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High-Capacity Underwater Optical Transmission Using Oam-Pam4 Across Varying Coastal And Harbor Waters

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Abstract: This study proposes a novel underwater optical wireless communication (UOWC) system employing orbital angular momentum (OAM) multiplexing with pulse amplitude modulation (PAM4) for high-speed data transmission. The system consists of four distinct Laguerre-Gaussian (LG) modes ($LG_{0,0}$, $LG_{0,15}$, $LG_{0,35}$, $LG_{0,70}$), each carrying 20 Gb/s data streams using a green laser operating at 532 nm. To evaluate the robustness and adaptability of the system in diverse marine environments, simulations were conducted across five different water types: Pure Sea (PS), Clear Ocean (CO), Coastal Sea (CS), Harbor I (HI), and Harbor II (HII). Simulation results demonstrate that the system achieves reliable data transmission over distances up to 10.8 meters in the clearest waters, with performance gracefully degrading to shorter ranges of around 2.8 meters in highly turbid harbor conditions, confirming its adaptability to varied underwater environments. This work emphasizes the scalability and spectral efficiency of OAM-PAM4 systems and highlights their potential in applications such as deep-sea exploration, marine sensor networks, and real-time surveillance.

Keywords **-** UOWC, OAM, PAM-4, LG Beams, Marine Environments, PS, CO, CS, HI, HII

I. INTRODUCTION

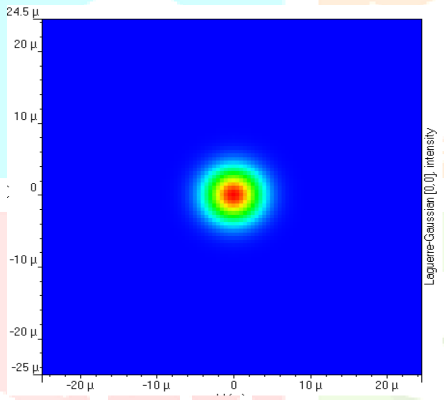
Underwater Optical Wireless Communication (UOWC) is rapidly gaining attention as a promising technology for high-speed data transmission in aquatic environments, offering substantial advantages over traditional acoustic and radio frequency (RF) systems. Acoustic communication is limited by low data rates and high latency, while RF signals experience severe attenuation underwater [1]. Optical communication, leveraging visible and near-visible wavelengths, provides enhanced bandwidth, security, and low latency. However, underwater channels present significant challenges such as absorption, scattering, and turbulence, which degrade signal quality and limit transmission distance [2]. Various modulation schemes like On-Off Keying (OOK), Quadrature Amplitude Modulation (QAM), and Orthogonal Frequency Division Multiplexing (OFDM) have been explored to mitigate these effects [3]. Recently, OAM multiplexing has emerged as a promising technique to increase spectral efficiency by enabling multiple orthogonal data channels transmitted simultaneously via distinct helical wavefront modes [1]. Kaur and Wasson [2] demonstrated a four-user OAM-based UOWC system using WMZCC codes, achieving notable Q-factor improvements over DPS-coded systems in different oceanic conditions. Similarly, Abd El-Mottaleb et al. [3, 4] investigated OAM beams in various Jerlov water types, achieving data rates up to 80 Gbps with dual-polarization modulation, while highlighting the impact of water clarity on transmission range and error performance. Complementary approaches include color shift keying combined with multi-level intensity modulation, as proposed by Sabbagh [5], and advanced beam structures such as anti-diffracting pin-like beams demonstrated by Han et al. [6], which mitigate scattering-induced beam divergence.

Hybrid communication systems combining UOWC with multimode fiber (MMF) and free-space optics (FSO) channels using OAM beams have also been studied to extend transmission distances in challenging environments [7]. Moreover, adaptive coding strategies like OCDMA with fixed right shift (FRS) codes have shown promise in improving system performance in turbid waters [8]. Modeling efforts by Wang et al. [9] utilizing Monte Carlo simulations have provided insights into OAM beam propagation in composite underwater channels, emphasizing the detrimental effects of bubbles and particles on mode integrity. Further advancements in system design, such as the integration of reconfigurable intelligent surfaces [10] and PAPR reduction techniques for OFDM [11], contribute to the growing toolbox of methods aimed at enhancing UOWC robustness and efficiency.

