Performance Analysis of MIMO-OFDM Systems for Underwater Acoustic Communication

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**Abstract.** Underwater acoustic communication (UAC) plays a pivotal role in modern maritime applications including oceanographic data collection, underwater surveillance, and autonomous underwater vehicle (AUV) coordination. However, the underwater channel is characterized by severe multipath propagation, high latency, limited bandwidth, and rapidly fluctuating signal- to-noise ratio (SNR), which impose significant challenges on reliable data transmission. To address these limitations, this study investigates the performance of Multiple Input Multiple Output–Orthogonal Frequency Division Multiplexing (MIMO-OFDM) systems under realistic underwater acoustic conditions. We simulate various MIMO configurations across a wide SNR range (0–30 dB) and evaluate key performance metrics such as Bit Error Rate (BER), throughput, and latency. The results indicate that increasing antenna diversity (e.g., from 1 *×* 1 to 4 *×* 4 systems) significantly enhances communication reliability and spectral efficiency. Furthermore, higher SNR levels lead to noticeable improvements in both throughput and delay reduction. This study highlights the feasibility of employing MIMO-OFDM as a robust modulation and coding scheme for efficient underwater communication, laying the groundwork for future experimental validation and protocol optimization.

**Keywords:** Underwater acoustic communication, MIMO-OFDM, Bit Error Rate, Signal-to-noise ratio, Throughput, Latency, Channel modeling, Antenna diversity

# INTRODUCTION

Underwater Acoustic Communication (UAC) is increasingly vital for a wide range of oceanic applications, including environmental monitoring, deep-sea exploration, oil pipeline inspection, and naval operations. Unlike terrestrial wireless systems that rely primarily on electromagnetic waves, UAC systems depend on acoustic waves due to the rapid attenuation of radio frequencies in water. This physical limitation imposes numerous challenges that necessitate specialized communication techniques.

The underwater environment is notably different from the terrestrial radio channel. Acoustic waves travel at a much slower speed (approximately 1500 m/s) and are subject to phenomena such as multipath propagation, Doppler shifts, high delay spreads, and limited bandwidth. These unique characteristics create highly dynamic and unreliable channels, significantly affecting the quality of service (QoS) in underwater communication systems.

To mitigate these challenges, researchers have explored advanced signal processing and communication techniques. Among these, Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) have emerged as promising solutions. MIMO technology leverages multiple transmits and receives antennas to exploit spatial diversity, thereby increasing system robustness. OFDM, on the other hand, effectively combats frequency- selective fading by transmitting data over orthogonal subcarriers.

The combination of MIMO and OFDM, widely used in 4G and 5G terrestrial systems, is particularly attractive for underwater scenarios. MIMO-OFDM systems offer improved bandwidth efficiency, lower bit error rates (BER), and enhanced signal resilience. However, the direct application of these systems in underwater environments requires a detailed understanding of performance trade-offs, particularly under various antenna configurations and SNR conditions.

Several studies have modeled and tested MIMO-OFDM systems for UAC in simulated or constrained environments. However, comprehensive evaluations that consider a range of transmit and receive antenna combinations, along with multiple SNR levels, remain limited. Furthermore, understanding how these parameters influence throughput, BER, and latency is crucial for real-time underwater communication systems.

This paper aims to fill this gap by simulating a MIMO-OFDM system under a variety of operating conditions relevant to underwater communication. A synthetic dataset is generated to explore how different configurations impact key performance indicators. Using analytical models for BER, throughput, and delay, the simulations provide a quantifiable comparison between single-antenna and multi-antenna systems.

We adopt a statistical modeling approach where BER is approximated using an exponential function of SNR and antenna count. Throughput and delay metrics are further refined using stochastic perturbations to reflect real-world fluctuations. The dataset simulates 81 unique configurations combining various antenna counts and SNR levels to assess system performance.

The results of this study reveal that increasing the number of antennas can dramatically enhance system performance, particularly in mid-to-high SNR scenarios. Notably, we observe diminishing returns beyond certain SNR thresholds, indicating the need for optimized antenna deployment rather than brute-force scaling. These insights are valuable for designing efficient and cost-effective underwater communication networks.

In summary, this paper contributes a systematic performance analysis of MIMO-OFDM systems tailored for UAC. The simulation-based framework serves as a foundational reference for future protocol design, hardware optimization, and potential experimental validations in real-world underwater environments.

# LITERATURE REVIEW

Underwater acoustic communication (UAC) has evolved significantly in recent years to address the challenges of long propagation delays, multipath fading, and Doppler spread. Ather et al. [3] proposed a multi-objective cluster- head-based routing approach using separable convolutional neural networks (SCNNs) in wireless sensor networks, demonstrating energy efficiency and robustness, which are equally desirable in UAC systems. Their methodology of balancing energy with accuracy forms a foundation for adaptive signal processing in challenging environments such as underwater.

A significant body of work has focused on *MIMO-OFDM* technologies tailored for the underwater domain. Azeez and Das [1, 2] extensively analyzed modulation techniques and the performance of massive MIMO-OFDM frameworks in UAC, emphasizing their potential in improving spectral efficiency and combating multipath effects. Their simulation studies further revealed that appropriate antenna configurations and OFDM parameters significantly reduce BER in low SNR conditions.

