



Performance Analysis of Intelligent Reflecting Surface Assisted Underwater Wireless Optical Communication Systems

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*To my teachers— the silent architects of my thoughts, the strength behind my confidence, and
the reason I learned to see possibilities where others saw limits.*

Certificate

This is to certify that the thesis titled **Performance Analysis of Intelligent Reflecting Surface Assisted Underwater Wireless Optical Communication Systems** is being submitted by **Rehana Salam** to the Indraprastha Institute of Information Technology-Delhi, for the award of the degree of **Doctor of Philosophy**, is an original research work carried out by her under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree/diploma.



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“Somewhere, something incredible is waiting to be known.”

– Carl Sagan, *Cosmos*

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Abstract

The rapid growth of underwater applications such as ocean exploration, environmental monitoring, offshore industries, and maritime defense has created a strong demand for reliable and high-data-rate underwater communication systems. Among the available technologies, underwater wireless optical communication (UWOC) has emerged as a promising solution due to its large bandwidth and low latency compared to conventional acoustic and radio-frequency (RF) systems. However, the performance of UWOC is significantly affected by absorption, scattering, oceanic turbulence, beam misalignment, and frequent link blockages. In addition, maintaining reliable communication in non-line-of-sight (NLoS) conditions remains a critical challenge in practical underwater environments.

To overcome these limitations, this thesis investigates intelligent reflecting surface (IRS)-assisted architectures for enhancing the performance of UWOC systems. The work begins with the analysis of a hybrid RF–UWOC framework, where a programmable RF-based IRS is employed to improve the terrestrial RF link prior to underwater optical transmission. The results demonstrate that IRS-assisted systems provide improved spectral efficiency (SE) and energy efficiency (EE) compared to conventional relaying approaches.

Building on this foundation, the thesis develops optical intelligent reflecting surface (OIRS)-assisted UWOC systems using mechanically adjustable mirror arrays (MAs) to enable passive beam steering and efficient NLoS communication. A comprehensive analytical framework is established to evaluate key performance metrics, including SE, EE, outage probability (OP), and bit error rate (BER) under realistic underwater channel conditions. The results show that OIRS-assisted systems significantly outperform conventional techniques such as plane mirror surfaces (PMS) and total internal reflection (TIR)-based approaches.

The work is further extended to multi-user UWOC scenarios, where efficient resource allocation becomes essential. To address this, intelligent mirror allocation strategies, namely distance-based mirror assignment (DMA) and equal mirror assignment (EMA), are proposed to improve system throughput and user fairness. The performance of these strategies is analyzed

in conjunction with multiple access schemes such as orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA), and rate-splitting multiple access (RSMA), demonstrating improved multi-user performance under varying channel conditions.

Furthermore, advanced optical architectures, including optical simultaneously transmitting and reflecting IRS (OSTAR-IRS) and liquid-crystal-based OSTAR-IRS (LC-OSTAR-IRS), are introduced to enable enhanced flexibility and adaptive beam control. Optimization frameworks are developed to efficiently design transmission and reflection parameters, improving overall system performance in dynamic environments.

Extensive simulation results validate the proposed analytical models and demonstrate significant improvements in reliability, SE, and EE. Overall, this thesis establishes OIRS-assisted UWOC systems as effective and practical solutions for next-generation underwater communication networks, providing both theoretical insights and design guidelines for high-capacity and energy-efficient underwater connectivity.

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Nomenclature

Notations

$\mathcal{R}$	Responsivity of the Photodetector
$CN(\mu, \sigma_n^2)$	Complex Gaussian Distribution with Mean μ and Variance σ_n^2
$\exp(\cdot)$	Exponential Function
$\mathbb{E}[\cdot]$	Expectation Operator
$\Gamma(\cdot)$	Gamma Function
ϱ	Roll Angle of the OSTAR-IRS Element
κ_i	Power Allocation Coefficient for the i^{th} User
$\log_2(\cdot)$	Base-2 Logarithm
$\min(\cdot)$	Minimum Operator
η_w	Refractive Index of Water
η_{LC}	Refractive Index of the Liquid Crystal Element
θ_c	Critical Angle for Total Internal Reflection
ξ^{LC}	Liquid Crystal Transition Coefficient
ζ	Yaw Angle of the OSTAR-IRS Element

Abbreviations

3GPP	3rd Generation Partnership Project
------	------------------------------------

5G	Fifth-Generation
6G	Sixth-Generation
APDs	Avalanche Photodiodes
ASE	Aggregate Spectral Efficiency
AUVs	Autonomous Underwater Vehicles
BER	Bit Error Rate
BS	Base Station
CSI	Channel State Information
DCM	Deep Chlorophyll Maximum
DF	Decode and Forward
DMA	Distance-Based Mirror Assignment
e2e	end-to-end
EE	Energy Efficiency
EGG	Exponential Generalized Gamma
EMA	Equal Mirror Assignment
FoV	Field-Of-View
HD	Half Duplex
IM/DD	Intensity Modulation with Direct Detection
IoT	Internet of Things
IRS	Intelligent Reflecting Surface
LC	Liquid Crystal
LEDs	Light Emitting Diodes
LoS	Line-of-Sight
LPF	Low Pass Filter

MA	Mirror Array
MILP	Mixed-Integer Linear Programming
MIMO	Multiple-input Multiple-output
NLoS	Non-Line-of-Sight
NOMA	Non-Orthogonal Multiple Access
OIRS	Optical Intelligent Reflecting Surface
OMA	Orthogonal Multiple Access
OOK	On-Off Keying
OP	Outage Probability
OSTAR-IRS	Optical Simultaneously Transmitting and Reflecting IRS
OTOPS	Oceanic Turbulence Optical Power Spectrum
PIN	P-Intrinsic-N
PMS	Plane Mirror Surface
PMTs	Photomultiplier Tubes
RF	Radio Frequency
ROVs	Remotely Operated Vehicles
RSMA	Rate Splitting Multiple Access
SE	Spectral Efficiency
SiPM	Silicon Photomultiplier
SNR	Signal-to-Noise Ratio
SPADs	Single-Photon Avalanche Diodes
TDMA	Time-Division Multiple Access
TIR	Total Internal Reflection
UMi	Urban Micro

UWOC	Underwater Wireless Optical Communication
UWSN	Underwater Wireless Sensor Networks
UWVLC	Underwater Visible Light Communication

Introduction

This chapter discusses the motivation and objectives for this work. Further, it also summarizes the dissertation's significant contributions and related publications.

1.1 Motivation

Over the past decade, the rapid expansion of ocean exploration, offshore resource management, environmental monitoring, underwater robotics, and maritime defense systems has created an unprecedented demand for reliable and high-data-rate underwater communication networks [1]. This growing demand aligns with the broader vision of ubiquitous connectivity, which is no longer limited to terrestrial and aerial domains but is increasingly extending to underwater environments [2]. Emerging applications such as underwater wireless sensor networks (UWSNs), autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and underwater Internet of Things (IoT) require robust communication links capable of supporting high throughput with low latency [1, 3].

Traditionally, underwater communication has relied on acoustic and radio frequency (RF) technologies. Acoustic communication provides long communication ranges but suffers from extremely low data rates and significant propagation delay [3]. RF communication, although more tolerant to turbulence and capable of crossing air–water boundaries, is limited to short communication ranges due to severe attenuation in water [4]. In contrast, underwater wireless optical communication (UWOC) has emerged as a promising alternative due to its ability to provide ultra-high data rates, low latency, and enhanced security [1, 5, 6]. The blue-green wavelength range (approximately 450–550 nm) exhibits the lowest attenuation in seawater, enabling high-speed optical communication over moderate distances [7].

Despite its advantages, UWOC faces several fundamental challenges. Optical signals propagating underwater experience severe absorption, scattering, turbulence-induced fading, beam divergence, and misalignment errors [5, 8]. Furthermore, due to obstacles and the dynamic nature of the underwater environment, line of sight (LoS) communication is often unreliable or unavailable. Non-line-of-sight (NLoS) communication therefore becomes essential for practical deployment. Conventional NLoS UWOC systems typically rely on total internal reflection (TIR) at the water–air interface. However, such approaches are restricted to shallow-water scenarios and are highly sensitive to sea surface variations, thereby limiting their applicability in deep-sea environments.

To overcome these limitations, recent advances in intelligent reflecting surface (IRS) have demonstrated the potential of manipulating electromagnetic wave propagation in wireless systems [9, 10]. In terrestrial RF communication, programmable IRS structures have been successfully used to enhance spectral efficiency (SE) and energy efficiency (EE) by intelligently controlling the phase of reflected signals without active retransmission [11]. Motivated by these developments, hybrid RF–UWOC systems employing RF-based IRS in the terrestrial link have been analyzed to improve end-to-end performance [12].

While RF-based IRS enhances terrestrial connectivity, directly controlling optical propagation within underwater environments requires optical intelligent reflecting surface (OIRS). Optical implementations can broadly be categorized into metasurface-based designs and mirror-array (MA)-based designs [13]. Although metasurfaces offer fine-grained control at subwavelength scales, they are technologically complex and not yet commercially mature at optical frequencies [9]. In contrast, MA-based OIRS provides a structurally simple, cost-effective, and analytically tractable solution. By mechanically adjusting the angular orientation of individual mirror elements, MA-based OIRS enables passive beam steering and coherent signal redirection without active power amplification [14].

Despite the growing interest in IRS-assisted wireless systems and recent explorations of optical reflective structures, several critical challenges remain insufficiently addressed in the context of underwater environments. Existing studies on hybrid RF–UWOC systems primarily emphasize conventional relaying mechanisms, with limited analytical characterization of IRS-assisted architectures in mixed RF–optical scenarios [15]. Furthermore, systematic modeling of submerged MA-based OIRS under realistic underwater channel impairments including absorption, scattering effects, turbulence-induced fading, pointing errors, and depth-dependent variations remains limited in the literature. Most existing NLoS UWOC approaches rely on TIR-based mechanisms that are inherently constrained to shallow-water conditions and lack controllable beam steering capabilities suitable for deep-sea deployment [16, 17].

Moreover, communication systems are inherently designed to serve multiple users; therefore, they employ various multiple access techniques to efficiently allocate resources such as time, frequency, power, and code [18]. The application of multiple access schemes in UWOC systems has been widely analyzed in the literature. In particular, techniques such as orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA), and rate-splitting multiple access (RSMA) have been explored to enhance spectral efficiency (SE) and system capacity in underwater optical networks [19–22]. However, the integration of these advanced multiple access strategies with OIRS-assisted UWOC systems, particularly in multi-user scenarios involving intelligent mirror allocation, has received limited attention in the literature.

Emerging architectures such as optical simultaneously transmitting and reflecting IRS (OSTAR-IRS) introduce additional degrees of freedom through simultaneous transmission and reflection [23, 24]. To the best of the author’s knowledge, this dissertation presents the first investigation of liquid-crystal (LC) enabled OSTAR-IRS architectures for UWOC systems. The proposed LC-OSTAR-IRS enables tunable beam steering and dynamic environmental adaptation in underwater optical environments. However, optimization frameworks for transmission and reflection coefficients, rigorous analytical performance characterization, and practical system-level design methodologies for OSTAR-IRS and LC-OSTAR-IRS-assisted UWOC systems remain underexplored.

Therefore, there exists a need for unified analytical modeling and optimization approaches that systematically model, analyze, and compare OIRS-assisted UWOC architectures under practical underwater channel conditions. Addressing these gaps is essential for enabling energy-efficient, scalable, and robust underwater communication systems capable of supporting future ubiquitous underwater connectivity.

Motivated by the above challenges and research gaps, this dissertation aims to develop comprehensive analytical frameworks and optimization techniques for IRS and OIRS-assisted UWOC systems, with particular emphasis on SE, EE, reliability, and multi-user performance in practical underwater environments.

1.2 Objectives

This dissertation aims to address the following specific research objectives:

- **Performance analysis of hybrid RF–UWOC systems:** To investigate the end-to-end performance of a mixed RF–UWOC architecture employing a programmable RF-based IRS in the terrestrial link. The objective is to analytically evaluate SE, EE, outage probability (OP), and bit error rate (BER), and to compare the IRS-assisted system with conventional decode and forward (DF) relaying schemes.

- **Analytical modeling of MA-based OIRS-assisted UWOC systems:** To develop a comprehensive analytical framework for submerged MA-based OIRS-assisted UWOC systems under realistic underwater channel impairments, including absorption, scattering, Exponential Generalized Gamma (EGG) turbulence, and pointing errors.
- **Comparative analysis of NLoS UWOC architectures:** To evaluate and compare the performance of conventional TIR-based systems, plane mirror surface (PMS)-assisted systems, and MA-based OIRS-assisted systems, particularly under NLoS conditions and varying ocean depths.
- **Multi-user mirror allocation strategies:** To design and analyze mirror element allocation schemes, including equal mirror assignment (EMA) and distance-based mirror assignment (DMA), for improving fairness and maximizing average sum rate in multi-user UWOC scenarios.
- **Integration of multiple access techniques:** To investigate the integration of OMA, NOMA, and RSMA with OIRS-assisted UWOC systems for enhanced multi-user performance.
- **OSTAR-IRS transmission-reflection coefficient optimization:** To formulate and solve the joint transmission and reflection coefficient optimization problem for OSTAR-IRS systems in order to maximize SE under practical constraints. The resulting non-convex optimization problem is addressed using constrained nonlinear programming via *fmincon* and mixed-integer linear programming (MILP).
- **Investigation of LC-OSTAR-IRS-assisted UWOC systems:** To analyze LC-OSTAR-IRS architectures for adaptive optical control, including mode selection strategies and aggregate spectral efficiency (ASE) effects in underwater environments.

1.3 Contributions

The major contributions of this dissertation are summarized below in chronological order along with the relevant publications.

- **Hybrid RF-UWOC system with RF-based IRS (2022):**

The performance of a mixed RF-UWOC system employing a programmable RF-based IRS in the terrestrial link is evaluated. A comparative analysis between IRS-assisted transmission and conventional DF relaying is conducted in terms of SE, EE, OP, and BER.

Closed-form analytical expressions are derived to characterize the end-to-end system performance under realistic channel conditions.

- R. Salam, A. Srivastava, V. A. Bohara, and A. Ashok, “Performance Comparison of IRS and DF Relay Assisted Mixed RF–Underwater Optical Communication System,” *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, Gandhinagar, India, 2022, pp. 129–134.

- **MA-based OIRS-assisted UWOC system (2023):**

A submerged MA-based OIRS-assisted UWOC system is introduced for NLoS communication. Analytical expressions for SE, EE, OP, and BER are derived by incorporating absorption, scattering and EGG turbulence effects. The performance of MA-based OIRS-assisted systems is compared with PMS and conventional TIR-based NLoS architectures.

- R. Salam, A. Srivastava, V. A. Bohara, and A. Ashok, “An Optical Intelligent Reflecting Surface-Assisted Underwater Wireless Communication System,” *IEEE Open Journal of the Communications Society*, vol. 4, pp. 1774–1786, 2023.

- **Dynamic mirror element allocation for multi-user UWOC (2023–2025):**

Multi-user MA-based OIRS-assisted UWOC system is investigated by proposing intelligent mirror allocation strategies, including EMA and DMA, to enhance fairness and maximize average sum rate. The analytical framework incorporates underwater attenuation, turbulence, pointing errors and depth-dependent channel variations.

- R. Salam, A. Srivastava, V. A. Bohara, and A. Ashok, “Dynamic Element Allocation for Optical IRS-Assisted Underwater Wireless Communication System,” *IEEE Global Communications Conference (GLOBECOM)*, Kuala Lumpur, Malaysia, 2023, pp. 4692–4697.
- R. Salam, V. A. Bohara, and A. Srivastava, “Smart Element Allocation Strategies for Dynamic Optical IRS in Underwater Wireless Communication,” *IEEE Transactions on Vehicular Technology*, vol. 74, no. 3, pp. 4349–4361, March 2025.

- **Advanced OIRS architectures: OSTAR-IRS and LC-OSTAR-IRS (2025–2026):**

Advanced OIRS architectures are developed to further enhance UWOC performance. First, OSTAR-IRS is introduced to enable simultaneous transmission and reflection for serving multiple users. A joint optimization framework is formulated to maximize SE by optimizing transmission and reflection coefficients under practical constraints.

The resulting non-convex optimization problem is solved using constrained nonlinear programming via *fmincon* and MILP.

Further, a tunable LC-OSTAR-IRS architecture is introduced to enable adaptive optical beam steering and dynamic environmental control. The impact of LC tunability, mode selection strategies, and ASE effects are analyzed.

- R. Salam, V. A. Bohara, and A. Srivastava, "Optical Multi-STAR-IRS Assisted Underwater Wireless Communication System," *IEEE Transactions on Green Communications and Networking*, vol. 10, pp. 3312–3323, 2026.
- R. Salam and V. A. Bohara, "LC-OSTAR-IRS: Tunable Liquid Crystal Surfaces for High-Performance UWOC," *IEEE Wireless Communications Letters*, vol. 15, pp. 1305–1309, 2026.

1.4 Other Contributions

Apart from the main contributions discussed in this dissertation, the author has also contributed to the following research works, which are closely related to intelligent optical surface design, experimental validation, and advanced UWOC system architectures.

- R. Salam, V. A. Bohara, and K. Joshi, "Circular Optical Intelligent Reflecting Surface Assisted Underwater Wireless Communication System," *IEEE Future Networks World Forum (FNWF)*, Bangalore, India, 2025, pp. 1–6.
- K. Joshi, R. Salam, and V. A. Bohara, "Experimental Validation for a Circular Optical Reflective Intelligent Surface Aided Indoor Visible Light Communication," under review in *IEEE Wireless Communications Letters*, 2026.
- R. Salam and V. A. Bohara, "OSTAR-IRS Assisted Underwater Wireless Optical Communication Systems: NOMA, RSMA, and Duplexing Perspectives," under review in *IEEE Wireless Communications Magazine*, 2026.
- R. Salam and V. A. Bohara, "Footprint-Aware OIRS Design for Enhanced NLoS UWOC Systems," under review in *IEEE ANTS*, 2026.
- R. Salam and V. A. Bohara, "LC-Prism-OSTAR-IRS for UWOC: Beam Steering with RSMA-Based Multi-User Communication," under review in *IEEE GLOBECOM Workshops*, 2026.

- R. Salam and V. A. Bohara, "Adaptive LC-Assisted Hybrid Prism–Metasurface OSTAR-IRS for Underwater Wireless Optical Communication," under review in *IEEE Transactions on Wireless Communications*, 2026.

Patents:

- R. Salam, K. Joshi and V. A. Bohara, "Circular Optical Intelligent Reflective Surface (C-OIRS): Apparatus and System Thereof," Indian Patent Application No. 202411100855, Application Date: 19/12/2024.
- R. Salam and V. A. Bohara, "Liquid-Crystal-Based OSTAR-IRS Assisted Underwater Wireless Optical Communication System and Method Thereof," Indian Patent Application No. 202511100371, Application Date: 16/10/2025.
- R. Salam and V. A. Bohara, "Hexagonal Optical Intelligent Reflecting Surface with Circular Grid Pattern for Non-Line-of Sight Optical Wireless Communication," Indian Patent Application No. 202611028169, Application Date: 10/03/2026.
- R. Salam and V. A. Bohara, "A Prism-based Optical Simultaneously Transmitting and Reflecting Intelligent Reflecting Surface for Underwater Wireless Optical Communication Systems," Indian Patent Application No. 202611055545, Application Date: 30/04/2026.

These works are not discussed in detail in this dissertation; however, they are relevant as they extend the theoretical frameworks toward practical implementations, experimental validation, architectural generalization, and translational research in OIRS-assisted UWOC systems.

1.5 Organization of the Thesis

The remainder of this dissertation is organized as follows:

- **Chapter 2** provides the necessary background and reviews the related literature pertinent to this dissertation. It outlines the fundamentals of UWOC, including absorption and scattering phenomena, turbulence modeling, and pointing error effects. The basic principles of IRS and OIRS are introduced, followed by a comprehensive review of RF–UWOC hybrid systems and OIRS-assisted underwater communication architectures.
- **Chapter 3** investigates the performance of a hybrid RF–UWOC system incorporating a programmable RF-based IRS in the terrestrial link. Closed form analytical expressions for SE, EE, OP, and BER are derived. A detailed comparison between IRS-assisted transmission and conventional DF relaying is presented.

- **Chapter 4** develops a comprehensive analytical framework for MA-based OIRS-assisted UWOC systems under NLoS conditions. The analysis incorporates absorption, scattering effects, and EGG turbulence models. The proposed architecture is compared with PMS and TIR-based systems.
- **Chapter 5** extends the MA-based OIRS-assisted framework to multi-user UWOC scenarios. Intelligent mirror allocation strategies, namely EMA and DMA, are formulated to enhance fairness and maximize ASE. The integration of OMA, NOMA, and RSMA schemes is analyzed to evaluate multi-user performance under practical underwater channel conditions.
- **Chapter 6** introduces advanced OIRS architectures for UWOC systems. The concept of OSTAR-IRS is presented, and a joint transmission–reflection coefficient optimization framework is formulated using constrained nonlinear programming and MILP. Furthermore, LC-OSTAR-IRS architectures are analyzed to enable adaptive optical beam steering and dynamic environmental control.
- **Chapter 7** presents a geometry-driven performance analysis of LC-OSTAR-IRS-assisted UWOC systems. The impact of angular-dependent Fresnel reflection, refraction, and TIR conditions is examined. Deployment guidelines and performance trade-offs are established through detailed SE and fairness analysis.
- **Chapter 8** concludes the dissertation by summarizing the major findings and contributions. It also outlines potential future research directions in IRS and OIRS-assisted UWOC systems, including advanced intelligent surface designs and hybrid underwater communication frameworks.

Background and Related Work

This chapter provides the necessary background on underwater wireless optical communication (UWOC) and intelligent reflecting surface (IRS) technology.

2.1 Underwater Wireless Optical Communication (UWOC)

2.1.1 Motivation for UWOC

The increasing deployment of underwater wireless sensor networks (UWSNs), autonomous underwater vehicles (AUVs), and remotely operated vehicles (ROVs) has intensified the need for reliable and high-data-rate underwater communication systems. Such systems are essential for applications including ocean exploration, environmental monitoring, offshore infrastructure inspection, disaster prevention, and maritime defense. Enabling efficient data exchange among these underwater platforms remains a fundamental challenge due to the unique propagation characteristics of the aquatic environment [25–27].

Traditionally, underwater communication has relied on acoustic and radio frequency (RF) technologies. Acoustic communication supports long transmission distances; however, it suffers from extremely limited bandwidth, high propagation delay, severe multipath effects, and Doppler spread [28, 29]. These limitations significantly restrict achievable data rates and increase communication latency. Conversely, RF communication experiences strong attenuation in seawater due to its high electrical conductivity, which limits practical communication ranges to only a few meters. Consequently, RF systems are generally unsuitable for medium and long-range underwater communication [5, 28].

To overcome these limitations, UWOC has emerged as a promising alternative capable of providing significantly higher data rates and lower latency compared to acoustic and RF systems

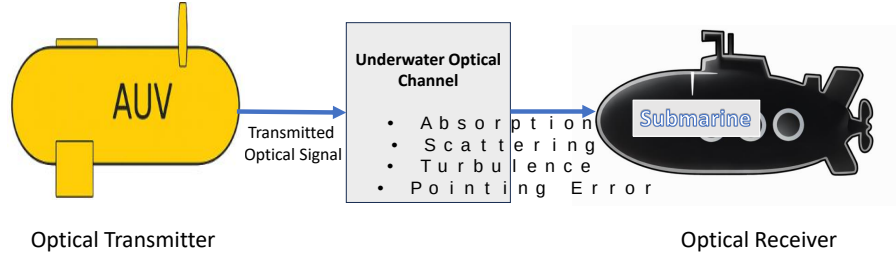


Figure 2.1: Generalized architecture of an underwater wireless optical communication (UWOC) system, consisting of an optical transmitter, underwater propagation channel with impairments, and an optical receiver.

[1, 5, 27, 28]. Optical transmission within the blue–green spectral window (approximately 450–550 nm) experiences relatively lower attenuation in seawater, enabling high-speed data transmission over moderate distances [30]. These characteristics make UWOC particularly attractive for applications that require high-capacity underwater links.

Despite these advantages, UWOC systems are affected by several physical impairments associated with underwater optical propagation. Absorption and scattering reduce signal strength as optical waves propagate through water [30, 31], while temperature and salinity variations introduce refractive index fluctuations that cause turbulence-induced fading [32–35]. Additionally, beam divergence and misalignment caused by platform mobility and underwater currents can further degrade link reliability [36–38]. These impairments collectively limit the achievable communication range and reliability of UWOC systems.

Therefore, accurate system modeling and realistic channel characterization are essential for the design and performance evaluation of UWOC systems. The following subsection presents the generalized architecture of a UWOC system.

2.1.2 Generalized UWOC System Architecture

A generalized UWOC system consists of three primary components: an optical transmitter, an underwater propagation channel, and an optical receiver as shown in Fig. 2.1.

At the transmitter, the electrical information signal is converted into optical intensity using intensity modulation techniques. Typically, intensity modulation with direct detection (IM/DD)

is employed due to its practical simplicity and compatibility with optical sources such as light-emitting diodes (LEDs) and laser diodes [1, 5]. The modulated optical signal is then launched into the underwater medium.

During propagation, the optical signal experiences attenuation due to absorption and scattering effects. Absorption reduces the optical energy of the transmitted signal, whereas scattering redistributes photons in different directions, leading to power loss and potential temporal dispersion [30, 31]. In addition to attenuation, underwater optical links are affected by turbulence-induced irradiance fluctuations caused by temperature and salinity variations [32–35]. Beam divergence and geometric spreading also influence the received power, particularly in long-distance links [36–38].

At the receiver, a photodetector, commonly a photodiode or silicon photomultiplier (SiPM) converts the received optical power into an electrical signal. The detected signal is subsequently amplified and processed to recover the transmitted information.

Depending on the deployment scenario, UWOC systems may operate under line-of-sight (LoS) or non-line-of-sight (NLoS) conditions. In LoS configurations, a direct optical path exists between the transmitter and receiver. Narrow-divergence laser sources are often used to maximize received power; however, precise alignment is required to maintain link stability. In practical underwater environments, obstacles, platform mobility, and environmental disturbances may disrupt the LoS path. Under such conditions, alternative transmission strategies are required to maintain connectivity [1, 5, 6].

The generalized UWOC architecture described above forms the foundation for channel modeling and analytical developments presented in the following subsections.

2.1.3 Underwater Wireless Optical Channel Modeling

A typical UWOC system consists of an optical transmitter, an underwater propagation channel, and an optical receiver. Under IM/DD, which is widely adopted in practical UWOC implementations, information is encoded onto the optical intensity of the transmitted signal and directly detected at the receiver. Since IM/DD systems depend directly on the instantaneous channel gain to determine the received signal amplitude, accurate modeling of the underwater optical channel is essential for reliable system design and performance evaluation.

Unlike terrestrial free-space optical (FSO) links, underwater optical propagation is strongly influenced by absorption, scattering, refractive index fluctuations, and beam misalignment. These effects jointly determine the received optical power. To capture these physical impairments, the instantaneous underwater optical channel coefficient is modeled as a composite of deterministic and stochastic components given by [39–41]:

$$h = h_{att} h_{\alpha} h_m, \quad (2.1)$$

where h_{att} denotes attenuation due to absorption and scattering, h_{α} represents turbulence-induced fading, and h_m models the pointing error effect.

2.1.3.1 Attenuation Modeling

As an optical beam propagates through water, its intensity decays exponentially due to absorption and scattering phenomena. Absorption converts optical energy into other forms such as heat, while scattering redistributes photons away from the original propagation direction. The deterministic attenuation component follows the Beer–Lambert law and is expressed as [30, 31]:

$$h_{att} = e^{-c(\lambda)d}, \quad (2.2)$$

where d denotes the propagation distance and $c(\lambda)$ is the extinction coefficient defined as the sum of the absorption coefficient $a(\lambda)$ and the scattering coefficient $b(\lambda)$, i.e., $c(\lambda) = a(\lambda) + b(\lambda)$. The extinction coefficient depends on the operating wavelength and the type of water medium, such as clear ocean, coastal, or harbor water. Increased turbidity and suspended particle concentration lead to larger values of $c(\lambda)$, thereby reducing the achievable communication range. This component represents the large-scale path loss of the underwater optical channel.

2.1.3.2 Turbulence Modeling

Underwater optical links experience stochastic irradiance fluctuations due to refractive index inhomogeneities. These variations arise from temperature gradients, salinity changes, and pressure fluctuations within the aquatic medium, resulting in turbulence-induced fading.

To statistically characterize underwater turbulence over weak-to-strong regimes, the Exponential Generalized Gamma (EGG) distribution is adopted due to its flexibility and ability to accurately match experimental data. The probability density function (PDF) of the turbulence-induced fading coefficient h_{α} is expressed as a weighted mixture of Exponential and Generalized Gamma distributions given by [32–35]:

$$f_{h_{\alpha}}(x) = n \frac{1}{\Lambda} \exp\left(-\frac{x}{\Lambda}\right) + (1-n) \frac{c x^{ac-1}}{b^{ac} \Gamma(a)} \exp\left[-\left(\frac{x}{b}\right)^c\right], \quad x \geq 0, \quad (2.3)$$

where $0 < n < 1$ is the mixture parameter controlling the relative contribution of weak and strong turbulence components, Λ is the mean of the exponential component, a , b , and c are

shaping parameters of the Generalized Gamma distribution, and $\Gamma(\cdot)$ denotes the gamma function. The exponential term captures weak turbulence conditions, while the generalized gamma component models moderate-to-strong irradiance fluctuations. The EGG model thus provides a unified statistical framework capable of representing various underwater turbulence environments.

2.1.3.3 Pointing Error Modeling

Beam misalignment may occur due to underwater currents, mechanical vibrations, and node mobility. Such misalignment reduces the fraction of collected optical power at the receiver and introduces additional fading. The impact becomes particularly significant in narrow-divergence laser-based systems, where small angular deviations can result in substantial power loss.

Assuming zero-boresight displacement, the PDF of the pointing error fading coefficient h_m is given by [36–38]:

$$f_{h_m}(h_m) = \frac{\rho^2}{A_0^{\rho^2}} h_m^{\rho^2-1}, \quad 0 \leq h_m \leq A_0, \quad (2.4)$$

where A_0 represents the maximum fraction of collected optical power under perfect alignment and is defined as $A_0 = \text{erf}(v)^2$, with $v = \sqrt{\frac{\pi}{2}} \frac{r}{n_z}$. In this formulation, r denotes the receiver aperture radius, n_z represents the beam width at the receiver plane, $\rho = \frac{n_{zeq}}{2\sigma_s}$ is the pointing error parameter, n_{zeq} denotes the equivalent beam width at the receiver, and σ_s^2 represents the variance of the pointing error displacement due to horizontal sway and elevation fluctuations. Larger values of ρ correspond to weaker misalignment effects, whereas smaller values indicate stronger pointing-induced fading.

The composite channel model in (2.1) therefore captures deterministic attenuation, turbulence-induced stochastic fading, and misalignment effects within a unified analytical framework. This representation forms the basis for the received signal model presented in the subsequent subsection.

2.1.4 Received Signal Model

Under IM/DD, the transmitted information is modulated onto the optical intensity of the carrier. Since optical intensity is inherently non-negative, the transmitted signal must satisfy the constraint $x(t) \geq 0$. Let $x(t)$ denote the transmitted optical intensity waveform and P_t denote the average transmitted optical power.

Considering the composite underwater optical channel coefficient defined in (2.1), the instantaneous received optical power can be expressed as:

$$P_r(t) = P_t h x(t), \quad (2.5)$$

where $h = h_{att} h_\alpha h_m$ represents the overall channel gain incorporating attenuation, turbulence-induced fading, and pointing error effects.

At the receiver, a photodetector converts the received optical power into an electrical signal. The generated photocurrent is proportional to the incident optical power and is given by:

$$y(t) = \mathcal{R} P_t h x(t) + n, \quad (2.6)$$

where $\mathcal{R}$ denotes the responsivity of the photodetector (A/W), and n represents the additive noise component. The noise term typically includes contributions from shot noise due to the discrete nature of photons and thermal noise originating from the receiver circuitry. For analytical tractability, n is commonly modeled as additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2 .