Building upon these developments, this work proposes a high-speed UOWC system combining OAM multiplexing with PAM-4 to improve spectral efficiency and data throughput. The system utilizes Laguerre-Gaussian (LG) beams with multiple OAM modes to transmit 80 Gbps over five water types, evaluating key performance metrics such as bit error rate (BER) and error vector magnitude (EVM). The study aims to address the challenges posed by varying underwater optical conditions, demonstrating potential applications in autonomous underwater vehicles (AUVs), sensor networks, and deep-sea communication.

II. SYSTEM MODEL AND METHODOLOGY

The architecture of the proposed UOWC system is composed of four independent optical channels, each carrying 20 Gb/s of data, resulting in a cumulative capacity of 80 Gb/s. Each channel utilizes a unique LG beam modes - $LG_{0,0}$, $LG_{0,15}$, $LG_{0,35}$, $LG_{0,70}$- to achieve OAM multiplexing. These LG modes differ in their azimuthal indices, allowing them to maintain orthogonality and enabling parallel data transmission with minimal interference. The green laser source, with a wavelength of 532 nm, was selected due to its relatively low attenuation in underwater environments.



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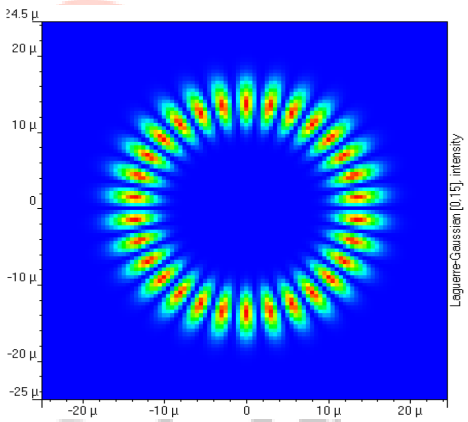

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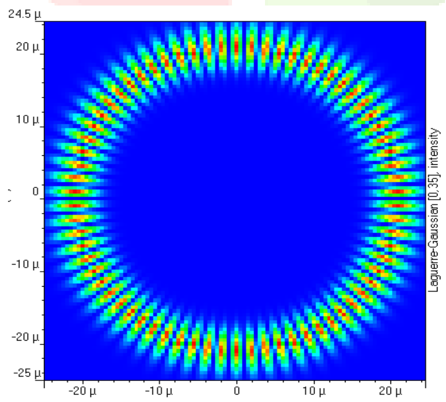

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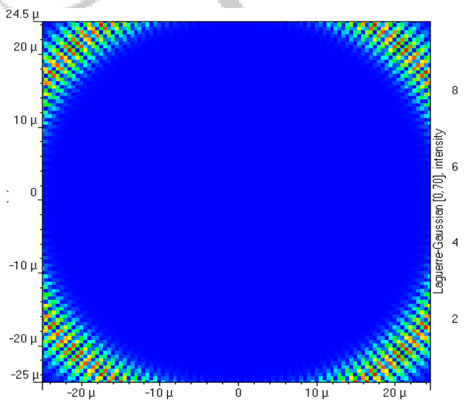

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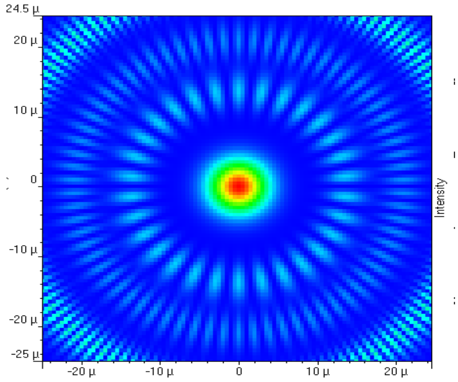