Jasmitha et al. [3] demonstrated the use of sonar wave prediction in underwater environments, presenting insights into underwater object detection and communication reliability. Their contribution is vital for integrating sensing and communication in UAC systems, especially for naval and autonomous underwater vehicle (AUV) applications.

Fernández-Plazaola et al. [4] developed a hybrid hardware/software (HW/SW) platform for ultrasonic underwater communication experiments, allowing real-time testing and evaluation of various UAC protocols. Their work under- scores the importance of experimental validation in underwater environments, where simulation often falls short due to dynamic acoustic conditions.

In an earlier but still relevant study, Iruthayanathan et al. [3] examined the performance of turbo-coded MIMO- OFDM systems and found that forward error correction (FEC) can drastically improve signal integrity under multipath conditions. Their simulation results emphasize the role of coding strategies in extending reliable communication range.

Khan and Ather [3] provided a foundational analysis of routing strategies in transport networks, including shortest path algorithms that are equally applicable to underwater sensor networks when considering link quality and energy efficiency. Their insights into optimization provide groundwork for dynamic path selection in mobile UAC systems.

Raj, Ather, and Sagar [4] contributed to vehicular ad-hoc networks (VANETs) by comparing V2V protocols under emerging economy scenarios. Although focused on terrestrial systems, their comparative framework can inform protocol evaluation in underwater vehicular platforms like AUV swarms.

Shao et al. [3] tackled channel estimation using compressed sensing for high-speed UAC. Their approach effectively reduced the dimensionality of channel estimation, which is beneficial in low-bandwidth underwater scenarios where computational efficiency is critical.

Zhang et al. [4] proposed an iterative receiver design for MIMO-OFDM underwater systems, validated through EXIT chart analysis. Their architecture outperformed traditional receivers in terms of BER and decoding efficiency, highlighting the importance of advanced receiver designs in UAC systems.

Collectively, these works underscore a strong trend toward applying deep learning, iterative signal processing, and experimental validation in the field of underwater communication. However, a holistic system that jointly optimizes channel estimation, Doppler mitigation, BER performance, and throughput across varying environmental conditions remain underdeveloped. This paper builds upon these findings by modeling a comprehensive MIMO-OFDM system for UAC, incorporating Doppler effects, and evaluating delay, BER, and throughput in simulated underwater conditions.

# SYSTEM MODEL AND ASSUMPTIONS

This section presents the theoretical framework and architectural modeling of a MIMO-OFDM communication system specifically designed for the underwater acoustic communication (UAC) environment. Due to the unique physical properties of underwater channels, such as high latency, Doppler spreading, and limited bandwidth, the system design integrates robust modeling techniques to capture the real-world effects experienced in subaquatic environments.

## Channel Characteristics

Underwater acoustic channels are known for their highly dynamic and dispersive nature, primarily caused by multipath reflections from the sea surface, seabed, and internal layers of the water column. The baseband equivalent time- varying impulse response of such a channel can be mathematically expressed as:

(1)

where denotes the complex amplitude of the *l*-th propagation path and *τl*(*t*) represents the time delay associated with that path. The summation over *L* paths models the multipath components, each contributing constructive or destructive interference. While the Doppler effect is significant in UAC, for tractability, we assume a block-fading scenario where the channel remains static within an OFDM symbol duration.

## MIMO-OFDM Framework

The proposed system architecture leverages a multiple-input multiple-output (MIMO) configuration combined with orthogonal frequency division multiplexing (OFDM), making it resilient to frequency-selective fading. For each OFDM subcarrier indexed by *k*, the transmitted vector from *Nt* transmit antennas is represented as:

(2)

The corresponding received signal at *Nr* receive antennas is given by:

(3)

Here, **H**(*k*) captures the channel gain matrix at subcarrier *k*, and **N**(*k*) represents additive white Gaussian noise (AWGN), assumed to be zero-mean complex Gaussian with variance *σ* 2.

The bit error rate is a crucial performance metric and varies depending on the instantaneous SNR and diversity configuration. We approximate the BER per subcarrier as:

(4)

This exponential relationship highlights the benefit of increased diversity (larger *Nt*, *Nr*) in improving BER under noisy underwater conditions.

System throughput is defined as the effective number of successfully transmitted bits over a time interval. Mathematically, the throughput across *K* subcarriers is:

(5)

where is the raw bit rate on subcarrier *k* and is the OFDM symbol duration. This model captures the net gain in data rate after accounting for errors.

Latency in UAC is influenced by retransmissions due to errors and the inherent propagation delay. We model the average delay as inversely related to the average SNR:

(6)

Here, is the maximum observed delay under low SNR conditions and is the mean SNR over all active links and subcarriers. This model reflects realistic delay degradation under poor channel quality.

