV. Results & Discussions

To comprehensively assess the effectiveness of the proposed beam-domain OFDM framework, multiple performance indicators are evaluated under varying signal-to-noise ratio (SNR) conditions. These metrics capture the system’s reliability, efficiency, and robustness under realistic underwater channel and noise scenarios.

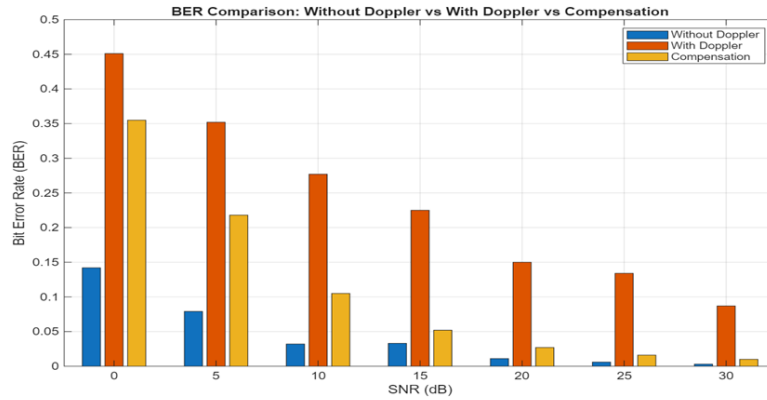


Figure 1: Simulation Results for SNR vs BER

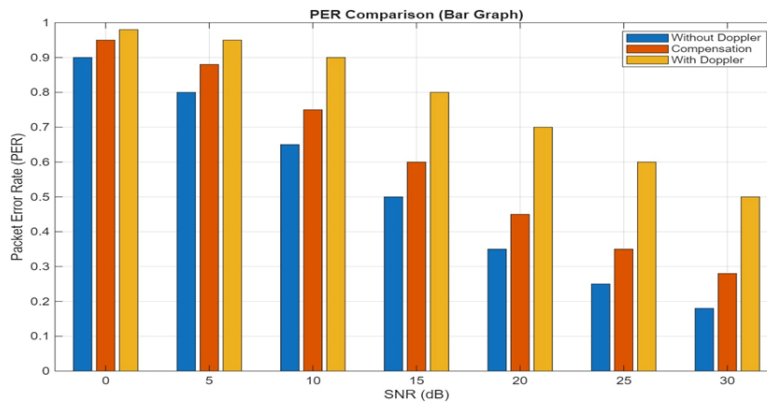


Figure 2: Simulation Results for SNR vs PER

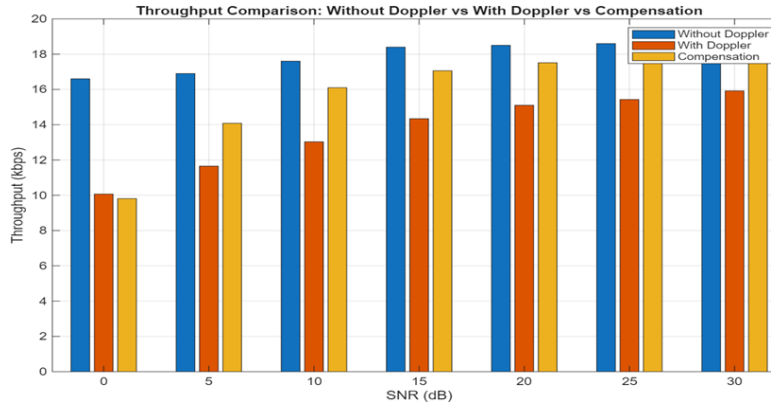


Figure 3: Simulation Results for SNR vs Throughput

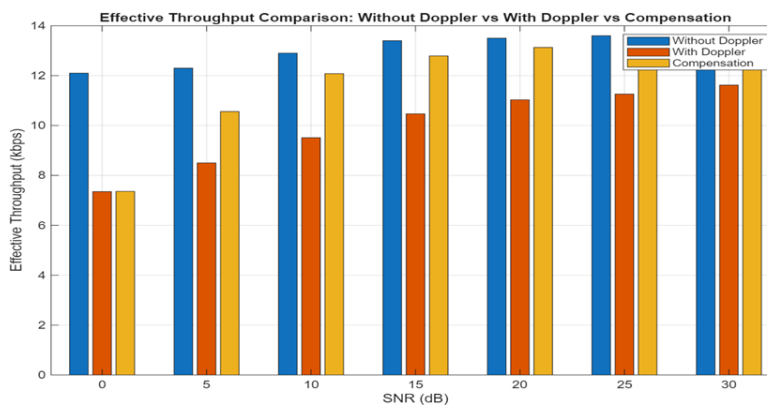


Figure 4: Simulation Results for SNR vs Effective Throughput

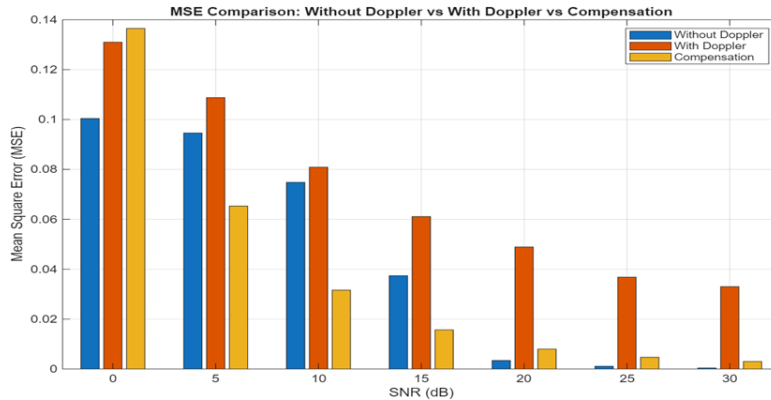


Figure 5: Simulation Results for SNR vs Channel Estimation Error (MSE)

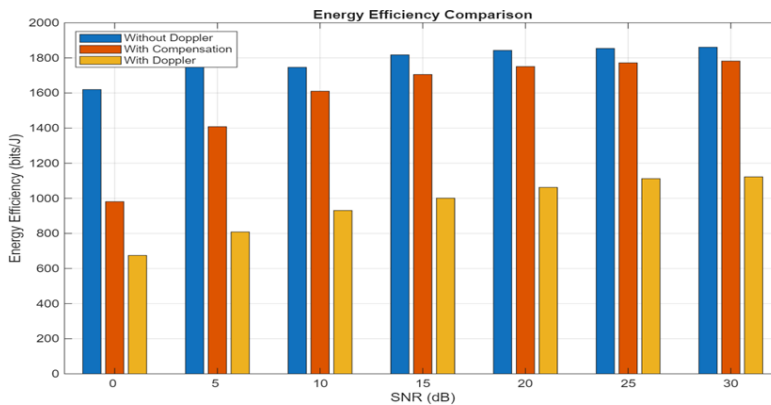


Figure 6: Simulation Results for SNR vs Energy Efficiency

V. Conclusion & Future Work

This paper presents a beam-domain framework based on Orthogonal Frequency Division Multiplexing (OFDM) to improve underwater acoustic communication systems, which usually face challenges such as multipath propagation, noise, and Doppler effects due to movement. The proposed approach evaluates system performance under three conditions—without Doppler, with Doppler, and with Doppler compensation—using MATLAB simulations. Various metrics like Bit Error Rate (BER), Packet Error Rate (PER), throughput, effective throughput, array gain, energy efficiency, Shannon capacity, mean subcarrier SNR, outage probability, and channel estimation MSE are used for analysis. The results indicate that Doppler effects significantly degrade communication performance by increasing errors, while applying Doppler compensation improves reliability, reduces errors, and enhances overall system efficiency. Future work can also focus on implementing this system in real-time underwater communication platforms and testing it in actual ocean conditions. The framework can be extended to support underwater sensor networks and autonomous underwater vehicles for applications such as ocean monitoring, marine exploration, and environmental data collection.

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