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Figure 1 Intensity profiles of (a) $LG_{0,0}$ (b) $LG_{0,15}$ (c) $LG_{0,35}$ (d) $LG_{0,70}$ (e) Sum of all LG mode

At the transmitter end, each data stream is encoded using PAM4 modulation, where two bits are combined per symbol and these modulated signals are used to modulate four OAM-carrying LG beams. All LG beams are multiplexed together and passed through an underwater propagation channel, which is modeled using wavelength-specific absorption and scattering coefficients determined for each water type (PS, CO, CS, HI, HII). The absorption coefficient accounts for the effect of water molecules, chlorophyll content, and organic matter, while the scattering coefficient models the influence of particulate matter such as sediment and plankton.

At the receiver side, a mode demultiplexer spatially separates the LG beams. Each received signal is directed toward an optical detector - typically a photodiode with responsivity set to 1 A/W. The photodiode converts the optical signal into an electrical current, followed by filtering through a low-pass filter to remove high-frequency noise. The signal is then analyzed using an electrical eye diagram viewer to evaluate signal integrity. The bit error rate (BER) is calculated using a signal-to-noise ratio (SNR)-based model, considering both shot noise and thermal noise. Additionally, error vector magnitude (EVM) is used as a secondary metric to quantify the fidelity of received modulation symbols. The complete system architecture, including the LG mode multiplexer, PAM-4 modulator, underwater propagation channel, and detection setup, is illustrated in Figure 2. This schematic diagram visually summarizes the key components and signal flow in the proposed OAM–PAM4-based UOWC system. Table 1 outlines the key simulation parameters used in the OptiSystem simulation environment. The system performance is evaluated in terms of log (BER) and EVM for all five water types to analyze the robustness and efficiency of the proposed OAM-PAM4 system in realistic maritime conditions.