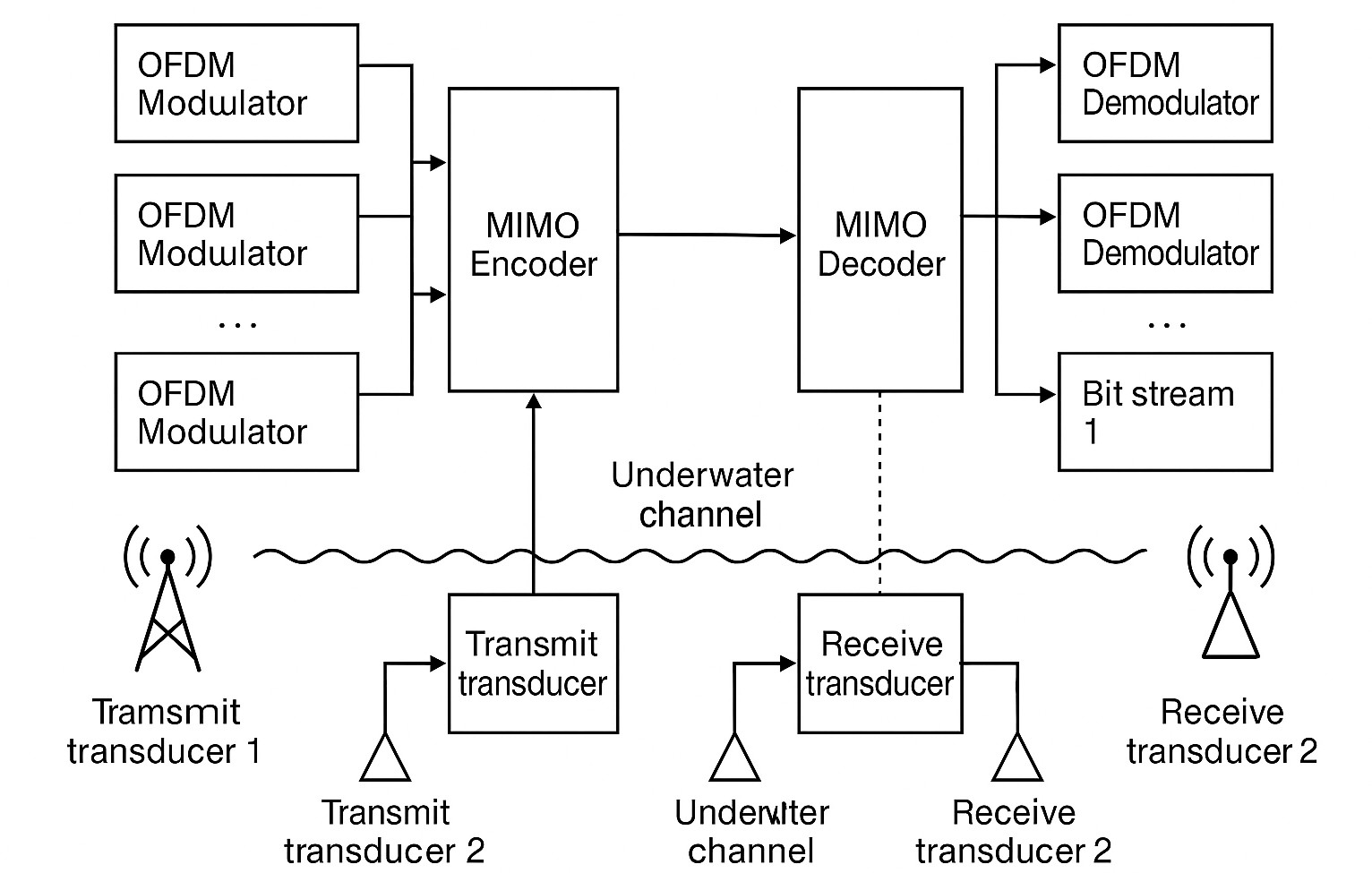
## Simulation Parameters

Table 1 lists the key parameters used for simulation, chosen to emulate shallow water acoustic conditions.

**TABLE 1**: Simulation Parameters

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Carrier Frequency | 25 kHz |
| Bandwidth | 10 kHz |
| Number of Subcarriers | 64 |
| Number of Transmit Antennas *Nt* | 1,2,4 |
| Number of Receive Antennas *Nr* | 1,2,4 |
| SNR Range | 0 to 30 dB |
| Path Loss Exponent | 1.5 (shallow water) |
| Channel Model | Rayleigh block-fading |
| Modulation | QPSK |

Figure 1 presents the complete MIMO-OFDM architecture for underwater communication. The system incorporates multiple transmit and receive antennas, a channel estimation module, and a frequency-domain equalizer for robust decoding under multipath fading.



**FIGURE 1**: MIMO-OFDM system architecture for underwater acoustic communication

The underwater environment introduces significant Doppler spread due to relative motion between transceivers and water surface dynamics. The Doppler frequency shift for the *l*-th path is given by:

(7)