Since IM/DD systems operate in the intensity domain, the received signal in (2.6) is multiplicative in the channel gain h and differs fundamentally from coherent RF systems, where fading affects the complex baseband signal. The non-negative and multiplicative nature of the underwater optical channel directly influences the statistical characterization of system performance metrics such as outage probability (OP) and spectral efficiency (SE).

The received signal model in (2.6) forms the basis for subsequent analytical performance evaluation of UWOC systems under composite fading conditions.

2.1.5 Related Work on UWOC

UWOC has gained significant research attention due to its capability to provide high data rates and low latency compared to acoustic and RF-based underwater communication systems [1, 26]. The severe bandwidth limitations and propagation delays of acoustic communication, along with the strong attenuation experienced by RF waves in seawater, have motivated the exploration of optical transmission within the blue–green spectral window [5, 29].

Initial investigations focused on characterizing absorption and scattering mechanisms in underwater environments. The survey in [1, 5, 6, 30] presented a detailed analysis of attenuation coefficients for different water types and demonstrated the feasibility of UWOC links over moderate distances. Monte Carlo based channel modeling techniques were later developed to accurately capture photon propagation in underwater media and characterize absorption and scattering effects [31, 42]. Experimental studies have confirmed the wavelength-dependent nature of underwater attenuation and the impact of turbidity on transmission range [6]. These observations are further summarized and discussed in recent survey works [27].

Statistical modeling of turbulence-induced fading has also been extensively studied. Refractive index fluctuations arising from temperature gradients, salinity variations, and pressure differences introduce stochastic irradiance variations in UWOC channels. Zedini *et al.* proposed a unified statistical framework to model turbulence-induced fading based on experimental data [43]. Jamali *et al.* characterized turbulence effects caused by air bubbles, temperature variations, and salinity fluctuations through extensive statistical analysis [33]. Subsequently, several works explored stochastic channel models for UWOC links under different environmental conditions [35, 44]. These studies provided flexible statistical tools for modeling underwater turbulence under diverse environmental conditions.

Several studies have analyzed the performance of LoS and NLoS UWOC configurations. Tang *et al.* evaluated NLoS-UWOC path loss through Monte Carlo simulations, emphasizing the impact of sea surface slopes and scattering properties on signal degradation [17]. Yildiz *et al.* derived analytical path loss expressions for reflector-assisted underwater optical links and experimentally validated the proposed models [45]. The authors in [16] examined LoS and NLoS configurations in underwater sensor networks while accounting for channel characteristics and communication parameters.

Another important impairment in UWOC systems is beam misalignment between the transmitter and receiver. Misalignment can occur due to platform motion, water currents, and pointing inaccuracies, which significantly degrade link reliability. Gabriel *et al.* analyzed misalignment effects in point-to-point UWOC links and demonstrated their impact on system performance [36]. More recently, Ghazy *et al.* analyzed angular multiple-input multiple-output (MIMO) architectures to improve alignment robustness and tracking capabilities in UWOC systems [37]. Analytical performance analysis of UWOC links under combined turbulence and pointing errors was further studied in [38].

Hybrid terrestrial-underwater architectures have been proposed to extend communication coverage and enhance system reliability. In [46], a mixed FSO-UWOC dual-hop transmission system was analyzed assuming Gamma-Gamma fading for the FSO link and EGG fading with pointing errors for the UWOC link. Closed-form expressions for OP, average BER, and average capacity were derived. Similarly, mixed RF-UWOC systems incorporating relaying techniques were investigated in [47], where outage and BER performance were evaluated under different water types. These studies demonstrate the feasibility of integrating UWOC with terrestrial communication technologies to overcome range limitations.

More recently, multi-user UWOC systems have been analyzed to improve spectral utilization. Elamassie *et al.* analyzed non-orthogonal multiple access (NOMA) based underwater visible light communication (VLC) systems under log-normal turbulence conditions [19]. Jain *et al.* derived analytical BER and average capacity expressions for NOMA-based underwater

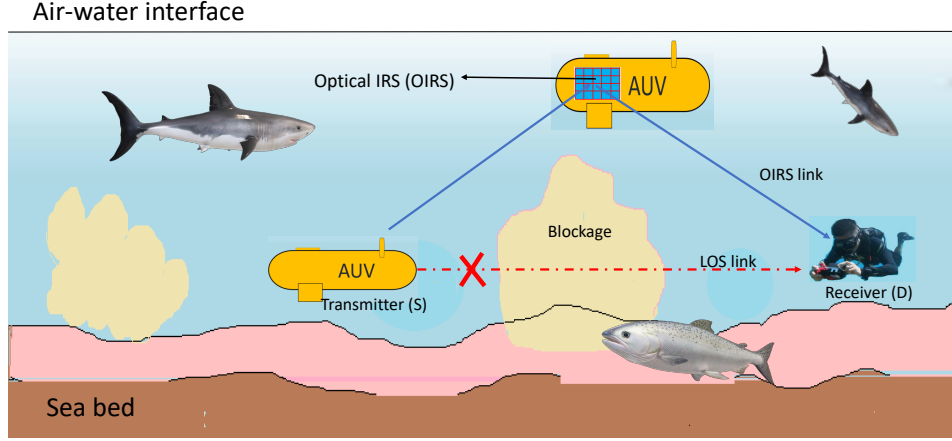


Figure 2.2: Illustration of an optical intelligent reflecting surface (OIRS)-assisted underwater wireless optical communication (UWOC) system, showing the transmitter, OIRS-enabled reflected link, and receiver.

visible light communication (UWVLC) systems under EGG fading [20]. Rate-splitting multiple access (RSMA) was introduced in UWOC systems to enhance ergodic rate performance under turbulence-induced fading [21, 22]. These studies highlight the increasing interest in advanced multi-user strategies for underwater optical networks.

Despite significant progress in attenuation modeling, turbulence characterization, LoS/NLoS system design, hybrid architectures, and multi-user access techniques, UWOC systems remain fundamentally constrained by severe attenuation, stochastic fading, and misalignment effects. These limitations motivate the exploration of advanced architectural enhancements capable of reconfiguring the propagation environment to improve reliability and SE. The following section introduces IRS technology as a promising approach to address these challenges.

2.2 Intelligent Reflecting Surfaces (IRS)

2.2.1 Motivation

Conventional wireless communication systems are traditionally designed by optimizing transmitter and receiver architectures while treating the propagation medium as an uncontrollable component [11, 14]. However, signal degradation in practical environments often arises due to blockage, severe path loss, shadowing, and NLoS conditions [48]. Increasing transmit power

or employing complex receiver processing alone is insufficient to overcome these limitations in a power-efficient manner.

IRS technology has emerged as a transformative paradigm that enables dynamic manipulation of the propagation environment. Unlike conventional relays that actively amplify and retransmit signals, IRS operate passively by adjusting the reflection characteristics of incident electromagnetic waves without generating additional transmit power. This passive operation results in enhanced energy efficiency (EE), reduced hardware complexity, and improved reliability [10, 14].

With the global commercialization of fifth-generation (5G) wireless networks, research efforts have rapidly shifted toward sixth-generation (6G) communication systems. The anticipated requirements of 6G networks include peak data rates on the order of $1 \sim 10$ Tbit/s, ultra-high connection density of up to 10^7 devices/km², and EE improvements of $10 \sim 100$ times compared to 5G systems [49]. These stringent performance targets necessitate innovative paradigms capable of enhancing SE while maintaining low power consumption. IRS, by transforming the wireless propagation environment into a smart reconfigurable medium [14], are considered one of the key enabling technologies for 6G networks [50].

Although IRS have been extensively studied in RF systems, their extension to optical frequencies has led to the development of OIRS. In UWOC systems, severe attenuation, turbulence-induced fading, and pointing errors significantly constrain communication range and link reliability. The capability of OIRS to dynamically redirect optical beams provides an effective mechanism to overcome blockage and enhance received signal strength in underwater environments. This motivates the investigation of OIRS for UWOC systems.

2.2.2 General Architecture and OIRS Fundamentals

An IRS consists of a planar array of programmable reflecting elements. In RF systems, these elements electronically adjust phase shifts to control the reflection of incident signals and achieve coherent beamforming gains [51]. This capability allows the wireless propagation environment to be dynamically reconfigured in order to improve link reliability and coverage.

At optical frequencies, intelligent reflection is achieved using OIRS, which are broadly classified into mirror-array (MA)-based and meta-surface-based structures [13, 52].

MA-based OIRS consists of multiple controllable micro-mirror elements arranged in a planar configuration. Each mirror can be mechanically rotated using micro-electro-mechanical systems (MEMS), enabling precise steering of incident optical beams toward desired directions [10]. By appropriately adjusting the orientation of individual mirrors, the reflected optical signal can be redirected toward the receiver to enhance the received signal strength. The

operation follows geometric reflection principles, making it analytically tractable for IM/DD based systems.

Meta-surface-based OIRS consists of sub-wavelength optical structures capable of manipulating the phase, amplitude, and polarization of incident waves [52]. Although meta-surfaces offer fine-grained wavefront control, fabrication complexity and technological maturity challenges make MA-based designs more practical for UWOC applications [53].

2.2.3 OIRS Channel Modeling for UWOC Systems

We consider a planar mirror-array-based OIRS composed of an equal number of rows and columns, containing n_m^2 mirror elements as shown in Fig. 2.2. Each mirror element has dimensions $\ell_m \times w_m$, where ℓ_m and w_m denote the length and width of the mirror element, respectively.

The channel gain of the reflected signal from the k^{th} row and l^{th} column OIRS element toward the user is expressed as [54, 55]:

$$G_{O_{k,l}}(\zeta, \varrho) = \begin{cases} R^{OIRS} \eta \frac{(m+1)A_{PD}}{2\pi(d_{sr}+d_{rd})^2} \cos^m(\Phi_{k,l}^s) \cos(\psi_{k,l}^s) \\ \times \cos(\Phi_d^{k,l}) \cos(\psi_d^{k,l}) T(\psi) G(\psi), & 0 \leq (\psi_d^{k,l}) \leq (\psi_{FoV}), \\ 0, & \text{otherwise} \end{cases}, \quad (2.7)$$

where R^{OIRS} is the OIRS element's reflection coefficient, η is LED's conversion efficiency, m is the Lambertian order, A_{PD} represents the area of the photodiode, d_{sr} and d_{rd}^i denotes the distance from the transmitter to OIRS and OIRS to i^{th} user, respectively. $\Phi_{k,l}^s$ is the angle of irradiance from the transmitter to the OIRS, $\psi_{k,l}^s$ denotes the angle of incidence on the OIRS, $\Phi_d^{k,l}$ is the angle of irradiance from the k^{th} row and l^{th} column OIRS element towards the user, and $\psi_d^{k,l}$ represents the angle of incidence on the user. $T(\psi)$ and $G(\psi)$ represents optical filter and concentrator gains, respectively, and ψ_{FoV} represent the field-of-view (FoV) of the receiver.

The angle of irradiance, $\Phi_d^{k,l}$, influenced by the mirror array's yaw (ζ) and roll angles (ϱ), is determined by [54]:

$$\begin{aligned} \cos(\Phi_d^{k,l}) = & \frac{(x_{k,l} - x_{d_i})}{d_{rd}^i} \sin(\zeta) \cos(\varrho) \\ & + \frac{(y_{k,l} - y_{d_i})}{d_{rd}^i} \cos(\zeta) \cos(\varrho) \\ & + \frac{(z_{k,l} - z_{d_i})}{d_{rd}^i} \sin(\varrho). \end{aligned} \quad (2.8)$$

where $(x_{k,l}, y_{k,l}, z_{k,l})$ and $(x_{d_i}, y_{d_i}, z_{d_i})$ denote the position vectors specifying the locations of the OIRS and the i^{th} receiver/user, respectively.

The orientation of each mirror element is determined through the unit normal vector [52]:

$$\widehat{\mathbf{N}}_{k,l} = \frac{\widehat{\mathbf{R}}_{k,l}\widehat{\mathbf{S}} + \widehat{\mathbf{R}}_{k,l}\widehat{\mathbf{D}}}{\sqrt{2 + 2\widehat{\mathbf{R}}_{k,l}\widehat{\mathbf{S}}^T\widehat{\mathbf{R}}_{k,l}\widehat{\mathbf{D}}}}, \quad (2.9)$$

where the $\widehat{\mathbf{R}}_{k,l}\widehat{\mathbf{S}}$ represents the corresponding incidence direction and $\widehat{\mathbf{R}}_{k,l}\widehat{\mathbf{D}}$ represents the reflection direction. Moreover, $\mathbf{S}$, $\mathbf{R}_{k,l}$ and $\mathbf{D}$ stand for the source coordinates of the source's centre, the centroid coordinates of the mirror in k^{th} row and l^{th} column, respectively, and the destination coordinates. The vectors $\mathbf{S}$, $\mathbf{R}_{k,l}$ and $\mathbf{D}$ are given as:

$$\mathbf{S} = \begin{bmatrix} -\left(x_s + \frac{w_m}{2} + (l-1)w_m\right) \\ y_s \\ -\left(z_s + \frac{\ell_m}{2} + (k-1)\ell_m\right) \end{bmatrix},$$

$$\mathbf{R}_{k,l} = \begin{bmatrix} \left(x_s + \frac{w_m}{2} + (l-1)w_m\right) \\ 0 \\ \left(z_s + \frac{\ell_m}{2} + (k-1)\ell_m\right) \end{bmatrix},$$

$$\mathbf{D} = \begin{bmatrix} x_d - \left(x_s + \frac{w_m}{2} + (l-1)w_m\right) \\ y_d \\ z_d - \left(z_s + \frac{\ell_m}{2} + (k-1)\ell_m\right) \end{bmatrix}.$$

Furthermore, the rotation angles can be computed using the obtained normal vector $\widehat{\mathbf{N}}_{k,l}$ as:

$$\zeta_{k,l} = \sin^{-1} \left(\widehat{\mathbf{N}}_{k,l}^T \mathbf{e}_3 \right), \quad (2.10)$$

$$\varrho_{k,l} = \sin^{-1} \left(\frac{\widehat{\mathbf{N}}_{k,l}^T \mathbf{e}_1}{\cos(\zeta_{k,l})} \right), \quad (2.11)$$

where $\mathbf{e}_c$ ($c \in \{1, 2, 3\}$) denotes the c^{th} column of a 3×3 identity matrix.

The overall OIRS-assisted channel gain toward a user is expressed as:

$$h_i = \sum_{k=1}^{n_m} \sum_{l=1}^{n_m} G_{O_{k,l}}(\zeta_{k,l}, \varrho_{k,l}). \quad (2.12)$$

Under IM/DD operation, the received electrical signal at the i^{th} user is given by:

$$y_i(t) = \mathcal{R}P_t h_i x(t) + n_i, \quad (2.13)$$

where $\mathcal{R}$ denotes photodetector responsivity, P_t is transmitted optical power, and n_i represents AWGN.

2.2.4 Related Work on OIRS-Assisted UWOC Systems

Recently, IRS technology has attracted significant attention as a promising approach for improving the reliability and coverage of UWOC systems. By enabling controllable manipulation of the optical propagation environment, OIRS can dynamically redirect optical beams toward desired directions, thereby facilitating communication in scenarios where direct LoS paths are unavailable and enabling reliable NLoS UWOC transmission. Recent survey works have also highlighted the growing interest in IRS-assisted underwater communication systems and their potential to address the propagation challenges inherent to UWOC systems. In particular, Waduge *et al.* [56] presented a comprehensive review of IRS technologies for underwater communication environments, discussing system architectures, channel challenges, and potential research directions for IRS-assisted UWOC networks.

Early investigations on reflective structures for UWOC demonstrated the feasibility of redirecting optical signals to extend communication range. Huang *et al.* [57] experimentally demonstrated mirror-assisted UWOC in a controlled water tank environment, where passive mirrors were used to redirect optical signals and extend the achievable transmission distance. More recently, Yildiz *et al.* [45] derived analytical expressions for reflector-assisted UWOC path loss and demonstrated that reflective surfaces can significantly improve NLoS communication performance compared with conventional LoS UWOC links.

Motivated by the success of IRS in wireless communication systems, several studies have explored the application of IRS in challenging propagation environments. Mohsan *et al.* [58] discussed the potential of IRS-assisted communication for underground and underwater internet of things (IoT) scenarios, highlighting the ability of intelligent surfaces to enhance link reliability in harsh environments. Similarly, Kisseleff *et al.* [59] investigated IRS deployment in challenging propagation conditions and demonstrated that IRS can mitigate severe attenuation and turbulence-induced fading effects.

More recently, dedicated OIRS-assisted UWOC system models have been studied. Naik *et al.* [39] analyzed the performance of a metasurface-based OIRS-assisted UWOC system by considering underwater turbulence, attenuation, blockage, and beam misalignment effects. The study evaluated system performance in terms of OP and BER under realistic underwater channel conditions. Ata *et al.* [40] further investigated IRS-assisted UWOC systems by

incorporating the oceanic turbulence optical power spectrum (OTOPS) model to characterize turbulence caused by temperature and salinity variations. Their results demonstrated that the deployment of multiple reflecting elements can significantly enhance system reliability and improve communication performance in turbulent underwater environments.

In addition to single-user scenarios, recent research has also explored advanced intelligent surface architectures for multi-user underwater optical networks. For example, Naik *et al.* [24] evaluated multi-user UWOC systems assisted by simultaneous transmit-and-reflect IRS architectures, demonstrating the capability of intelligent surfaces to improve SE and support multi-user communication in underwater optical networks.

Despite the promising advancements in OIRS-assisted UWOC systems, several important challenges remain open. Existing studies have demonstrated the potential of intelligent surfaces for improving the reliability and coverage of UWOC links. However, many of these works primarily focus on specific system configurations or simplified modeling assumptions. In particular, comprehensive analytical frameworks that jointly consider realistic underwater channel impairments, such as absorption–scattering attenuation, turbulence-induced fading, and pointing errors together with intelligent mirror control and system-level optimization remain relatively limited. Furthermore, the investigation of multi-user communication strategies and advanced intelligent surface architectures in OIRS-assisted UWOC systems continues to be an active research area.

2.2.5 Research Gap

Despite significant progress in UWOC and IRS technologies, several important challenges remain insufficiently addressed. Most existing UWOC studies primarily focus on conventional relaying techniques or direct LoS communication links. In scenarios where LoS communication is unavailable, earlier NLoS UWOC approaches often relied on natural reflection mechanisms such as total internal reflection (TIR) at the water–air interface. While these approaches enable indirect optical communication, they are limited by environmental conditions and do not provide controllable beam steering capabilities.

More recently, OIRS-assisted UWOC systems have been investigated to enable reconfigurable optical propagation environments. Some studies have analyzed OIRS-assisted UWOC systems while considering realistic channel impairments such as absorption, scattering, oceanic turbulence, and beam misalignment. However, most existing works primarily focus on performance evaluation under fixed system configurations, and comprehensive analytical frameworks that jointly address system design aspects such as MA control and system-level optimization remain relatively limited.

Additionally, existing investigations largely focus on single-user communication scenarios, whereas practical UWOC networks typically involve multiple users requiring efficient resource allocation and interference management strategies. The integration of advanced multiple access techniques such as NOMA and RSMA with OIRS-assisted UWOC systems has received limited attention in the existing literature.

Furthermore, emerging optical intelligent surface architectures such as optical simultaneous transmitting and reflecting OIRS (OSTAR-IRS) and liquid-crystal (LC)-based OSTAR-IRS (LC-OSTAR-IRS) remain largely unexplored in underwater communication environments, particularly with respect to transmission–reflection optimization and geometry-dependent propagation behavior.

Moreover, most existing UWOC models assume depth-independent channel parameters, whereas in practical underwater environments optical propagation characteristics vary significantly with depth due to temperature, salinity, and pressure variations. The impact of such depth-dependent channel characteristics on OIRS-assisted UWOC systems has received limited attention in the existing literature.

Therefore, there is a clear need for unified analytical and optimization frameworks capable of systematically modeling, analyzing, and optimizing OIRS-assisted UWOC systems under realistic channel impairments.

Performance Comparison of IRS and DF Relay Assisted Mixed RF-Underwater Optical Communication System

Following the background discussion on underwater wireless optical communication (UWOC) and intelligent reflecting surfaces (IRS) presented in Chapter 2, this chapter investigates the integration of terrestrial radio frequency (RF) communication with UWOC in hybrid communication architectures. In practical ocean monitoring and offshore communication scenarios, terrestrial base stations often communicate with underwater nodes through intermediate surface buoys. In such systems, RF transmission is typically used for the terrestrial link due to its robustness over long distances, while UWOC provides high data rate communication for underwater links.

However, the terrestrial RF link between the base station (BS) and the buoy may experience severe attenuation or blockage due to environmental obstacles. To address this challenge, alternative transmission strategies such as IRS-assisted transmission and decode-and-forward (DF) relay-assisted transmission can be employed to enhance signal propagation in the RF link. While IRS enables passive beamforming through programmable reflecting elements, DF relaying relies on active signal regeneration at intermediate nodes.

3.1 Chapter Overview

This chapter investigates the performance of IRS-assisted and DF relay-assisted transmission in a mixed RF–UWOC system. Unlike most IRS studies that primarily focus on terrestrial wireless systems, this work considers an integrated communication architecture in which RF

transmission is employed for the terrestrial segment, while UWOC is utilized for underwater transmission.

The primary objective of this chapter is to examine whether passive beamforming through IRS can outperform active DF relaying in hybrid RF–UWOC systems in terms of spectral efficiency (SE) and energy efficiency (EE). Although UWOC links inherently support high data rates, their communication range is severely constrained due to absorption and scattering losses in water. Consequently, the terrestrial RF segment becomes the dominant bottleneck in determining the end-to-end (e2e) system performance. Therefore, enhancing the RF segment through IRS or DF relaying plays a crucial role in improving overall system efficiency.

The main contributions of this chapter are summarized as follows:

- A unified analytical framework for IRS-assisted and DF relay-assisted mixed RF–UWOC architectures under obstructed direct RF link conditions is developed.
- Closed-form expressions for the SE and EE of the RF and UWOC segments are derived.
- The e2e performance is characterized using the minimum-rate bottleneck principle.
- A comparative analysis between passive IRS beamforming and active DF relaying is presented under practical power consumption constraints.
- The impact of reflecting elements, transmit power, and buoy positioning on system performance is systematically investigated.

3.1.1 Scope and Objective of This Chapter

It is important to emphasize that the objective of this chapter is to develop an analytical framework for evaluating the e2e performance of the proposed mixed RF–UWOC communication system rather than to formulate a joint optimization problem across the RF and UWOC links. Although the terrestrial RF and underwater optical links are physically and statistically independent, they are connected in cascade through the buoy, which acts as the interface between the RF and optical segments. Consequently, successful e2e communication depends on the successful transmission over both hops, and the overall system performance is fundamentally constrained by the weaker link. Therefore, the e2e SE and EE are evaluated using the bottleneck (minimum-rate) criterion, which accurately characterizes the achievable performance of dual-hop cascaded systems.

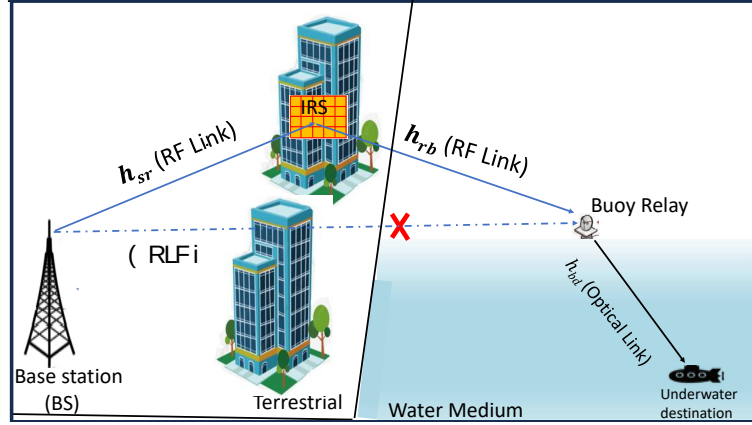


Figure 3.1: A conceptual diagram of the mixed RF-underwater optical communication system architecture that is being studied in this work.

3.2 System Model

In this chapter, a mixed RF–UWOC architecture is considered in which a terrestrial BS communicates with an underwater destination through an intermediate buoy positioned at the air–water interface, as illustrated in Fig. 3.1. The communication process consists of two cascaded segments: a terrestrial RF link between the BS and the buoy, followed by an underwater optical wireless link between the buoy and the underwater destination.

The direct RF link between the BS and the buoy may experience blockage due to environmental or structural obstructions. To mitigate this limitation, two alternative transmission strategies are investigated, namely IRS-assisted transmission and half-duplex (HD) DF relay-assisted transmission. In both cases, the objective is to enhance the received signal strength at the buoy under obstructed propagation conditions.

Upon reception of the RF signal at the buoy, the information-bearing waveform is converted into an optical signal using intensity modulation and transmitted underwater. At the underwater destination, direct detection is performed using a photodetector. Consequently, the overall system can be modeled as a dual-hop architecture consisting of a terrestrial RF segment and an underwater optical segment. Since these two segments operate in series, the e2e performance is fundamentally constrained by the weaker of the two links.

Practical Assumptions: For analytical tractability, the proposed IRS-assisted hybrid RF–UWOC system is evaluated assuming perfect channel state information (CSI), continuous IRS phase control, and ideal alignment between the transmitter, IRS, and receiver. These assumptions establish an upper-bound performance benchmark and enable a fair analytical comparison with the DF relay-assisted architecture. In practical deployments, however, channel

estimation errors, finite-resolution IRS phase control, hardware imperfections, and alignment inaccuracies may degrade the achievable performance. Consequently, the results presented in this chapter should be interpreted as an upper performance bound under ideal operating conditions. While the current analytical framework provides a useful benchmark for evaluating the potential gains of IRS-assisted hybrid RF-UWOC systems, a detailed sensitivity analysis considering CSI errors and alignment inaccuracies would further strengthen the engineering relevance of the results. The development of robust transmission schemes under such practical impairments remains an important direction for future research.

3.3 Channel Model

3.3.1 RF Link

3.3.1.1 Direct RF Link

When the direct link between the BS and the buoy is available, the complex baseband received signal at the buoy can be expressed as:

$$y = h_{sb}\sqrt{P_t}x_s + n_b, \quad (3.1)$$

where h_{sb} denotes the small-scale fading coefficient of the BS-to-buoy RF channel, P_t represents the transmit power at the BS, and x_s is the unit-power transmitted symbol satisfying $\mathbb{E}[|x_s|^2] = 1$. The additive noise term at buoy (n_b) is modeled as additive white Gaussian noise (AWGN) with zero mean and variance σ_b^2 , i.e., $n_b \sim \mathcal{CN}(0, \sigma_b^2)$.

3.3.1.2 IRS-Assisted RF Link

When the direct BS-to-buoy link is obstructed, an IRS comprising N passive reflecting elements is deployed to assist the transmission. The channel between the BS and IRS is denoted by $\mathbf{h}_{sr} \in \mathbb{C}^{N \times 1}$, while the channel between the IRS and buoy is denoted by $\mathbf{h}_{rb} \in \mathbb{C}^{N \times 1}$.

The IRS applies adjustable phase shifts to the incident signal, represented by the diagonal reflection matrix:

$$\Theta = \text{diag}(r_1 e^{j\phi_1}, \dots, r_N e^{j\phi_N}), \quad (3.2)$$

where r_i denotes the amplitude reflection coefficient and ϕ_i denotes the phase shift introduced by the i^{th} reflecting element.

The received signal at the buoy is therefore given by:

$$y = \left(h_{sb} + \mathbf{h}_{sr}^T \mathbf{\Theta} \mathbf{h}_{rb} \right) \sqrt{P_t} x_s + n_b. \quad (3.3)$$

3.3.1.3 DF Relay-Assisted RF Link

In the DF relay-assisted architecture, communication between the BS and buoy occurs over two orthogonal time slots due to HD operation.

During the first phase, the BS transmits the signal, and the received signals at the relay and buoy are given by:

$$y_{1,r} = h_{sr} \sqrt{P_s} x_s + n_r, \quad (3.4)$$

$$y_{1,b} = h_{sb} \sqrt{P_s} x_s + n_b, \quad (3.5)$$

where h_{sr} and h_{sb} denote the BS-to-relay and BS-to-buoy channel coefficients, respectively, and P_s denotes the source transmit power (BS). The noise terms n_r represent AWGN at the relay receiver with $n_r \sim \mathcal{CN}(0, \sigma_r^2)$. In the second phase, the relay decodes and forwards the re-encoded signal to the buoy as:

$$y_{2,b} = h_{rb} \sqrt{P_{rl}} x_r + n_b. \quad (3.6)$$

where P_{rl} denotes the relay transmit power and x_r represents the unit-power re-encoded signal transmitted by the relay after decoding the source message.

3.3.2 UWOC Link

The underwater optical channel between the buoy and the underwater destination follows the attenuation model derived in Chapter 2. The deterministic path loss component is denoted by h_{att} , which incorporates both geometric spreading loss and medium attenuation governed by Beer–Lambert’s law.

Under weak oceanic turbulence conditions, the optical intensity fluctuations are accurately modeled using a lognormal distribution. Accordingly, the overall underwater channel gain is expressed as:

$$h_{bd} = h_{\text{att}} \beta, \quad (3.7)$$

where β represents the turbulence-induced fading coefficient.

Under weak oceanic turbulence conditions, the optical intensity fluctuations are modeled using a lognormal distribution. In this case, the logarithm of the turbulence-induced fading

coefficient follows a Gaussian distribution expressed as:

$$\ln(\beta) \sim \mathcal{N}(\mu_\beta, \sigma_\beta^2), \quad (3.8)$$

where μ_β and σ_β^2 denote the mean and variance of the log-amplitude fluctuations, respectively.

The corresponding probability density function of β is given by:

$$f_\beta(\beta) = \frac{1}{\beta\sqrt{2\pi\sigma_\beta^2}} \exp\left(-\frac{(\ln(\beta) - \mu_\beta)^2}{2\sigma_\beta^2}\right), \quad \beta > 0. \quad (3.9)$$

The turbulence strength is characterized through the scintillation index defined as:

$$\sigma_I^2 = \frac{\mathbb{E}[I^2] - \mathbb{E}[I]^2}{\mathbb{E}[I]^2}, \quad (3.10)$$

which is related to the log-amplitude variance by:

$$\sigma_I^2 = \exp(\sigma_\beta^2) - 1. \quad (3.11)$$

After optical-to-electrical conversion under intensity modulation with direct detection (IM/DD), the received signal at the underwater destination can be written as:

$$y = P_b \mathcal{R} h_{bd} \tilde{x} + n_b, \quad (3.12)$$

where h_{bd} represent the buoy to destination underwater link, P_b denotes the optical transmit power at the buoy, $\mathcal{R}$ is the responsivity of the photodetector and $\tilde{x}$ represents the transmitted optical signal.

3.4 SE and EE Evaluation

3.4.1 RF Links

3.4.1.1 Direct Link

For the direct BS-to-buoy RF transmission, the instantaneous signal-to-noise ratio (SNR) at the buoy can be expressed as:

$$\text{SNR}_{drt} = \frac{P_t |h_{sb}|^2}{\sigma_b^2}, \quad (3.13)$$

where P_t denotes the transmit power at the BS, h_{sb} represents the complex channel coefficient of the direct RF link, and σ_b^2 is the noise variance.

Accordingly, the achievable SE of the direct RF link is given by:

$$SE_{drt} = \log_2 \left(1 + \frac{P_t |h_{sb}|^2}{\sigma_b^2} \right). \quad (3.14)$$

3.4.1.2 IRS-Assisted RF Link

For the IRS-assisted RF transmission, the received signal at the buoy experiences coherent combination of the reflected components. The effective channel gain is given by:

$$h_{\text{eff}} = h_{sb} + \mathbf{h}_{sr}^T \mathbf{\Theta} \mathbf{h}_{rb}. \quad (3.15)$$

Therefore, the instantaneous SNR becomes:

$$\text{SNR}_{IRS} = \frac{P_t |h_{sb} + \mathbf{h}_{sr}^T \mathbf{\Theta} \mathbf{h}_{rb}|^2}{\sigma_b^2}. \quad (3.16)$$

The corresponding SE is expressed as:

$$SE_{IRS}(N) = \log_2 \left(1 + \frac{P_t}{\sigma_b^2} |h_{sb} + \mathbf{h}_{sr}^T \mathbf{\Theta} \mathbf{h}_{rb}|^2 \right), \quad (3.17)$$

where N denotes the number of reflecting elements of the IRS.