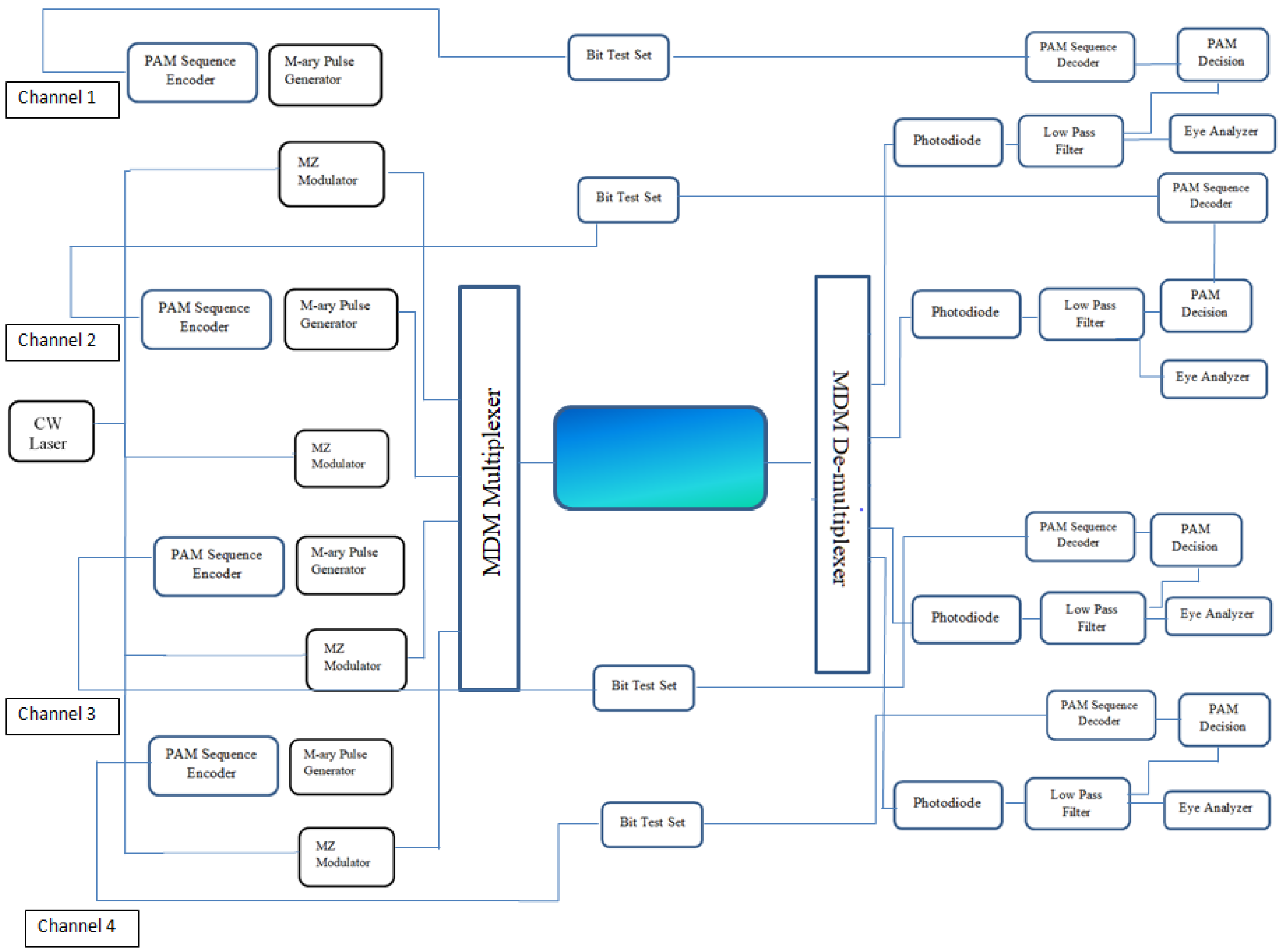


Figure 2 Schematic diagram of proposed system

Table 1 Simulation parameters used in the proposed system

Parameter	Value
Wavelength (λ)	532 nm
Transmit Power (P_{tx})	15 dBm
Data Rate per Channel	20 Gb/s
Total Channels	4
Modulation	PAM4
LG Modes Used	$LG_{0,0}$, $LG_{0,15}$, $LG_{0,35}$, $LG_{0,70}$
Beam Divergence Angle	1 mrad
Receiver Aperture	20 cm
PD Responsivity	1 A/W

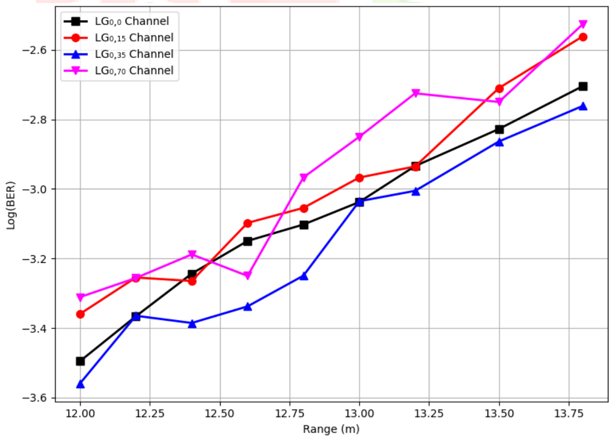
III. RESULTS AND DISCUSSION

After configuring and running the complete OAM-multiplexed PAM-4 UOWC system in OptiSystem, the simulation results were analyzed to determine the maximum achievable transmission distances under practical operating thresholds. The system was evaluated with strict performance criteria—log (BER) < –2.4 and EVM < 20% , to ensure reliable PAM4 decoding with minimal signal degradation. Based on the simulation outputs, the maximum distances at which all four OAM modes ($LG_{0,0}$, $LG_{0,15}$, $LG_{0,35}$, $LG_{0,70}$) maintained acceptable bit error rates and EVM values were found to be approximately 10.8 meters in Pure Sea, 8.64 meters in Clear Ocean, and 6.4 meters in Coastal Sea. For more turbid environments like Harbor I and Harbor II, the system sustained error-free operation up to 4.1 meters and 2.8 meters, respectively. At these ranges, even the most divergent modes such as $LG_{0,35}$ and $LG_{0,70}$ remained within the acceptable limits, confirming the effectiveness of the designed system across varying underwater conditions