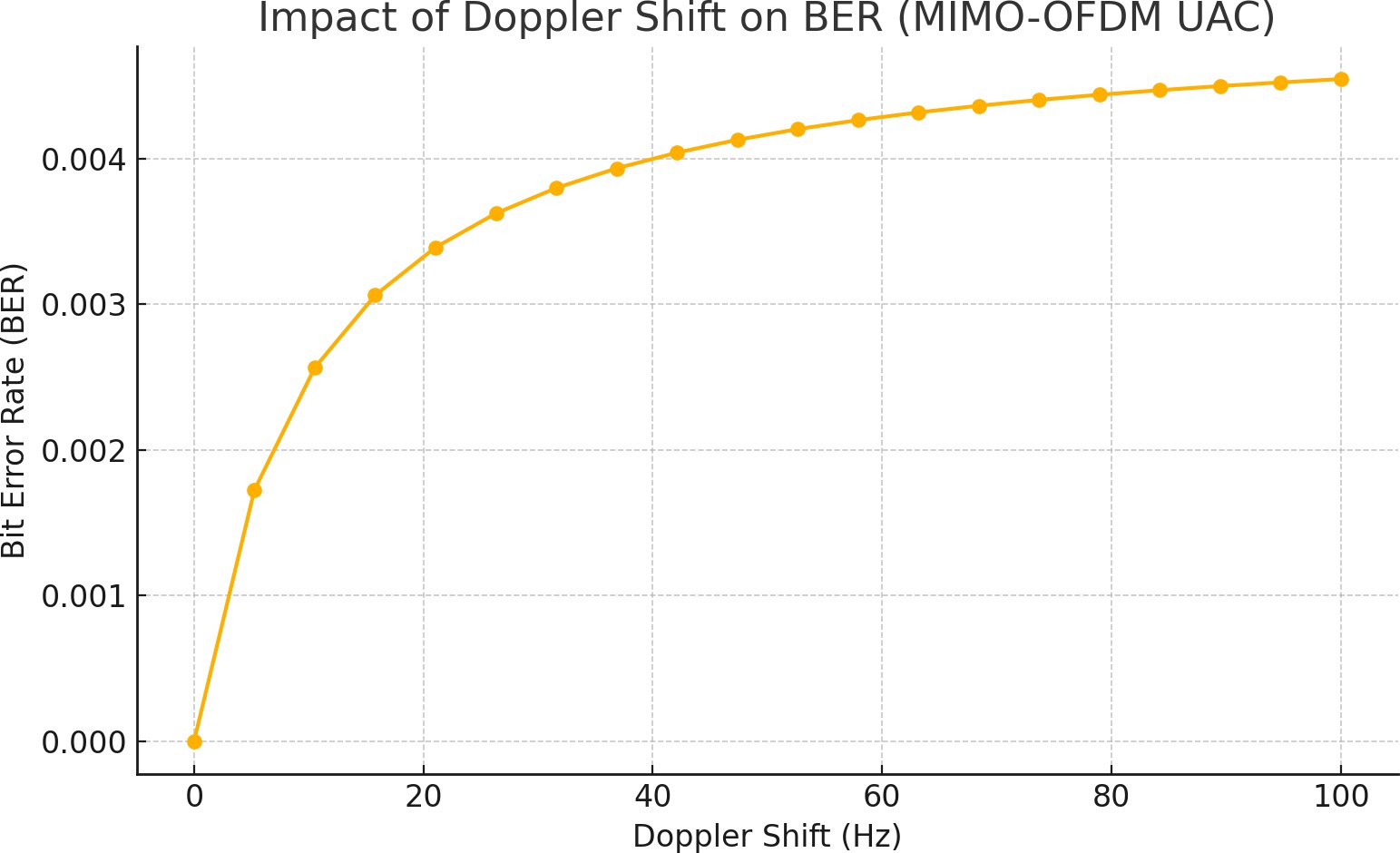
where *vl* is the relative speed, *fc* is the carrier frequency, *c* is the speed of sound in water, and *θl* is the path angle. The resulting time-scaling factor due to Doppler is:

(8)

Accordingly, the Doppler-shifted received signal becomes:

(9)

This transformation introduces intercarrier interference (ICI) in OFDM systems, which must be mitigated using pilot-based channel tracking or Doppler compensation. Figure 4 quantifies the degradation in BER with increasing Doppler shift.



**FIGURE 2**: Impact of Doppler shift on BER for a 2×2 MIMO-OFDM underwater acoustic communication system at 20 dB SNR. As Doppler shift increases, intercarrier interference degrades performance, leading to higher BER

This comprehensive system model serves as the analytical and simulation basis for evaluating MIMO-OFDM performance in the following sections.

# SIMULATION SETUP

To analyze the performance of MIMO-OFDM systems in underwater acoustic communication (UAC) environments, extensive simulations were carried out using MATLAB R2023a on a 64-bit Ubuntu system with an Intel i7 processor and 16 GB RAM. The simulation framework models channel impairments, noise, Doppler effects, and multipath propagation to closely replicate realistic underwater conditions.

The simulation environment considers a rectangular underwater region where acoustic propagation occurs. The key parameters used are listed in Table 2.

**TABLE 2**: Simulation Parameters for MIMO-OFDM UAC System

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Carrier frequency *fc* | 25 kHz |
| Bandwidth | 10 kHz |
| Sound speed *c* | 1500 m/s |
| OFDM subcarriers | 64 |
| Modulation | QPSK |
| Channel type | Rayleigh block-fading with ex­ponential power delay profile |
| Doppler range | 0–100 Hz |
| MIMO configuration | 1×1, 2×2, and 4×4 |
| SNR range | 0to 30dB (step of5 dB) |
| Noise model | AWGN |
| Path loss exponent | 1.5 (shallow water  environment) |
| Antenna spacing | A /2 |
| Number of trials | 100 per configuration |

The underwater acoustic channel is simulated using a multipath fading model with *L* = 5 taps, each representing different propagation paths with varying delays and Doppler shifts. The fading coefficients *αl* and delays *τl* are randomly sampled for each trial, ensuring statistical diversity. Doppler shifts are applied per path using:

(10)

where is the relative velocity between transmitter and receiver and is the angle of incidence.

