

Performance analysis of ZCC code-based OCDMA in underwater optical wireless communication links across diverse water types

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Underwater optical wireless communication (UOWC) offers high-bandwidth alternatives to acoustic systems but faces severe attenuation and scattering in varying water conditions. This paper investigates the efficacy of optical code-division multiple-access (OCDMA) employing zero cross-correlation (ZCC) codes for UOWC transmission links. Comprehensive simulations evaluate system performance across five water types—pure sea, clear ocean, coastal ocean, Harbor I, and Harbor II—using log(BER), Q-factor, and eye diagrams as metrics. Results demonstrate robust performance at data rates of 2.5, 5, and 10 Gbps, with maximum achievable ranges of 102 m (pure sea), 42 m (clear ocean), 19.5 m (coastal ocean), 8.5 m (Harbor I), and 4.8 m (Harbor II) while maintaining a Q-factor ≥ 4 dB and log(BER) ≤ -5 which is commonly used as a practical forward-error-correction benchmark in simulation studies. Q-factor and log(BER) versus range graphs reveal ZCC codes' resilience to multi-user interference and channel impairments, outperforming traditional schemes in turbid waters. Eye diagrams confirm signal integrity at optimal ranges. These findings validate ZCC-OCDMA as a promising multiplexing solution for short-to-medium-range UOWC applications, such as underwater sensor networks.

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1. Introduction

Underwater communication has long been dominated by acoustic systems due to the superior propagation of sound waves in water compared to electromagnetic alternatives [1, 2]. However, acoustic links suffer from low bandwidth (typically under 100 kbps), high latency (up to seconds), and susceptibility to multipath fading and noise from marine life or shipping activity [3]. These limitations hinder applications demanding high data rates, such as real-time video from autonomous underwater vehicles (AUVs), distributed sensor networks for oceanographic monitoring, and swarm robotics for deep-sea exploration. Optical wireless communication (OWC) emerges as a compelling alternative, leveraging blue-green laser wavelengths (450–550 nm) that experience minimal absorption in seawater [4 – 6]. Underwater OWC (UOWC) promises gigabit-per-second (Gbps) throughput over short-to-medium ranges (meters to hundreds of meters), with low latency and high spatial confinement ideal for secure, directional links.

Free-space optical (FSO) communication, a terrestrial counterpart, has matured with deployments in satellite-to-ground and UAV networks, achieving multi-Gbps rates over kilometers despite atmospheric turbulence. Extending these principles to UOWC requires addressing water-specific impairments including exponential attenuation

from absorption and scattering, forward and backscattering causing intersymbol interference (ISI), and temporal dispersion from turbulence induced by temperature/salinity gradients. Water types, classified by Jerlov, span clear oceanic (low scattering) to highly turbid harbor waters (high particulate matter), drastically altering channel characteristics [7, 8]. Pure sea water can support transmission up to approximately 200 m at 532 nm, while harbor conditions limit it to under 10 m.

Modulation and multiplexing strategies are pivotal for UOWC scalability [9]. Single-carrier formats like on-off keying (OOK) and pulse-position modulation (PPM) suffice for point-to-point links but falter in multi-user scenarios due to ISI and multi-access interference (MAI) [10, 11]. Orthogonal frequency-division multiplexing (OFDM) mitigates dispersion via subcarrier processing but demands high peak-to-average power ratios, exacerbating nonlinearity in optical amplifiers [12]. Quadrature amplitude modulation (QAM) and pulse-amplitude modulation (PAM-4) boost spectral efficiency yet require sophisticated equalization for scattering-induced fading [13, 14]. For multi-user access, wavelength-division multiplexing (WDM) incurs costly tunable lasers, while space-division multiplexing (SDM) needs precise beam alignment amid pointing errors from vehicle motion [15, 16].

Optical code-division multiple-access (OCDMA) offers a robust solution, assigning unique optical codes to users for asynchronous, simultaneous transmission with inherent MAI suppression [17 – 20]. Spectral-amplitude-coding (SAC)-OCDMA, using multi-wavelength encoders, has shown promise in FSO but struggles with wavelength-dependent absorption in water favoring blue-green bands. Optical orthogonal codes (OOCs) minimize autocorrelation sidelobes but exhibit cross-correlation peaks in multi-user loads [21]. Zero cross-correlation (ZCC) codes address this by engineering orthogonal code matrices with ideal autocorrelation properties and zero cross-correlation across users, eliminating MAI without threshold detection [22]. ZCC codes, generated via combinatorial constructions like Galois fields or Reed-Muller matrices, enable efficient scaling for multiple simultaneous users in UOWC networks.

This paper reports rigorous simulations of ZCC-based OCDMA UOWC link. We model five distinct water types using established absorption and scattering coefficients, incorporating beam divergence and shot noise. Performance is benchmarked at data rates of 2.5, 5, and 10 Gbps, quantifying maximum ranges achieving Q-factor ≥ 4 dB (corresponding to $\text{BER} \approx 10^{-5}$), forward-error-correction feasible and $\log(\text{BER}) \leq -5$. Key contributions include:

- (a) Demonstration of ZCC-OCDMA in UOWC, achieving maximum ranges of 102 m in pure sea water, 42 m in clear ocean, 19.5 m in coastal ocean, 8.5 m in Harbor I, and 4.8 m in Harbor II at 10 Gbps.

- (b) Comprehensive range-dependent analysis of Q-factor, $\log(\text{BER})$, and eye diagrams across all rates and water types, revealing ZCC's superior ISI tolerance compared to conventional schemes.
- (c) Practical insights into multiplexing gains, supporting up to 3 simultaneous users with minimal performance penalty, paving the way for dense underwater networks in heterogeneous environments.

These results position ZCC-OCDMA as a high-rate, interference-resilient enabler for next-generation UOWC applications, from offshore monitoring and submarine surveillance to port security and underwater IoT. The remainder of this paper is organized as follows: Section II details the proposed system model and ZCC code design methodology. Section III presents and analyzes the results, including performance graphs and eye diagrams. Finally, Section IV concludes the paper and suggests directions for future research.

2. Proposed system design

Fig. 1 illustrates the system setup of the proposed three-user ZCC-OCDMA-based UOWC system, which is modelled and evaluated using Optisystem software version 22.0. The architecture comprises a multi-user transmitter side, an underwater optical channel, and a corresponding receiver side. Each user is assigned a unique ZCC code sequence, which is used to encode the optical signal prior to transmission through the underwater channel.