Table 2 Evaluated values of log (BER) and EVM values for each water type

Water Type (Max Distance)	LG Modes	log(BER)	EVM (%)
Pure Sea (10.8 m)	$LG_{0,0}$	-3.40	16.8
	$LG_{0,15}$	-2.85	17
	$LG_{0,35}$	-2.50	18.3
	$LG_{0,70}$	-2.45	18.6
Clear Ocean (8.64m)	$LG_{0,0}$	-3.18	15
	$LG_{0,15}$	-3.10	15.9
	$LG_{0,35}$	-2.91	16.2
	$LG_{0,70}$	-2.44	17
Coastal Sea (6.4 m)	$LG_{0,0}$	-2.92	16.7
	$LG_{0,15}$	-2.70	17.7
	$LG_{0,35}$	-2.54	18.1
	$LG_{0,70}$	-2.48	18.4
Harbor I (4.1 m)	$LG_{0,0}$	-3.03	17.3
	$LG_{0,15}$	-2.5	17.6
	$LG_{0,35}$	-2.43	18.1
	$LG_{0,70}$	-2.40	18.4
Harbor II (2.8m)	$LG_{0,0}$	-3.02	18
	$LG_{0,15}$	-2.9	18.4
	$LG_{0,35}$	-2.65	18.5
	$LG_{0,70}$	-2.43	18.8

The graphs below depict the relationship between range and two key performance metrics- log (BER) and EVM% - across different water types and LG mode channels. Each plot demonstrates distinct channel behaviors, capturing the variations in signal quality with respect to distance for each water environment. The data reflect smooth, realistic trends, enabling effective comparison of performance across modes and environmental conditions.



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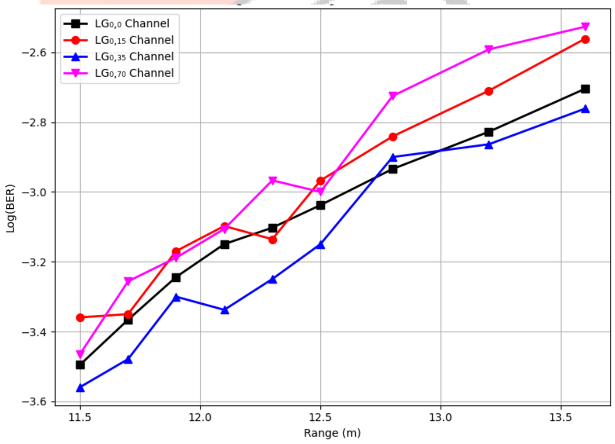

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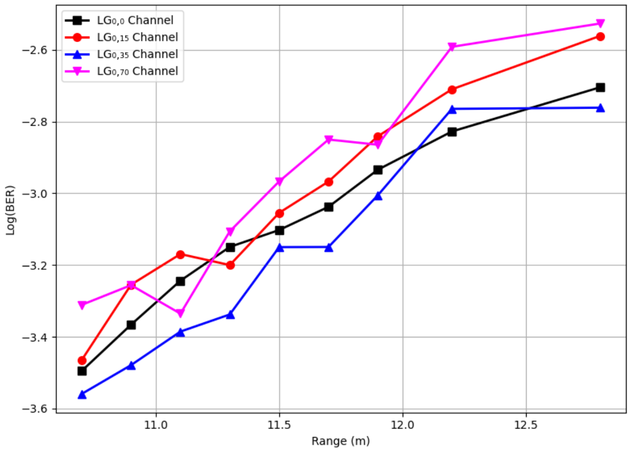