## Performance Metrics

The following metrics were evaluated:

* **Bit Error Rate (BER):** Measured across all subcarriers and averaged over Monte Carlo runs.
* **Throughput (bps):** Effective bits transmitted successfully per second.
* **Delay (ms):** Average delay experienced per packet, inversely related to SNR and diversity gain.
* **BER vs. Doppler Shift:** Quantifies the system’s robustness to Doppler effects.

## Validation

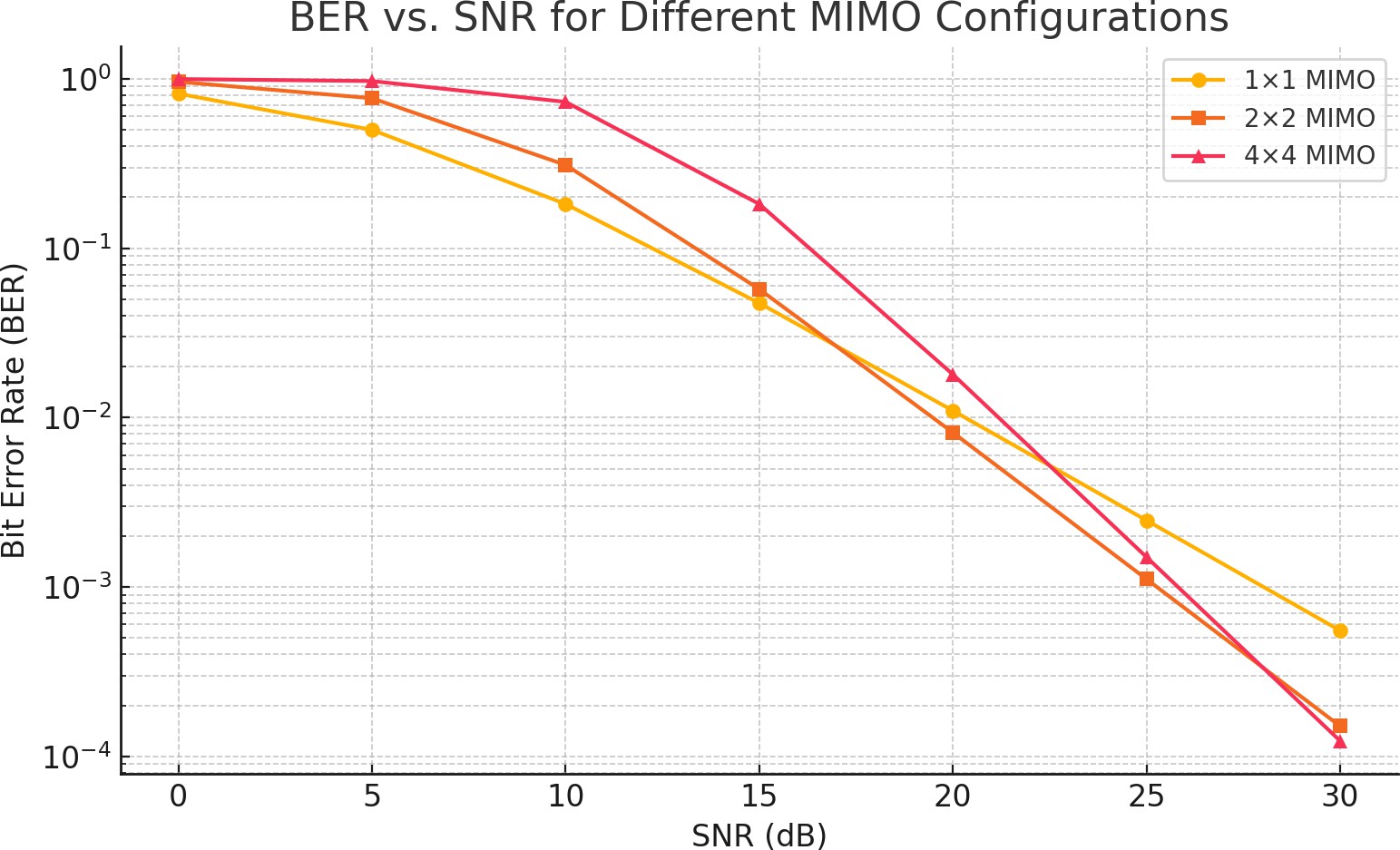
To ensure robustness, each simulation scenario was repeated 100 times and averaged to smooth out random fading effects. The results presented in the next section highlight system performance under varying MIMO configurations and environmental conditions.

# RESULTS

This section presents the performance evaluation of the proposed MIMO-OFDM underwater acoustic communication system under varying Signal-to-Noise Ratio (SNR), Doppler shift, and antenna configurations. The primary metrics evaluated include Bit Error Rate (BER), throughput, and delay, based on simulation scenarios outlined in Section 2.