3.4.1.3 DF Relay-Assisted RF Link

In the DF relay-assisted architecture, the achievable rate is constrained by the weaker of the two hops due to decode-and-forward operation. Considering half-duplex transmission, the achievable SE is given by:

$$SE_{Re} = \frac{1}{2} \log_2 \left(1 + \min \left(\frac{P_s |h_{sr}|^2}{\sigma_r^2}, \frac{P_s |h_{sb}|^2}{\sigma_b^2} + \frac{P_{rl} |h_{rb}|^2}{\sigma_b^2} \right) \right), \quad (3.18)$$

where h_{sr} and h_{rb} represent the BS-to-relay and relay-to-buoy channel coefficients.

For fair comparison with IRS-assisted transmission under equal total power constraint P_t , optimal power allocation between the two phases can be employed. Under the condition

$|h_{sb}|^2 \leq |h_{sr}|^2$, the SE simplifies to:

$$SE_{Re} = \frac{1}{2} \log_2 \left(1 + \frac{2P_t |h_{sr}|^2 |h_{rb}|^2}{(|h_{sr}|^2 + |h_{rb}|^2 - |h_{sb}|^2) \sigma_b^2} \right). \quad (3.19)$$

3.4.2 UWOC Link

For the underwater optical segment operating under IM/DD, the electrical SNR at the photodetector is determined by the received optical power and the noise variance.

The received optical power at the underwater destination is given by:

$$P_r = P_b h_{bd} = P_b h_{att} \beta, \quad (3.20)$$

where P_b denotes the optical transmit power at the buoy, h_{att} represents the deterministic attenuation component defined in Chapter 2, and β denotes the lognormal turbulence-induced fading coefficient.

The generated signal current at the photodetector is expressed as:

$$i_s = \mathcal{R}P_r, \quad (3.21)$$

The total noise current consists of shot noise and thermal noise. Under the assumption that ambient and dark currents are negligible, the total noise variance is given by:

$$i_n^2 = 2e i_s B + \frac{4K_B T B}{R_L}, \quad (3.22)$$

where e denotes the electronic charge, B is the system bandwidth, K_B is the Boltzmann constant, T is the absolute temperature, and R_L is the load resistance.

Accordingly, the instantaneous SNR of the UWOC link is:

$$\text{SNR}_{UW} = \frac{(\mathcal{R}P_r)^2}{2e \mathcal{R}P_r B + \frac{4K_B T B}{R_L}}. \quad (3.23)$$

The achievable SE of the UWOC link is therefore:

$$SE_{UW} = \log_2 (1 + \text{SNR}_{UW}). \quad (3.24)$$

3.4.3 End-to-End (e2e) Links

Since the overall system operates as a cascaded dual-hop architecture comprising a terrestrial RF segment followed by an underwater optical segment, successful e2e communication requires reliable transmission over both hops. Consequently, the overall system performance is fundamentally constrained by the weaker of the two links. Based on this bottleneck principle, the achievable e2e SE is expressed as:

$$SE_{e2e} = \min(SE_{RF}, SE_{UW}), \quad (3.25)$$

where SE_{RF} corresponds to the SE of the considered RF architecture (direct, IRS-assisted, or DF relay-assisted) and SE_{UW} is the SE of the UWOC link.

3.4.4 Energy Efficiency

Energy efficiency (EE) is defined as the ratio of the achievable SE to the total consumed power of the communication system. In general, it can be expressed as:

$$EE = \frac{SE}{P_{\text{total}}}, \quad (3.26)$$

where P_{total} includes both transmit power and circuit power dissipation of all active hardware components.

1) e2e Direct Link

For the direct transmission architecture, the total consumed power consists of the transmit power scaled by the power amplifier efficiency and the circuit power dissipations at the source, buoy, and underwater destination. Thus, the e2e EE of the direct link is given by:

$$EE_{e2e}^{drt} = \frac{SE_{e2e}^{drt}}{\frac{P_t}{\nu} + p_d^s + p_d^b + p_d^d}, \quad (3.27)$$

where ν denotes the power amplifier efficiency, p_d^s , p_d^b , and p_d^d represent the circuit power dissipations at the source, buoy, and underwater destination, respectively.

2) e2e IRS-Assisted Link

In the IRS-assisted architecture, the total power consumption additionally includes the circuit power consumed by each reflecting element. Since the IRS comprises N passive elements, the

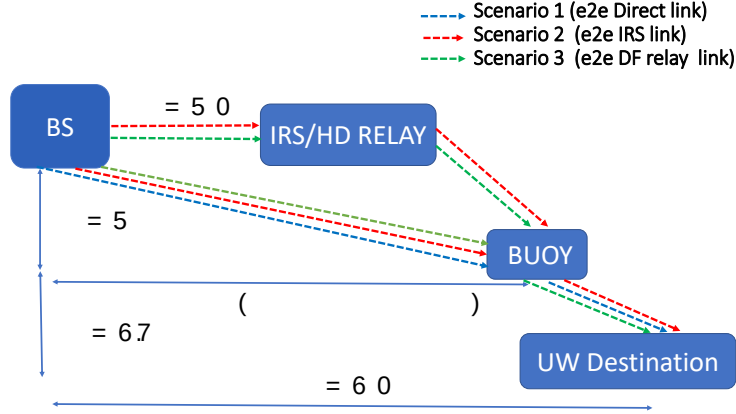


Figure 3.2: Simulation setup.

Table 3.1: Simulation Parameters for RF link

Parameter	Simulation Value
d_{sr}	50 m
d_v	5 m
BS antenna gain	5 dBi
Relay/IRS antenna gain	5 dBi
buoy antenna gain	0 dBi
carrier frequency	3 GHz

cumulative dissipation scales linearly with N . Therefore, the EE of the e2e IRS-assisted system is expressed as:

$$EE_{e2e}^{IRS} = \frac{SE_{e2e}^{IRS}}{\frac{P_t}{v} + p_d^s + Np_d^e + p_d^b + p_d^d}, \quad (3.28)$$

where p_d^e denotes the power dissipation of each IRS reflecting element.

3) e2e DF Relay-Assisted Link

For the DF relay-assisted architecture, the total consumed power includes the relay circuit dissipation. Moreover, due to HD operation, the source and relay transmit only for half of the transmission duration, which effectively scales the transmit power contribution. Accordingly, the EE of the e2e DF relay-assisted system is given by:

$$EE_{e2e}^{Re} = \frac{SE_{e2e}^{Re}}{\frac{1}{2} \frac{P_t}{v} + p_d^s + p_d^r + p_d^b + p_d^d}, \quad (3.29)$$

where p_d^r denotes the circuit power dissipation of the DF relay.

Table 3.2: Simulation Parameters for UWOC link

Parameter	Simulation Value
D_V	6.7 m
$\theta_{1/2}$	20°
Wavelength	532 nm
refractive index of water	1.331
Field of view (FOV)	90°
Absorption coefficient	0.179 m^{-1}
Scattering coefficient	0.217 m^{-1}
σ_I^2	0.1

3.5 Simulation Results

In this section, numerical results are presented to validate the analytical expressions derived for SE and EE and to compare the performance of IRS-assisted and DF relay-assisted architectures in the mixed RF–UWOC system.

In the considered system model, the RF channel gain from source to buoy is modeled using 3rd Generation Partnership Project (3GPP) urban micro (UMi) pathloss model [51]. The shadow fading is neglected so that we have a deterministic channel gain which is a distance-dependent function and to clearly highlight the performance differences arising from passive beamforming and active relaying mechanisms. It can be expressed as:

$$PL(d) [\text{dB}] = G_t [\text{dBi}] + G_r [\text{dBi}] + \begin{cases} -37.5 - 22\log_{10}(d/1 \text{ m}) & \text{if LoS,} \\ -35.1 - 36.7\log_{10}(d/1 \text{ m}) & \text{if NLoS,} \end{cases} \quad (3.30)$$

Computational Aspects: The objective of this chapter is to establish the analytical performance framework for IRS-assisted hybrid RF-UWOC systems and to compare it with the conventional DF relay-assisted architecture. Accordingly, the IRS reflection coefficients are assumed to be configured by the IRS controller based on the available channel information, and no iterative optimization algorithm is developed in this chapter. The computational complexity associated with dynamic resource allocation and joint optimization is investigated in the subsequent chapters, where practical optimization frameworks for OIRS and OSTAR-IRS-assisted UWOC systems are presented.

3.5.1 Simulation Setup

The geometric configuration considered for numerical evaluation is illustrated in Fig. 3.2. The BS is positioned at a height d_v above the sea surface, while the underwater destination is located at a depth D_v below the water surface. The IRS or DF relay is deployed at a fixed horizontal distance $d_{sr} = 50$ m from the BS.

Let d denote the horizontal distance between the BS and the buoy. The corresponding three-dimensional link distances are expressed as:

$$d_{sb} = \sqrt{d^2 + d_v^2}, \quad (3.31)$$

$$d_{rb} = \sqrt{(d - d_{sr})^2 + d_v^2}, \quad (3.32)$$

$$d_{bd} = \sqrt{(d_{sd} - d)^2 + D_v^2}, \quad (3.33)$$

where d_{sd} represents the fixed horizontal projection distance between the BS and the underwater destination.

For the UWOC segment, the turbulence is modeled using the lognormal distribution corresponding to weak oceanic turbulence conditions. The scintillation index is set to $\sigma_I^2 = 0.1$, representing weak-to-moderate turbulence typically encountered in coastal water environments.

To ensure fairness in performance comparison, the total transmit power available for IRS-assisted and DF relay-assisted architectures is maintained identical. In the DF relay case, optimal power allocation between source and relay is applied under the same total power constraint. Hardware power dissipation parameters are selected based on practical values reported in the literature, including the circuit power consumption per IRS reflecting element.

Parameter Selection: The simulation parameters employed in this chapter are selected to represent practical hybrid RF–UWOC communication scenarios. The RF deployment parameters correspond to a representative short-range BS–buoy communication link following the IRS-assisted RF communication framework in [51]. The UWOC channel parameters, including the operating wavelength, refractive index, attenuation and scattering coefficients, field-of-view (FoV), and turbulence characteristics, are adopted from representative underwater optical communication literature [5, 60–63]. These parameter values correspond to realistic operating conditions while enabling a consistent performance evaluation of the proposed hybrid RF–UWOC architectures and facilitating comparison with existing studies.

The complete RF and UWOC simulation parameters are summarized in Table 3.1 and 3.2.

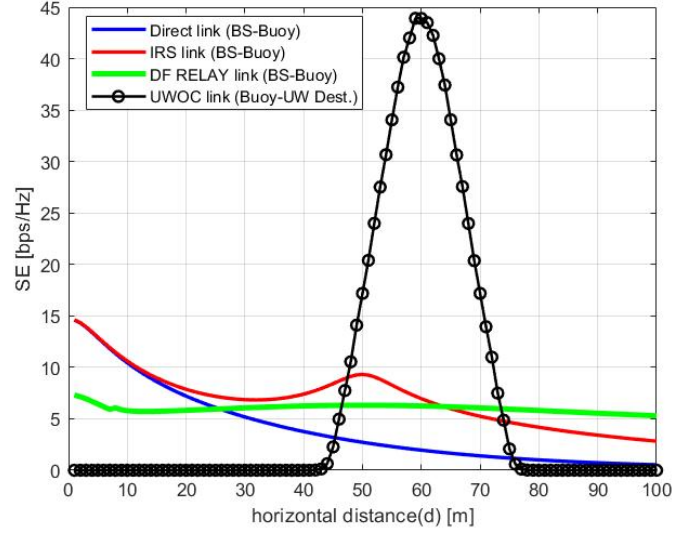


Figure 3.3: SE vs. horizontal distance (d) comparison.

3.5.2 Spectral Efficiency (SE) Analysis

Fig. 3.3 illustrates the variation of SE with respect to the horizontal buoy distance (d) for individual links. It is observed that the UWOC link achieves significantly higher SE within its feasible operating range due to the high optical carrier frequency and strong directivity. However, because the attenuation component h_{att} decays exponentially with d_{bd} , the UWOC link becomes infeasible beyond a limited transmission range.

As described in (3.33), the buoy-to-destination distance d_{bd} depends on the geometric configuration of the system. For the considered simulation parameters ($d_{sd} = 60$ m and $D_V = 6.7$ m), underwater communication is achievable only when d_{bd} remains approximately below 17 m. Beyond this distance, the exponential attenuation governed by Beer–Lambert’s law significantly reduces the received optical power, resulting in negligible SE.

For small values of d , the IRS-assisted RF link outperforms the DF relay-assisted link. This improvement is attributed to the coherent beamforming gain of the IRS. In contrast, the DF relay-assisted link is limited by the weaker of its two hops and the inherent $\frac{1}{2}$ spectral penalty due to HD operation.

As d increases, the path loss of the direct BS-to-buoy link increases significantly. In this regime, the DF relay architecture becomes advantageous since it divides the long RF link into two shorter segments, thereby reducing the path loss experienced by each hop.

The observed trend confirms that the IRS-assisted architecture maintains higher SE over a wider range of distances compared to the DF relay-assisted system. This is because the passive beamforming gain of the IRS compensates for the distance-dependent path loss, whereas the

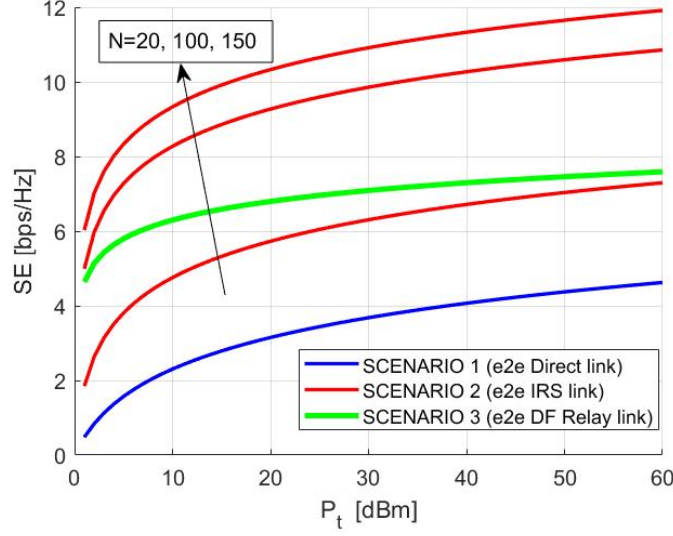


Figure 3.4: SE vs. Transmit power (P_t) for different N at $d = 55$ m.

DF relay suffers from the HD SE penalty. Consequently, the IRS-assisted link is particularly effective for short-to-medium terrestrial ranges, whereas DF relaying becomes advantageous only for longer links where dividing the path into two hops reduces the overall path loss.

Fig. 3.4 presents the variation of e2e SE with transmit power for different numbers of reflecting elements at $d = 55$ m. When $N = 20$, the DF relay-assisted architecture achieves higher SE at low transmit power. However, when N increases to 100 or beyond, the IRS-assisted architecture surpasses the DF relay system due to the substantial beamforming gain.

The beamforming gain scales approximately with N^2 under optimal phase alignment, demonstrating that IRS can outperform active relaying when sufficient reflecting elements are deployed. The performance gain becomes more pronounced at higher transmit powers, where the coherent combining gain of the IRS becomes more effective.

Fig. 3.5 shows the variation of SE as a function of the number of reflecting elements N . The SE increases monotonically with N due to constructive signal combination at the buoy, which enhances the effective channel gain of the IRS-assisted link. However, the rate of improvement gradually decreases as N becomes large. This behavior occurs because the SE grows logarithmically with the received SNR, resulting in diminishing performance gains for large SNR values. Furthermore, once the RF link becomes sufficiently strong, the overall e2e SE may become constrained by the UWOC link according to the bottleneck principle.

Two scenarios are examined in Fig. 3.5: obstructed and unobstructed direct RF link conditions. In the unobstructed case, the direct BS-to-buoy link follows the LoS path loss model of the 3GPP UMi channel. In the obstructed case, the direct link is modeled using the

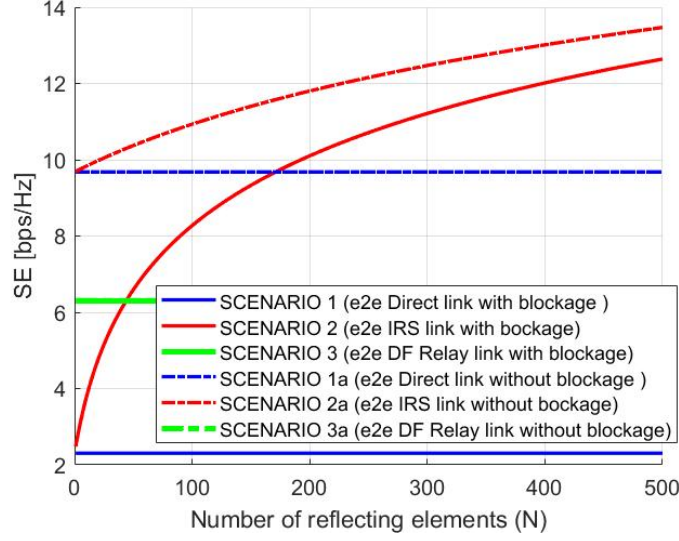


Figure 3.5: SE vs Number of reflecting elements (N).

NLoS path loss model, which represents the effect of blockage between the BS and the buoy. When the direct link is unobstructed, both the direct and IRS-assisted architectures benefit from the additional propagation path, resulting in improved SE. However, when the direct link is obstructed, the IRS-assisted architecture provides a more significant performance improvement by creating an alternative reflected propagation path between the BS and the buoy. In contrast, the DF relay performance remains largely unaffected since its operation inherently relies on two-hop transmission.

The performance gap between the unobstructed and obstructed direct link scenarios highlights the effectiveness of IRS in providing an alternative propagation path under blockage conditions.

3.5.3 Energy Efficiency Analysis

Fig. 3.6 illustrates the variation of EE with transmit power at $d = 55$ m and $N = 100$. The EE is computed as the ratio of SE to total consumed power, including circuit dissipation.

It is observed that although the IRS-assisted architecture can achieve higher SE for large N , its EE may degrade due to the cumulative circuit power consumption of reflecting elements. The total power dissipation in the IRS case includes the term Np_d^e , which becomes significant for large-scale deployments. In contrast, the DF relay-assisted system involves additional relay circuitry but does not scale with N , resulting in comparatively better EE performance in certain regimes.

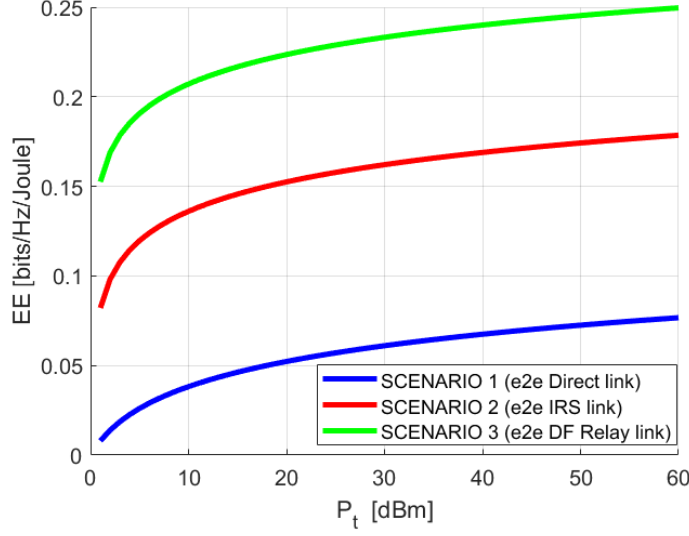


Figure 3.6: EE vs Transmit power (P_t) at $d = 55$ m and $N = 100$.

Furthermore, as transmit power increases, EE initially improves due to SE growth but eventually saturates when the transmit power dominates total energy consumption.

Although the IRS-assisted architecture achieves higher SE than the DF relay-assisted system, its EE is consistently lower across all transmit power levels due to the cumulative circuit power consumption associated with the N reflecting elements (Np_d^e). This is because each IRS element consumes circuit power for control and phase adjustment, whereas the DF relay involves only a single active forwarding stage. Consequently, the choice between IRS and DF relaying involves a trade-off between SE gains and energy consumption.

3.6 Conclusion

This chapter presented a comprehensive performance comparison between IRS-assisted and DF relay-assisted architectures in a mixed RF–UWOC communication system. A unified analytical framework was developed to evaluate the SE and EE of both the terrestrial RF segment and the underwater optical segment under obstructed and unobstructed direct link conditions.

The analysis demonstrated that although the UWOC link is capable of achieving substantially higher SE within short transmission ranges, its performance rapidly degrades due to exponential attenuation in water. Consequently, the terrestrial RF segment frequently becomes the dominant bottleneck governing the overall end-to-end system performance. This establishes that improving the RF segment is critical for enhancing the performance of integrated terrestrial–underwater communication systems.

From a SE perspective, the IRS-assisted architecture provides significant performance gains when a sufficiently large number of reflecting elements is deployed. The coherent beamforming capability of IRS enables substantial signal enhancement under blockage conditions, allowing it to outperform DF relay-assisted transmission in high-element regimes. However, the achievable gain strongly depends on practical deployment size and propagation geometry.

In contrast, from an EE standpoint, the DF relay-assisted architecture exhibits competitive and, in certain operating regions, superior performance. While IRS offers notable rate improvements, the cumulative circuit power consumption associated with large-scale reflecting elements can reduce its EE advantage. Therefore, the trade-off between passive beamforming gains and hardware power overhead must be carefully considered in system design.

Furthermore, the positioning of the buoy was shown to play a crucial role in balancing the RF and optical segments. Since both RF path loss and underwater attenuation are highly distance-dependent, optimal buoy placement is essential to prevent premature bottleneck transitions and to maximize overall system performance.

In summary, IRS-assisted transmission is particularly effective for enhancing SE in blockage-dominated environments, whereas DF relaying remains attractive from an EE perspective under realistic hardware constraints. The insights obtained in this chapter provide fundamental design guidelines for hybrid RF–UWOC systems and establish a performance baseline for the advanced architectures explored in the subsequent chapters of this dissertation.

An Optical Intelligent Reflecting Surface-Assisted Underwater Wireless Communication System

Building upon the hybrid radio frequency (RF)–underwater wireless optical communication (UWOC) architecture investigated in Chapter 3, this chapter shifts the focus to a fully optical underwater communication framework. While Chapter 3 analyzed the performance trade-offs between intelligent reflecting surface (IRS)-assisted and decode and forward (DF) relay-assisted RF links in mixed RF–UWOC systems, the present chapter concentrates exclusively on optical intelligent reflecting surface (OIRS)-assisted underwater communication under non-line-of-sight (NLoS) conditions. By eliminating the terrestrial RF link and directly addressing underwater beam steering challenges, this chapter extends the thesis from hybrid dual-hop architectures to fully optical adaptive reflection-based communication systems.

4.1 Chapter Overview

This chapter investigates an OIRS-assisted UWOC system and presents a comprehensive analytical framework to evaluate its performance in practical underwater environments.

UWOC systems reported in the literature can broadly be categorized into point-to-point line-of-sight (LoS), diffused LoS, retro-reflector-based LoS, and NLoS configurations [5]. In point-to-point LoS systems, narrow-divergence optical beams establish direct links but require strict alignment [6]. Diffused LoS configurations relax alignment constraints at the cost of reduced received power, while retro-reflector-based LoS systems enable duplex communication but remain sensitive to alignment and backscattering effects [1].

In practical underwater environments, maintaining strict LoS alignment is often difficult due to obstructions, node mobility, and environmental dynamics. As a result, NLoS UWOC systems have been explored, which primarily rely on total internal reflection (TIR) at the water–air interface [5]. However, such approaches are inherently limited to shallow-water deployments and are sensitive to surface variations and wave-induced effects [6, 16, 64, 65]. Moreover, their operation relies on the fundamental condition of TIR, wherein light must propagate from a denser to a rarer medium and the angle of incidence must exceed the critical angle. This requirement significantly restricts deployment flexibility in deep-water scenarios, thereby limiting their practical applicability.

Motivated by these limitations, this chapter considers an alternative NLoS architecture based on an OIRS. Specifically, a mirror-array (MA)-based OIRS is employed to controllably redirect the optical beam toward the intended receiver at arbitrary underwater depths. Compared to plane mirror surfaces (PMS) with fixed orientation, and conventional TIR-based NLoS systems, the OIRS provides controllable beam redirection with greater flexibility in deployment. To the best of the author’s knowledge at the time of this work, the application of a controllable MA-based OIRS for underwater optical beam steering within such a framework was not been extensively explored in the existing UWOC literature.

Within this framework, a unified system and channel model is developed by incorporating three-dimensional geometric propagation along with key underwater channel impairments, including absorption–scattering attenuation and turbulence-induced fading modeled using the Exponential Generalized Gamma (EGG) distribution.

The main contributions of this chapter are summarized as follows:

1. An OIRS and PMS-assisted UWOC system is analyzed for underwater communication between the transmitter and receiver and compared with the conventional NLoS UWOC configuration, taking into account underwater attenuation and turbulence effects.
2. Generalized closed-form analytical expressions for the probability density function (PDF), cumulative distribution function (CDF), outage probability (OP), average spectral efficiency (SE), average energy efficiency (EE), and average bit error rate (BER) are derived using advanced special functions such as Meijer’s G-function and the bivariate Fox’s H-function. The analytical expressions are validated through Monte Carlo simulations.
3. An asymptotic analysis for average SE in the high-signal-to-noise ratio (SNR) regime is presented to illustrate the impact of channel parameters on system performance, and the asymptotic results are shown to accurately match the analytical expressions.

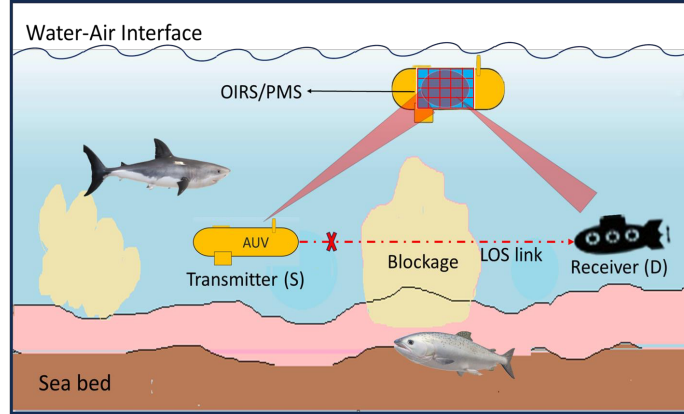


Figure 4.1: Illustration of the OIRS/PMS-aided UWOC system.

4. The efficient deployment regions of the OIRS are analyzed, demonstrating that the placement of the reflecting surface significantly affects system performance and that certain geometric configurations may lead to performance degradation.

4.2 System Model

In this section, the system architecture and geometrical modeling of the proposed OIRS-assisted UWOC system are described. For performance comparison, PMS-assisted and conventional NLoS-assisted UWOC systems are also considered. A unified three-dimensional coordinate framework is adopted to enable fair analytical comparison among the three configurations.

Due to the presence of obstacles, mobility of underwater nodes, and environmental disturbances, direct LoS communication is often not feasible in practical underwater scenarios. Therefore, NLoS-based transmission mechanisms are considered in this work.

A static UWOC system operating in pure seawater is assumed for analytical tractability. The transmitter, reflector (OIRS/PMS or water–air interface), and receiver are assumed to be stationary as shown in Fig. 4.1. The effects of ocean currents and sea surface slope variations are neglected in the present analysis. A single autonomous underwater vehicle (AUV) serves as the optical transmitter, while the receiver is equipped with a high-sensitivity photodetector, i.e., a silicon photomultiplier (SiPM), which consists of an array of single-photon avalanche diodes (SPADs) .

The use of SiPM is motivated by its high sensitivity and photon-counting capability, making it particularly suitable for UWOC environments characterized by severe attenuation and low received optical power. Unlike conventional photodetectors such as P-intrinsic-N (PIN) photodetectors and avalanche photodiodes (APDs), SiPMs provide high internal gain

through avalanche multiplication and enable reliable detection in photon-starved conditions. Additionally, SiPMs offer compact size, lower operating voltage compared to photomultiplier tubes (PMTs), and improved robustness, making them a practical choice for UWOC systems [66].

Fig. 4.2 illustrates the three-dimensional coordinate models corresponding to the OIRS-assisted, PMS-assisted, and conventional NLoS-assisted UWOC systems. In all configurations, the communication between the transmitter and receiver occurs via a reflected optical path, as the direct LoS path is assumed to be blocked.

4.2.1 OIRS-Assisted UWOC System

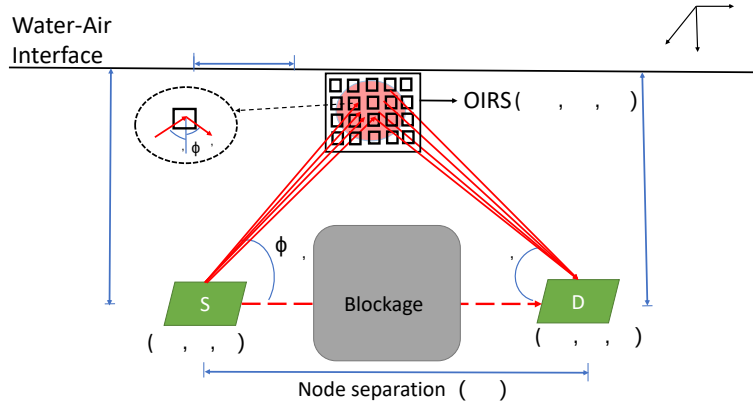
In the proposed framework, an OIRS is employed to enable NLoS underwater communication between the transmitter and the receiver. The OIRS is modeled as a MA-based reflecting surface mounted on a submerged AUV. It is assumed that the OIRS is positioned such that it maintains direct LoS with both the transmitter and the receiver, while the direct transmitter–receiver link is blocked.

The OIRS consists of $n_m \times n_m$ mirror elements, where each element has dimensions $\ell_m \times w_m$. Unlike plane reflecting surfaces, each mirror element in the OIRS can be individually oriented using a mechanical steering mechanism. By appropriately adjusting the angular orientation (yaw and roll angle) of each element, the reflected optical beam can be steered toward the intended receiver.

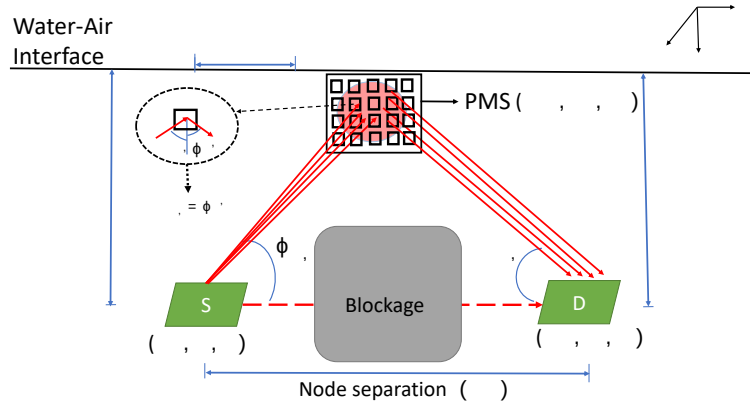
The transmitter is modeled as an LED source located at coordinates (x_s, y_s, z_s) , while the receiver is located at (x_d, y_d, z_d) . The centroid of the $(k, l)^{\text{th}}$ OIRS element is represented by $(x_{k,l}, y_{k,l}, z_{k,l})$. The distances from the transmitter to the OIRS and from the OIRS to the receiver are denoted by d_{sr} and d_{rd} , respectively.

The optical signal transmitted from the source is first incident on the OIRS plane. By properly selecting the yaw and roll angles of each mirror element, the reflected beam is directed toward the receiver in accordance with the law of reflection. The mirror orientation is obtained by determining the unit normal vector to the reflecting surface such that the angle of incidence equals the angle of reflection, consistent with the law of specular reflection. This modeling is valid for MA-based OIRS, where beam steering is achieved through mechanical orientation of mirror elements rather than phase-gradient control as in metasurface-based designs.