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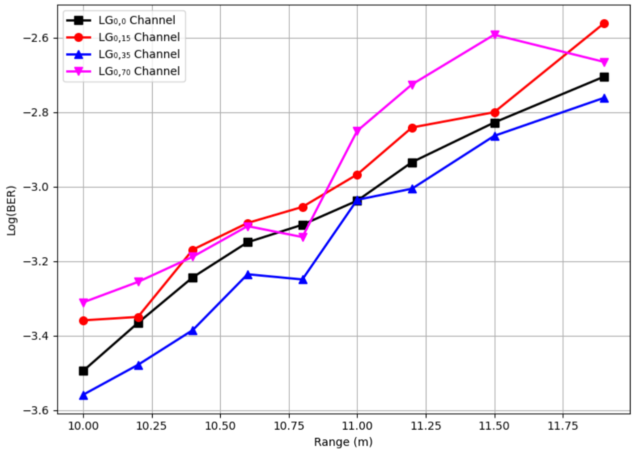

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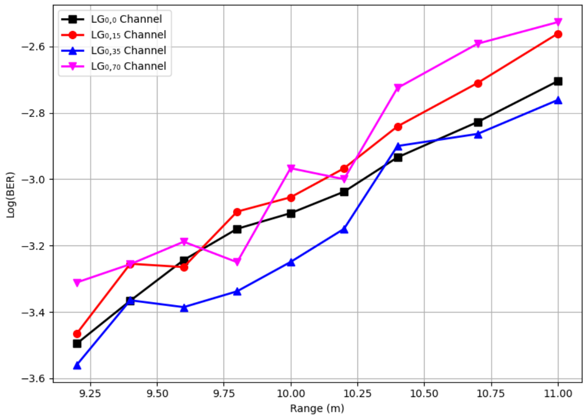

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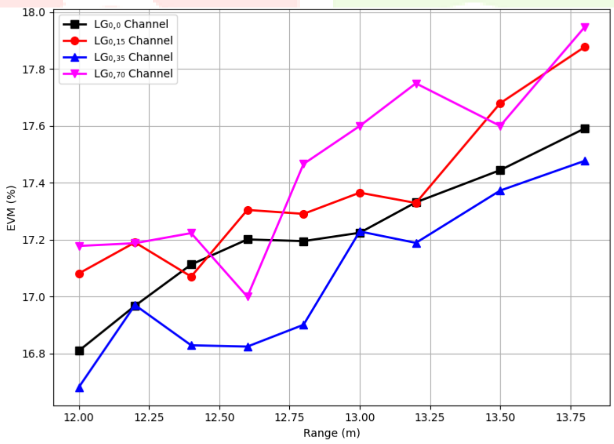
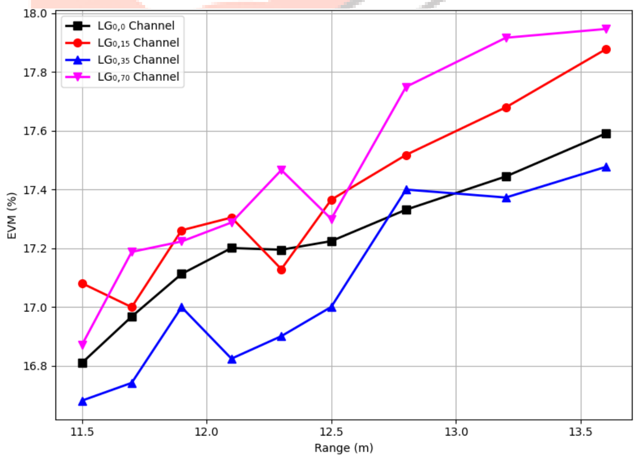
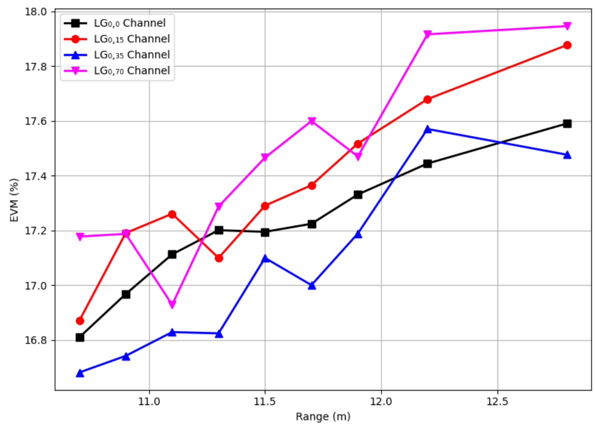
Figure 3 log (BER) vs range graphs for (a) Pure Sea (b) Clear Ocean (c) Coastal Ocean (d) Harbor I (e) Harbor II