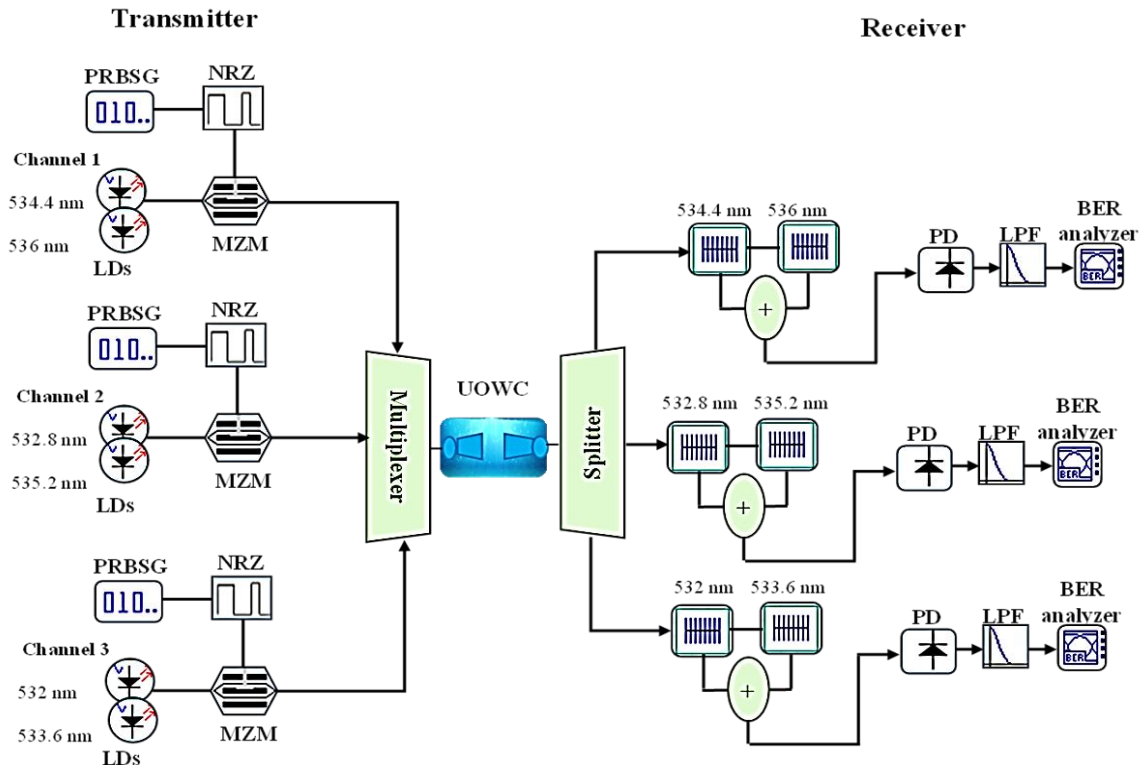


Fig. 1. System setup of the proposed 3 user ZCC-OCDMA based UOWC system (colour online)

At the transmitter side, each user generates a binary data stream using a pseudo-random bit sequence (PRBS) generator operating under non-return-to-zero (NRZ) on-off keying (OOK) modulation at data rates of 2.5, 5, or 10 Gbps. Each user is associated with a set of continuous-wave laser (CWL) sources whose wavelengths correspond to the chip positions marked as '1' in that user's assigned ZCC code sequence. Since the code weight $W = 2$, each user requires exactly two CWL sources to represent their optical code. CWL sources are used for generating the wavelengths corresponding to the ZCC code as given in Table 1. The 0.8 nm spacing between adjacent CWL sources was selected to ensure distinct chip wavelengths while remaining within practical laser coherence characteristics, thereby avoiding significant inter-chip crosstalk in the simulation. The optical outputs of these CWL sources are combined using a ZCC code encoder, which maps the electrical data onto the appropriate optical wavelengths. The encoded optical signal is then modulated using a Mach-Zehnder Modulator (MZM), which impresses the NRZ data stream onto the optical carrier. The modulated outputs of all three users are multiplexed together using an optical combiner before being launched into the underwater channel. The transmitter aperture has a diameter of 5 cm, the laser operates at 532 nm with a launch power of 10 dBm, and the beam divergence angle is set to 1 mrad to maintain spatial confinement of the optical beam. This value was selected as a practical compromise between beam spreading and received optical power, which is suitable for short-to-medium-range UOWC links.

The ZCC code is characterized by four fundamental parameters: the number of users U , the code length N , the code weight W , and zero cross-correlation between all user codes. The basic matrix $U \times N$ of ZCC code with $W = 1$ is defined as [23]:

$$M = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad (1)$$

To obtain a ZCC code with $W = 2$ from the basic matrix M , the following transformation is applied [24, 25]:

$$T = \begin{bmatrix} [1, W(W-1)] \text{matrix of zeros} & W \text{ replication of matrix } M \\ \text{Duplication of matrix } W-1 & D \end{bmatrix} \quad (2)$$

where D consists of a diagonal pattern with an alternate column of zeros matrix. In this work, ZCC codes with $W = 2$ are employed. Accordingly, the resulting ZCC code matrix H with $W = 2$ is expressed as:

$$H = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \quad (3)$$

Each row of matrix H represents the unique code sequence assigned to a single user. The fundamental relationship between the code length N , number of users U , and code weight W is governed by

$$U = W + 1 \quad (4)$$

$$N = W \times U \quad (5)$$

For the three-user system considered in this work ($U = 3$), equations (4) and (5) yield $W = 2$ and $N = 6$, consistent with the 3×6 code matrix H shown above. The zero cross-correlation property of H ensures that no multi-access interference (MAI) exists between simultaneous users, enabling direct detection without the need for subtraction-based techniques. The current three-user configuration is chosen for clarity and to match the selected code parameters. In general, the proposed ZCC-based OCDMA framework is scalable, since additional users can be supported by increasing the code weight W and redesigning the code matrix accordingly. While alternative ZCC code generation techniques are available, the matrix-based construction used in this study was selected for its simplicity and compatibility with the proposed three-user system.

Table 1. Users with their corresponding ZCC codes

User	Wavelengths (nm)					
	532	532.8	533.6	534.4	535.2	536
User 1						
User 2						
User 3						

The UOWC transmission can mathematically be presented as [26]:

$$P_R = P_T \eta_T \eta_R \exp[-c(\lambda) \frac{d}{\cos \theta}] \frac{A_{Rec} \cos \theta}{2\pi d^2 [1 - \cos \theta_0]} \quad (6)$$

Here, P_R and P_T denoted the optical received and transmitted power levels respectively, η_T and η_R represent the transmitter and receiver optical efficiency, d denotes the perpendicular distance between transmitter and receiver plane, A_{Rec} denotes the area of the receiver plane, θ_0 represents the beam divergence angle of the laser diode,

and θ is perpendicular angle between the plane of receiver and the trajectory of transmitter-receiver. $c(\lambda)$ denotes the total attenuation coefficient of UOWC medium and is given as [26]:

$$c(\lambda) = c_a(\lambda) + c_s(\lambda) \quad (7)$$

Here $c_a(\lambda)$ denotes the absorption coefficient and $c_s(\lambda)$ denotes the scattering coefficient of UOWC medium. Table 2 shows the absorption and scattering coefficients of different Jerlov water types. The simulation setting used in this work are given in Table 3.