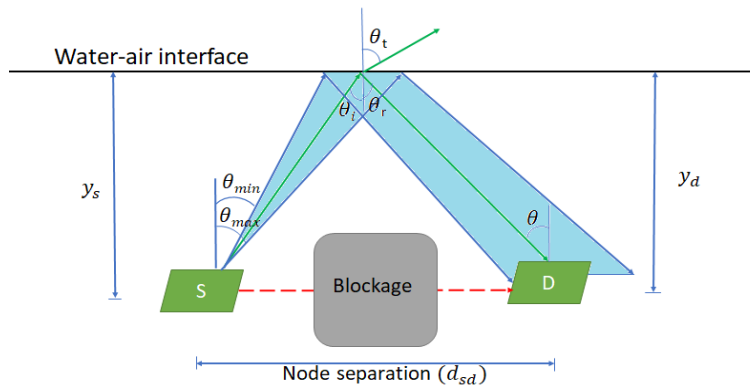
It is assumed that the OIRS controller has knowledge of the channel state information (CSI), enabling optimal orientation of the mirror elements. Furthermore, to maintain analytical tractability, the underwater devices are assumed to be stationary and perfectly aligned during transmission.



(a) OIRS-aided UWOC System.



(b) PMS-aided UWOC System.



(c) NLoS-aided UWOC System.

Figure 4.2: 3D-Coordinate System Model for the considered UEWOC configurations.

Under these assumptions, the received signal at the destination through the OIRS-assisted link can be expressed as:

$$y = G_O h_{att} h_\alpha x + n_o, \quad (4.1)$$

where G_O represents the overall OIRS channel gain, h_{att} denotes the attenuation loss, h_α models underwater turbulence, defined in Chapter 2, x denotes the transmitted signal, and n_o is the additive white Gaussian noise (AWGN) component.

4.2.2 PMS-Assisted UWOC System

For performance comparison, a PMS-assisted UWOC system is also considered. The PMS consists of the same $n_m \times n_m$ mirror elements with dimensions $\ell_m \times w_m$, identical to the OIRS configuration. However, unlike the OIRS, the mirror elements in the PMS are fixed and cannot be adaptively oriented.

In the PMS-assisted configuration, the reflected signal follows the conventional law of reflection determined solely by the geometric placement of the surface. Since the mirror elements are not dynamically controllable, beam steering toward the receiver depends entirely on the inherent geometrical alignment between the transmitter, PMS, and receiver.

The transmitter and receiver coordinates remain (x_s, y_s, z_s) and (x_d, y_d, z_d) , respectively. The distances d_{sr} and d_{rd} denote the separation between the transmitter and PMS, and PMS and receiver, respectively.

Under these assumptions, the received signal through the PMS-assisted link can be expressed as:

$$y = G_P h_{att} h_\alpha x + n_p, \quad (4.2)$$

where G_P denotes the PMS channel gain, and n_p is the AWGN component.

4.2.3 NLoS-Assisted UWOC System

For baseline comparison, the conventional NLoS-assisted UWOC system based on TIR at the water–air interface is considered. In this configuration, no OIRS or PMS is deployed. Instead, the water–air boundary acts as a reflecting surface.

The optical beam transmitted from the source is directed toward the water–air interface. When the angle of incidence θ_i exceeds the critical angle θ_c , defined as:

$$\theta_c = \sin^{-1} \left(\frac{\mu_a}{\mu_w} \right), \quad (4.3)$$

the incident optical wave undergoes TIR and is reflected back into the water medium toward the receiver. Here, μ_w and μ_a denote the refractive indices of water and air, respectively.

If $\theta_i < \theta_c$, partial transmission into air occurs, and only a portion of the incident optical power is reflected back into the water medium. Therefore, the performance of the NLoS-assisted UWOC system depends strongly on the incidence angle relative to the critical angle.

In this configuration, communication occurs via reflection from the smooth water–air interface. The received signal for the NLoS-assisted UWOC system can be expressed as:

$$y = G_N h_{att} h_{\alpha} x + n_N, \quad (4.4)$$

where G_N denotes the NLoS channel gain associated with reflection at the interface, and n_N is the AWGN component.

In this work, perfect mechanical alignment of the OIRS elements is assumed, and pointing errors or surface-induced misalignment effects are neglected. This assumption allows the analysis to focus on turbulence-induced fading and geometrical beam steering characteristics. Furthermore, a static network topology is assumed in which the transmitter, OIRS, and receiver locations remain fixed during one transmission interval. This static assumption is adopted solely for analytical tractability to enable closed-form performance analysis and establish the fundamental performance limits of the proposed system. Although underwater node mobility provides one important motivation for employing OIRS, the proposed framework is equally applicable to scenarios involving temporary link blockage, and deployment constraints caused by underwater obstacles or infrastructure. The LoS assumption for both the transmitter-OIRS and OIRS-receiver links represents an ideal deployment scenario that can be achieved through appropriate installation of the OIRS at predetermined locations where both optical paths remain unobstructed. It is important to note that while the direct transmitter-receiver path may be blocked, the OIRS is strategically positioned to maintain clear optical paths to both the transmitter and the receiver. The impact of dynamic misalignment, pointing errors, and intermittent LoS conditions is identified as an important direction for future research.

Practical Implementation Considerations: The proposed OIRS employs individually steerable mirror elements whose orientations are adjusted to direct the reflected optical beam toward the desired receiver. In a practical implementation, the reconfiguration process is subject to the response time and angular positioning accuracy of the employed actuators. Calibration errors and synchronization inaccuracies among individual mirror elements may also result in deviations from the ideal orientations assumed in the analytical model and can consequently affect the achievable beam-steering gain. These actuator-level effects are not explicitly mod-

eled in the present communication-theoretic analysis and are therefore identified as practical implementation considerations for future hardware-oriented investigation.

The energy consumption associated with the MA is incorporated into the EE analysis through the power dissipation assigned to each OIRS element. Increasing the number of reflecting elements improves SE but also increases the circuit power consumption. This creates a fundamental trade-off between SE and EE in MA-based OIRS design, which will be examined in the simulation results.

4.3 Channel Model

In this section, the underwater channel characteristics are described. The UWOC link is affected by deterministic attenuation due to absorption and scattering, as well as random fluctuations caused by turbulence. Accordingly, the overall channel incorporates both attenuation loss and turbulence-induced fading, along with additive noise effects. Unless otherwise stated, the attenuation, and oceanic turbulence models adopted in this chapter follow the generalized UWOC channel model presented in Chapter 2. Only the chapter-specific system models and analytical developments are introduced in this chapter.

4.3.1 Attenuation Model

The deterministic attenuation component h_{att} follows the Beer–Lambert formulation established in Chapter 2 and depends on the total propagation distance $(d_{sr} + d_{rd})$ and the wavelength-dependent attenuation coefficient $c(\lambda)$.

4.3.2 Turbulence Model

Unlike Chapter 3, where weak turbulence was modeled using the lognormal distribution, this chapter adopts the more generalized EGG distribution to characterize weak, moderate, and strong turbulence regimes.

The turbulence-induced fading coefficient h_α follows the EGG distribution introduced in Chapter 2. The statistical parameters $(\omega, \Lambda, a, b, c)$ characterize the turbulence strength and are selected according to the desired scintillation index corresponding to weak, moderate, and strong turbulence conditions as given in Table 4.1.

For completeness, the PDF of h_α is given as:

$$h_\alpha(\alpha) = \omega f(\alpha; \Lambda) + (1 - \omega) g(\alpha; [a, b, c]), \quad (4.5)$$

where $f(\cdot)$ and $g(\cdot)$ denote the exponential and generalized Gamma distributions, respectively. The parameters ω , Λ , a , b , and c characterize the turbulence strength and satisfy $0 < \omega < 1$.

4.3.3 Noise Model

The additive noise component n_i ($i \in \{O, P, N\}$) consists of signal-dependent shot noise, dark current noise, background noise, and thermal noise [67]. The total noise variance is expressed as:

$$\sigma_{n_i}^2 = \sigma_{\text{sh},i}^2 + \sigma_d^2 + \sigma_b^2 + \sigma_{\text{th}}^2, \quad (4.6)$$

where $\sigma_{\text{sh},i}^2 = 2eGFI_{s,i}$, $\sigma_d^2 = 2eGFI_d$, and $\sigma_{\text{th}}^2 = \frac{4K_B T B}{R_L}$ denotes the variances of the signal shot noise, dark noise and thermal noise, respectively, wherein e , G , K_B , T , F , B and R_L denote the electron charge, SiPM gain, Boltzmann constant, the receiver equivalent temperature in kelvin, the photodetector excess noise factor, the bandwidth of the receiver's lowpass filter (LPF), and the load resistance, respectively. Also, I_d represent the SiPM dark current and $I_{s,i} = \mathcal{R}G_i h_{\text{att}} h_\alpha$ represent the useful signal, wherein $\mathcal{R}$ is the SiPM responsivity. For the sake of simplicity, the impact of solar radiation background noise is ignored; thus, the variance of background noise (σ_b^2) = 0 [67].

4.3.4 OIRS Channel Gain Modeling

In this section, the channel gain of the OIRS-assisted UWOC system is characterized. The geometrical formulation of the OIRS configuration follows the model developed in Chapter 2. For clarity and to facilitate comparison with the PMS and NLoS-assisted configurations considered in this chapter, the resulting element-wise and overall DC channel gain expressions are restated below.

4.3.4.1 Element-Wise Channel Gain

The DC channel gain corresponding to the $(k, l)^{\text{th}}$ OIRS mirror element is expressed as [54, 55]:

$$G_{O_{k,l}}(\zeta, \varrho) = \begin{cases} \frac{R^{\text{OIRS}} \eta(m+1) A_{PD}}{2\pi(d_{sr} + d_{rd})^2} C_1 C_2 C_3 C_4 T(\psi) G(\psi), & 0 \leq \psi_d^{k,l} \leq \psi_{Fov}, \\ 0, & \text{otherwise,} \end{cases} \quad (4.7)$$

where R^{OIRS} denotes the reflection coefficient of the mirror element, η represents the LED electro-optical conversion efficiency, A_{PD} is the photodetector area, and m is the Lambertian order of emission defined by the semi-angle at half power. The distances d_{sr} and d_{rd} denote the transmitter-to-OIRS and OIRS-to-receiver distances, respectively. The cosine terms C_1 , C_2 , C_3 , and C_4 account for the irradiance and incidence angles at both the OIRS and the receiver, and their explicit geometrical definitions are provided in Chapter 2. The term $T(\psi)$ represents the optical filter gain, while $G(\psi)$ denotes the optical concentrator gain within the receiver field-of-view (ψ_{FoV}).

It is important to emphasize that, unlike conventional plane mirrors, the OIRS elements possess adaptive orientation capability. The orientation angles (ζ, ϱ) of each mirror element are dynamically adjusted to maximize constructive reflection toward the receiver, thereby enhancing the effective channel gain.

4.3.4.2 Overall OIRS Channel Gain

The total DC channel gain of the OIRS-assisted UWOC system is obtained by summing the contributions of all $n_m \times n_m$ reflecting elements as:

$$H_{OIRS} = \sum_{k=1}^{n_m} \sum_{l=1}^{n_m} G_{O_{k,l}}(\zeta, \varrho) h_{att} h_{\alpha}. \quad (4.8)$$

Assuming that the mirror element dimensions are sufficiently small compared to the propagation distances, the element-wise gains can be approximated as identical. Consequently, the overall DC gain can be expressed in simplified form as:

$$H_{OIRS} \approx n_m^2 G_{O_{k,l}}(\zeta, \varrho) h_{att} h_{\alpha}. \quad (4.9)$$

Accordingly, the received optical power at the destination is given by:

$$P_R = \mathcal{R} P_t H_{OIRS}, \quad (4.10)$$

where P_t denotes the transmit optical power and $\mathcal{R}$ represents the SiPM responsivity which is given as [67–69]:

$$\mathcal{R} = \left(\frac{\Upsilon_{PDE}}{E_{ph}} \right) (1 + P_{AP} + P_{CT}) e \mathcal{G},$$

Here, E_{ph} is the photon energy, $\mathcal{G}$, Υ_{PDE} , P_{AP} , and P_{CT} , denote the SiPM gain, the photon detection efficiency, the probability of after-pulsing, and the probability of crosstalk, respectively.

The above formulation clearly highlights that the OIRS-assisted configuration enhances the channel gain through adaptive beam steering while incorporating attenuation and turbulence effects multiplicatively. This structure will serve as the basis for the statistical and performance analysis presented in the subsequent sections.

4.3.5 PMS Channel Gain Modeling

In this subsection, the channel gain of the PMS-assisted UWOC system is derived. The PMS consists of the same $n_m \times n_m$ mirror elements with dimensions $\ell_m \times w_m$ as considered for the OIRS. However, unlike the OIRS, the mirror elements in the PMS are fixed and do not possess adaptive orientation capability.

The element-wise channel gain for the $(k, l)^{\text{th}}$ PMS element is expressed as:

$$G_{P_{k,l}} = \begin{cases} \frac{R^{PMS} \eta(m+1) A_{PD}}{2\pi(d_{sr} + d_{rd})^2} C_1 C_2 C_3 C_4 T(\psi) G(\psi), & 0 \leq \psi_d^{k,l} \leq \psi_{FoV} \\ 0, & \text{otherwise,} \end{cases} \quad (4.11)$$

where $R^{PMS} = R^{OIRS}$, η , A_{PD} , m , $T(\psi)$ and $G(\psi)$ retain the same definitions as in the OIRS-assisted configuration. The cosine terms C_1 , C_2 , C_3 , and C_4 are determined purely by the geometric placement of the transmitter, PMS, and receiver.

Since the PMS elements are fixed, the reflection direction is governed by Snell's law and the inherent geometry of the system. Consequently, beam steering capability is absent, and only a subset of reflected rays may fall within the receiver field-of-view (FoV).

The overall DC channel gain for the PMS-assisted UWOC system is obtained by summing the contributions of all mirror elements as:

$$H_{PMS} = \sum_{k=1}^{n_m} \sum_{l=1}^{n_m} G_{P_{k,l}} h_{att} h_{\alpha}. \quad (4.12)$$

Accordingly, the received optical power at the destination is given as:

$$P_R = \mathcal{R} P_t H_{PMS}, \quad (4.13)$$

4.3.6 NLoS Channel Gain Modeling

In this subsection, the channel gain of the conventional NLoS-assisted UWOC system based on TIR at the water–air interface is derived. In this configuration, the water–air boundary acts as the reflecting surface.

Fig. 4.2 (c) provides an illustration of the NLoS-assisted UWOC system. In this system, the LED transmits a cone of light defined by an angle pair called $\theta_{\min}$ and $\theta_{\max}$ in the direction of the air-water contact/interface, which is reflected towards the underwater receiver obeying TIR¹. The main condition for TIR is that the signal must be traveling from a denser medium to a rarer medium and the angle of incidence is greater than the critical angle. At TIR, the interface acts as a perfect mirror and reflects the whole of the light back into the same medium. The channel gain of the NLoS UWOC system can be expressed as [1]:

$$G_N = \begin{cases} \frac{\eta A_{PD} \cos(\theta_i)}{2A_{\text{ann}}} [(R_s)^2 + (R_p)^2], & \theta_{\min} \leq \theta_i \leq \theta_c \\ \frac{\eta A_{PD} \cos(\theta_i)}{2A_{\text{ann}}}, & \theta_c \leq \theta_i \leq \theta_{\max} \\ 0, & \text{otherwise,} \end{cases} \quad (4.14)$$

where θ_i and θ_c denote the angles of incidence and the critical angle, respectively and A_{ann} represents the annular surface.

The annular surface area illuminated at the water–air interface is given as [16]:

$$A_{\text{ann}} = 2\pi(y_s + y_d)^2 [\cos(\theta_{\min}) - \cos(\theta_{\max})]. \quad (4.15)$$

where y_s and y_d denote the depths of the transmitter and the receiver from the sea surface, respectively.

The Fresnel reflection coefficients for s - and p -polarized components are expressed as [70]:

$$R_s = \left[\frac{\mu_w \cos(\theta_i) - \mu_a \cos(\theta_t)}{\mu_w \cos(\theta_i) + \mu_a \cos(\theta_t)} \right]^2 = \left[\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \right]^2, \quad (4.16)$$

$$R_p = \left[\frac{\mu_w \cos(\theta_t) - \mu_a \cos(\theta_i)}{\mu_w \cos(\theta_t) + \mu_a \cos(\theta_i)} \right]^2 = \left[\frac{\tan(\theta_t - \theta_i)}{\tan(\theta_t + \theta_i)} \right]^2, \quad (4.17)$$

where θ_t denote the angles of transmission, μ_w and μ_a denote the refractive indices of water and air, respectively.

¹The TIR phenomenon states that when the incidence angle is greater than the critical angle $\theta_c = \sin^{-1} \left(\frac{\mu_a}{\mu_w} \right)$, the light is reflected back into the same medium (water) after illuminating an annular area at the sea surface.

Due to the scattering nature of the underwater medium, the optical wave arriving at the water–air interface is assumed to be unpolarized. Therefore, the effective reflectivity is given as:

$$R_{eff} = \frac{1}{2}(R_s + R_p). \quad (4.18)$$

The overall channel gain of the NLoS-assisted UWOC system incorporating attenuation and turbulence effects is expressed as:

$$H_{NLoS} = G_N h_{att} h_\alpha. \quad (4.19)$$

Accordingly, the received optical power at the destination is given as [1]:

$$P_R = \mathcal{R}P_t H_{NLoS} T(\psi) G(\psi). \quad (4.20)$$

4.3.7 Statistical Characterization of SNR

In this section, the statistical characterization of the instantaneous electrical SNR is derived under the combined effects of underwater attenuation and turbulence.

Lemma 4.1: The PDF of the turbulence-induced fading coefficient h_α under EGG distribution is expressed in terms of the Fox–H function as:

$$f_{h_\alpha}(\alpha) = \frac{\omega}{\alpha} H_{0,1}^{1,0} \left[\frac{\alpha}{\Lambda} \middle| \begin{matrix} - \\ (1, 1) \end{matrix} \right] + \frac{1-\omega}{\alpha \Gamma(a)} H_{0,1}^{1,0} \left[\frac{\alpha}{b} \middle| \begin{matrix} - \\ (a, 1/c) \end{matrix} \right]. \quad (4.21)$$

Proof: The result follows by applying Mellin transform techniques to the exponential and generalized gamma components of the EGG distribution and utilizing the definition of the Fox–H function. The detailed derivation is provided in Appendix 4.A.

Lemma 4.2: Next, we use (4.21) to analyze the UWOC system performance. Assuming intensity modulation with direct detection (IM/DD) technique and on-off keying (OOK) modulation with $x \in \{0, \sqrt{2}P_t\}$ and P_t as average transmitted optical power, therefore the instantaneous received electrical SNR is given as [67]:

$$\gamma = \frac{\mathcal{R}^2 P_t^2 G_i^2 h_{att}^2 h_\alpha^2}{\sigma_{n_i}^2} = \bar{\gamma} h_\alpha^2, \quad (4.22)$$

where $\bar{\gamma} = \frac{\mathcal{R}^2 P_t^2 G_i^2 h_{att}^2}{\sigma_{n_i}^2}$ denotes the average electrical SNR. Then, applying the transformation of random variable $\gamma = \bar{\gamma} h_\alpha^2$, the PDF of SNR for the UWOC system under the effect of the seawater turbulence in terms of the Fox-H function can be expressed as:

$$f_\gamma(\gamma) = \frac{\omega}{2\gamma} H_{0,1}^{1,0} \left[\frac{1}{\Lambda} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} - \\ (1,1) \end{matrix} \right] + \frac{1-\omega}{2\gamma\Gamma(a)} H_{0,1}^{1,0} \left[\frac{1}{b} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} - \\ (a,1/c) \end{matrix} \right]. \quad (4.23)$$

Proof: The result is obtained by applying transformation of random variables to $\gamma = \bar{\gamma} h_\alpha^2$ and substituting the PDF of h_α from Lemma 4.1. Detailed steps are provided in Appendix 4.B.

Lemma 4.3: The cumulative distribution function (CDF) of the instantaneous SNR is expressed as:

$$F_\gamma(\gamma) = \omega H_{1,2}^{1,1} \left[\frac{1}{\Lambda} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} (1,1) \\ (1,1), (0,1) \end{matrix} \right] + \frac{1-\omega}{\Gamma(a)} H_{1,2}^{1,1} \left[\frac{1}{b} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} (1,1) \\ (a,1/c), (0,1) \end{matrix} \right]. \quad (4.24)$$

Proof: The CDF is obtained by integrating the PDF of γ and applying properties of the Fox–H function. The complete derivation is provided in Appendix 4.C.

4.4 Performance Analysis

4.4.1 Outage Probability (OP)

The OP is defined as the probability that the instantaneous SNR falls below a predefined threshold γ_{th} , and is expressed as:

$$P_{\text{out}} = \Pr(\gamma < \gamma_{\text{th}}) = F_\gamma(\gamma_{\text{th}}), \quad (4.25)$$

where $F_\gamma(\cdot)$ is the CDF derived in the previous section.

4.4.2 Average Spectral Efficiency (SE):

The average SE for the UWOC system is defined as [71]:

$$\overline{SE} = \int_0^\infty \log_2(1 + \tau\gamma) f_\gamma(\gamma) d\gamma, \quad (4.26)$$

where $\tau = \frac{e}{2\pi}$ for IM/DD transmission [72].

Using the Fox–H representation of the logarithmic function [73, eq. (8.4.6/5)]:

$$\log_2(1 + \tau\gamma) = 1.44 H_{2,2}^{1,2} \left[\tau\gamma \middle| \begin{matrix} (1,1), (1,1) \\ (1,1), (0,1) \end{matrix} \right], \quad (4.27)$$

the average SE can be expressed as:

$$\overline{SE} = 0.72\omega H_{p+2,q+3}^{m+3,n+1} \left[\frac{1}{\Lambda} \sqrt{\frac{1}{\tau\bar{\gamma}}} \left| \begin{array}{c} (0, 1/2), (1, 1/2) \\ (1, 1), (0, 1/2), (0, 1/2) \end{array} \right. \right] \quad (4.28)$$

$$+ 0.72 \frac{1-\omega}{\Gamma(a)} H_{p+2,q+3}^{m+3,n+1} \left[\frac{1}{b} \sqrt{\frac{1}{\tau\bar{\gamma}}} \left| \begin{array}{c} (0, 1/2), (1, 1/2) \\ (a, 1/c), (0, 1/2), (0, 1/2) \end{array} \right. \right], \quad (4.29)$$

where p, q, m, and n are determined according to the Fox–H representation of the turbulence PDF derived in Lemma 4.1.

For high SNR ($\bar{\gamma} \gg 1$), the asymptotic expression of the average SE is obtained as [74, eq. (8.360/1)]:

$$\overline{SE} \approx 1.44 \left[\log(\tau) + \omega \left(\log(\Lambda^2 \bar{\gamma}) + 2\psi(1) \right) + (1-\omega) \left(\log(b^2 \bar{\gamma}) + \frac{2}{c} \psi(a) \right) \right], \quad (4.30)$$

where ψ function is given as $\psi(x) = \frac{d}{dx} \ln \Gamma(x)$

4.4.3 Average Energy Efficiency (EE)

The average EE is defined as the average SE divided by the total power consumed [75]:

$$\overline{EE} = \frac{\overline{SE}}{P_t + P_{\text{diss}}}, \quad (4.31)$$

where P_{diss} denotes power dissipation in the system's hardware components.

Therefore, average EE can be calculated as:

$$\overline{EE} = \frac{\overline{SE}}{P_t + p_d^s + p_d^d + n_m^2 p_d^o}, \quad (4.32)$$

where p_d^s, p_d^d, p_d^o denote the power dissipation at the source/transmitter, receiver, and each OIRS element, respectively.

4.4.4 Average Bit Error Rate (BER)

The average BER is expressed as [76]:

$$\overline{BER} = \frac{\delta}{2\Gamma(\phi)} \sum_{n=1}^N q_n^\phi \int_0^\infty \gamma^{\phi-1} \exp(-q_n \gamma) F_\gamma(\gamma) d\gamma, \quad (4.33)$$

where the parameter set $\{N, \delta, \phi, q_n\}$ vary according to the modulation and detection technique used [32]. Substituting $\exp(-q_n\gamma) = G_{0,1}^{1,0} \left[q_n\gamma \mid \begin{matrix} - \\ 0 \end{matrix} \right]$ and $F_\gamma(\gamma)$ from (4.24) in above equation and converting the Meijer's G-function into Fox-H function, we get:

$$\begin{aligned} \overline{BER} = & \frac{\delta}{2\Gamma(\phi)} \sum_{n=1}^N q_n^\phi \int_0^\infty \gamma^{\phi-1} \\ & H_{0,1}^{1,0} \left[\begin{matrix} - \\ (0,1) \end{matrix} \mid q_n\gamma \right] \left(\omega H_{1,2}^{1,1} \left[\frac{1}{\Lambda} \sqrt{\frac{\gamma}{\bar{\gamma}}} \mid \begin{matrix} (1,1) \\ (1,1)(0,1) \end{matrix} \right] \right. \\ & \left. + \frac{(1-\omega)}{2\gamma\Gamma(a)} H_{1,2}^{1,1} \left[\frac{1}{b} \sqrt{\frac{\gamma}{\bar{\gamma}}} \mid \begin{matrix} (1,1) \\ (a,1/c)(0,1) \end{matrix} \right] \right) d\gamma. \end{aligned} \quad (4.34)$$

After applying [77, eq. (2.8.4)] in (4.34), the closed-form expression for the average BER can be expressed in terms of bivariate Fox's H function as:

$$\begin{aligned} \overline{BER} = & \frac{\delta}{2\Gamma(\phi)} \sum_{n=1}^N \left(\omega H_{2,2}^{1,2} \left[\frac{1}{\Lambda} \left(\frac{1}{q_k\bar{\gamma}} \right)^{1/2} \mid \begin{matrix} (1,1)(1-\phi, \frac{1}{2}) \\ (1,1)(0,1) \end{matrix} \right] \right. \\ & \left. + \frac{(1-\omega)}{\Gamma(a)} H_{2,2}^{1,2} \left[\frac{1}{b} \left(\frac{1}{q_k\bar{\gamma}} \right)^{\frac{1}{2}} \mid \begin{matrix} (1,1)(1-\phi, \frac{1}{2}) \\ (a, \frac{1}{c})(0,1) \end{matrix} \right] \right). \end{aligned} \quad (4.35)$$

4.5 Simulation Results

The simulation study evaluates the proposed OIRS-assisted UWOC system under representative underwater operating conditions, including different turbulence regimes, water types, and propagation scenarios. For clarity, each figure primarily investigates the influence of one design parameter while keeping the remaining parameters fixed, thereby isolating its individual impact on the system performance and facilitating a clear interpretation of the observed trends. Although the presented results already demonstrate the robustness of the proposed framework under diverse environmental conditions, a comprehensive multi-parameter sensitivity analysis may provide additional insight into parameter interactions and constitutes an interesting direction for future research.

In this section, the numerical results obtained through the proposed schemes are presented and compared with the baseline scenario of conventional NLoS-aided UWOC system. The

Table 4.1: Simulation Parameters

Parameter	Symbol	Value
Transmit power [78]	P_t	-10 to 60 dBm
Total node separation	d_{sd}	30 m
Wavelength [5]	λ	532 nm
Refractive index of water [16]	μ_w	1.33643
Refractive index of air	μ_a	1
Extinction coefficient of pure seawater [79]	$c(\lambda)$	0.056 m^{-1}
Modulation parameters [32]	N, δ, ϕ, q_n	1, 1, 1/2, 1/4
Length of OIRS element	ℓ_m	8 cm
Width of OIRS element	w_m	8 cm
Reflection efficiency of mirror element [75]	R^{OIRS}	0.8
Lambertian order [75]	m	2
Depth of Transmitter	y_s	40 m
Depth of receiver	y_d	40 m
SiPM area	A_{PD}	0.0314 m^2
Optical filter gain [54]	T	1
SiPM gain [67]	$\mathcal{G}$	10^6
SiPM dark current [67]	I_d	$10 \mu\text{A}$
SiPM prob. of cross-talk [67]	P_{CT}	0.03%
SiPM prob. of after pulsing [67]	P_{AP}	0.2%
SiPM excess noise factor [67]	F	1.1
Speed of light in water	C_{water}	$2.25 \times 10^8 \text{ m/sec}$
Charge on electron [67]	e	$1.6 \times 10^{-19} \text{ C}$
Transmitter inclination angles [16]	$\theta_{min}, \theta_{max}$	$0^0, 68^0$
Scintillation index [32]	σ_I^2	{0.2178, 1.9328, 3.1952}
EGG distribution parameters corresponding to different σ_I^2 [32]	$\{\omega\}_{i=1}^3$ $\{\Lambda\}_{i=1}^3$ $\{a\}_{i=1}^3$ $\{b\}_{i=1}^3$ $\{c\}_{i=1}^3$	{0.1665, 0.6238, 0.7210} {0.1207, 0.1094, 0.1479} {0.1559, 0.0111, 0.0121} {1.5216, 4.4750, 7.4189} {22.8754, 105.3550, 65.6983}.
Power dissipation in transceiver [75]	$p_d^s + p_d^d$	30 dBm
Power dissipation in each OIRS element [80]	p_d^o	10 dBm

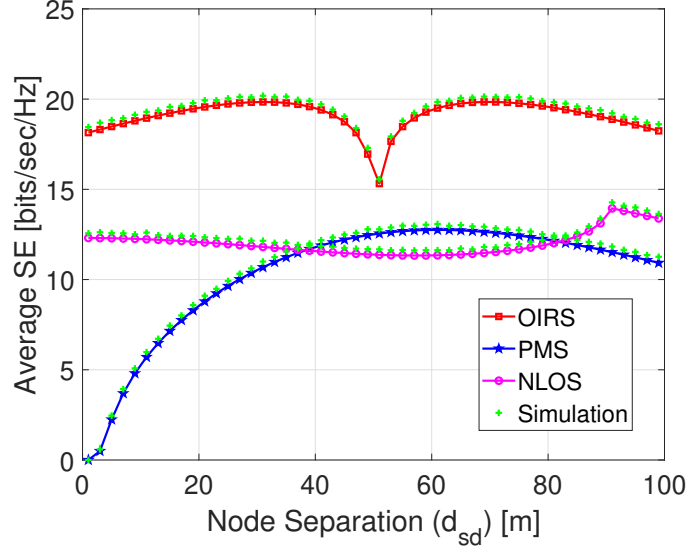


Figure 4.3: Average SE vs. node separation for different UWOC systems.

OIRS and PMS consist of $n_m \times n_m$ mirror elements with a dimension of $\ell_m = 0.08$ m and $w_m = 0.08$ m. The speed of light in water (C_{water}) is assumed to be 2.25×10^8 m/sec, and the performance is demonstrated by positioning the OIRS/PMS perfectly in the middle of the transmitter and receiver when $y_s = y_d = 40$ m, if not specified otherwise. The key simulation parameters are summarized in Table 4.1. All the presented results have been obtained through Monte Carlo simulation. MATLAB is used for calculating Meijer's G function and MATHEMATICA for Fox's H function.

4.5.1 Average SE Analysis

In this subsection, the average SE performance of the OIRS, PMS, and conventional NLoS-assisted UWOC systems is evaluated under various geometric and channel conditions. The MA (OIRS/PMS) of area (a_o) = 1 m² ($n_m^2 = a_o/\ell_m^2 = 169$), is fixed at a horizontal distance of 50 m from the source i.e., $z_{kl} = 50$ m. The operating wavelength is fixed at 532 nm corresponding to the blue-green optical window. Pure seawater is considered with extinction coefficient $c(\lambda) = 0.056$ m⁻¹, and weak turbulence is assumed with scintillation index $\sigma_I^2 = 0.2178$, unless otherwise varied.