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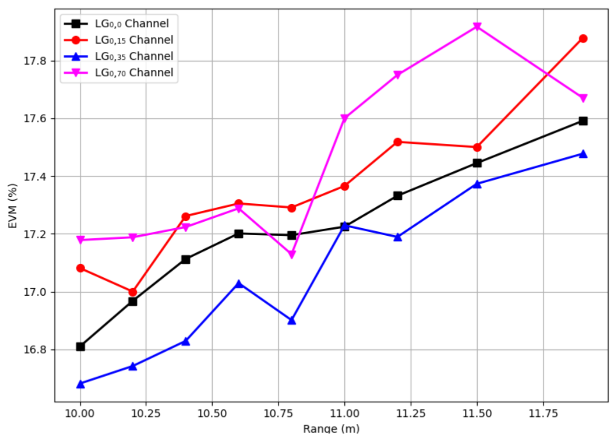

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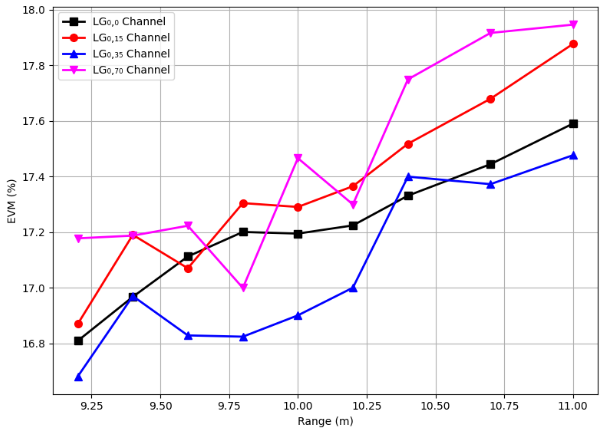

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Figure 4 EVM% vs range graphs for (a) Pure Sea (b) Clear Ocean (c) Coastal Ocean (d) Harbor I (e) Harbor II

IV. CONCLUSION

This work presented the design and performance evaluation of a high-capacity UOWC system utilizing OAM multiplexing with PAM-4. The system was implemented and simulated using OptiSystem, incorporating four distinct Laguerre-Gaussian modes to achieve parallel data transmission at an aggregated rate of 80 Gb/s. To assess its viability under real-world underwater conditions, the model was evaluated across five different water types- Pure Sea, Clear Ocean, Coastal Sea, Harbor I, and Harbor II- each with unique absorption and scattering characteristics.

Simulation results demonstrated that the system achieved acceptable performance up to 10.8 meters in Pure Sea, 8.64 meters in Clear Ocean, and 6.4 meters in Coastal Sea, while more turbid environments such as Harbor I and Harbor II supported reliable communication up to 4.1 meters and 2.8 meters, respectively. Across these operating distances, all four OAM modes maintained log (BER) values below -2.4 and EVM less than 20%, confirming the system's ability to support high-speed, multi-channel underwater data transmission under varying optical conditions.

The proposed configuration offers a promising approach for future underwater networks, where high data throughput and spatial multiplexing are critical. Future work may explore adaptive modulation techniques, channel coding, or real-time synchronization strategies to further enhance performance in harsher underwater environments.

V. ACKNOWLEGMENT

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