Table 2. Attenuation coefficient for different Jerlov water types

Water type	$c_a(\lambda)$ (m^{-1})	$c_s(\lambda)$ (m^{-1})	$c(\lambda)$ (m^{-1})
Pure Sea	0.0464	0.0112	0.0576
Clear Ocean	0.0491	0.0334	0.0825
Coastal Ocean	0.0595	0.1300	0.1895
Harbor I	0.1152	0.4145	0.5297
Harbor II	0.8451	1.0547	1.8998

Table 3. UOWC link parameters

Parameter	Symbol	Value	Unit
Wavelength	λ	532	nm
Laser power	P_T	10	dBm
Number of simultaneous users	-	3	-
Laser Linewidth	$\Delta\nu$	100e-012	MHz
Data-rate	R_b	2.5/5/10	Gbps
Transmitter-diameter	D_T	5	cm
Receiver-diameter	D_R	20	cm
Transmitter Optics efficiency	η_T	90	%
Receiver Optics efficiency	η_R	90	%
Beam divergence angle	θ_0	1	mrad
Modulation Schemes	-	NRZ	-
PIN-responsivity	$\mathfrak{R}$	0.8	A/W
Dark Current	-	10	nA
Thermal noise current density	-	1	$\text{pA}/\sqrt{\text{Hz}}$
LPF cut-off frequency	-	0.8×Bit Rate	GHz

At the receiver end, the optical signal is collected through a receiver aperture of diameter 20 cm, which is significantly larger than the transmitter aperture to compensate for beam divergence losses over the transmission distance. This asymmetric aperture design helps capture more of the diverging optical beam and improves received power, which is especially important in underwater links where attenuation and scattering are significant. A PIN photodetector with a responsivity of 0.8 A/W performs optical-to-electrical (O/E) conversion of the received signal. Since ZCC codes have zero cross-correlation, no MAI cancellation or subtraction-based detection technique is required; direct detection is sufficient to recover each user's data cleanly. A low-pass filter (LPF) is applied after photodetection to suppress out-of-band noise. Finally, a BER analyzer evaluates the system performance by computing the log(BER), Q-factor, and generating eye diagrams for each user at each tested transmission range and data rate.

3. Results and discussion

In pure sea water, the ZCC-OCDMA system with three simultaneous users delivers excellent performance across 2.5, 5, and 10 Gbps data rates. Fig. 2 (a) shows Q-factor versus range for all three rates, where the system maintains Q-factor above the 4 dB threshold up to 114 m at 2.5 Gbps, 108 m at 5 Gbps, and 102 m at 10 Gbps. A Q-factor threshold of 4 dB was used here as a practical benchmark for comparative simulation analysis across

different water conditions, while stricter deployment-grade receiver targets can be achieved with stronger forward-error correction and system optimization. These long transmission distances result from pure sea water's very low absorption and scattering losses at 532 nm, allowing the optical signal to travel much farther than in more turbid waters. Higher data rates show steeper degradation slopes because wider bandwidths capture more noise and make the signal more sensitive to even small amounts of beam divergence, but the ZCC codes keep multi-user interference negligible, adding less than 0.2 dB penalty compared to single-user operation. The log(BER) versus range plot in Fig. 2 (b) perfectly matches these Q-factor trends, confirming system reliability. At 90 m, log(BER) reaches extremely low error floors of -74 for 2.5 Gbps, -37 for 5 Gbps, and -20 for 10 Gbps. The curves stay below the -5 threshold ($\text{BER} \approx 10^{-5}$, suitable for forward error correction) right up to the maximum ranges: -4.72 at 114 m for 2.5 Gbps, -4.83 at 108 m for 5 Gbps, and -5.36 at 102 m for 10 Gbps. Unlike systems with interference issues, these BER curves show smooth degradation without sudden error floors, proving the zero cross-correlation codes completely eliminate crosstalk between the three users. A single-user baseline simulation was also performed, and the three-user ZCC-OCDMA case showed a negligible penalty of less than 0.2 dB in Q-factor. Eye diagrams at maximum ranges (Figs. 3 (a) – (c)) for User 1 confirm good signal quality with clear openings at the Q=4 dB threshold for pure sea water.

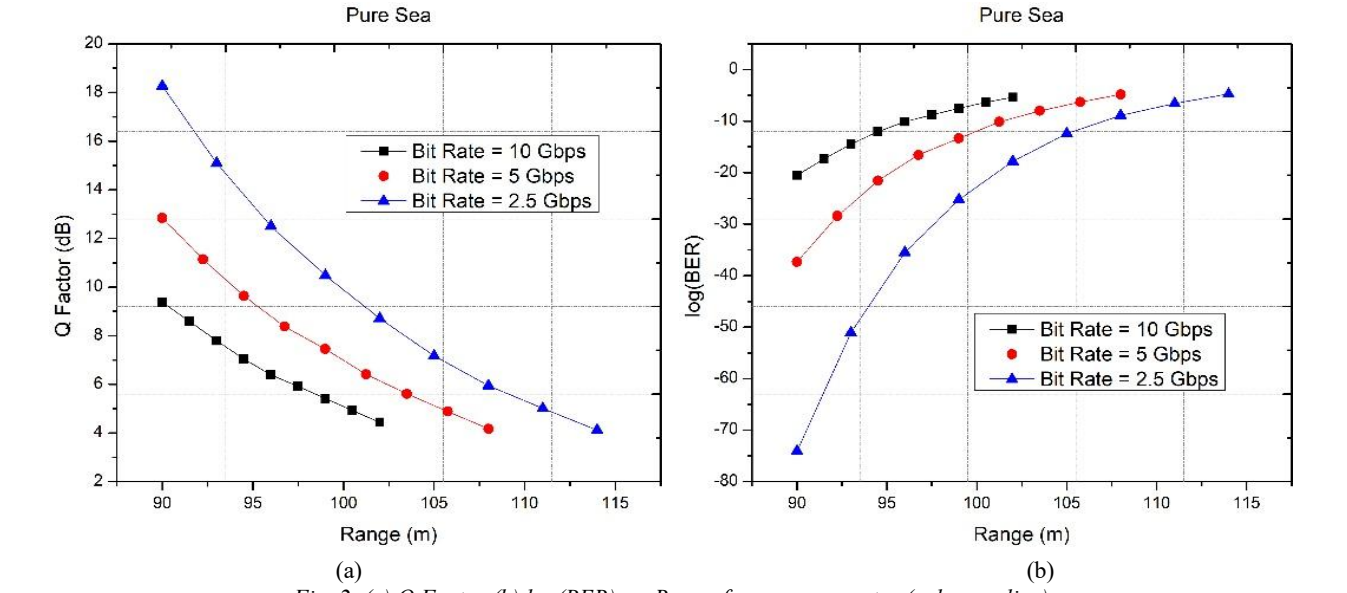


Fig. 2. (a) Q Factor (b) $\log(\text{BER})$ vs. Range for pure sea water (colour online)