4.5.1.1 Impact of Node Separation Distance

Fig. 4.3 illustrates the variation of the average SE with respect to the node separation distance (d_{sd}). It is observed that the OIRS-assisted configuration consistently achieves the highest SE across a wide range of separation distances. For moderate values of d_{sd} , the SE initially

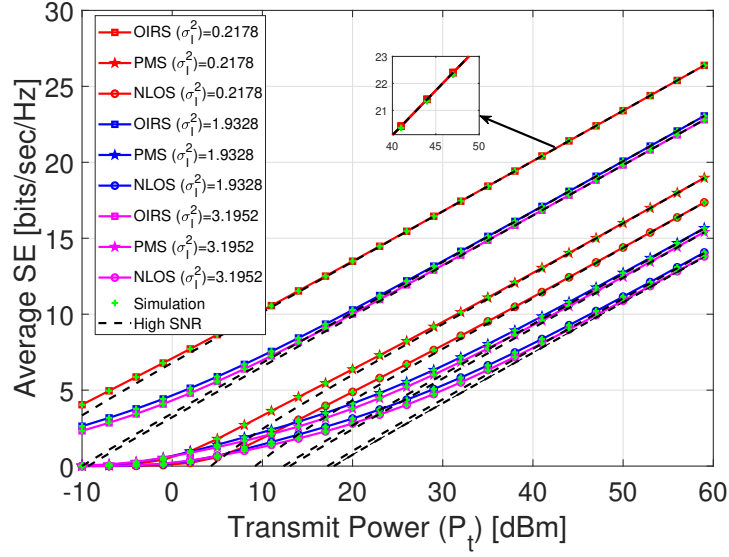


Figure 4.4: Average SE vs. transmit power for different UWOC systems.

increases. This improvement is attributed to the reduction in the effective propagation distance between the transmitter, reflector, and receiver, which enhances the received optical power according to the attenuation behavior derived in the channel model.

When the receiver is positioned directly beneath the OIRS plane, a noticeable dip in SE is observed. This behavior arises due to unfavorable incidence geometry. In this configuration, the angle of irradiance reduces the effective cosine components in the channel gain expression, thereby decreasing the received optical power. As the separation distance increases further, the total propagation distance increases and attenuation becomes dominant, resulting in gradual SE degradation.

The PMS-assisted system exhibits a smoother SE variation without a sharp dip. Since PMS elements lack adaptive orientation capability, reflected rays arrive at the receiver from multiple directions, allowing partial power capture even under non-ideal alignment conditions.

The conventional NLoS-assisted configuration strongly depends on the incidence angle relative to the critical angle governing total TIR at the water–air interface. Under specific geometric conditions, TIR enhances reflection efficiency; however, this configuration remains restricted to near-surface deployment scenarios and lacks the flexibility offered by adaptive OIRS beam steering.

4.5.1.2 Impact of Transmit Power and Turbulence

Fig. 4.4 presents the variation of average SE with respect to transmit power P_t under weak, moderate, and strong turbulence conditions characterized by $\sigma_I^2 = \{0.2178, 1.9328, 3.1952\}$.

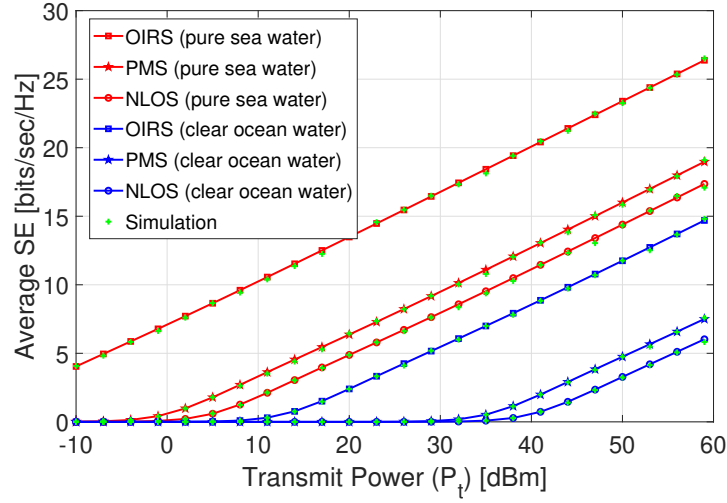


Figure 4.5: Average SE vs. transmit power for different water types.

For all configurations, the SE increases monotonically with transmit power. This behavior is consistent with the electrical SNR scaling under IM/DD transmission, as established in the analytical derivations.

Among the three configurations, the OIRS-assisted system consistently achieves superior SE across all turbulence regimes. The adaptive orientation of mirror elements enables constructive redirection of optical energy toward the receiver, thereby maximizing the effective channel gain.

Increasing turbulence strength results in noticeable SE degradation. Strong turbulence introduces severe irradiance fluctuations, increasing the probability of deep fading events and consequently reducing the average achievable rate. The close agreement between analytical and Monte Carlo simulation results validates the accuracy of the derived statistical expressions.

4.5.1.3 Impact of Water Type

Fig. 4.5 compares SE performance under different water types characterized by distinct attenuation coefficients.

It is observed that pure seawater achieves higher SE compared to more absorptive water types. This behavior is governed by the exponential attenuation term in the channel model, which causes the received optical power to decay rapidly with increasing extinction coefficient. Even moderate increases in the attenuation coefficient significantly reduce effective channel gain due to the exponential nature of optical absorption.

These results confirm that water type plays a critical role in determining UWOC system performance and highlight the importance of adaptive reflecting architectures in environments with moderate attenuation levels.

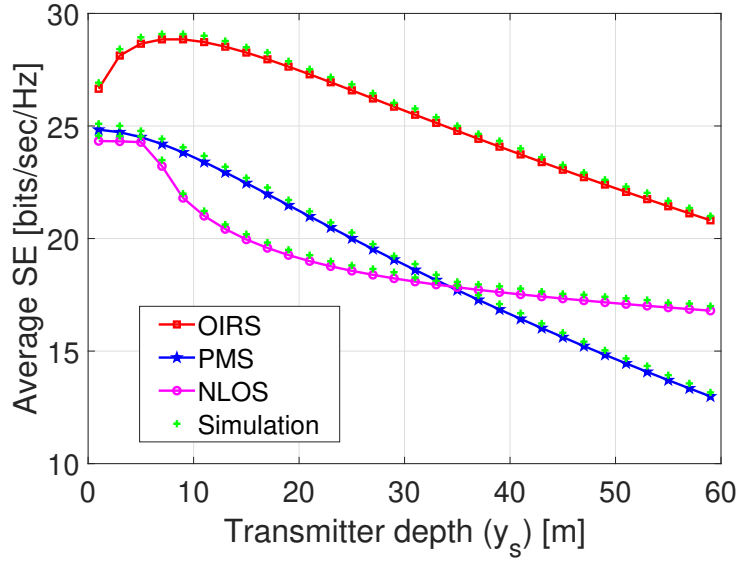


Figure 4.6: Average SE vs. transmitter depth for different UWOC systems.

Table 4.2: Incidence angle (θ_i) for varying transmitter depths (y_s).

Transmitter depth (y_s) [m]	Incidence angle (θ_i)
1	55.0079
2	53.7461
5	50.1944
6	49.0856
7	$48.0127 < \theta_c$

4.5.1.4 Impact of Transmitter Depth

Fig. 4.6 illustrates the variation of average SE with respect to transmitter depth y_s .

When the transmitter is located very close to the reflecting plane, the incidence angle at the reflector becomes large, reducing the effective cosine components in the channel gain expression. This behavior arises from the operational constraints of the MA reflector, where the rotational degrees of freedom of each reflecting element are limited to the range $[-\pi/2, \pi/2]$. As a result, extreme incidence angles restrict beam steering capability, leading to reduced SE.

As the transmitter depth increases, the incidence geometry becomes more favorable, improving constructive redirection of optical energy and increasing SE. However, beyond a certain depth, the total propagation distance increases and attenuation dominates, resulting in a gradual average SE reduction.

In the case of PMS, as the signal from all of the PMS elements doesn't fall on the receiver FoV, so its average SE is less than that of the OIRS scenario. In the conventional NLoS

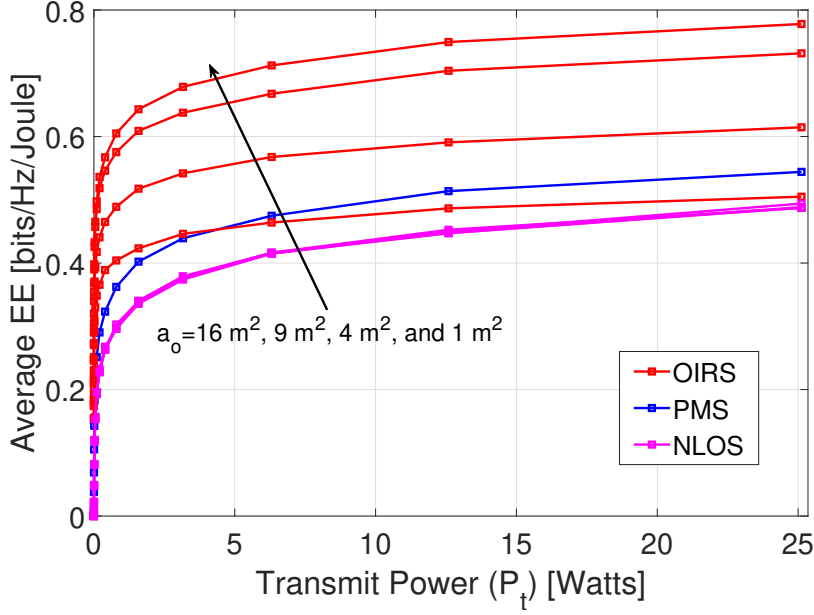


Figure 4.7: Average EE vs. transmit power for different UWOC systems.

scenario, the average SE is initially high until $y_s = 7$ m; the reason behind this high SE is the TIR occurring at the water-air interface as θ_i is more than the $\theta_c = 48.4401$. After $y_s = 7$ m, as $\theta_i < \theta_c$, therefore the average SE reduces as a function of both pathloss and reflectivity. Table 4.2 shows the values of incidence angle for various transmitter depths.

A similar geometric trend is observed when varying receiver depth. These observations highlight the strong dependence of UWOC system performance on deployment geometry and demonstrate the flexibility advantage of adaptive OIRS compared to plane reflecting mechanisms.

4.5.2 Average EE Analysis

In this subsection, the average EE performance of the considered UWOC architectures is evaluated. Weak turbulence with scintillation index $\sigma_I^2 = 0.2178$ is assumed. The reflecting surface area is set to $a_o = 1$ m², and the OIRS/PMS is positioned midway between the transmitter and receiver. The circuit power dissipation parameters are given in Table 4.1.

Fig. 4.7 presents the variation of the average EE with respect to the transmit power P_t . It is observed that the EE initially increases with transmit power for all configurations. This behavior occurs because the SE improves as P_t increases, resulting in a higher achievable data rate relative to the consumed power. However, beyond a certain transmit power level, the EE growth gradually saturates. This phenomenon arises from the logarithmic dependence of SE

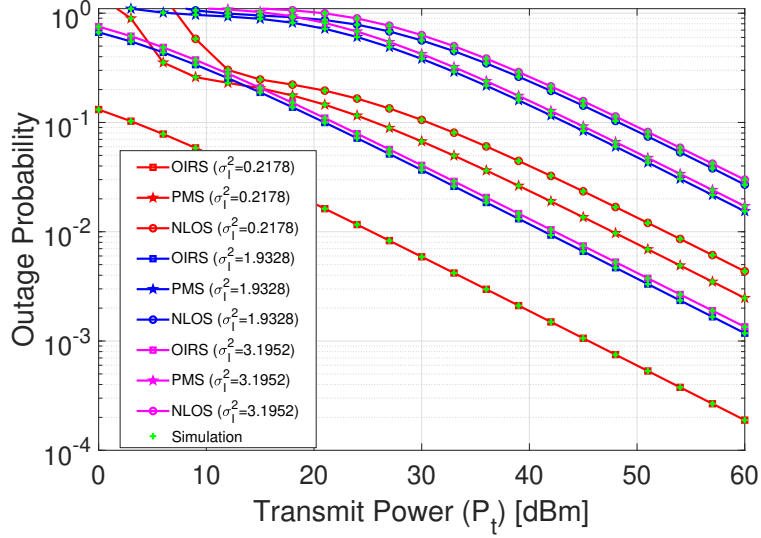


Figure 4.8: OP vs. transmit power for different UWOC systems.

on SNR, whereas the total consumed power increases linearly with P_t . Consequently, further increases in transmit power yield diminishing returns in terms of EE.

Among the considered configurations, the OIRS-assisted system achieves higher SE due to adaptive beam steering. Nevertheless, its overall EE performance is influenced by the circuit power dissipation associated with the reflecting elements according to (4.32). As the number of reflecting elements increases, the hardware power consumption grows linearly, while the SE improvement gradually saturates. Therefore, excessively large reflecting surfaces may reduce overall EE despite improving SE.

The PMS-assisted configuration exhibits moderate EE performance. Although it does not require adaptive control circuitry for each element, its achievable SE remains lower than that of OIRS due to the absence of beam steering capability.

These results highlight the inherent tradeoff between SE and EE in adaptive reflecting UWOC systems. Practical system design should therefore consider joint optimization of transmit power and reflecting surface size to achieve a balanced SE–EE performance.

4.5.3 Outage Probability (OP) Analysis

Fig. 4.8 illustrates the OP performance of the OIRS, PMS, and NLoS-assisted UWOC systems under different turbulence conditions. The outage threshold is fixed at $\gamma_{th} = 4$ dB. The remaining system parameters follow the values specified in the simulation parameters table (Table 4.1).

It is observed that the OP decreases monotonically with increasing transmit power for all considered configurations. This behavior is expected since higher transmit power improves

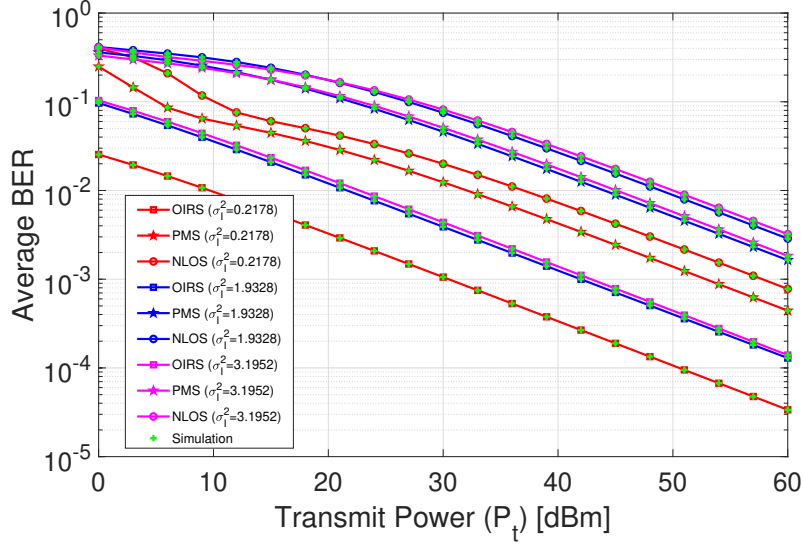


Figure 4.9: Average BER vs. transmit power for different UWOC systems.

the received SNR, thereby reducing the probability that the instantaneous SNR falls below the outage threshold.

Among the considered architectures, the OIRS-assisted UWOC system achieves the lowest OP across all turbulence regimes.

The PMS-assisted configuration exhibits intermediate outage performance. Although mirror reflection improves received power compared to the conventional NLoS configuration, the absence of adaptive beam steering limits the fraction of reflected power captured within the receiver FoV.

The conventional NLoS-assisted system demonstrates comparatively higher OP, particularly under moderate and strong turbulence conditions. Reflection losses at the water–air interface and the dependence on the critical angle condition contribute to additional signal degradation.

Furthermore, increasing the turbulence strength results in a noticeable increase in OP for all configurations. Stronger turbulence induces more severe irradiance fluctuations, increasing the likelihood of deep fading events and consequently elevating OP.

The analytical results closely match the Monte Carlo simulations, validating the accuracy of the derived statistical expressions under the adopted EGG turbulence model.

4.5.4 Average BER Analysis

In this subsection, the average BER performance of the OIRS, PMS, and conventional NLoS-assisted UWOC systems is evaluated under IM/DD transmission with OOK modulation. Fig. 4.9 presents the variation of the average BER with respect to the transmit power P_t .

It is observed that the average BER decreases monotonically with increasing transmit power for all considered configurations. This behavior is consistent with the improvement in the average received SNR, which enhances symbol detection reliability and reduces the probability of erroneous decisions under OOK modulation.

Among the considered architectures, the OIRS-assisted configuration consistently achieves the lowest BER across all turbulence conditions.

The PMS-assisted configuration exhibits moderate BER performance. The conventional NLoS-assisted UWOC system demonstrates comparatively higher BER in most scenarios. Reflection losses at the water–air interface, combined with medium attenuation and turbulence-induced irradiance fluctuations, reduce the received SNR and increase the probability of symbol errors.

Furthermore, increasing the scintillation index leads to noticeable BER degradation for all configurations. Strong turbulence introduces severe intensity fluctuations, increasing the occurrence of deep fading events and consequently raising the average BER. Under weak turbulence, the BER reduction with increasing transmit power is more pronounced, whereas under strong turbulence, performance improvement is comparatively slower due to dominant fading effects.

The performance analysis in this chapter assumes perfect CSI at the OIRS controller for optimal mirror orientation. In practical UWOC deployments, channel estimation errors may affect the achievable beamforming gain and system performance. Therefore, the presented results represent an upper performance bound under ideal CSI conditions. Extending the analysis to account for imperfect CSI and robust beamforming design is a promising direction for future research.

4.6 Conclusions

In this chapter, an OIRS-assisted UWOC system employing a MA-based architecture has been evaluated and compared with PMS-assisted and conventional NLoS-assisted configurations. A comprehensive analytical framework was developed by incorporating underwater attenuation modeled via Beer–Lambert law and turbulence effects characterized using the EGG distribution.

Closed-form expressions for the PDF and CDF of the instantaneous SNR were derived in terms of the Fox–H function. Based on these statistical characterizations, analytical expressions for OP, average SE, average EE, and average BER were obtained. The analytical results were validated through Monte Carlo simulations, confirming the accuracy of the proposed framework.

The numerical analysis demonstrated that adaptive beam steering enabled by the OIRS provides significant performance improvement over plane mirror reflection and TIR-based conventional NLoS configurations across various deployment scenarios. In particular, OIRS-assisted UWOC systems achieved superior SE and lower OP and BER under weak, moderate, and strong turbulence conditions.

The results also highlighted the importance of deployment geometry. It was analytically and numerically observed that improper placement of the reflecting surface, such as positioning it extremely close to the transmitter or receiver, can degrade performance due to unfavorable incidence angles. Furthermore, while increasing the reflecting surface area enhances SE, it may reduce EE due to increased circuit power consumption, indicating the existence of an optimal reflecting surface size.

Overall, the proposed OIRS-assisted architecture offers enhanced flexibility and improved performance compared to conventional NLoS-based underwater optical communication systems.

Appendix 4.A: Proof of Lemma 4.1

The EGG distribution is defined as a weighted mixture of exponential and generalized Gamma distributions as:

$$f_{h_\alpha}(\alpha) = \omega f(\alpha; \Lambda) + (1 - \omega)g(\alpha; a, b, c), \quad (4.36)$$

where

$$f(\alpha; \Lambda) = \frac{1}{\Lambda} \exp\left(-\frac{\alpha}{\Lambda}\right), \quad (4.37)$$

and

$$g(\alpha; a, b, c) = c \frac{\alpha^{ac-1} \exp\left[-\left(\frac{\alpha}{b}\right)^c\right]}{b^{ac} \Gamma(a)}. \quad (4.38)$$

For any random variable z , the PDF can be obtained by using inverse mellin transform as:

$$f_Z(z) = \frac{1}{2\pi iz} \int_{\zeta-i\infty}^{\zeta+i\infty} z^{-n} \mathbb{E}[Z^n] dn, \quad (4.39)$$

where $\zeta - i\infty$ to $\zeta + i\infty$ denotes the line integral, $\mathbb{E}[\cdot]$ denotes the expectation operator and $\mathbb{E}[X^n]$ denotes the the n^{th} order moment. The n^{th} order moment of h_α is expressed as:

$$\mathbb{E}[h_\alpha^n] = \int_0^\infty h_\alpha^n f_{h_\alpha}(h_\alpha) dh_\alpha. \quad (4.40)$$

Now substituting (4.5) in (4.40) and then using [74, eqs. (3.351/3) and (3.478/1)], we get:

$$\mathbb{E}[h_\alpha^n] = \left(\omega \Lambda^n \Gamma(1+n) + \frac{(1-\omega) b^n \Gamma(a+n/c)}{\Gamma(a)} \right). \quad (4.41)$$

Now using (4.41) in (4.39) and then applying the inverse Mellin transform and using the definition of the Fox–H function [77], the PDF of h_α can be expressed as:

$$f_{h_\alpha}(\alpha) = \frac{\omega}{\alpha} H_{0,1}^{1,0} \left[\frac{\alpha}{\Lambda} \left| \begin{matrix} - \\ (1, 1) \end{matrix} \right. \right] + \frac{1-\omega}{\alpha \Gamma(a)} H_{0,1}^{1,0} \left[\frac{\alpha}{b} \left| \begin{matrix} - \\ (a, 1/c) \end{matrix} \right. \right]. \quad (4.42)$$

The convergence of the above Fox–H representation follows from standard Mellin transform inversion conditions, which are satisfied for $0 < \omega < 1$, $a > 0$, $b > 0$, and $c > 0$.

This completes the proof.

Appendix 4.B: Proof of Lemma 4.2

The instantaneous SNR is related to the turbulence coefficient using (4.22) as:

$$\gamma = \bar{\gamma} h_\alpha^2. \quad (4.43)$$

Let $h_\alpha = \sqrt{\frac{\gamma}{\bar{\gamma}}}$. Using transformation of random variables, the PDF of γ is obtained as:

$$f_\gamma(\gamma) = f_{h_\alpha} \left(\sqrt{\frac{\gamma}{\bar{\gamma}}} \right) \left| \frac{dh_\alpha}{d\gamma} \right|. \quad (4.44)$$

Since:

$$\frac{dh_\alpha}{d\gamma} = \frac{1}{2\sqrt{\bar{\gamma}\gamma}}, \quad (4.45)$$

we obtain:

$$f_\gamma(\gamma) = f_{h_\alpha} \left(\sqrt{\frac{\gamma}{\bar{\gamma}}} \right) \frac{1}{2\sqrt{\bar{\gamma}\gamma}}. \quad (4.46)$$

Substituting the PDF expression of h_α from Lemma 4.1 and simplifying yields:

$$f_\gamma(\gamma) = \frac{\omega}{2\gamma} H_{0,1}^{1,0} \left[\frac{1}{\Lambda} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} - \\ (1, 1) \end{matrix} \right] + \frac{1-\omega}{2\gamma\Gamma(a)} H_{0,1}^{1,0} \left[\frac{1}{b} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} - \\ (a, 1/c) \end{matrix} \right]. \quad (4.47)$$

This completes the proof.

Appendix 4.C: Proof of Lemma 4.3

The CDF is defined as:

$$F_\gamma(\gamma) = \int_0^\gamma f_\gamma(t) dt. \quad (4.48)$$

Substituting the PDF of γ from Lemma 4.2, we evaluate the integral using the following Fox-H function identity [77]:

$$\int x^{-1} H_{p,q}^{m,n} [ax^\zeta] dx = H_{p+1,q+1}^{m+1,n} [ax^\zeta]. \quad (4.49)$$

Applying this identity to both mixture components yields

$$F_\gamma(\gamma) = \omega H_{1,2}^{1,1} \left[\frac{1}{\Lambda} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} (1,1) \\ (1,1), (0,1) \end{matrix} \right] + \frac{1-\omega}{\Gamma(a)} H_{1,2}^{1,1} \left[\frac{1}{b} \sqrt{\frac{\gamma}{\bar{\gamma}}} \middle| \begin{matrix} (1,1) \\ (a, 1/c), (0,1) \end{matrix} \right]. \quad (4.50)$$

This completes the proof.

Optical IRS Assisted Multi-User UWOC with Smart Element Allocation

In Chapter 4, the performance of a mirror-array (MA)-based optical intelligent reflecting surface (OIRS)-assisted underwater wireless optical communication (UWOC) system was analytically investigated under realistic attenuation and oceanic turbulence effects. Closed-form statistical expressions for the instantaneous signal-to-noise ratio (SNR) and key performance metrics were derived for a single-user configuration.

However, practical underwater optical networks inherently operate in multi-user environments, where multiple nodes share limited optical resources and compete for reliable connectivity. In addition, beam misalignment caused by water currents, platform instability, and node mobility introduces significant performance degradation, which was not incorporated in the previous analysis. Furthermore, underwater channel characteristics are strongly influenced by depth-dependent variations, as attenuation, turbulence strength, and geometric propagation conditions vary with ocean depth, thereby affecting link reliability and overall system performance.

Therefore, extending the analytical framework to a multi-user scenario while incorporating pointing errors and depth-dependent channel variations becomes essential for realistic system design and performance optimization. This chapter builds upon the single-user foundation established in Chapter 4 and develops a comprehensive analytical framework for multi-user MA-based OIRS-assisted UWOC systems. In particular, intelligent mirror allocation strategies are introduced to efficiently distribute OIRS elements among users, enabling improved spectral efficiency (SE) and fairness under practical underwater conditions.

5.1 Chapter Overview

This chapter extends the single-user OIRS-assisted UWOC framework developed in the previous chapter to a multi-user underwater communication scenario. While the analytical results in Chapter 4 provided important insights into the performance gains, reliability, and feasibility of OIRS-assisted UWOC links under single-user configurations, practical underwater optical networks inherently operate in multi-user environments, where multiple users coexist within the coverage region and compete for limited optical resources. Therefore, intelligent resource management becomes essential for maximizing system performance while maintaining fairness among users. In addition, practical underwater environments are affected by beam misalignment and depth-dependent channel variations, which must be incorporated for realistic system modeling.

In multi-user UWOC systems, efficient resource allocation becomes a critical design challenge. Unlike conventional acoustic systems, underwater optical channels experience severe distance-dependent attenuation and turbulence-induced fading, which cause significant disparity among users located at different positions. Consequently, uniform resource allocation may lead to severe performance imbalance and reduced aggregate spectral efficiency (ASE).

Existing studies on OIRS-assisted UWOC systems primarily focus on single-user scenarios or static reflecting configurations. However, in multi-user deployments, uniform mirror allocation leads to inefficient resource utilization and fairness degradation. Furthermore, the joint impact of mirror allocation and multiple access techniques has not been analytically characterized under realistic underwater conditions.

Furthermore, underwater environments are inherently dynamic. Water currents, platform vibrations, and node mobility introduce beam misalignment, resulting in pointing errors that further degrade link reliability. Although attenuation and turbulence were analyzed previously, the combined impact of multi-user resource allocation and pointing errors has not been systematically addressed.

Moreover, underwater optical channels exhibit strong depth-dependent characteristics. As the operating depth increases, variations in water composition, pressure, and temperature lead to changes in attenuation coefficients, turbulence strength, and geometric propagation conditions. These variations directly influence the received signal strength and user-specific channel quality, thereby impacting both SE and fairness in multi-user systems. Therefore, incorporating depth-dependent effects is essential for accurately modeling practical UWOC environments.

To address these challenges, a submerged MA-based OIRS is employed to enable non-line-of-sight (NLoS) communication and dynamic beam redirection toward multiple users. Unlike conventional reflecting mechanisms, the MA-based OIRS allows flexible allocation of

mirror elements, thereby providing an additional spatial degree of freedom for performance enhancement.

The primary objective of this chapter is to design and analyze dynamic mirror allocation strategies for multi-user OIRS-assisted UWOC systems. In particular, a distance-based mirror assignment (DMA) scheme is proposed to allocate mirror elements according to user distances, while an equal mirror assignment (EMA) scheme is considered as a benchmark. Furthermore, the performance of the OIRS-assisted UWOC system is analyzed under different multiple access schemes, including orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA), and rate-splitting multiple access (RSMA), to illustrate the impact of multiple access techniques on system performance.

A comprehensive analytical framework is developed by incorporating attenuation, oceanic turbulence, pointing error effects, and depth-dependent channel variations. Closed-form statistical expressions for the instantaneous SNR are derived, and performance metrics such as ASE and fairness index are analytically evaluated. The analytical results are validated through extensive Monte Carlo simulations.

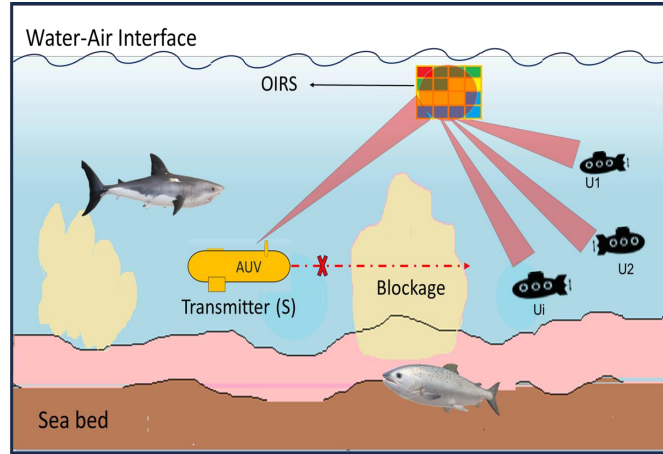


Figure 5.1: A conceptual diagram of OIRS assisted UWOC system architecture.

The main contributions of this chapter are summarized as follows:

1. A multi-user MA-based OIRS-assisted UWOC system model is developed under NLoS conditions, incorporating depth-dependent attenuation, Exponential Generalized Gamma (EGG)-distributed oceanic turbulence, and zero-boresight pointing errors.
2. A DMA strategy is proposed to dynamically allocate OIRS mirror elements according to user distances, thereby compensating for distance-dependent pathloss and enhancing ASE.

3. An EMA scheme is considered as a benchmark to evaluate the effectiveness of the proposed DMA strategy in terms of SE and fairness.
4. Closed-form statistical expressions for the instantaneous SNR are derived using the Mellin transform and Fox's H-function framework, enabling analytical evaluation of SE, ASE, and Jain's fairness index.
5. The performance of the system is analyzed under multiple access techniques, including OMA, NOMA, and RSMA, providing insights into the trade-off between SE and fairness in multi-user OIRS-assisted UWOC systems.
6. Extensive Monte Carlo simulations are conducted to validate the analytical derivations and to investigate the impact of turbulence strength, pointing error parameters, oceanic depth, and number of users on system performance.

5.2 System Model

In this section, the mathematical model of the proposed multi-user MA-based OIRS-assisted UWOC system is developed. The fundamental optical propagation principles, including attenuation and turbulence modeling, follow the framework established in Chapter 4. However, the system is now extended to a multi-user downlink configuration where multiple users are simultaneously served through dynamic mirror allocation as shown in 5.1.

Compared to the single-user analysis presented previously, four major extensions are incorporated in this chapter. First, the OIRS is partitioned into dynamically assigned mirror subsets to serve multiple users. Second, zero-boresight pointing errors are explicitly modeled to account for beam misalignment caused by underwater dynamics. Third, depth-dependent channel variations are incorporated to capture the impact of ocean depth on attenuation, turbulence, and geometric propagation conditions. Fourth, multiple access schemes, namely OMA, NOMA, and RSMA, are integrated into the analytical framework to evaluate interference management and SE trade-offs. The composite channel gain of each user therefore consists of three multiplicative components: deterministic attenuation loss, turbulence-induced fading, and pointing error fading, combined with the geometrically controlled OIRS reflection gain as discussed in Chapter 2. Based on this composite channel model, the instantaneous SNR expressions and performance metrics are derived in subsequent sections.

5.3 Channel Model

We consider a downlink multi-user UWOC system employing intensity modulation with direct detection (IM/DD). The optical transmitter consists of a light emitting diode (LED) array operating in the blue-green spectrum, while each user is equipped with a P-Intrinsic-N (PIN) photodetector. Since IM/DD transmission is adopted, the transmitted signal is real-valued and non-negative, and the received electrical signal is proportional to the incident optical intensity.

The direct line-of-sight (LoS) path between the transmitter and users is assumed to be blocked due to underwater obstacles or deployment geometry. To enable NLoS communication, a submerged planar MA based OIRS is deployed to redirect the transmitted optical beam toward the intended users as shown in 5.1.

The underwater channel for each user is modeled as the product of independent attenuation loss, turbulence-induced fading, and pointing error fading components. The attenuation component is deterministic and distance-dependent, whereas the turbulence and pointing error components are modeled as statistically independent random variables. The additive noise at each receiver is assumed to be signal-independent Gaussian noise resulting from thermal and shot noise effects.