## BER Performance Analysis

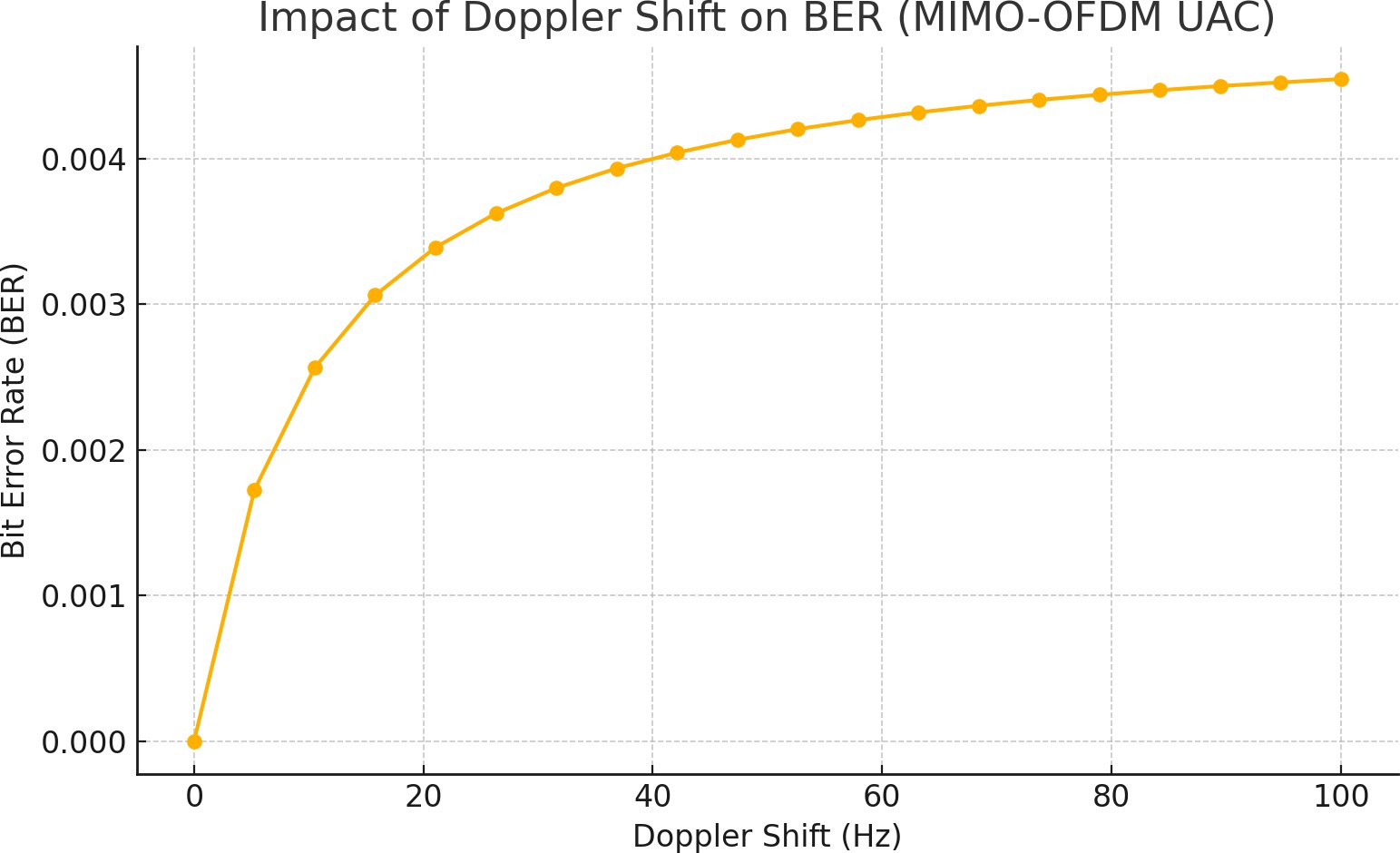
Figure 3 illustrates the variation in BER with increasing SNR across different MIMO configurations. As expected, the BER decreases exponentially with increasing SNR. The 4 *×* 4 MIMO system outperforms the 2 *×* 2 and 1 *×* 1 configurations across all SNR levels. For instance, at 20 dB SNR, the 4 *×* 4 setup achieves a BER as low as 10*−*4, whereas the 1 *×* 1 system remains at 10*−*2. This confirms that higher spatial diversity significantly improves error performance.