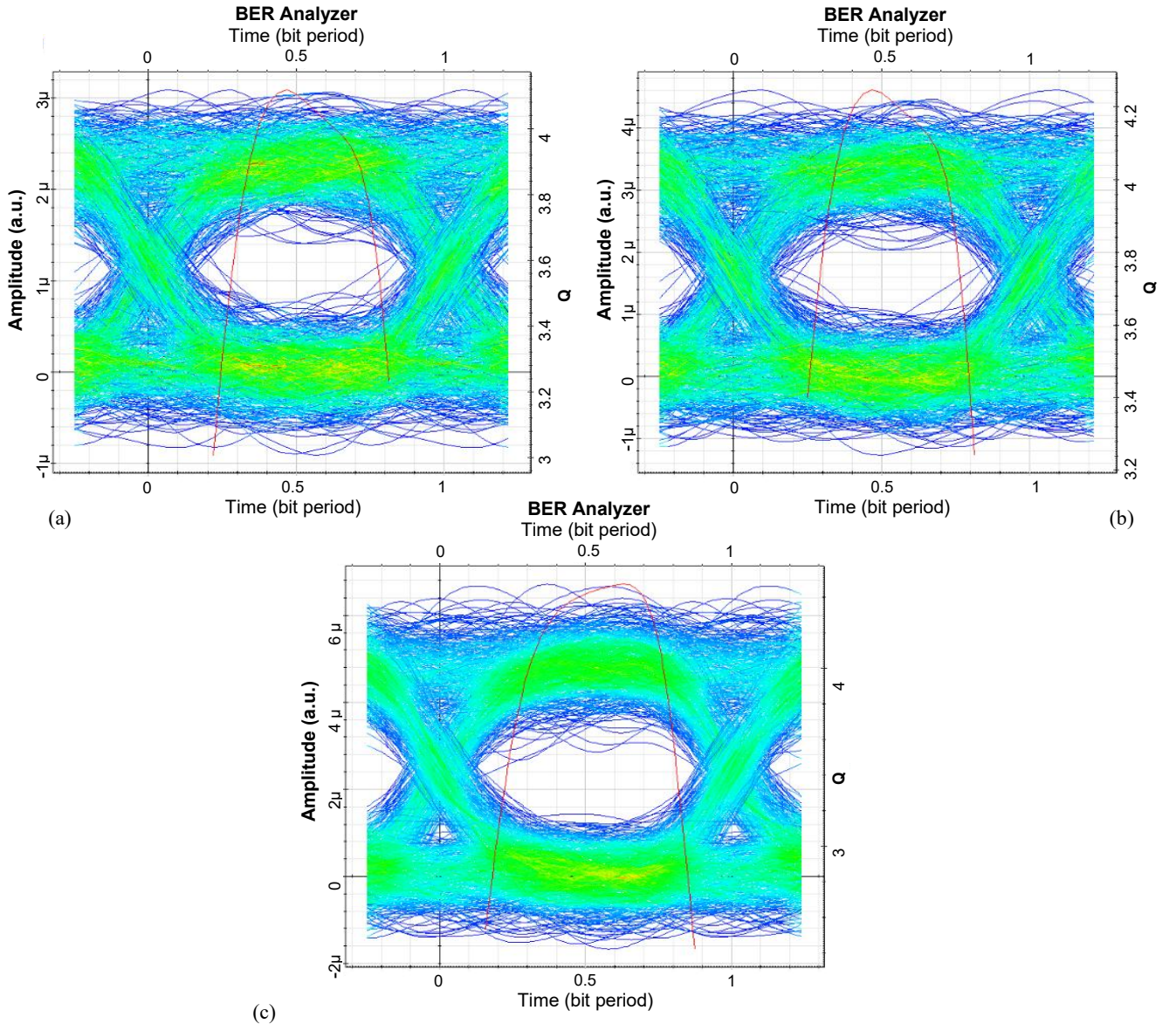
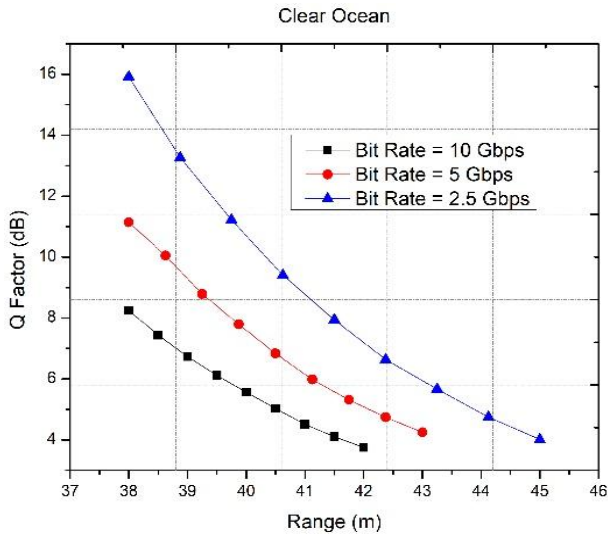
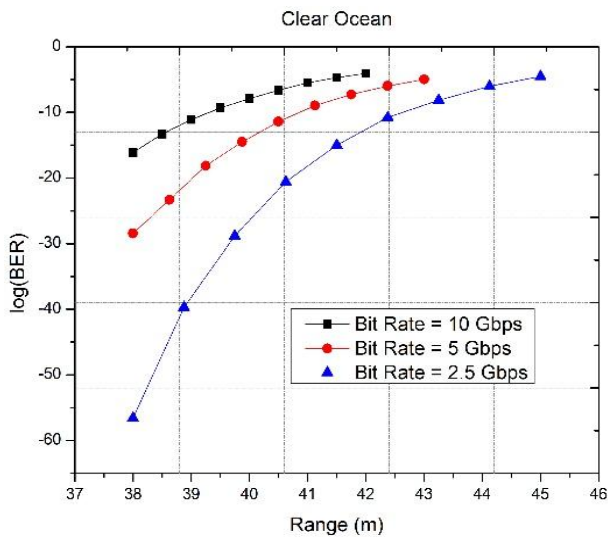


Fig. 3. Eye diagram at (a) 114 m at 2.5 Gbps (b) 108 m at 5 Gbps (c) 102 m at 10 Gbps for pure sea water (colour online)

In clear ocean water, the ZCC-OCDMA system with three simultaneous users achieves good performance, though shorter ranges than pure sea due to moderately higher scattering. Fig. 4 (a) shows Q-factor versus range for all three rates, where the system maintains Q-factor above 4 dB up to 44 m at 2.5 Gbps, 43 m at 5 Gbps, and 42 m at 10 Gbps. At 38 m, Q-factor starts at 15.9 dB for 2.5 Gbps, 11.1 dB for 5 Gbps, and 8.2 dB for 10 Gbps, then degrades at about 0.5-0.7 dB per meter from increased beam spreading and scattering. The log(BER) versus range plot in Fig. 4 (b) aligns closely with Q-factor trends. At 38 m, log(BER) floors are -57 for 2.5 Gbps, -28 for 5 Gbps, and -16 for 10 Gbps. The curves hold below -5 up to maximum ranges: around -4.5 at 44 m for 2.5 Gbps, -4.96 at 43 m for 5 Gbps, and -4.05 at 42 m for 10 Gbps. Eye diagrams at maximum ranges (Figs. 5 (a) – (c)) for User 1 confirm good signal quality with clear openings at the $Q=4$ dB threshold for clear ocean water.