The source is located at $(0, y_s, 0)$, and N users are randomly distributed within a circular region with coordinates (x_{di}, y_{di}, z_{di}) , where $i \in \{1, 2, \dots, N\}$. The OIRS is positioned on the x - z plane at $(x_{k,l}, 0, z_{k,l})$, consisting of $n_m \times n_m$ mirror elements, each with dimensions $\ell_m \times w_m$.

Under these assumptions, the received electrical signal at the i^{th} user can be expressed as [54, 55]:

$$y_i = G_i h_{att_i} h_{\alpha_i} h_{m_i} x_i + n_i, \quad (5.1)$$

where G_i denotes the OIRS channel gain, h_{att_i} represents attenuation loss, h_{α_i} models oceanic turbulence, h_{m_i} denotes pointing errors, and n_i is additive white Gaussian noise (AWGN) with variance $\sigma_{n_i}^2$. Unless otherwise stated, the attenuation, oceanic turbulence, and pointing error models adopted in this chapter follow the generalized UWOC channel model presented in Chapter 2. However, this chapter extends the attenuation model to incorporate depth-dependent variations using the Haltrin bio-optical model, which is essential for accurate characterization of multi-user UWOC systems at different ocean depths. Only the chapter-specific system models, analytical developments, and mirror allocation strategies are introduced in this chapter.

5.3.1 OIRS Channel Gain Modeling

In this multi-user configuration, the MA based OIRS operates under the same geometric reflection principles described in Chapter 4. However, unlike the single-user case, the total set of reflecting elements is dynamically partitioned among multiple users according to the adopted mirror allocation strategy.

Let $\mathcal{M}_i$ denote the subset of mirror elements assigned to the i^{th} user, where $|\mathcal{M}_i| = n_m^i$ and

$$\sum_{i=1}^N n_m^i = n_m^2.$$

The mirror subset $\mathcal{M}_i$ denotes the set of OIRS elements actively configured to steer the reflected optical beam toward the i^{th} user. Since $\sum_{i=1}^N n_m^i = n_m^2$, every mirror element is assigned to some user. For each user i , the assigned mirrors $\mathcal{M}_i$ are oriented to steer the reflected beam toward that user. Under the assumption of ideal beam steering and narrow receiver FoV, the contribution of mirrors assigned to other users to the i^{th} user's received signal is neglected. This assumption enables tractable performance analysis while emphasizing the performance gains achieved through the proposed mirror allocation strategies. Modeling residual crosstalk arising from beam divergence, imperfect steering, or stray reflections from non-intended mirror orientations constitutes an important direction for future research.

The channel gain corresponding to the $(k, l)^{th}$ mirror element directed toward the i^{th} user follows the same optical reflection model established previously and is expressed as:

$$G_{i,k,l}(\zeta, \varrho) = \begin{cases} R^{OIRS} \eta \frac{(m+1)A_{PD}}{2\pi(d_{sr}+d_{rd}^i)^2} \cos^m(\Phi_{k,l}^s) \cos(\psi_{k,l}^s) \\ \times \cos(\Phi_d^{k,l}) \cos(\psi_d^{k,l}) T(\psi) G(\psi), & 0 \leq (\psi_d^{k,l}) \leq (\psi_{FoV}), \\ 0, & \text{otherwise} \end{cases}, \quad (5.2)$$

where R^{OIRS} is the OIRS element's reflection coefficient, η is LED's conversion efficiency, m is the Lambertian order, A_{PD} represents the area of the photo diode, d_{sr} and d_{rd}^i denotes the distance from the transmitter to OIRS and OIRS to i^{th} user, respectively. $\Phi_{k,l}^s$ is the angle of irradiance from the transmitter to the OIRS, $\psi_{k,l}^s$ denotes the angle of incidence on the OIRS, $\Phi_d^{k,l}$ is the angle of irradiance from the k^{th} row and l^{th} column OIRS element towards the user, and $\psi_d^{k,l}$ represents the angle of incidence on the user. $T(\psi)$ and $G(\psi)$ represents optical filter and concentrator gains, respectively. Additionally, the mirror array is characterized by its yaw and roll angles, denoted by ζ and ϱ , respectively.

Since only the subset $\mathcal{M}_i$ contributes to the received signal of the i^{th} user, the effective OIRS gain for user i is obtained by summing over the allocated mirror elements:

$$G_i = \sum_{(k,l) \in \mathcal{M}_i} G_{i_{k,l}}(\zeta, \varrho). \quad (5.3)$$

Assuming that the mirror array subtends relatively small solid angles with respect to both the transmitter and the receiver, or equivalently, that the mirror element dimensions are sufficiently small compared to the propagation distances¹, the propagation distances and the corresponding incidence/reflection angles across the mirror elements can be approximated as identical. Consequently, the overall DC channel gain can be expressed in the simplified form as:

$$G_i \approx n_m^i G_{i_{k,l}}(\zeta, \varrho). \quad (5.4)$$

This formulation explicitly shows that the user-specific OIRS gain scales linearly with the number of allocated mirror elements, thereby enabling dynamic performance control through intelligent mirror assignment.

5.3.1.1 Attenuation Loss

The attenuation model follows the formulation introduced in Chapter 4; however, it is extended here to incorporate depth-dependent variations in underwater optical channels. Specifically, the absorption and scattering coefficients are modeled as functions of depth to capture the impact of oceanic inhomogeneity on signal propagation.

Therefore, the attenuation model is reformulated to explicitly capture the dependence of absorption and scattering coefficients on depth, while retaining the fundamental Beer–Lambert structure.

Absorption and scattering are the primary mechanisms governing attenuation in underwater optical channels. Absorption reduces the optical signal energy during propagation, while scattering redistributes photons in different directions, leading to power loss, temporal dispersion,

¹This simplification is based on the small-reflector assumption and does not rely on a far-field (Fraunhofer) approximation. For the considered system parameters, the practical underwater communication distance is limited to tens of meters due to severe absorption and scattering (e.g., for pure seawater with $c(\lambda) = 0.056 \text{ m}^{-1}$, the $1/e$ attenuation distance is approximately 18 m). In contrast, the Rayleigh distance for an individual 8 cm mirror element is $z_R = D^2/\lambda = (0.08)^2/(4.9 \times 10^{-7}) \approx 13 \text{ km}$. For the array considered in this chapter with $n_m = 4$, the total aperture is 32 cm, yielding a Rayleigh distance of approximately 209 km. Since the practical communication distance is significantly smaller than the Rayleigh distance, the system operates in the near-field regime. The small-reflector assumption remains valid because the element dimensions are much smaller than the propagation distances and the solid angles subtended by the array are sufficiently small. This assumption is consistent with the approach employed in the existing literature on MA-based IRS for optical wireless systems [55].

and multipath effects. To model the attenuation loss for the i^{th} user, the Beer–Lambert law is employed, which characterizes the exponential decay of optical intensity as a function of the propagation distance and the wavelength-dependent attenuation coefficient as [1]:

$$h_{att_i} = e^{-c(\lambda)(d_{sr} + d_{rd}^i)}, \quad (5.5)$$

Here, $c(\lambda)$ is the wavelength-dependent extinction/attenuation coefficient, which is the sum of the absorption coefficient $a(\lambda)$ and the scattering coefficient $b(\lambda)$ [5]. Thus:

$$c(\lambda) = a(\lambda) + b(\lambda). \quad (5.6)$$

Further the underwater light absorption coefficient is decomposed as [81]:

$$\begin{aligned} a(\lambda) = & a_w(\lambda) + a_f^0 C_f \exp(-k_f \lambda) \\ & + a_h^0 C_h \exp(-k_h \lambda) + a_c^0(\lambda) \left(C_c / C_c^0 \right)^{0.602}, \end{aligned} \quad (5.7)$$

where $a_w(\lambda)$ is the pure water absorption coefficient in unit of inverse meter (m^{-1}); a_f^0 is specific absorption coefficient of fulvic acid ($a_f^0 = 35.959 \text{ m}^2/\text{mg}$); a_h^0 is the specific absorption coefficient of humic acid ($a_h^0 = 18.828 \text{ m}^2/\text{mg}$); $a_c^0(\lambda)$ is the specific absorption coefficient of chlorophyll in m^{-1} ; C_f is the concentration of fulvic acid in mg/m^3 ; C_h is the concentration of humic acid in mg/m^3 ; C_c is the concentration of chlorophyll in mg/m^3 ($C_c^0 = 1 \text{ mg}/\text{m}^3$); k_f is the fulvic acid exponential coefficient in units of inverse nanometer ($k_f = 0.0189 \text{ nm}^{-1}$), and k_h is the humic acid exponential coefficient ($k_h = 0.01105 \text{ nm}^{-1}$). The values of pure water absorption coefficient are given in [82] and specific chlorophyll absorption are calculated using the following relation, which is typical in open surface conditions:

$$a_c^0(\lambda) = A(\lambda) C_c^{-B(\lambda)}, \quad (5.8)$$

where A , B represent empirical constants, a full list of which is given in [83].

The scattering coefficient for underwater light propagation can also be presented as a summation of different scattering factors [81]:

$$b(\lambda) = b_w(\lambda) + b_s^0(\lambda) C_s + b_l^0(\lambda) C_l, \quad (5.9)$$

where $b_w(\lambda)$ is the pure water scattering coefficient in m^{-1} ; b_s^0 is the scattering coefficient for small particulate matter in m^2/g ; b_l^0 is the scattering coefficient for large particulate matter in m^2/g ; C_s is the concentration of small particles in g/m^3 , and C_l is the concentration of large

particles in g/m^3 . The spectral dependencies for the scattering coefficients of small and large particulate matter are given by the following equations [84], [85], [86]:

$$b_w(\lambda) = 0.005826(400/\lambda)^{4.322}, \quad (5.10)$$

$$b_s^0(\lambda) = 1.1513(400/\lambda)^{1.7}, \quad (5.11)$$

$$b_l^0(\lambda) = 0.3411(400/\lambda)^{0.3}. \quad (5.12)$$

Scattering contributes much less to the overall attenuation coefficient than absorption, though it is much greater in particulate-rich areas.

Haltrin *et al.* determined a single-parameter model for attenuation that simplifies (5.7) and (5.9) by finding the relationship between the concentrations of different particulates in [81]. This model correlates the C_c with two concentrations of colored dissolved organic matter (i.e, humic and fulvic acid) and two concentration of scattering particles (i.e, terrigenous and biogenic suspensions). It was reported that choosing C_c as the main parameter, the other parameters can be represented in terms of this main parameter as [81]:

$$C_f = 1.74098C_c \exp(0.12327C_c), \quad (5.13)$$

$$C_h = 0.19334C_c \exp(0.12343C_c), \quad (5.14)$$

$$C_s = 0.01739C_c \exp(0.11631C_c), \quad (5.15)$$

$$C_l = 0.76284C_c \exp(0.03092C_c). \quad (5.16)$$

Thus, if the chlorophyll concentration at any location in the ocean is known, the scattering and absorption coefficients may be calculated.

The chlorophyll distribution at a depth $z_d(m)$ below the surface can be described by a Gaussian function with five parameters determined numerically, as outlined in [87]:

$$C_c(z_d) = B_0 + Sz_d + \frac{V}{\sigma_c \sqrt{2\pi}} \exp\left[-\frac{(z_d - z_{d\max})^2}{2\sigma_c^2}\right], \quad (5.17)$$

Here, B_0 signifies the background C_c at the surface, S denotes the vertical concentration gradient (always negative), V represents the total chlorophyll content above background levels, and $z_{d\max}$ indicates the depth of the deep chlorophyll maximum (DCM). The standard deviation σ_c of C_c is calculated by:

$$\sigma_c = \frac{V}{\sqrt{2\pi} [C_{\text{chl}}(z_{d\max}) - B_0 - Sz_{d\max}]}. \quad (5.18)$$

where C_{chl} represents surface chlorophyll concentration.

Now, the absorption and scattering formulas from (5.7) and (5.9), respectively, can be updated to incorporate depth dependency as:

$$a(\lambda, z_d) = a_w(\lambda) + a_f^0 \exp(-k_f \lambda) C_f(z_d) + a_h^0 \exp(-k_h \lambda) C_h(z_d) + a_c^0(\lambda, z_d) [C_c(z_d)]^{0.602}, \quad (5.19)$$

and

$$b(\lambda, z_d) = b_w(\lambda) + b_s^0(\lambda) C_s(z_d) + b_l^0(\lambda) C_l(z_d). \quad (5.20)$$

Here, $C_f(z_d)$, $C_h(z_d)$, $C_s(z_d)$, and $C_l(z_d)$ represent the depth-dependent profiles of fulvic acid, humic acid, small particles, and large particles, respectively. These profiles are derived by substituting the chlorophyll profile from (5.17) into the Haltrin relations in (5.13)-(5.16). Additionally, the specific attenuation of chlorophyll, $a_c^0(\lambda, y)$, now includes depth dependency as:

$$a_c^0(\lambda, z_d) = A(\lambda) C_c(z_d)^{-B(\lambda)}. \quad (5.21)$$

Utilizing (5.19)-(5.21), the attenuation profile can be fully characterized with varying depth and wavelength, based solely on the position of the communication system.

5.3.1.2 Oceanic Turbulence Model

The statistical characterization of oceanic turbulence follows the EGG distribution introduced in Chapter 4. The EGG model has been shown to accurately capture weak, moderate, and strong underwater turbulence conditions [32, 40].

Accordingly, the turbulence-induced fading coefficient for the i^{th} user, denoted by h_{α_i} , is modeled using the EGG mixture distribution. The probability density function (PDF) is expressed as:

$$f_{h_{\alpha_i}}(\alpha) = \omega f_{\exp}(\alpha; \Lambda) + (1 - \omega) f_{GG}(\alpha; a, b, c), \quad (5.22)$$

where $0 < \omega < 1$ is the mixture weight.

The exponential component is given by:

$$f_{\exp}(\alpha; \Lambda) = \frac{1}{\Lambda} \exp\left(-\frac{\alpha}{\Lambda}\right), \quad (5.23)$$

while the generalized Gamma component is expressed as:

$$f_{\text{GG}}(\alpha; a, b, c) = \frac{c\alpha^{ac-1}}{b^{ac}\Gamma(a)} \exp\left[-\left(\frac{\alpha}{b}\right)^c\right], \quad (5.24)$$

where $a > 0$, $b > 0$, and $c > 0$ are turbulence shaping parameters and $\Gamma(\cdot)$ denotes the Gamma function.

The selected parameter sets corresponding to different scintillation index values are summarized in Table 5.1.

5.3.1.3 Pointing Error Model

The misalignment fading model follows the zero-boresight pointing error formulation introduced in Chapter 2. In practical underwater deployments, transmitter–receiver misalignment may occur due to water currents, platform vibrations, and mechanical instability.

Assuming a zero-boresight displacement and circular detection aperture, the PDF of the pointing error coefficient h_{m_i} is given by [40]:

$$f_{h_{m_i}}(h_m) = \frac{\rho^2}{A_0^{\rho^2}} h_m^{\rho^2-1}, \quad 0 \leq h_m \leq A_0, \quad (5.25)$$

where A_0 denotes the fraction of collected power at perfect alignment, and ρ is the pointing error parameter defined as the ratio between the equivalent beam radius and the jitter standard deviation.

The overall channel experienced by the i^{th} user is characterized by the combined effect of attenuation loss, oceanic turbulence, and pointing error fading. Since these components are statistically independent, the composite channel gain can be expressed as the product of the individual channel coefficients.

Accordingly, the received signal model and the corresponding instantaneous SNR are derived in the following subsection by incorporating all three channel impairments along with the OIRS gain.

5.3.2 Instantaneous Signal-to-Noise Ratio

The received signal at the i^{th} user is expressed as:

$$y_i = \mathcal{R}P_t G_i h_{\text{att}_i} h_{\alpha_i} h_{m_i} x_i + n_i, \quad (5.26)$$

Based on the above signal model, the instantaneous electrical SNR at the i^{th} user can be written as:

$$\gamma_i = \frac{\mathcal{R}^2 P_t^2 G_i^2 h_{att_i}^2 h_{\alpha_i}^2 h_{m_i}^2}{\sigma_{n_i}^2}. \quad (5.27)$$

For notational simplicity, the overall channel gain is defined as:

$$H_i = G_i h_{att_i} h_{\alpha_i} h_{m_i}, \quad (5.28)$$

which captures the combined effect of attenuation, turbulence, and pointing errors.

For analytical convenience, the average SNR is defined as:

$$\bar{\gamma}_i = \frac{\mathcal{R}^2 P_t^2 G_i^2 h_{att_i}^2}{\sigma_{n_i}^2}, \quad (5.29)$$

which contains only deterministic system parameters.

Accordingly, the instantaneous SNR can be compactly expressed as:

$$\gamma_i = \bar{\gamma}_i h_i^2, \quad (5.30)$$

where the composite random fading coefficient is:

$$h_i = h_{\alpha_i} h_{m_i}. \quad (5.31)$$

5.3.3 Signal Transmission and Multiple Access Schemes

In the considered downlink MA-based OIRS-assisted multi-user UWOC system, different multiple access strategies are adopted to serve N users. Let x_i denote the unit-power information symbol intended for the i^{th} user, i.e., $\mathbb{E}[|x_i|^2] = 1$.

Multiple access techniques play a fundamental role in enabling efficient communication in multi-user systems by determining how resources such as time, frequency, and power are allocated among users [18]. In this chapter, three widely adopted schemes, OMA, NOMA, and RSMA are considered to evaluate their performance in the proposed OIRS-assisted UWOC system.

5.3.3.1 OMA Scheme

In the OMA scheme, users are served in an orthogonal manner such that only one user is active per resource block. In this work, a time-division multiple access (TDMA) strategy is adopted, where all OIRS elements are assigned to a single user within a given time slot.

For a system with N users, transmission occurs over N equal time slots, thereby eliminating inter-user interference.

Accordingly, the received signal at the i^{th} user is expressed as:

$$y_i^{\text{OMA}} = \mathcal{R}P_t H_i x_i + n_i, \quad (5.32)$$

where H_i denotes the overall channel gain.

The instantaneous SNR of the i^{th} user is therefore given by:

$$\gamma_i^{\text{OMA}} = \frac{\mathcal{R}^2 P_t^2 |H_i|^2}{\sigma_{n_i}^2} = \gamma_i. \quad (5.33)$$

Due to orthogonal time allocation, the achievable rate is reduced by a factor of $\frac{1}{N}$. Hence, the instantaneous achievable rate is:

$$SE_i^{\text{OMA}} = \frac{1}{N} \log_2 (1 + \tau \gamma_i) \quad (5.34)$$

Here, $\tau = \frac{e}{2\pi}$ denotes the IM/DD scaling factor commonly adopted in the optical communication literature to account for the IM/DD signaling constraint.

5.3.3.2 NOMA Scheme

NOMA enables simultaneous transmission of multiple users over the same time and frequency resources by employing power-domain multiplexing [88]. In the considered OIRS-assisted UWOC system, users are ordered according to their channel gains as:

$$|H_1|^2 \leq |H_2|^2 \leq \dots \leq |H_N|^2, \quad (5.35)$$

where User 1 is the weakest and User N is the strongest.

The power allocation coefficients are defined as [89]:

$$\kappa_i = \begin{cases} \mu^{\text{NOMA}} (1 - \mu^{\text{NOMA}})^{i-1}, & 1 \leq i < N, \\ (1 - \mu^{\text{NOMA}})^{i-1}, & i = N, \end{cases} \quad (5.36)$$

where $\mu^{\text{NOMA}} \in (0.5, 1]$ and $\sum_{i=1}^N \kappa_i = 1$ [90].

The transmitted signal using superposition coding is given by:

$$x^{\text{NOMA}} = \sum_{i=1}^N \sqrt{\kappa_i P_t} x_i. \quad (5.37)$$

Thus, the received signal at the i^{th} user is:

$$y_i^{\text{NOMA}} = \mathcal{R}H_i \left(\sum_{j=1}^N \sqrt{\kappa_j P_t} x_j \right) + n_i. \quad (5.38)$$

Successive interference cancellation (SIC) is applied at the receivers. The i^{th} user decodes and removes the signals of users $1, \dots, i-1$, while treating signals of users $j > i$ as interference.

Accordingly, the instantaneous signal-to-interference-plus-noise ration (SINR) of the i^{th} user is given by:

$$\gamma_i^{\text{NOMA}} = \frac{\kappa_i \gamma_i}{\gamma_i \sum_{j=1}^{i-1} \kappa_j + 1}, \quad (5.39)$$

The instantaneous achievable rate is:

$$SE_i^{\text{NOMA}} = \log_2 \left(1 + \tau \gamma_i^{\text{NOMA}} \right). \quad (5.40)$$

5.3.3.3 RSMA Scheme

RSMA is an advanced multiple access technique that generalizes both OMA and NOMA by flexibly managing interference through rate splitting [18, 91]. In the considered one-layer RSMA scheme, each user's message is divided into a common part and a private part.

The transmitted signal is expressed as:

$$x^{\text{RSMA}} = \sqrt{a_c P_t} x_c + \sum_{i=1}^N \sqrt{a_{p_i} P_t} x_i, \quad (5.41)$$

where a_c and a_{p_i} denote the power allocation coefficients for the common and private messages, respectively, satisfying $a_c + \sum_{i=1}^N a_{p_i} = 1$. We assume equal allocation among private messages, i.e., $a_{p_i} = \frac{a_p}{N}$.

The received signal at the i^{th} user is given by:

$$y_i^{\text{RSMA}} = \mathcal{R}H_i \left(\sqrt{a_c P_t} x_c + \sum_{j=1}^N \sqrt{a_{p_j} P_t} x_j \right) + n_i. \quad (5.42)$$

Decoding is performed in two stages. First, the common message is decoded while treating all private messages as interference. The corresponding SINR is given as:

$$\gamma_i^{\text{RSMA}_c} = \frac{a_c \gamma_i}{1 + \gamma_i (1 - a_c)}. \quad (5.43)$$

After removing the common message via SIC, each user decodes its private message. The corresponding SINR is given by:

$$\gamma_i^{\text{RSMA}_p} = \frac{a_{p_i} \gamma_i}{1 + \gamma_i \sum_{j=1, j \neq i}^N a_{p_j}}. \quad (5.44)$$

The instantaneous achievable rate of the i^{th} user is given as:

$$SE_i^{\text{RSMA}} = \frac{1}{N} SE_i^{\text{RSMA}_c} + \log_2 \left(1 + \tau \gamma_i^{\text{RSMA}_p} \right), \quad (5.45)$$

where $SE_i^{\text{RSMA}_c}$ denotes the achievable common rate. The common rate is constrained by the weakest user and is given by:

$$SE_i^{\text{RSMA}_c} = \log_2 \left(1 + \tau \gamma_i^{\text{RSMA}_c} \right). \quad (5.46)$$

Applicability of the Achievable-Rate Formulation: The achievable-rate expressions adopted in this thesis follow the analytical framework commonly employed in the IM/DD optical communication literature for both UWOC and optical IRS/VLC systems, where the achievable SE is expressed as $SE_i = \log_2(1 + \tau \gamma_i)$, with $\tau = \frac{e}{2\pi}$ denoting the IM/DD scaling factor accounting for the IM/DD signaling constraint [22, 32, 90]. It is important to note that the exact capacity of the IM/DD channel remains an open problem in the general case; the adopted formulation represents a well-known achievable-rate approximation (capacity lower bound) for IM/DD optical channels. The adopted formulation is employed to provide analytical tractability and enable a fair and consistent comparative performance evaluation of the proposed OIRS-assisted NOMA and RSMA transmission schemes under a unified analytical framework. Although this formulation is widely adopted for system-level performance analysis, it represents an achievable-rate approximation rather than the exact information-theoretic capacity of IM/DD optical communication systems because of the non-negativity and average optical power constraints imposed on the transmitted optical signal. Therefore, the SE results presented in this thesis should be interpreted as comparative performance metrics rather than exact IM/DD channel capacity limits. Incorporating tighter IM/DD capacity bounds into the proposed analytical framework constitutes an important direction for future research.

Implementation Trade-offs of RSMA: Although RSMA provides flexible interference management and can offer improved SE and fairness, these gains are accompanied by additional receiver-side processing. In the considered one-layer RSMA scheme, each receiver first decodes the common message and subsequently decodes its private message after removing

the common component through SIC. This additional decoding stage may increase receiver processing requirements and decoding latency compared with OMA, where users are served over orthogonal resources without requiring inter-user interference cancellation. NOMA also requires SIC-based decoding and therefore introduces receiver-side processing overhead. Consequently, the comparison among OMA, NOMA, and RSMA involves a trade-off between SE/fairness gains and receiver-side implementation requirements. The present chapter primarily evaluates ASE and user fairness; detailed hardware-dependent decoder complexity, processing energy consumption, and exact decoding latency are not explicitly modeled and constitute potential directions for future investigation.

5.4 Performance Analysis

To facilitate statistical analysis, the instantaneous SNR of the i^{th} user from (5.30) is expressed in a compact form as:

$$\gamma_i = \bar{\gamma}_i h_i^2, \quad (5.47)$$

where $\bar{\gamma}_i$ denotes the average SNR, and h_i represents the composite fading coefficient defined as:

$$h_i = h_{\alpha_i} h_{m_i}. \quad (5.48)$$

Here, h_{α_i} follows the EGG turbulence distribution [32], while h_{m_i} follows the zero-boresight pointing error model described in Chapter 2.

Since h_{α_i} and h_{m_i} are statistically independent, the PDF of the composite fading coefficient h_i is derived in Lemma 5.1 (see Appendix 5.A) using the Mellin transform approach. The resulting PDF is expressed in terms of the Fox's H -function as:

$$f_{h_i}(h_i) = \omega \rho^2 h_i H_{1,2}^{2,0} \left[\frac{h_i}{\Lambda A_0} \middle| \begin{matrix} (1 + \rho^2, 1) \\ (1, 1), (\rho^2, 1) \end{matrix} \right] + \frac{(1 - \omega) \rho^2}{\Gamma(a)} h_i H_{1,2}^{2,0} \left[\frac{h_i}{b A_0} \middle| \begin{matrix} (1 + \rho^2, 1) \\ (a, \frac{1}{c}), (\rho^2, 1) \end{matrix} \right]. \quad (5.49)$$

By applying the transformation of random variables to $\gamma_i = \bar{\gamma}_i h_i^2$, the PDF of the instantaneous SNR is obtained in Lemma 5.2 (see Appendix 5.B) as:

$$f_{\gamma_i}(\gamma_i) = \omega \frac{\rho^2}{2 \gamma_i} H_{1,2}^{2,0} \left[\frac{1}{\Lambda A_0} \sqrt{\frac{\gamma_i}{\bar{\gamma}_i}} \middle| \begin{matrix} (1 + \rho^2, 1) \\ (1, 1), (\rho^2, 1) \end{matrix} \right] + \frac{(1 - \omega) \rho^2}{2 \gamma_i \Gamma(a)} H_{1,2}^{2,0} \left[\frac{1}{b A_0} \sqrt{\frac{\gamma_i}{\bar{\gamma}_i}} \middle| \begin{matrix} (1 + \rho^2, 1) \\ (a, \frac{1}{c}), (\rho^2, 1) \end{matrix} \right]. \quad (5.50)$$

This PDF serves as the basis for evaluating the average SE.

5.4.1 Average Spectral Efficiency (SE)

The average SE of the i^{th} user under a given multiple access scheme $s \in \{\text{OMA}, \text{NOMA}, \text{RSMA}\}$ is defined as:

$$SE_i^{(s)} = \mathbb{E} \left[\log_2 \left(1 + \tau \gamma_i^{(s)} \right) \right] = \int_0^\infty \log_2(1 + \tau \gamma_i) f_{\gamma_i}(\gamma_i) d\gamma_i, \quad (5.51)$$

where $\gamma_i^{(s)}$ denotes the instantaneous SNR ratio (or SINR ratio) corresponding to the considered multiple access scheme and $\tau = \frac{e}{2\pi}$ for IM/DD systems.

Accordingly, the ASE of the system under scheme s is given by:

$$ASE^{(s)} = \sum_{i=1}^N SE_i^{(s)}. \quad (5.52)$$

Substituting the PDF of γ_i and utilizing the integral identities of the Fox's H -function [73, eq. (8.4.6/5)], the closed-form expression of $SE_i^{(s)}$ is obtained as:

$$SE_i^{(s)} = \frac{1}{\ln(2)} \left[\omega H_{2,3}^{3,1} \left(\frac{\tau \bar{\gamma}_i}{(\Lambda A_0)^2} \middle| \begin{matrix} (1,1), (1,1) \\ (1,1), (1,1), (\rho^2, 1) \end{matrix} \right) + \frac{1-\omega}{\Gamma(a)} H_{2,3}^{3,1} \left(\frac{\tau \bar{\gamma}_i}{(b A_0)^2} \middle| \begin{matrix} (1,1), (1,1) \\ (a, \frac{1}{c}), (1,1), (\rho^2, 1) \end{matrix} \right) \right]. \quad (5.53)$$

5.4.2 High-SNR Asymptotic Analysis

At high SNR, the logarithmic function can be approximated as:

$$\log_2(1 + \tau \gamma_i) \approx \log_2(\tau \gamma_i). \quad (5.54)$$

Using the moment generating property of the Fox's H -function, the asymptotic SE is obtained in Lemma 5.3 (see Appendix 5.C) as [74, eq. (8.360/1)]:

$$SE_i^{(s)} \approx 1.44 \left[\log(\tau) + \omega \left(\log(\Lambda^2 \bar{\gamma}_i) + 2\psi(1) \right) + (1-\omega) \left(\log(b^2 \bar{\gamma}_i) + \frac{2}{c} \psi(a) \right) \right], \quad (5.55)$$

where $\psi(\cdot)$ denotes the digamma function and is given as $\psi(x) = \frac{d}{dx} \ln \Gamma(x)$.

5.4.3 Aggregate Spectral Efficiency (ASE)

The ASE of the system is defined as the sum of the average spectral efficiencies of all users. For both DMA and EMA schemes, the ASE is given by:

$$ASE^{\text{DMA/EMA}} = \sum_{i=1}^N SE_i. \quad (5.56)$$

The ASE expressions for DMA and EMA share the same mathematical form; however, they differ through the user-specific channel gains H_i , which depend on the adopted mirror allocation strategy. Consequently, the instantaneous SNR under DMA/EMA is expressed as:

$$\gamma_i^{\text{DMA/EMA}} = \frac{\mathcal{R}^2 P_t^2 |H_i|^2}{\sigma_{n_i}^2}. \quad (5.57)$$

For OMA, due to orthogonal time allocation among N users, the ASE is reduced by a factor of $\frac{1}{N}$ and is expressed as:

$$ASE^{\text{OMA}} = \sum_{i=1}^N SE_i. \quad (5.58)$$

For NOMA, by replacing γ_i with γ_i^{NOMA} in the SE expression, the ASE is given by:

$$ASE^{\text{NOMA}} = \sum_{i=1}^N SE_i^{\text{NOMA}}. \quad (5.59)$$

For RSMA, the ASE consists of both common and private rate components. Accordingly, the ASE is expressed as [18]:

$$ASE^{\text{RSMA}} = \min_{i \in \{1,2,\dots,N\}} SE_i^{\text{RSMA}_c} + \sum_{i=1}^N SE_i^{\text{RSMA}_p}. \quad (5.60)$$

5.4.4 Fairness Analysis

To evaluate fairness among users, Jain's fairness index is adopted and defined as [92]:

$$J = \frac{\left(\sum_{i=1}^N SE_i \right)^2}{N \sum_{i=1}^N SE_i^2}. \quad (5.61)$$

A value of $J = 1$ indicates perfect fairness among users.

5.5 Proposed Mirror Allocation Algorithms

Execution Framework: The proposed OIRS-assisted multi-user UWOC system follows a sequential execution framework. First, the mirror allocation algorithm (DMA or EMA) determines the subset of OIRS reflecting elements assigned to each user. In the DMA scheme, the mirror assignment is performed according to the total propagation distance between the source, the OIRS, and each user, whereas the EMA scheme distributes the available mirror elements equally among all users. Based on the resulting mirror assignment, the effective user-specific OIRS channel gains and the corresponding instantaneous SNR values are subsequently computed using the analytical expressions developed in Section 5.4. Thereafter, the selected multiple access scheme (OMA, NOMA, or RSMA) is employed over the established user-specific channels using the adopted transmission model and the corresponding power allocation strategy. Therefore, mirror allocation and multiple access constitute two sequential stages of the proposed framework rather than a jointly optimized resource allocation problem.