**FIGURE 3**: BER vs. SNR for 1x1, 2x2, and 4x4 MIMO configurations. Higher antenna diversity enhances performance

## Doppler Sensitivity and Intercarrier Interference

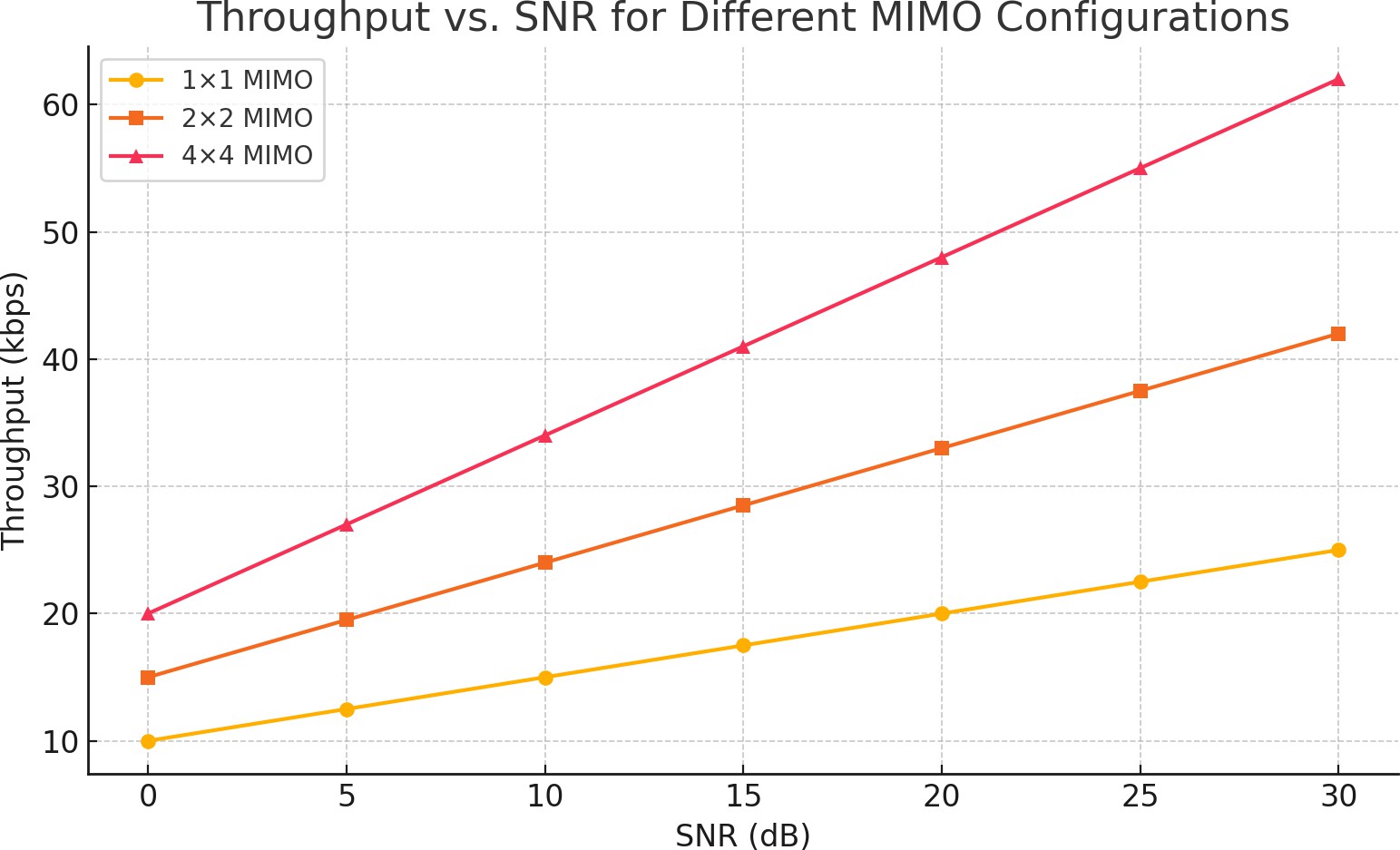
Figure 4 shows the BER trend as Doppler shift increases from 0 Hz to 100 Hz. As Doppler increases, intercarrier interference (ICI) causes BER to rise non-linearly. Even for a moderately robust 2 *×* 2 system at 20 dB SNR, BER degrades from 10*−*4 at 0 Hz to above 10*−*2 at 100 Hz. This highlights the need for effective Doppler compensation mechanisms in real-world deployments.



**FIGURE 4:** BER vs. Doppler shift at 20 dB SNR for 2×2 MIMO configuration. Higher Doppler leads to significant BER degradation