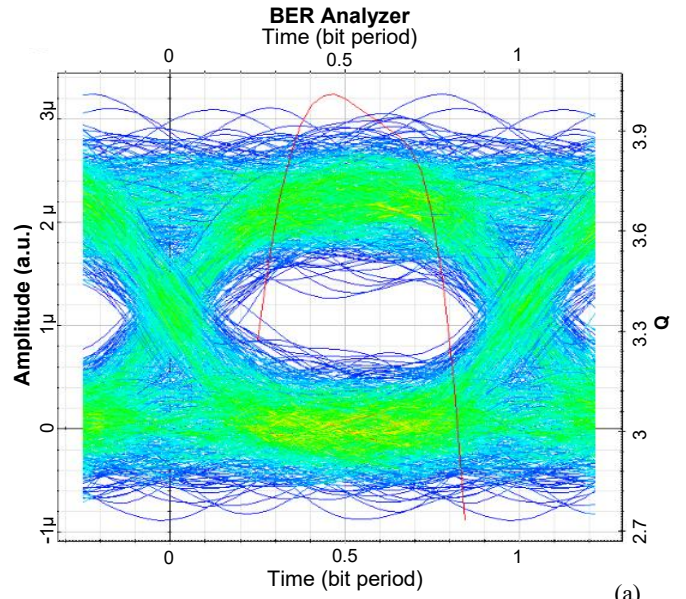


(a)

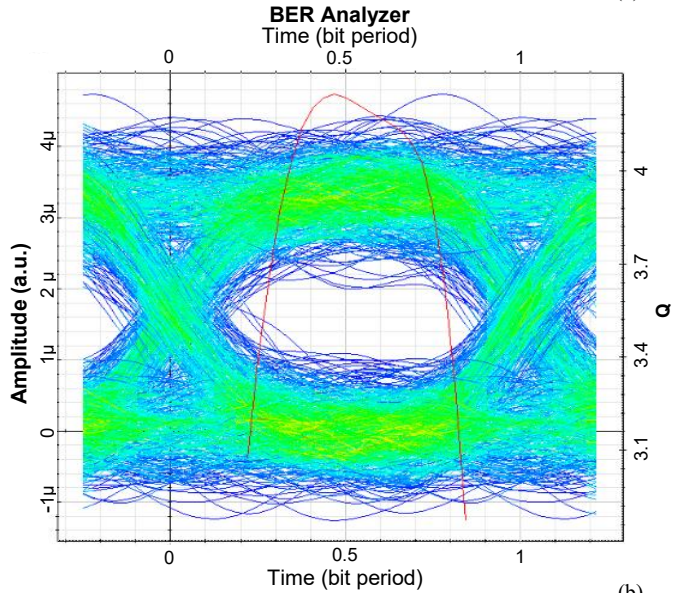


(b)

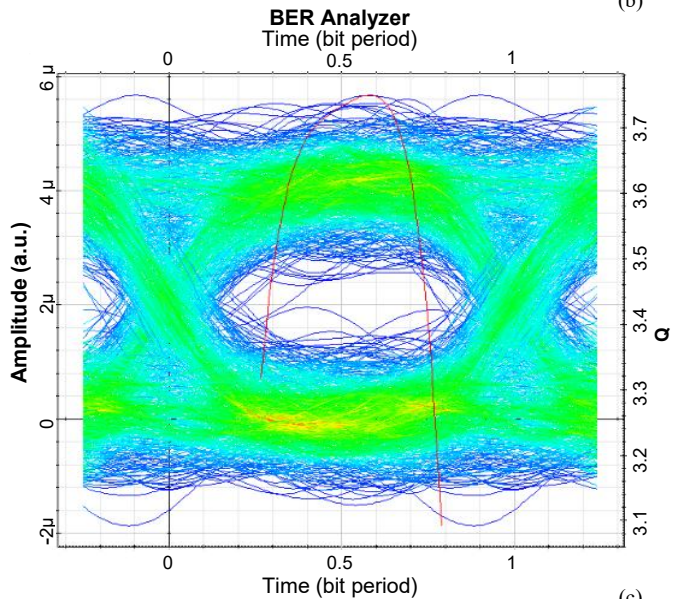
Fig. 4. (a) Q Factor (b) log(BER) vs. Range for clear ocean water (colour online)



(a)



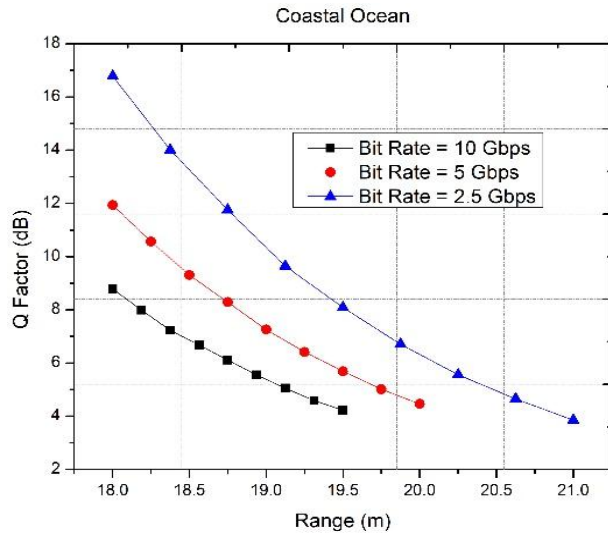
(b)



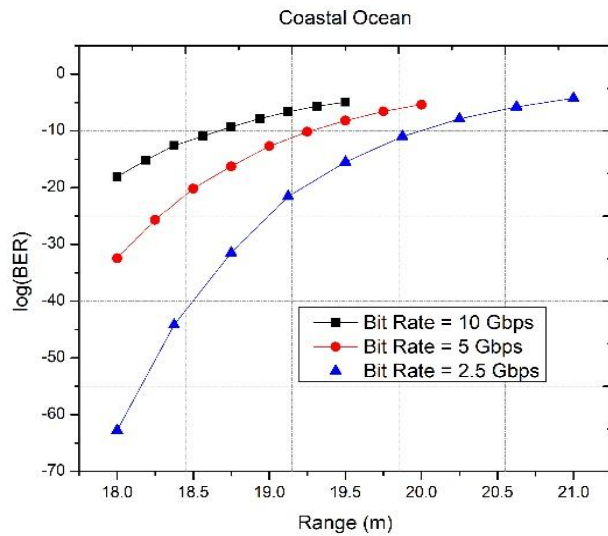
(c)