Implementation Framework: For practical implementation, the proposed mirror allocation algorithms are assumed to be executed by a centralized network controller (e.g., a surface buoy or terrestrial base station) based on the user's propagation distances defined in the system model. Following the mirror assignment, the OIRS is configured accordingly. Subsequently, the source transmitter performs signal encoding and transmission according to the selected multiple access scheme (OMA, NOMA, or RSMA), while the underwater users perform only signal reception and decoding. This centralized implementation avoids imposing additional computational overhead on energy-constrained underwater sensor nodes and autonomous underwater vehicles (AUVs). The sequential execution pipeline is illustrated in Fig. 5.2. The flowchart depicts the complete processing chain, starting from system parameter acquisition at the centralized network controller, followed by mirror allocation (DMA or EMA), OIRS configuration, channel gain and SNR computation, source transmitter operation with the selected multiple access scheme, and finally user reception and decoding.

In this section, two mirror allocation strategies are proposed for the MA-based OIRS-assisted multi-user UWOC system, namely DMA and EMA.

Let the total number of reflecting elements be n_m^2 and the number of users be N . The objective is to determine the number of mirror elements n_m^i allocated to the i^{th} user such that:

$$\sum_{i=1}^N n_m^i = n_m^2, \quad (5.62)$$

while improving ASE and maintaining fairness among users.

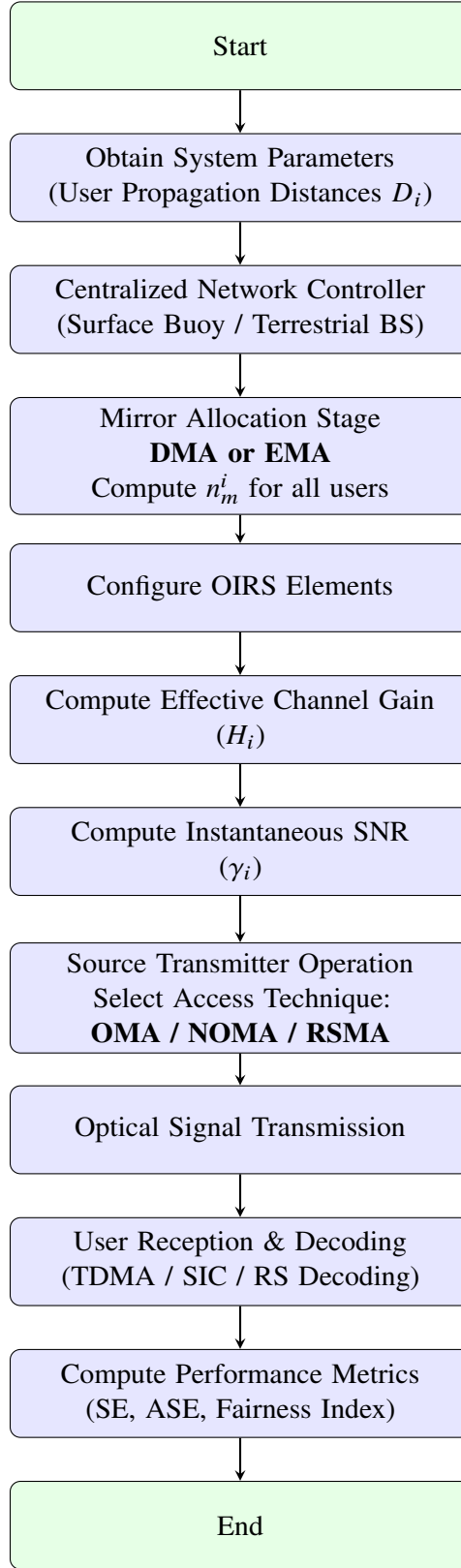


Figure 5.2: Execution framework of the proposed DMA/EMA-assisted multi-user OIRS-UWOC system. The centralized network controller performs mirror allocation based on the user's propagation distances, followed by OIRS configuration. The source transmitter subsequently employs the selected multiple access scheme (OMA, NOMA, or RSMA), while the underwater users perform signal reception and decoding.

5.5.1 Distance-Based Mirror Assignment (DMA)

In underwater optical communication, the received optical power decays exponentially with the total propagation distance due to attenuation and turbulence effects. Therefore, users located farther from the OIRS experience more severe pathloss.

To compensate for this distance-dependent degradation, DMA allocates mirror elements proportionally to the total propagation distance between the source, OIRS, and the i^{th} user.

Let

$$D_i = d_{sr} + d_{rd}^i \quad (5.63)$$

denote the total propagation distance of the i^{th} user. The normalized distance weight is defined as:

$$w_i = \frac{D_i}{\sum_{k=1}^N D_k}. \quad (5.64)$$

The number of mirror elements allocated to the i^{th} user is then given by:

$$n_m^i = \lfloor w_i n_m^2 \rfloor. \quad (5.65)$$

To ensure that the total number of allocated mirrors equals n_m^2 , any remaining mirrors after flooring operation are assigned sequentially to users with the largest distance values.

After mirror allocation, the effective user-specific OIRS channel gains and the corresponding instantaneous SNR values are first computed using the analytical expressions developed in Section 5.4. Subsequently, the selected multiple access scheme (OMA, NOMA, or RSMA) is employed to determine the ASE and other performance metrics.

5.5.2 Equal Mirror Assignment (EMA)

In the EMA scheme, the mirror elements are equally distributed among all users irrespective of their distances. The number of mirrors allocated to each user is given by:

$$n_m^i = \left\lfloor \frac{n_m^2}{N} \right\rfloor. \quad (5.66)$$

Any remaining mirror elements are distributed uniformly among users.

Unlike DMA, EMA does not adapt to distance variations and therefore serves as a baseline scheme for performance comparison.

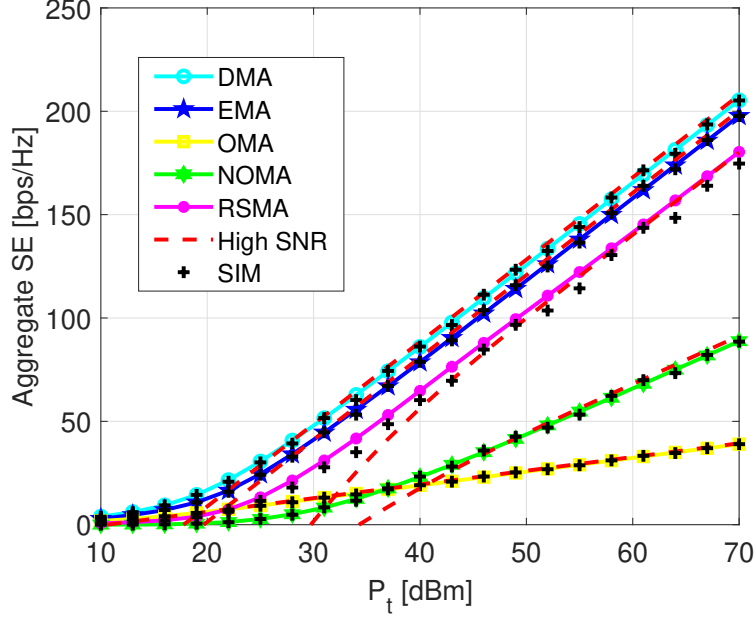


Figure 5.3: Average sum rate with respect to transmit power for different assignment schemes, when $N = 3$.

5.6 Numerical Results

In this section, analytical and Monte Carlo simulation results are presented to evaluate the performance of the proposed MA-based OIRS-assisted multi-user UWOC system under DMA and EMA mirror allocation strategies and for OMA, NOMA, and RSMA multiple access schemes.

Unless otherwise specified, the total number of OIRS mirror elements is $n_m^2 = 16$, with each element having dimensions $8 \times 8 \text{ cm}^2$. Users are uniformly distributed within a circular region of radius 30 m. The operating wavelength is set to $\lambda = 490 \text{ nm}$. The key simulation parameters are summarized in Table 5.1.

The underwater channel incorporates depth-dependent attenuation based on the Haltrin model, EGG-distributed oceanic turbulence, and zero-boresight pointing errors. The turbulence parameters correspond to weak and moderate conditions with scintillation indices $\sigma_I^2 = \{0.2178, 1.9328\}$.

Unless otherwise stated, the number of users is $N = 6$, and all analytical results are validated via Monte Carlo simulations averaged over 10^7 independent channel realizations.

Table 5.1: Simulation Parameters

Parameter	Symbol	Value
Transmit power	P_t	10 to 70 dBm
Attenuation coefficient	$c(\lambda)$	0.056
Total OIRS elements	n_m^2	16
Wavelength	λ	490 nm
Length of OIRS element	ℓ_m	8 cm
Width of OIRS element	w_m	8 cm
Reflection efficiency of mirror element	R^{OIRS}	0.9
Number of users	N	6
Lambertian order	m	2
PD area	A_{PD}	0.0314 m ²
Current to light conversion efficiency	η	0.9
Responsivity	$\mathcal{R}$	1 A/W
Pointing parameter	ρ	1, 6
NOMA power allocation coefficient	μ^{NOMA}	0.6
RSMA power allocation coefficient for common message	a_c	0.6
RSMA power allocation coefficient for private messages	a_p	0.4
noise variance	$\sigma_{n_i}^2$	10 ⁻¹⁵
Pointing error parameters	A_0, ρ^2	0.0032, (1, 6)
Scintillation index	σ_I^2	{0.2178, 1.9328}
Parameters corresponding to $S1$	$\{C_{chl}\}$ $\{B_0\}$ $\{S(10^{-3})\}$ $\{V\}$ $\{z_{d\max}\}$ $\{C_{chl}(z_{d\max})\}$	$\{< 0.04(mg/m^3)\}$ $\{0.0429(mg/m^3)\}$ $\{-0.103(mg/m^2)\}$ $\{11.87(mg)\}$ $\{115.4(m)\}$ $\{0.708(mg/m^3)\}$
Parameters corresponding to $S8$	$\{C_{chl}\}$ $\{B_0\}$ $\{S(10^{-3})\}$ $\{V\}$ $\{z_{d\max}\}$ $\{C_{chl}(z_{d\max})\}$	$\{0.8 - 2.2(mg/m^3)\}$ $\{1.01(mg/m^3)\}$ $\{-9.03(mg/m^2)\}$ $\{20.31(mg)\}$ $\{20.38(m)\}$ $\{4.556(mg/m^3)\}$
EGG distribution parameters corresponding to different σ_I^2	$\{\omega\}_{i=1}^2$ $\{\Lambda\}_{i=1}^2$ $\{a\}_{i=1}^2$ $\{b\}_{i=1}^2$ $\{c\}_{i=1}^2$	$\{0.1665, 0.6238\}$ $\{0.1207, 0.1094\}$ $\{0.1559, 0.0111\}$ $\{1.5216, 4.4750\}$ $\{22.8754, 105.3550\}$

5.6.1 Aggregate Spectral Efficiency (ASE) Analysis

In this subsection, the ASE performance of the proposed MA-based OIRS-assisted multi-user UWOC system is investigated under DMA and EMA mirror allocation strategies along with OMA, NOMA, and RSMA schemes. The ASE is defined as the sum of the individual user's spectral efficiencies as derived in Section 5.3.

5.6.1.1 Impact of Transmit Power

Fig. 5.3 illustrates the variation of ASE with respect to the transmit power P_t for different mirror allocation and multiple access schemes.

It is observed that the ASE increases monotonically with transmit power for all considered schemes. This behavior follows directly from the logarithmic dependence of SE on the instantaneous SNR, i.e., $SE_i = \mathbb{E}[\log_2(1 + \tau\gamma_i)]$, where $\gamma_i \propto P_t^2$.

Among the multiple access techniques, RSMA consistently achieves the highest ASE, followed by NOMA and OMA. The superior performance of RSMA is attributed to its ability to partially decode common messages while treating private streams as interference, thereby achieving a more efficient interference management compared to pure superposition coding in NOMA and orthogonal resource allocation in OMA.

In addition to the impact of multiple access techniques, the mirror allocation strategy also plays a critical role in determining system performance. In both DMA and EMA schemes, equal transmit power is allocated to all users; however, the difference arises from the spatial allocation of OIRS elements. Specifically, DMA outperforms EMA across all transmit power levels due to its distance-aware mirror allocation strategy. By assigning a larger number of reflecting elements to users with higher propagation distances, DMA effectively compensates for the exponential attenuation term. This results in a more balanced SNR distribution among users and consequently improves the overall ASE compared to EMA, where mirror elements are uniformly distributed regardless of user channel conditions.

5.6.1.2 Impact of Number of Users

Fig. 5.4 presents the ASE as a function of the number of users N .

For RSMA and NOMA, the ASE increases with N due to enhanced spectral utilization enabled by simultaneous multi-user transmission. In contrast, OMA exhibits slower growth since resources are divided orthogonally among users, resulting in a $1/N$ scaling factor in achievable rate.

It is further observed that the performance gap between DMA and EMA becomes more pronounced as N increases. This behavior is attributed to increased heterogeneity in user

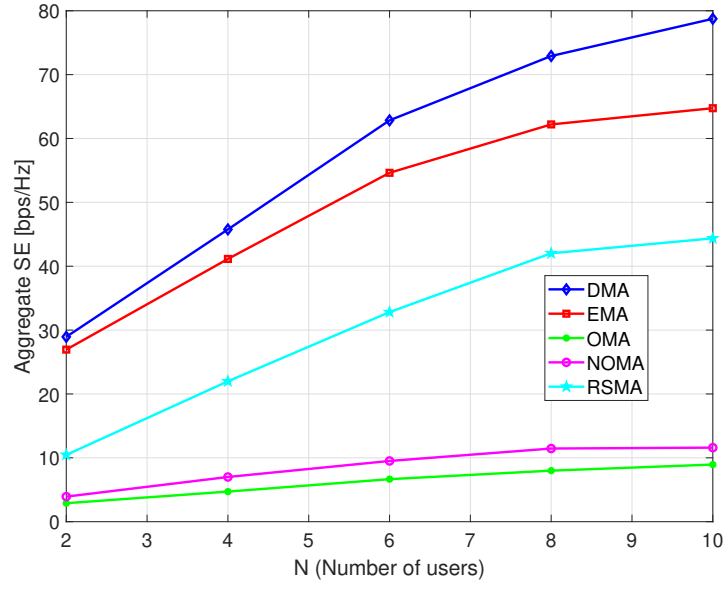


Figure 5.4: Aggregate SE Vs. Number of users for different schemes.

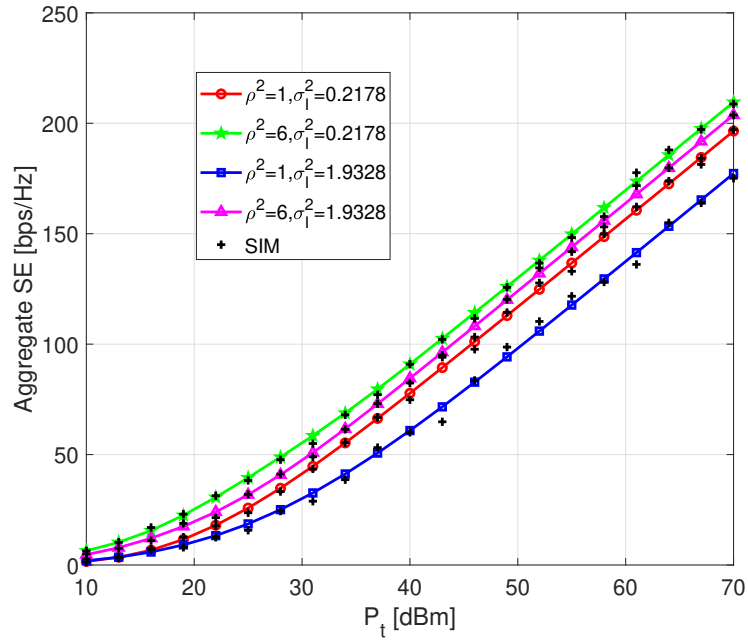


Figure 5.5: Aggregate SE vs. transmit power for different turbulence and pointing parameters.

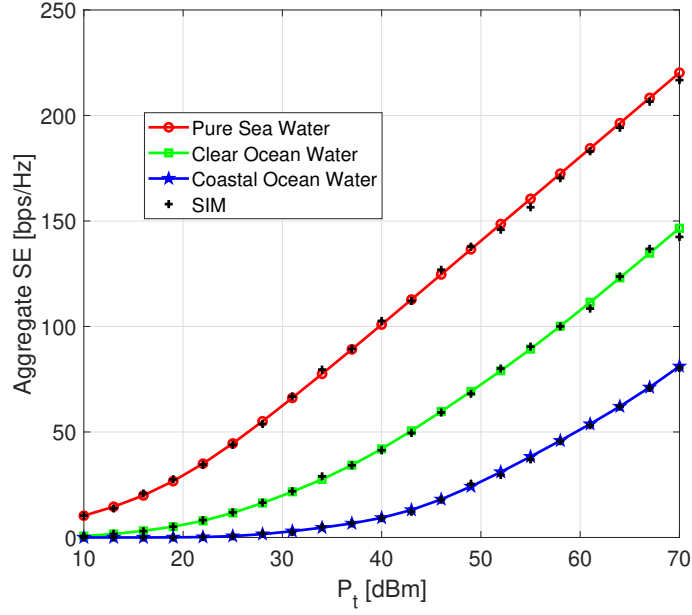


Figure 5.6: Aggregate SE vs. transmit power for different water types.

distances in dense deployments. Since DMA allocates mirrors proportionally to propagation distance, it better mitigates distance-induced SNR imbalance, thereby maintaining higher aggregate throughput compared to EMA.

5.6.1.3 Impact of Turbulence and Pointing Errors

Fig. 5.5 illustrates the impact of oceanic turbulence and pointing error parameters on the ASE of the proposed DMA-based UWOC system for $N = 6$. It is observed that the ASE increases significantly as the pointing error parameter ρ^2 increases from 1 to 6, indicating improved alignment between the transmitter and receiver. Conversely, the ASE degrades as the turbulence strength increases from $\sigma_I^2 = 0.2178$ to $\sigma_I^2 = 1.9328$, due to enhanced fading effects in the underwater channel.

Specifically, the highest ASE is achieved under low turbulence and weak pointing error conditions, i.e., $\sigma_I^2 = 0.2178$ and $\rho^2 = 6$. In contrast, the worst performance is observed under strong turbulence and severe pointing errors, i.e., $\sigma_I^2 = 1.9328$ and $\rho^2 = 1$. These results highlight the sensitivity of the system performance to channel impairments even under the DMA scheme.

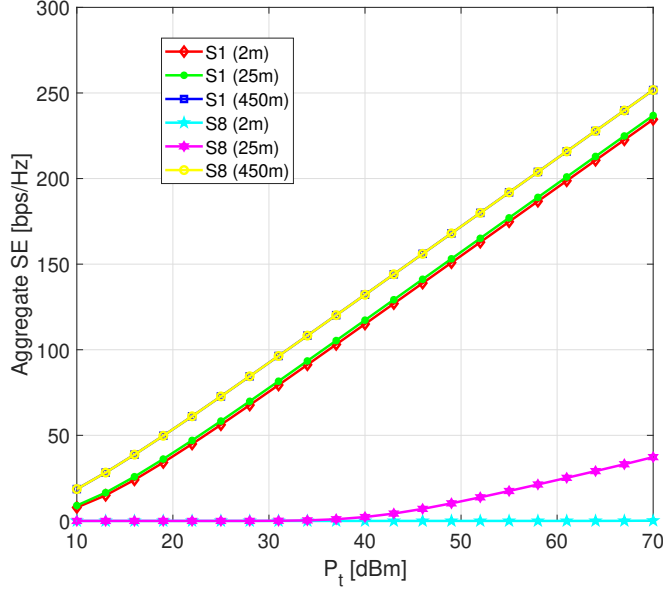


Figure 5.7: Aggregate SE vs. transmit power at different oceanic depths.

5.6.1.4 Impact of Water Type

Fig. 5.6 depicts the ASE versus transmit power for different water types characterized by distinct attenuation coefficients $c(\lambda)$ for DMA case.

It is observed that water environments with lower attenuation coefficients yield significantly higher ASE. Since the channel attenuation follows the exponential decay $e^{-c(\lambda)D_i}$, even moderate increases in $c(\lambda)$ substantially reduce the received optical power.

5.6.1.5 Impact of Oceanic Depth

In this subsection, the effect of oceanic depth on the ASE of the proposed MA-based OIRS-assisted multi-user UWOC system is investigated.

The attenuation coefficient $c(\lambda, z_d)$ is depth-dependent and is computed using the Haltrin single-parameter bio-optical model [81], where:

$$c(\lambda, z_d) = a(\lambda, z_d) + b(\lambda, z_d), \quad (5.67)$$

and both absorption $a(\lambda, z_d)$ and scattering $b(\lambda, z_d)$ depend on the chlorophyll concentration profile $C_c(z_d)$.

Near the ocean surface, chlorophyll concentration is generally higher due to biological activity and solar illumination, leading to increased absorption and scattering. Consequently,

the attenuation coefficient $c(\lambda, z_d)$ attains larger values at shallow depths, which results in stronger exponential decay of the received optical power through the term $e^{-c(\lambda, z_d)D_i}$.

As the depth increases, the chlorophyll concentration decreases, particularly in oligotrophic water conditions (e.g., scenario *S1*). This reduction lowers both absorption and scattering coefficients, thereby decreasing $c(\lambda, z_d)$. As a result, the exponential attenuation term becomes less severe, improving the average received SNR and consequently increasing ASE.

For highly productive coastal waters (scenario *S8*), the attenuation coefficient near the surface is significantly larger due to elevated chlorophyll levels. However, at greater depths (e.g., beyond several hundred meters), the attenuation coefficients of different water types tend to converge, resulting in comparable ASE performance.

It is observed from Fig. 5.7 for DMA case that ASE is lowest at shallow depths and improves as the system is deployed deeper. This improvement is consistent with the exponential dependence of the average SNR on the attenuation coefficient.

It is important to note that the same EGG turbulence model is employed for all depth scenarios.² Variations in refractive index due to salinity, temperature gradients, pressure changes, and stratified water layers are neglected in this study, as their impact is relatively small compared to absorption and scattering effects [93, 94].

5.6.2 Fairness Index Analysis

The fairness performance of the proposed system is evaluated using Jain's fairness index in Fig. 5.8.

It is observed that OMA achieves the highest fairness across different user counts due to orthogonal resource allocation. The proposed DMA scheme achieves fairness performance close to OMA while significantly improving ASE. This confirms that distance-aware mirror allocation effectively balances SE and user fairness.

RSMA demonstrates a balanced tradeoff between throughput and fairness, whereas NOMA exhibits fairness degradation as the number of users increases due to sensitivity to power allocation and SIC ordering.

²Scintillation from turbulent water, variations in the refractive index due to variations in flow, salinity, and temperature, and effects of stratified layers of water with depth are ignored for the purposes of this study because they are considered to be less significant than absorption and scattering [93]. Although water is relatively incompressible, its refractive index rises with increasing depth and pressure. This change is relatively small with the increase of about 1.37×10^{-4} for 100 meters depth. The temperature dependence on the refractive index is near a maximum of 4°C at about 1.334 and decreases with temperature to about 1.3319 at 30°C . The impact of salinity is larger still with one part per thousand increase in salinity (1 gr/kilogram) resulting in 1.92×10^{-4} increase in refractive index. The highest expected salinity in sea water is roughly ~ 40 g/kg, while the least is ~ 5 g/kg for arctic water with a lot of ice melt [93], [94].

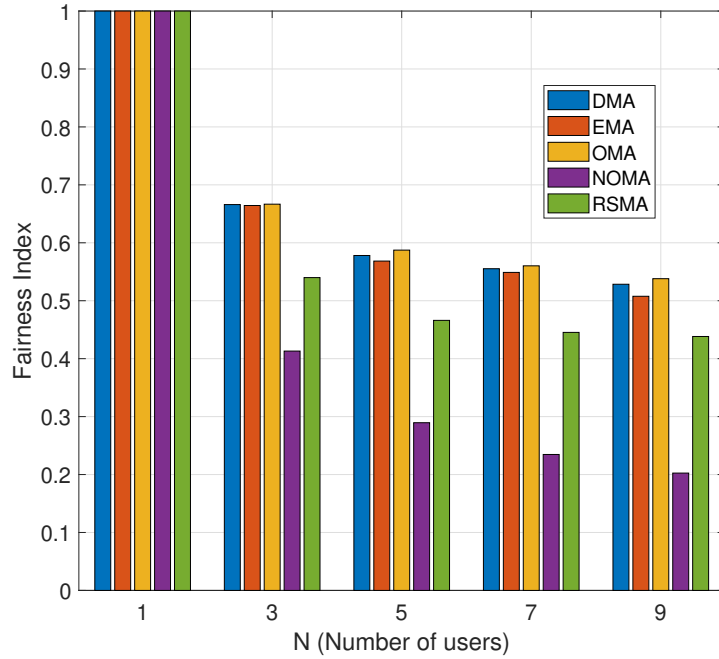


Figure 5.8: Fairness index variation with varying number of users.

The simulation results presented in this chapter are obtained under the assumption of perfect channel state information (CSI) and perfect SIC. These assumptions enable analytical tractability and establish an upper bound on the performance benchmark. In practical underwater environments, channel estimation errors and residual interference due to imperfect SIC may degrade the achievable ASE and fairness. Investigating robust mirror allocation and power allocation strategies under imperfect CSI and SIC remains an important direction for future work.

5.7 Conclusions

In this chapter, a comprehensive analytical framework for a multi-user MA-based OIRS-assisted UWOC system operating under NLoS conditions has been developed. The proposed model incorporates depth-dependent attenuation based on the Haltrin bio-optical model, EGG-distributed oceanic turbulence, and zero-boresight pointing errors to accurately characterize realistic underwater channel impairments.

Closed-form expressions for the statistical characterization of the composite channel and the instantaneous SNR were derived using the Mellin transform and Fox's H -function framework.

Based on these results, analytical expressions for the SE of OMA, NOMA, and RSMA schemes were obtained, along with high-SNR approximations providing additional performance insights.

To enhance system performance in multi-user scenarios, two mirror allocation strategies, namely DMA and EMA, were proposed and analyzed. The DMA strategy is motivated by the distance-dependent attenuation characteristics of underwater optical channels, where the received signal strength decays exponentially with propagation distance. Accordingly, DMA allocates a larger number of reflecting elements to users with longer propagation distances, thereby approximating an SNR-balancing allocation. This distance-aware allocation provides partial compensation for the exponential attenuation effects and improves overall system performance compared to uniform allocation in EMA.

Numerical results demonstrated that RSMA consistently achieves the highest ASE among the considered multiple access schemes due to its efficient interference management capability. Furthermore, DMA significantly improves ASE compared to EMA by compensating for distance-dependent attenuation while maintaining competitive fairness performance. The performance advantages of DMA become more pronounced as the number of users increases and under heterogeneous deployment conditions.

The impact of oceanic depth, water type, turbulence strength, and pointing errors is thoroughly investigated. It is shown that attenuation remains the dominant performance-limiting factor, particularly in shallow and highly productive waters, whereas deeper deployments yield improved SE due to reduced absorption and scattering.

Overall, this chapter establishes that intelligent mirror allocation combined with advanced multiple access strategies plays a critical role in improving throughput and fairness in multi-user OIRS-assisted UWOC systems. The presented analytical framework provides valuable design insights for the development of adaptive and geometry-aware underwater optical communication networks.

Appendix 5.A: Proof of Lemma 5.1

In this subsection, we derive closed-form expression for the PDF of SNR considering combined EGG distributed oceanic turbulence and pointing errors, along with underwater attenuation, for the OIRS-assisted UWOC system.

The PDF of any random variable z can be obtained using the inverse Mellin transform as follows:

$$f_Z(z) = \frac{1}{2\pi iz} \int_{\zeta-i\infty}^{\zeta+i\infty} z^{-n} \mathbb{E}[Z^n] dn, \quad (5.68)$$

where $\zeta - i\infty$ to $\zeta + i\infty$ denotes the line integral, $\mathbb{E}[\cdot]$ denotes the expectation operator, and $\mathbb{E}[Z^n]$ denotes the n^{th} order moment. The n^{th} order moment of h_{α_i} is expressed as:

$$\mathbb{E}[h_{\alpha_i}^n] = \int_0^\infty h_{\alpha_i}^n f_{h_{\alpha_i}}(h_{\alpha_i}) dh_{\alpha_i}. \quad (5.69)$$

By substituting $f_{h_{\alpha_i}}(h_{\alpha_i})$ from (5.22) in (5.69) and utilizing [74, eqs. (3.351/3) and (3.478/1)], we obtain:

$$\mathbb{E}[h_{\alpha_i}^n] = \left(\omega \Lambda^n \Gamma(1+n) + \frac{(1-\omega) b^n \Gamma(a+n/c)}{\Gamma(a)} \right). \quad (5.70)$$

Substituting (5.70) into (5.68) and employing the definition of the Fox-H function, the PDF of the oceanic turbulent channel (h_{α_i}) is derived as:

$$\begin{aligned} f_{h_{\alpha_i}}(h_{\alpha_i}) &= \frac{\omega}{\alpha_i} H_{0,1}^{1,0} \left[\frac{\alpha_i}{\Lambda} \mid \begin{matrix} - \\ (1,1) \end{matrix} \right] \\ &\quad + \frac{(1-\omega)}{\alpha_i \Gamma(a)} H_{0,1}^{1,0} \left[\frac{\alpha_i}{b} \mid \begin{matrix} - \\ (a, 1/c) \end{matrix} \right]. \end{aligned} \quad (5.71)$$

Next, we express the instantaneous received SNR from (5.30) as:

$$\gamma_i = \frac{\mathcal{R}^2 P_t^2 |H_i|^2}{\sigma_{n_i}^2} = \frac{\mathcal{R}^2 P_t^2 G_i^2 h_{att_i}^2 h_{\alpha_i}^2 h_{m_i}^2}{\sigma_{n_i}^2} = \bar{\gamma}_i h_i^2, \quad (5.72)$$

where $\bar{\gamma}_i = \frac{\mathcal{R}^2 P_t^2 G_i^2 h_{att_i}^2}{\sigma_{n_i}^2}$ is the average SNR and $h_i = h_{\alpha_i} h_{m_i}$.

By applying the theory of product distribution, the PDF of h_i is obtained as:

$$f_{h_i}(h_i) = \int_0^{A_0} \frac{1}{h_{m_i}} f_{h_{m_i}}(h_{m_i}) f_{h_{\alpha_i}}\left(\frac{h_i}{h_{m_i}}\right) dh_{m_i}. \quad (5.73)$$

Upon substituting (5.25) and (5.71) into (5.73) and applying the definition of the Fox-H function, we obtain:

$$\begin{aligned} f_{h_i}(h_i) = & \frac{\omega \rho^2}{h_i} H_{1,2}^{2,0} \left[\frac{h_i}{\Lambda A_0} \mid \begin{matrix} (1 + \rho^2, 1) \\ (1, 1), (\rho^2, 1) \end{matrix} \right] \\ & + \frac{(1 - \omega) \rho^2}{h_i \Gamma(a)} H_{1,2}^{2,0} \left[\frac{h_i}{b A_0} \mid \begin{matrix} (1 + \rho^2, 1) \\ (a, 1/c), (\rho^2, 1) \end{matrix} \right]. \end{aligned} \quad (5.74)$$

This completes the proof.

Appendix 5.B: Proof of Lemma 5.2

The instantaneous SNR is defined as:

$$\gamma_i = \bar{\gamma}_i h_i^2. \quad (5.75)$$

To derive the PDF of γ_i , we apply the transformation of random variables.