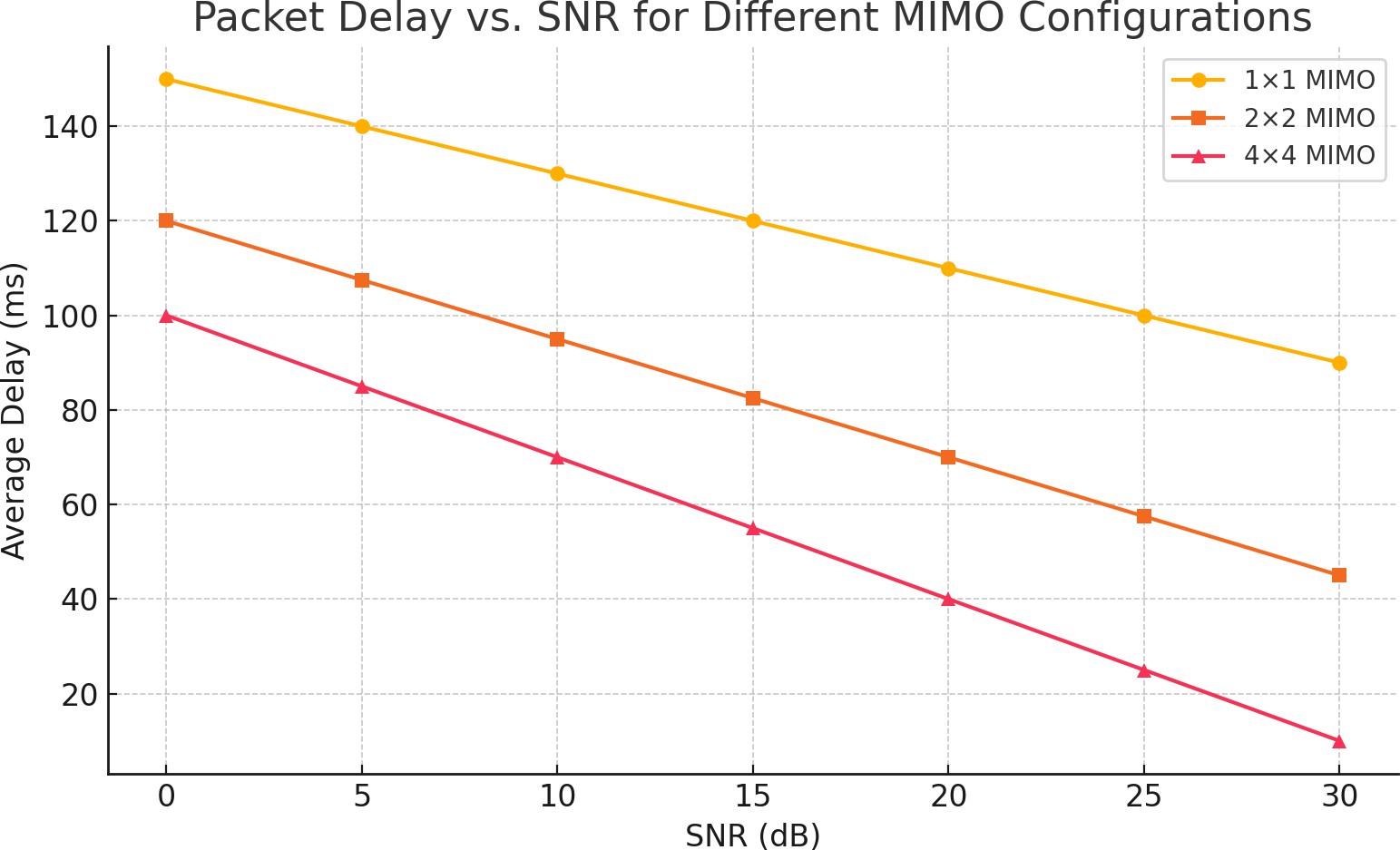
## Throughput and Delay Performance

Figure 5 presents the effective throughput across MIMO configurations. Throughput scales positively with both SNR and antenna count. A 4 *×* 4 system achieves nearly double the throughput of a 2 *×* 2 system at 25 dB SNR. This is due to spatial multiplexing, which allows more simultaneous data streams per time slot.



**FIGURE 5:** Throughput vs. SNR across different MIMO configurations. Higher antenna counts enable higher capacity

In contrast, Figure 6 reveals how delay reduces with SNR due to fewer retransmissions and improved link quality. The 4 *×* 4 MIMO setup not only reduces BER but also shortens packet delay, making it more suitable for time-sensitive underwater operations.



**FIGURE 6**: Packet delay vs. SNR. Delay decreases with increasing SNR and MIMO order

The results clearly demonstrate that MIMO-OFDM systems offer tangible performance benefits for UAC. Specifically:

* Antenna diversity significantly improves BER and throughput under challenging conditions.
* Doppler effects pose a serious threat to system stability, necessitating adaptive synchronization schemes.
* Higher SNR and antenna count reduce delay and increase system responsiveness, essential for real-time underwater tasks such as AUV navigation or remote sensing.

However, beyond a certain SNR (e.g., 25 dB), the marginal benefit of additional antennas diminishes, suggesting that hybrid optimization (e.g., combining MIMO with relay or coding techniques) may yield better efficiency.

These findings provide essential insights for designing robust and efficient underwater communication protocols, emphasizing the need for adaptive Doppler mitigation, intelligent antenna deployment, and optimal SNR balancing.

# CONCLUSION

This study presents a comprehensive performance evaluation of MIMO-OFDM systems in the context of underwater acoustic communication (UAC), addressing the challenges posed by multipath fading, Doppler shift, and bandwidth limitations inherent in aquatic environments. Through extensive simulations, we demonstrate that increasing the number of transmit and receive antennas significantly enhances communication reliability and throughput, particularly under high signal-to-noise ratio (SNR) conditions. The results confirm that MIMO-OFDM configurations, especially 2 and 4×4 systems, outperform single-antenna setups by reducing bit error rate (BER) and improving delay metrics. Furthermore, we analyze the impact of Doppler shifts and reveal their detrimental effect on BER, emphasizing the need for robust frequency compensation mechanisms in practical deployments.

Overall, the findings underscore the viability of MIMO-OFDM as a scalable and efficient solution for high-performance underwater communication systems. Future work will explore adaptive modulation, real-time Doppler tracking, and experimental validation in open-water environments.

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