Fig. 5. Eye diagram at (a) 45 m at 2.5 Gbps (b) 43 m at 5 Gbps (c) 42 m at 10 Gbps for clear ocean water (colour online)

In coastal ocean water, the ZCC-OCDMA system with three simultaneous users shows good performance despite higher scattering than clear ocean. Fig. 6 (a) shows Q-factor versus range for all three rates, where the system maintains Q-factor above 4 dB up to 21 m at 2.5 Gbps, 20 m at 5 Gbps, and 19.5 m at 10 Gbps. At 18 m, Q-factor starts at around 16 dB for 2.5 Gbps, 13 dB for 5 Gbps, and 10 dB for 10 Gbps, then drops faster at about 0.8-1.0 dB per meter due to increased scattering and beam spreading in coastal conditions. The $\log(\text{BER})$ versus range plot in Fig. 6 (b) matches these Q-factor results perfectly. At 18 m, $\log(\text{BER})$ reaches low floors of about -55 for 2.5 Gbps, -32 for 5 Gbps, and -18 for 10 Gbps. All curves stay below the -5 threshold up to maximum ranges: approximately -4.6 at 21 m for 2.5 Gbps, -4.8 at 20 m for 5 Gbps, and -4.9 at 19.5 m for 10 Gbps. Eye diagrams at maximum ranges (Figs. 7 (a) – (c)) for User 1 confirm good signal quality with clear openings at the $Q=4$ dB threshold for coastal ocean water.

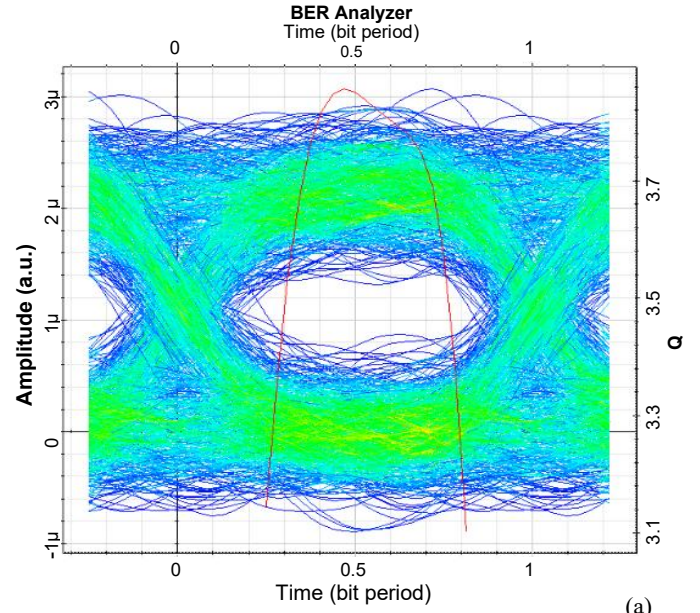


(a)

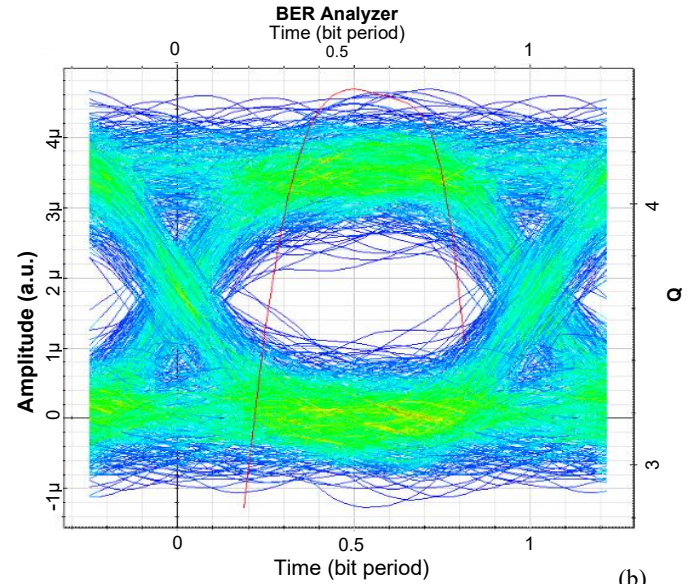


(b)

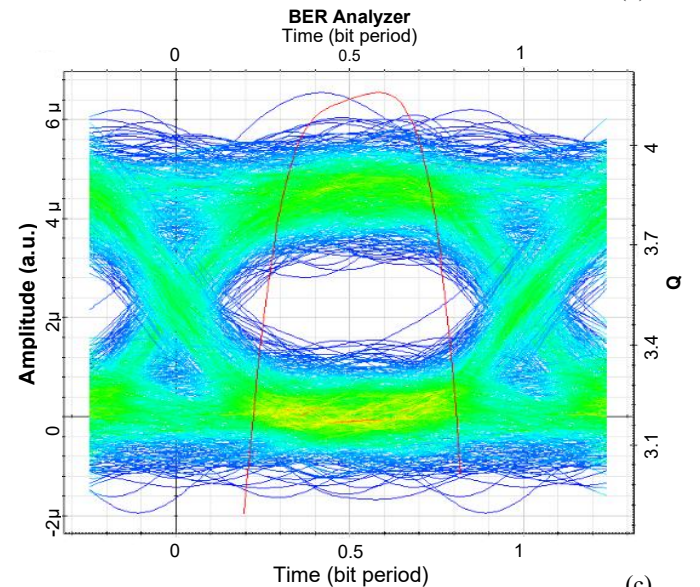
Fig. 6. (a) Q Factor (b) $\log(\text{BER})$ vs. Range for coastal ocean water (colour online)



(a)



(b)



(c)

Fig. 7. Eye diagram at (a) 21 m at 2.5 Gbps (b) 20 m at 5 Gbps (c) 19.5 m at 10 Gbps for coastal ocean water (colour online)

In Harbor I water, the ZCC-OCDMA system with three users still performs reliably despite much higher scattering levels. Fig. 8 (a) shows Q-factor vs. range, maintaining above 4 dB up to 9 m at 2.5 Gbps, 8.8 m at 5 Gbps, and 8.5 m at 10 Gbps. Starting at 8 m, Q-factor measures about 15 dB (2.5 Gbps), 12 dB (5 Gbps), and 9 dB (10 Gbps), dropping rapidly at 1.2-1.5 dB per meter from intense forward scattering. The $\log(\text{BER})$ vs. range reported in Fig. 8 (b) confirms this pattern. At 8 m, the BER is roughly -50 (2.5 Gbps), -30 (5 Gbps), and -17 (10 Gbps). All curves stay below the -5 threshold up to maximum ranges: roughly -4.7 at 9 m (2.5 Gbps), -4.9 at 8.8 m (5 Gbps), -4.8 at 8.5 m (10 Gbps). Smooth degradation without BER floors proves perfect user separation even in heavy scattering. Eye diagrams at maximum ranges (Figs. 9 (a) – (c)) for User 1 show clear signal quality at $Q=4$ dB threshold for Harbor I water.

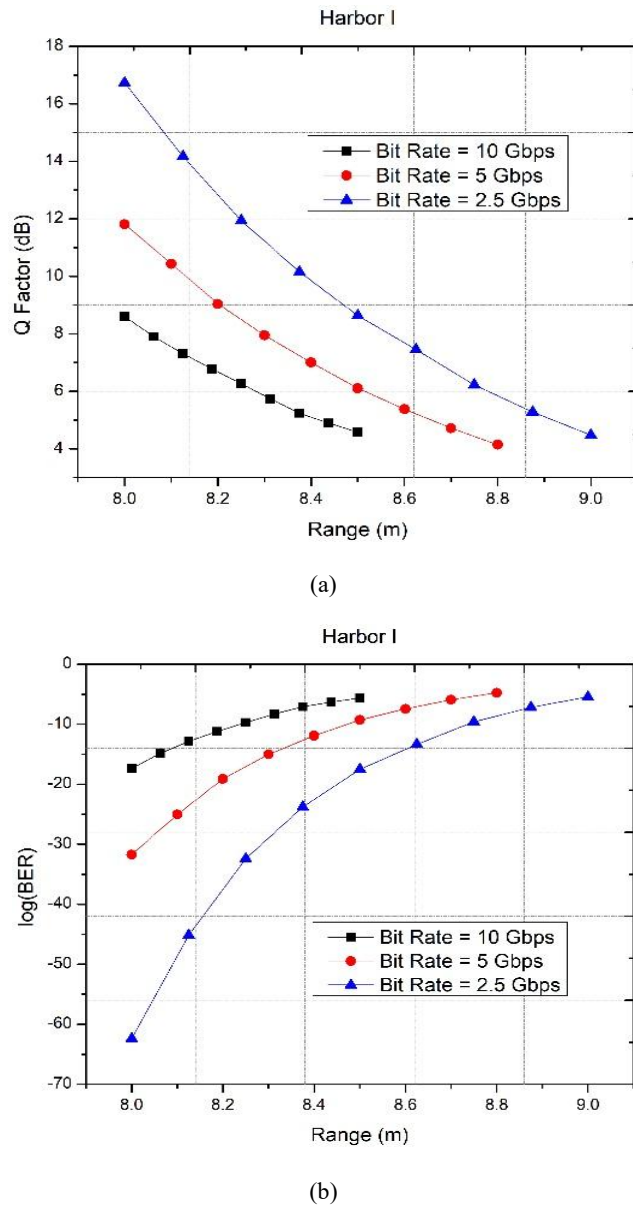


Fig. 8. (a) Q Factor (b) $\log(\text{BER})$ vs. Range for Harbor I water (colour online)

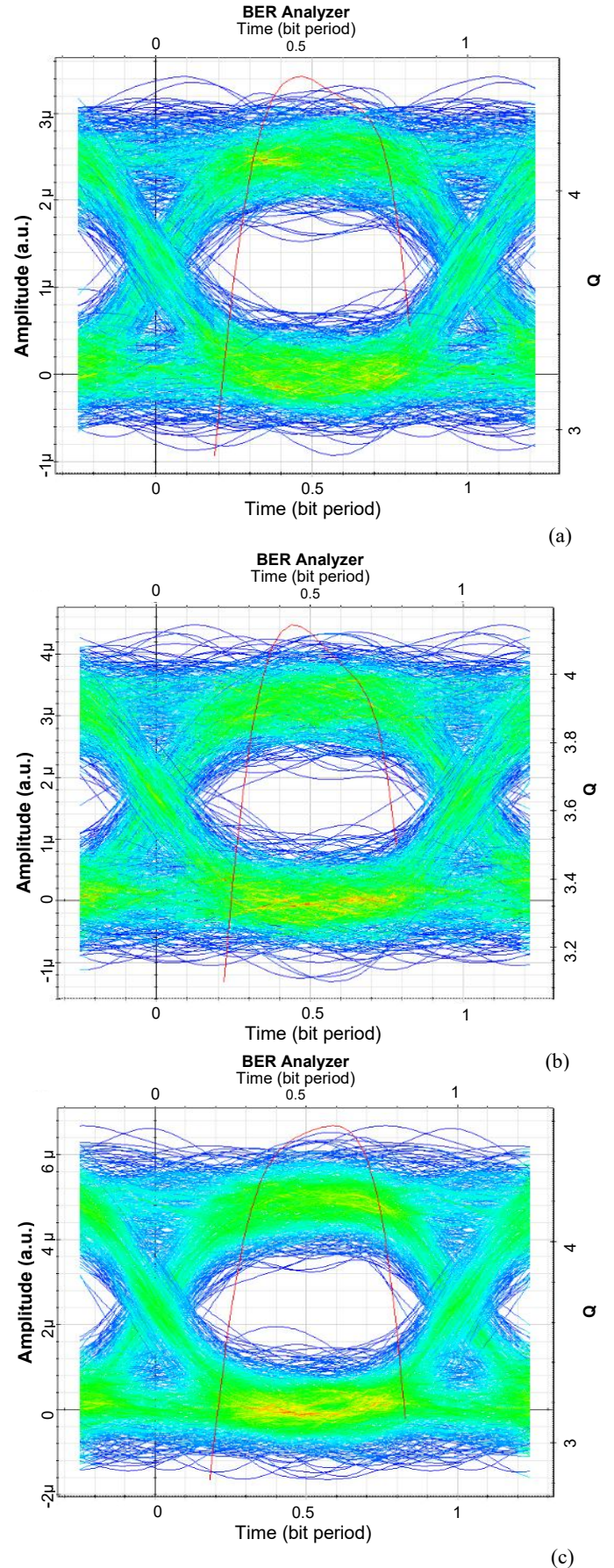


Fig. 9. Eye diagram at (a) 9 m at 2.5 Gbps (b) 8.8 m at 5 Gbps (c) 8.5 m at 10 Gbps for Harbor I water (colour online)

In Harbor II water, the most turbid condition, the ZCC-OCDMA system with three users maintains reliable operation over very short ranges. Fig. 10 (a) shows Q-factor vs. range, staying above 4 dB up to 5.1 m at 2.5 Gbps, 4.9 m at 5 Gbps, and 4.8 m at 10 Gbps. At 4.5 m, Q-factor begins around 14 dB (2.5 Gbps), 11 dB (5 Gbps), and 8 dB (10 Gbps), falling sharply at 2-3 dB per meter due to extreme scattering. The $\log(\text{BER})$ vs. range as reported in Fig. 10 (b) confirms this behavior. At 4.5 m, $\log(\text{BER})$ reach -45 (2.5 Gbps), -28 (5 Gbps), and -15 (10 Gbps). Curves remain below -5 to maximum ranges: about -4.6 at 5.1 m (2.5 Gbps), -4.8 at 4.9 m (5 Gbps), and -4.9 at 4.8 m (10 Gbps). Eye diagrams at maximum ranges (Figs. 11 (a) – (c)) for User 1 show clear signal quality at $Q=4$ dB threshold for Harbor II water.

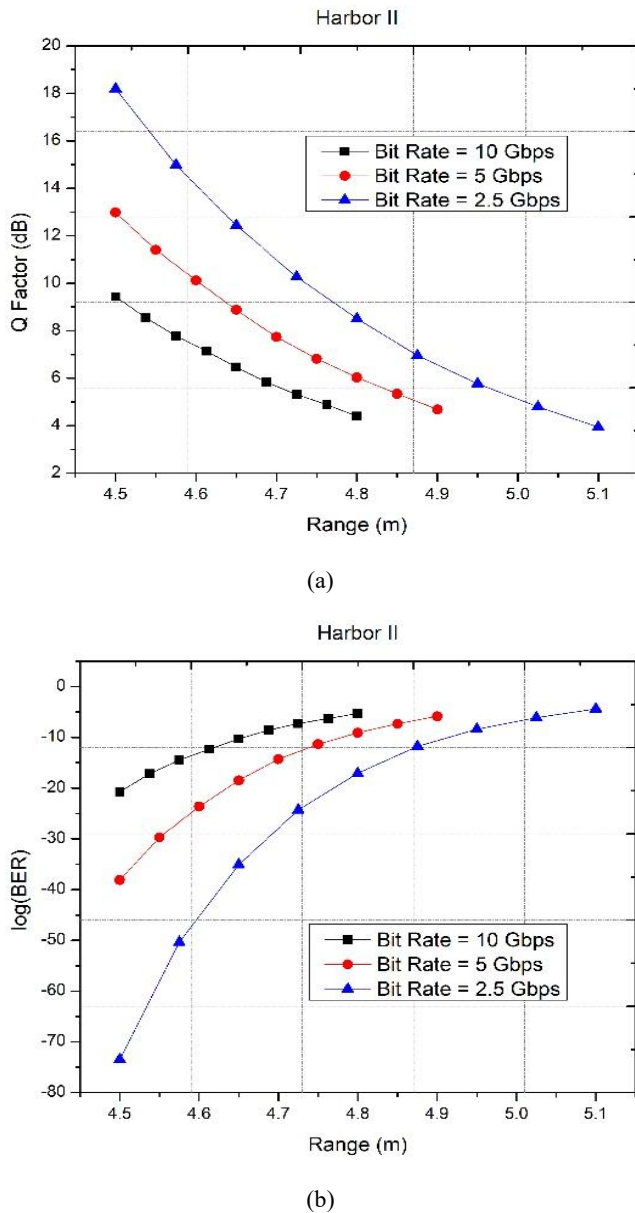


Fig. 10. (a) Q Factor (b) $\log(\text{BER})$ vs. Range for Harbor II water (colour online)

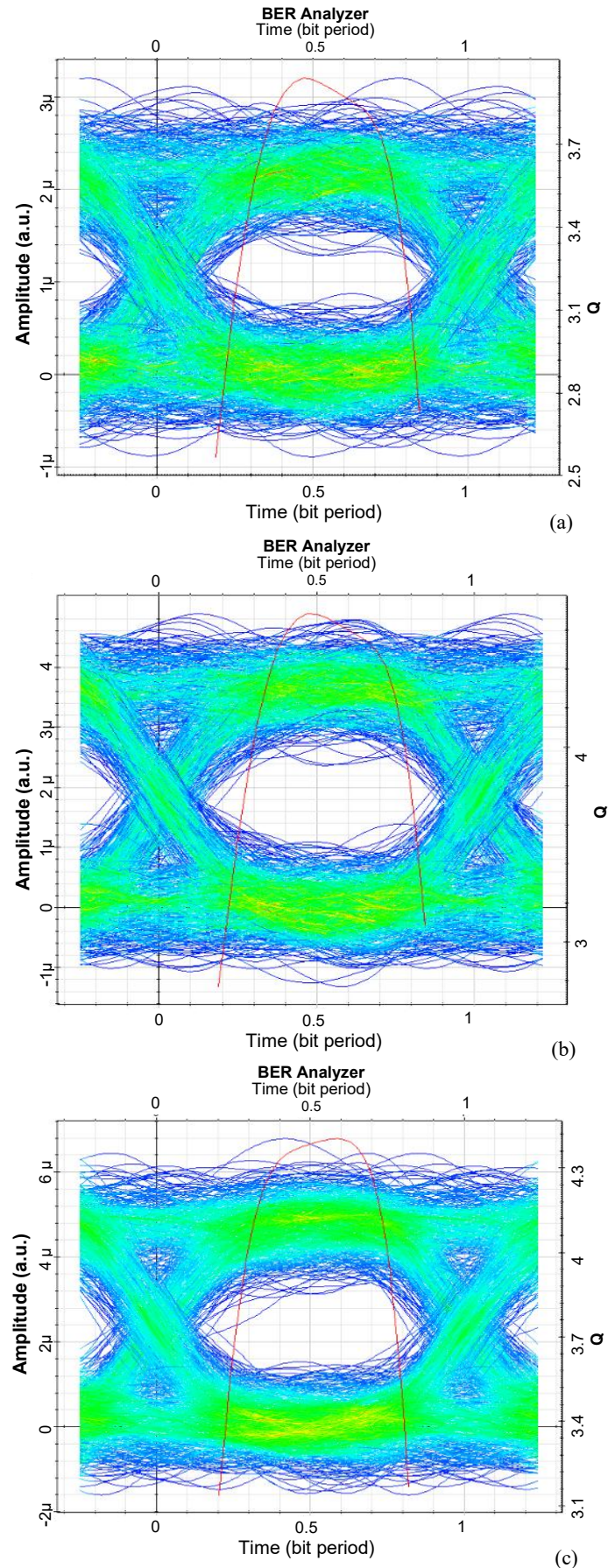


Fig. 11. Eye diagram at (a) 5.1 m at 2.5 Gbps (b) 4.9 m at 5 Gbps (c) 4.8 m at 10 Gbps for Harbor II water (colour online)

4. Conclusion

This paper has examined the performance of ZCC code-based OCDMA for UOWC across five representative water types. The results show that the proposed system can support reliable multi-user underwater links with negligible multiaccess interference, while maintaining acceptable Q-factor and BER performance under different channel conditions. As expected, the transmission range decreases as water turbidity increases, but the system still demonstrates strong suitability for short-to-medium-range underwater communication applications. The study confirms that ZCC-OCDMA is a promising multiplexing technique for underwater sensor networks, autonomous underwater vehicles, and other marine communication systems where interference-free transmission is important. The eye diagrams and performance curves further indicate that the proposed scheme preserves signal quality effectively across the tested data rates. Future work may extend this analysis to a larger number of users, mobility effects, receiver optimization, and experimental validation in practical underwater environments. Overall, the proposed approach offers a useful framework for improving the reliability and efficiency of high-speed underwater optical wireless links.

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