Let

$$h_i = \sqrt{\frac{\gamma_i}{\bar{\gamma}_i}}.$$

The transformation rule yields:

$$f_{\gamma_i}(\gamma_i) = \frac{1}{2\sqrt{\bar{\gamma}_i \gamma_i}} f_{h_i}\left(\sqrt{\frac{\gamma_i}{\bar{\gamma}_i}}\right). \quad (5.76)$$

Substituting the PDF of h_i derived in Appendix 5.A and simplifying using standard Fox-H function properties, the closed-form expression of the instantaneous SNR PDF is obtained in terms of the Fox-H function as:

$$\begin{aligned} f_{\gamma_i}(\gamma_i) = & \frac{\omega \rho^2}{2\gamma_i} H_{1,2}^{2,0} \left[\frac{1}{\Lambda A_0} \sqrt{\frac{\gamma_i}{\bar{\gamma}_i}} \mid \begin{matrix} (1 + \rho^2, 1) \\ (1, 1), (\rho^2, 1) \end{matrix} \right] \\ & + \frac{(1 - \omega) \rho^2}{2\gamma_i \Gamma(a)} H_{1,2}^{2,0} \left[\frac{1}{b A_0} \sqrt{\frac{\gamma_i}{\bar{\gamma}_i}} \mid \begin{matrix} (1 + \rho^2, 1) \\ (a, 1/c), (\rho^2, 1) \end{matrix} \right]. \end{aligned} \quad (5.77)$$

This completes the proof.

Appendix 5.C: Proof of Lemma 5.3

The average SE is defined as:

$$SE_i = \int_0^\infty \log_2(1 + \tau\gamma_i) f_{\gamma_i}(\gamma_i) d\gamma_i. \quad (5.78)$$

At high SNR, the logarithmic term can be approximated as:

$$\log_2(1 + \tau\gamma_i) \approx \log_2(\tau\gamma_i). \quad (5.79)$$

Substituting $\gamma_i = \bar{\gamma}_i h_i^2$ and using the logarithmic identity, we obtain:

$$SE_i \approx \log_2(\tau\bar{\gamma}_i) + 2\mathbb{E}[\log_2(h_i)]. \quad (5.80)$$

The expectation term can be evaluated using the moment generating properties of the Fox–H function and the identity in [74, eq. (8.360/1)].

After simplification, the asymptotic SE expression becomes:

$$SE_i \approx 1.44 \left[\log(\tau) + \omega \left(\log(\Lambda^2 \bar{\gamma}_i) + 2\psi(1) \right) + (1 - \omega) \left(\log(b^2 \bar{\gamma}_i) + \frac{2}{c} \psi(a) \right) \right], \quad (5.81)$$

where $\psi(\cdot)$ denotes the digamma function.

This completes the derivation.

Optimization and Mode Operation of LC-OSTAR-IRS

In Chapter 5, a multi-user underwater wireless optical communication (UWOC) framework assisted by mirror-array (MA)-based optical intelligent reflecting surfaces (OIRS) was developed. By incorporating realistic underwater channel impairments, namely attenuation h_{att} , turbulence-induced fading h_{α} , and misalignment fading h_m , and integrating advanced multiple access schemes such as orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA), and rate-splitting multiple access (RSMA), intelligent mirror allocation strategies including equal mirror assignment (EMA) and distance-based mirror assignment (DMA) were formulated to enhance aggregate spectral efficiency (ASE) and fairness.

Although the MA-OIRS architecture demonstrated substantial performance gains in non-line-of-sight (NLoS) underwater scenarios, it inherently operates in a reflection-only mode. Consequently, the achievable coverage region remains restricted to a single half-space determined by the reflective orientation of the surface. Users located in spatial regions opposite to the reflective direction cannot be simultaneously served without mechanical reorientation or deployment of additional reflecting structures. In practical underwater environments, where users may be distributed in multiple spatial clusters around the intelligent surface, such half-space coverage limitations reduce spatial flexibility and system adaptability.

Therefore, to overcome this structural constraint and further enhance multi-user connectivity, it becomes necessary to extend the reflection-only OIRS framework toward an architecture capable of simultaneous transmission and reflection. Enabling concurrent transmission–reflection operation introduces an additional degree of freedom in surface control, allowing dynamic service of users located on both sides of the surface and improving spatial coverage efficiency.

Motivated by this limitation of reflection-only architectures, this chapter investigates optical simultaneously transmitting and reflecting intelligent reflecting surfaces (OSTAR-IRS) for multi-user UWOC systems and develops a unified optimization framework for their operational modes.

6.1 Chapter Overview

This chapter presents a comprehensive system-level framework for OSTAR-IRS assisted multi-user UWOC systems. Unlike conventional OIRSs that provide only reflective functionality, the proposed OSTAR-IRS architectures enable simultaneous transmission and reflection, thereby overcoming the half-space coverage limitation of traditional MA based designs.

Two novel architectures are investigated: (i) a Liquid Crystal based OSTAR-IRS (LC-OSTAR-IRS), which exploits the electrically tunable birefringence of liquid crystal (LC) elements to achieve dynamic reflection and refraction, and (ii) a Hybrid OSTAR-IRS (H-OSTAR-IRS), which integrates MA reflectors and LC-based refractors to provide full 360° coverage.

The proposed architectures are analyzed under advanced multiple access techniques, namely NOMA and RSMA, with optimized dynamic power allocation. Furthermore, two practical operating strategies, Energy Splitting (ES) and Mode Switching (MS) [18], are considered. A unified optimization framework is developed to maximize the ASE subject to physical and operational constraints.

The performance of the proposed system is evaluated in terms of ASE, energy efficiency (EE), fairness index, and computational complexity. The results demonstrate the superiority of RSMA over NOMA and highlight the trade-off between fairness and computational complexity in ES and MS modes. This chapter establishes a system-level baseline for adaptive and energy-efficient UWOC networks assisted by OSTAR-IRS.

Although MA based optical IRS designs improve NLoS-UWOC performance, they remain constrained by reflection-only operation and half-space coverage [10]. Metasurface-based approaches provide theoretical bidirectional control but suffer from slow reconfiguration speed and practical implementation challenges in underwater environments [95]. Furthermore, existing UWOC studies integrating intelligent reflecting surface (IRS) primarily focus on single-user scenarios or fixed power allocation strategies, limiting system adaptability [41, 56].

Another key limitation in existing work is the absence of unified system-level optimization that jointly considers OIRS architecture, operational modes, and advanced multiple access schemes. In multi-user underwater networks, efficient interference management and dynamic resource allocation are essential to maintain fairness and spectral efficiency (SE).

Motivated by these gaps, this chapter develops a unified OSTAR-IRS assisted multi-user UWOC framework with the following key contributions:

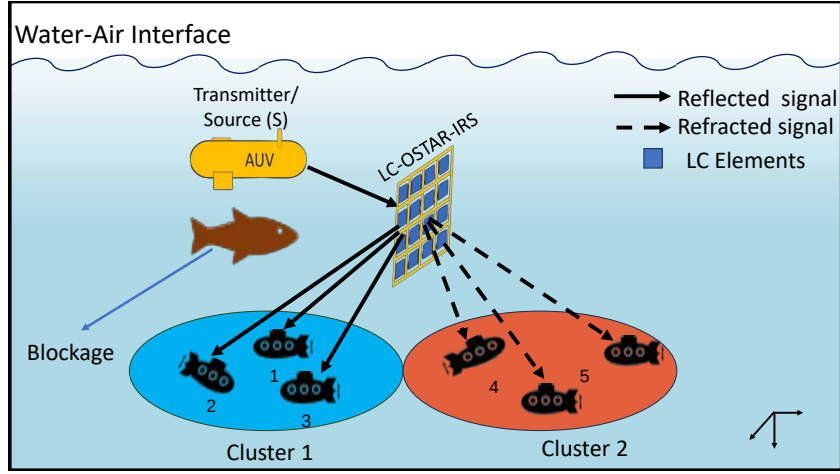
1. Two novel OSTAR-IRS architectures are introduced for UWOC systems:
 - LC-OSTAR-IRS, which leverages electrically tunable LC elements to achieve simultaneous transmission and reflection through a single surface.
 - H-OSTAR-IRS, a hybrid architecture combining MA reflectors and LC-based refractors to provide full 360° coverage.
2. A joint optimization framework is developed to maximize ASE under both ES and MS operation modes.
3. Advanced multiple access schemes, namely NOMA and RSMA, are integrated with optimal power allocation (OPA) based on instantaneous channel state information (CSI).
4. Comprehensive performance evaluation is conducted in terms of ASE, EE, fairness index, and computational complexity.
5. A detailed trade-off analysis between ES and MS modes is presented, highlighting that ES achieves superior fairness while MS offers lower computational complexity.

To the best of our knowledge, this is the first work that presents a unified framework integrating OSTAR-IRS architecture design, simultaneous transmission–reflection control, multi-user interference management, and operational mode optimization in UWOC systems.

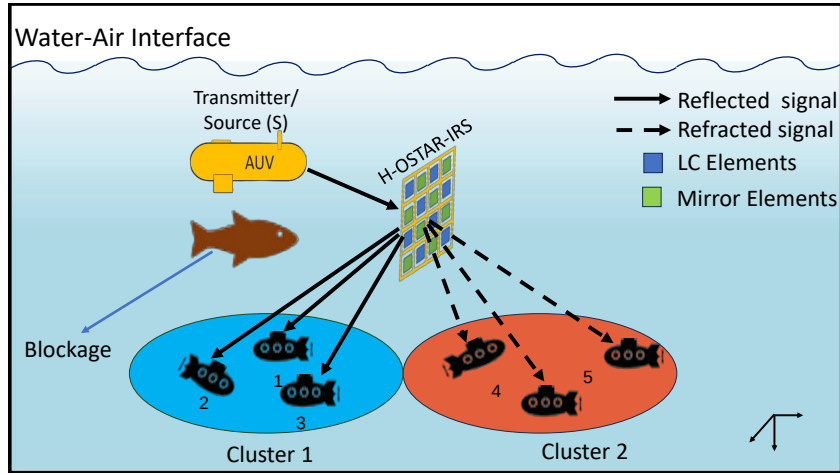
6.2 System Model

In this section, the geometrical framework and signal model of the developed OSTAR-IRS-assisted multi-user UWOC system are presented. A unified three-dimensional coordinate system is adopted to facilitate analytical modeling and enable a consistent comparison between the LC-OSTAR-IRS and H-OSTAR-IRS architectures.

Due to underwater obstacles, node mobility, beam misalignment, and environmental disturbances, maintaining reliable direct LoS communication between the transmitter and multiple underwater users is often challenging. Therefore, a reconfigurable optical surface is deployed to establish NLoS communication through controlled reflection and transmission mechanisms as shown in [6.1](#).



(a) LC-OSTAR-IRS-aided UWOC System.



(b) H-OSTAR-IRS-aided UWOC System.

Figure 6.1: System Model for H/LC-OSTAR-IRS Assisted UWOC System.

A static UWOC system operating in pure seawater is assumed for analytical tractability. This assumption is introduced solely to facilitate the analytical development of the proposed OSTAR-IRS optimization framework. While the numerical analysis presented in this chapter considers a baseline pure seawater scenario, the proposed optimization methodology is not restricted to this specific environmental model. The adopted composite channel formulation continues to account for attenuation, oceanic turbulence-induced fading, and pointing error effects through the channel coefficients h_{att} , h_{α} , and h_m , respectively, with their detailed statistical characterization provided in Chapters 2 and 5. Furthermore, the proposed ES and MS resource scheduling policies can be readily extended to more comprehensive underwater environments, including the depth-dependent Haltrin bio-optical model presented in Chapter 5, by updating the corresponding channel parameters and effective channel gains. Although additional underwater

impairments may influence the absolute ASE, EE, and fairness performance, the underlying optimization framework and resource allocation methodology remain applicable.

The autonomous underwater vehicle (AUV) acts as the optical transmitter and is equipped with a light emitting diode (LED) array. The OSTAR-IRS is deployed in the x - z plane. The underwater users, equipped with photodetectors, are divided into two spatial clusters. The direct transmitter-user links are assumed to be completely blocked.

The transmitter is located at coordinates (x_s, y_s, z_s) , and the i^{th} user is positioned at (x_{di}, y_{di}, z_{di}) . The centroid of the $(k, l)^{\text{th}}$ OSTAR-IRS element is denoted by (x_{kl}, y_{kl}, z_{kl}) . The distances between the transmitter and the OSTAR-IRS, and between the OSTAR-IRS and the i^{th} user, are represented by d_{sr} and d_{rd}^i , respectively.

In the LC-OSTAR-IRS architecture as shown in Fig. 6.1 (a), each LC element simultaneously performs reflection and transmission depending on the applied electric field. Users located in Cluster 1 are served via reflection, whereas users in Cluster 2 are served via transmission (refraction). In contrast, the H-OSTAR-IRS architecture in Fig. 6.1 (b) employs MA elements for reflection (Cluster 1) and LC-based elements for transmission (Cluster 2), thereby enabling full 360° coverage.

Under the above assumptions, the received signal at the i^{th} user can be expressed as:

$$y_i = G_i^{MA/LC} h_{att,i} h_{\alpha,i} h_{m,i} x_i + n_i, \quad (6.1)$$

where $G_i^{MA/LC}$ denotes the overall OSTAR-IRS channel gain corresponding to MA or LC-based transmission, $h_{att,i}$ represents the attenuation loss due to absorption and scattering, $h_{\alpha,i}$ models the oceanic turbulence-induced fading, $h_{m,i}$ denotes the pointing error fading component, x_i is the transmitted signal intended for the i^{th} user, and n_i is the additive white Gaussian noise (AWGN) with variance $\sigma_{n_i}^2$.

The overall channel gain is therefore composed of deterministic path loss, turbulence-induced random fading, pointing error effects, and the controllable gain introduced by the OSTAR-IRS elements. In the following section, each channel component is modeled in detail.

6.3 Channel Model

The underwater optical channel model adopted in this chapter follows the composite formulation developed in the earlier chapters (see Chapters 2 and 5).

The cascaded channel gain between the transmitter and the i^{th} user is modeled as:

$$H_i = G_i^{MA/LC} h_{att,i} h_{\alpha,i} h_{m,i}, \quad (6.2)$$

where $h_{att,i}$ denotes the attenuation component governed by the Beer–Lambert law, $h_{\alpha,i}$ represents the turbulence-induced fading modeled using the Exponential-Generalized Gamma (EGG) distribution, and $h_{m,i}$ corresponds to the misalignment fading component. The detailed statistical characterization of $h_{att,i}$, $h_{\alpha,i}$, and $h_{m,i}$ is provided earlier and is not repeated here for brevity.

In contrast to Chapter 5, where only MA-based reflection was considered, the present chapter introduces transmission–reflection controllable gain $G_i^{MA/LC}$, which depends on the operational mode of the OSTAR-IRS architecture.

6.3.1 OSTAR-IRS Channel Gain Modeling

The geometric channel gain for the MA-based OIRS has been derived previously and is adopted here for the considered multi-user framework. For completeness, the element-wise gain expression is briefly recalled here without re-derivation.

Assuming that the mirror array subtends relatively small solid angles with respect to both the transmitter and the receiver, or equivalently, that the mirror element dimensions are sufficiently small compared to the propagation distances, the propagation distances and the corresponding incidence/reflection angles across the mirror elements can be approximated as identical. Consequently, the aggregated MA-based channel gain toward the i^{th} user can be expressed as [55]:

$$H_i^{MA} \approx n_m^2 G_{ik,l}^{MA} h_{att,i} h_{\alpha,i} h_{m,i}, \quad (6.3)$$

where n_m^2 is the total number of OIRS elements and $G_{ik,l}^{MA}$ represents the geometric gain component defined in Chapter 4.

In contrast to the reflection-only MA-OIRS considered previously, the OSTAR-IRS architecture enables simultaneous transmission and reflection, providing additional flexibility in controlling the optical signal propagation. Therefore, the LC-based channel gain is modified to incorporate transmission–reflection controllable parameters and field-dependent transmission efficiency variation, yielding [96]:

$$H_i^{LC} \approx n_m^2 G_{ik,l}^{LC} h_{att,i} h_{\alpha,i} h_{m,i} \exp(AD) \xi^{LC}. \quad (6.4)$$

Here, $G_{ik,l}^{LC}$ denotes the geometric gain component, which follows the same geometric formulation as the MA case, while ξ^{LC} and $\exp(AD)$ represent the transmission characteristics of the LC medium. The detailed formulation of these terms is provided in the following subsection.

The exponential term $\exp(AD)$ in (6.4) follows the analytical LC model adopted from the existing literature on LC-based IRS [96, 97], where it is introduced to model the effective

field-dependent transmission variation due to refractive index modulation under an applied electric field. It is important to emphasize that the LC medium operates as a passive electro-optic material and does not introduce external optical amplification. The passive electro-optic effect in LCs is well-established, where an applied electric field reorients the LC molecules, altering the refractive index and thereby modulating the transmission of incident light without the addition of optical gain [98, 99]. The term $\exp(AD)$ captures the variation in optical transmission efficiency arising from the electrically tunable birefringence of the LC elements, rather than physical signal gain. Under the adopted analytical framework, the coefficient A is expressed as:

$$A = \frac{2\pi\eta_{LC}^3}{\cos(\psi_d^{k,l})\lambda_o} r_{\text{eff}} E, \quad (6.5)$$

where η_{LC} is the refractive index of the LC element, λ_o is the optical wavelength, r_{eff} denotes the electro-optic coefficient, E represents the applied electric field, and $\psi_d^{k,l}$ is the angle of irradiance from the $(k, l)^{\text{th}}$ LC element towards the user. D denotes the LC cell depth. This formulation is consistent with the electro-optic modeling approach commonly employed in LC-IRS and LC-OSTAR-IRS system analysis and should be interpreted within the assumptions of that model. In practical LC implementations, the achievable transmission efficiency variation is bounded by the material properties and the tunable range of the refractive index.

6.3.1.1 Channel Gain for LC-Based OSTAR-IRS

In the LC-OSTAR-IRS architecture, each LC element can operate in transmission or reflection mode depending on the applied electric field. For users in Cluster 2 in Fig. 6.1 (a), the LC elements primarily operate in transmission mode.

The element-wise gain is given by:

$$G_{ik,l}^{LC} = \begin{cases} \frac{\beta_{k,l}^t \eta (m+1) A_{PD}}{2\pi (d_{sr} + d_{rd}^i)^2} \cos^m(\Phi_{k,l}^s) \cos(\psi_{k,l}^s) \\ \quad \times \cos(\Phi_d^{k,l}) \cos(\psi_d^{k,l}) T(\psi) G(\psi), & 0 \leq \psi_d^{k,l} \leq \psi_{FoV}, \\ 0, & \text{otherwise.} \end{cases} \quad (6.6)$$

Here, $\beta_{k,l}^t$ represents the transmission coefficient of the LC element, η is LED's conversion efficiency, m is the Lambertian order, A_{PD} represents the area of the photo diode, d_{sr} and d_{rd}^i denotes the distance from the transmitter to OSTAR-IRS and OSTAR-IRS to i^{th} user, respectively. $\Phi_{k,l}^s$ is the angle of irradiance from the transmitter to the OSTAR-IRS, $\psi_{k,l}^s$ denotes the angle of incidence on the OSTAR-IRS, $\Phi_d^{k,l}$ is the angle of irradiance from the k^{th} row and l^{th} column OSTAR-IRS element towards the user, and $\psi_d^{k,l}$ represents the angle

of incidence on the user. $T(\psi)$ and $G(\psi)$ represents optical filter and concentrator gains, respectively.

The transition coefficient (ξ^{LC}) in (6.4) of the LC element is defined as [96]:

$$\xi^{LC} = \begin{cases} T_{wc}(\psi_{k,l}^s)T_{cw}(\Phi_d^{k,l}), & \text{if LC operates in transmission mode,} \\ R_{wc}(\psi_{k,l}^s), & \text{if LC operates in reflection mode.} \end{cases} \quad (6.7)$$

where $T_{wc}(\psi_{k,l}^s)$ and $T_{cw}(\Phi_d^{k,l})$ are the angular transmittances as the optical signal enters and exits the LC cell from the water medium. Since the LC cell does not absorb any incident light, the angular transmittances can be expressed as $T_{wc}(\psi_{k,l}^s) = 1 - R_{wc}(\psi_{k,l}^s)$ and $T_{cw}(\Phi_d^{k,l}) = 1 - R_{cw}(\Phi_d^{k,l})$, where $R_{wc}(\psi_{k,l}^s)$ and $R_{cw}(\Phi_d^{k,l})$ are the angular reflectances.

6.3.1.2 Received Power Expression

Based on the derived channel gain expressions, the received optical power at the i^{th} user can now be formulated. The received power depends on the transmit power, photodetector responsivity, and the cascaded channel gain introduced by the OSTAR-IRS-assisted link.

For a general OSTAR-IRS-assisted link, the received optical power at the i^{th} user is expressed as:

$$P_{R,i} = \mathcal{R}P_t H_i, \quad (6.8)$$

where $\mathcal{R}$ denotes the responsivity of the photodetector, P_t is the transmit optical power, and H_i represents the overall cascaded channel gain.

A. Received Power for MA-Based H-OSTAR-IRS

For users located in Cluster 1 and served through MA-based reflection in the H-OSTAR-IRS architecture, the received power is obtained by substituting H_i^{MA} from (6.3) into (6.8), yielding:

$$P_{R,i}^{MA} = \mathcal{R}P_t \left(n_m^2 G_{ik,l}^{MA} h_{att,i} h_{\alpha,i} h_{m,i} \right). \quad (6.9)$$

B. Received Power for LC-Based OSTAR-IRS

For users located in Cluster 1 and Cluster 2, the received power under LC-based operation is obtained by substituting H_i^{LC} from (6.4) into (6.8), yielding:

$$P_{R,i}^{LC} = \mathcal{R}_e P_t \left(n_m^2 G_{ik,l}^{LC} h_{att,i} h_{\alpha,i} h_{m,i} \exp(AD) \xi^{LC} \right). \quad (6.10)$$

The serving cluster depends on the operating mode of the LC element, i.e., transmission or reflection, as defined in (7.7).

From (6.10), it can be observed that the LC-based architecture introduces additional controllable factors, namely $\exp(AD)$ and ξ^{LC} , which enhance flexibility in channel shaping compared to conventional MA-based reflection.

6.3.2 Multiple Access Transmission Model

The multiple access framework adopted in this chapter follows the formulations developed in Chapter 5. For completeness, the key signal expressions are briefly recalled here, while the detailed theoretical background on OMA, NOMA, and RSMA is not repeated.

6.3.2.1 NOMA Transmission

Under power-domain NOMA, the transmitted superposition signal is expressed as:

$$x^{\text{NOMA}} = \sum_{i=1}^N \sqrt{\kappa_i P_t} x_i, \quad (6.11)$$

where κ_i denotes the power allocation coefficient of the i^{th} user and satisfies $\sum_{i=1}^N \kappa_i = 1$, N is the total number of users.

6.3.2.2 RSMA Transmission

For RSMA, each message is divided into common and private components. The transmitted signal is expressed as:

$$x^{\text{RSMA}} = \sqrt{a_c P_t} x_c + \sum_{i=1}^N \sqrt{\kappa_i P_t} x_i, \quad (6.12)$$

where a_c is the power coefficient allocated to the common message, and κ_i denotes the power coefficient allocated to the private message of the i^{th} user. These coefficients satisfy the constraint $a_c + a_p = 1$, where $a_p = \sum_{i=1}^N \kappa_i$ [22], which denotes the total power coefficient allocated to private message.

The corresponding SINR expressions are obtained by substituting the updated channel gain H_i into the derivations provided in Chapter 5.

6.3.3 SINR Analysis

In this subsection, the SINR expressions for NOMA and RSMA transmission are derived based on the received power expressions and power allocation models introduced earlier.

6.3.3.1 SINR for NOMA

Substituting the NOMA superposition signal from (6.11) into the received signal model in (6.1), the received signal at the i^{th} user can be written as:

$$y_i = H_i \sum_{j=1}^N \sqrt{\kappa_j P_t} x_j + n_i. \quad (6.13)$$

In NOMA, users are ordered according to their effective channel gains such that:

$$|H_1|^2 \leq |H_2|^2 \leq \dots \leq |H_N|^2.$$

The i^{th} user first decodes the signals of users with weaker channel gains ($j < i$) using successive interference cancellation (SIC), and then decodes its own signal while treating the remaining stronger-user signals as interference.

Accordingly, the signal-to-interference-plus-noise ratio (SINR) at the i^{th} user for decoding its own signal is given by:

$$\gamma_i^{\text{NOMA}} = \frac{\kappa_i P_t |H_i|^2}{P_t |H_i|^2 \sum_{j=i+1}^N \kappa_j + \sigma_{n_i}^2}. \quad (6.14)$$

The denominator consists of residual inter-user interference from users with stronger channel gains and the additive noise power.

6.3.3.2 SINR for RSMA

For the RSMA scheme, substituting (6.12) into (6.1), the received signal at the i^{th} user becomes:

$$y_i = H_i \left(\sqrt{a_c P_t} s_c + \sum_{j=1}^N \sqrt{\kappa_j P_t} s_j \right) + n_i. \quad (6.15)$$

In RSMA, each user first decodes the common message while treating all private streams as interference. The SINR for decoding the common stream at the i^{th} user is therefore expressed as:

$$\gamma_i^{\text{RSMA}_c} = \frac{a_c P_t |H_i|^2}{P_t |H_i|^2 \sum_{j=1}^N \kappa_j + \sigma_{n_i}^2}. \quad (6.16)$$

After successfully decoding and removing the common message via SIC, the i^{th} user proceeds to decode its private message. The SINR for decoding the private stream is given by:

$$\gamma_i^{\text{RSMA}_p} = \frac{\kappa_i P_t |H_i|^2}{P_t |H_i|^2 \sum_{j \neq i} \kappa_j + \sigma_{n_i}^2}. \quad (6.17)$$

The RSMA structure therefore partially decodes interference through the common stream, which improves interference management compared to conventional NOMA.

6.4 Performance Metrics

In order to evaluate the effectiveness of the OSTAR-IRS-assisted UWOC system, several key performance metrics are considered. These include ASE, EE, fairness index and computational complexity. These metrics enable comprehensive comparison between NOMA and RSMA schemes under both LC-OSTAR-IRS and H-OSTAR-IRS architectures.

6.4.1 Aggregate Spectral Efficiency (ASE)

The ASE represents the total achievable data rate per unit bandwidth across all users.

For the NOMA scheme, the ASE is expressed as:

$$\text{ASE}^{\text{NOMA}} = \sum_{i=1}^N \log_2 \left(1 + \tau \gamma_i^{\text{NOMA}} \right). \quad (6.18)$$

Here, $\tau = \frac{e}{2\pi}$ denotes the intensity-modulation with direct-detection (IM/DD) scaling factor commonly adopted in the optical communication literature to account for the IM/DD signaling constraint [22, 32].

For the RSMA scheme, the ASE consists of the common rate and the sum of private rates expressed as:

$$\text{ASE}^{\text{RSMA}} = \min_{i \in \{1, 2, \dots, N\}} \log_2 \left(1 + \tau \gamma_i^{\text{RSMA}_c} \right) + \sum_{i=1}^N \log_2 \left(1 + \tau \gamma_i^{\text{RSMA}_p} \right) \quad (6.19)$$

The ASE metric captures the overall system throughput improvement enabled by OSTAR-IRS and advanced multiple access techniques.

It is worth noting that the proposed optimization framework is developed under the same achievable-rate formulation for both NOMA and RSMA. Consequently, although tighter IM/DD capacity bounds may influence the absolute achievable-rate and ASE values, the comparative performance evaluation and optimization outcomes presented in this work remain consistent within the adopted analytical framework.

6.4.2 Energy Efficiency (EE)

The EE quantifies the number of successfully transmitted bits per unit power consumption. It is defined as the ratio of ASE to the total consumed power.

The total power consumption includes the transmit power and hardware dissipation components, expressed as [96]:

$$P_{\text{total}} = P_t + P_{\text{circuit}}, \quad (6.20)$$

where P_{circuit} includes power consumed by the LED driver, IRS control circuitry, and photodetector processing units.

Accordingly, the EE for the NOMA and RSMA schemes is expressed as:

$$\text{EE} = \frac{\text{ASE}}{P_t + P_{\text{circuit}}}. \quad (6.21)$$

This metric enables evaluation of the trade-off between spectral gain and power consumption introduced by the OSTAR-IRS architectures.

6.4.3 Fairness Index

To evaluate the fairness of rate distribution among users, Jain's fairness index is adopted. It is defined as [92]:

$$J = \frac{\left(\sum_{i=1}^N SE_i\right)^2}{N \sum_{i=1}^N SE_i^2}. \quad (6.22)$$

The fairness index satisfies:

$$\frac{1}{N} \leq J \leq 1.$$

A value of $J = 1$ indicates perfect fairness, whereas lower values indicate imbalance in user rate allocation.

This metric is particularly important in NOMA-based systems, where unequal power allocation may lead to rate disparities among users.

6.4.4 Optimal Power Allocation (OPA) in NOMA and RSMA

Efficient power allocation plays a critical role in maximizing SE and fairness in multi-user NOMA and RSMA systems. Many existing UWOC studies, such as [89] and [22], employ fixed power allocation strategies in which the power coefficients remain constant regardless of channel variations. However, such static allocation leads to suboptimal performance in dynamic underwater environments characterized by fading, attenuation, and misalignment effects.

To address this limitation, we adopt a dynamic CSI-based power allocation strategy that prioritizes users with weaker channel conditions. The objective is to ensure that the far (weak) user satisfies a predefined target rate r^{th} before allocating the remaining power to stronger users.

Two-User NOMA Case

For a two-user NOMA system consisting of a far user (f) and a near user (u), the achievable spectral efficiencies are given by:

$$SE_f = \log_2 \left(1 + \frac{|H_f|^2 P_t \alpha_f}{|H_f|^2 P_t \alpha_u + \sigma_n^2} \right), \quad (6.23)$$

$$SE_u = \log_2 \left(1 + \frac{|H_u|^2 P_t \alpha_u}{\sigma_n^2} \right), \quad (6.24)$$

where α_f and α_u denote the power allocation coefficients satisfying $\alpha_f + \alpha_u = 1$, and H_f , H_u represent the composite channel gains.

To guarantee that the far user achieves its target rate r^{th} , the following condition must hold:

$$\frac{|H_f|^2 P_t \alpha_f}{|H_f|^2 P_t \alpha_u + \sigma_n^2} \geq \Xi, \quad (6.25)$$

where $\Xi = 2^{r^{\text{th}}} - 1$.

Solving the above constraint yields the optimal far-user power coefficient as:

$$\alpha_f = \min \left(1, \frac{\Xi (|H_f|^2 P_t + \sigma_n^2)}{|H_f|^2 P_t (1 + \Xi)} \right), \quad (6.26)$$

and

$$\alpha_u = 1 - \alpha_f. \quad (6.27)$$

Multi-User NOMA Extension

For the general N -user case, users are ordered according to increasing channel strength, and power is sequentially allocated to ensure that each user satisfies its minimum rate requirement. The power allocation coefficient for the i^{th} user is obtained as:

$$\kappa_i = \min \left(1, \frac{\Xi \left(\sigma_n^2 + P_t |H_i|^2 \prod_{j=1}^{i-1} (1 - \kappa_j) \right)}{P_t |H_i|^2 (1 + \Xi)} \right). \quad (6.28)$$

Finally, the coefficients are normalized to satisfy the total power constraint:

$$\kappa_i = \frac{\kappa_i}{\sum_{m=1}^N \kappa_m}. \quad (6.29)$$

Extension to RSMA

For the RSMA scheme, the same CSI-based dynamic power allocation principle as in NOMA is adopted for the private streams. This approach prioritizes users with weaker channel conditions by ensuring that their target rate is satisfied before allocating the remaining power to stronger users. The common stream is incorporated within the transmission while preserving the interference management benefits of RSMA.

Practical Considerations on CSI Acquisition and SIC: The proposed optimization framework assumes that accurate instantaneous CSI is available at the centralized network controller responsible for OSTAR-IRS configuration and resource allocation. This assumption is adopted to establish an analytical performance benchmark and to isolate the performance gains achieved by the proposed OSTAR-IRS architectures. In practical UWOC systems, CSI acquisition may be affected by channel estimation errors, feedback delay, pilot signaling overhead, and residual SIC errors, which may reduce the achievable spectral efficiency, EE, and fairness compared with the ideal results presented in this chapter. Furthermore, the specific uplink mechanism for CSI feedback (e.g., underwater acoustic links or directed optical uplinks) introduces additional latency and overhead that are not modeled in the present framework. Consequently, the reported performance should be interpreted as an upper bound on the performance under ideal CSI and perfect SIC assumptions. The development of robust resource allocation algorithms under

imperfect CSI, practical CSI feedback mechanisms, and residual SIC therefore remains an important direction for future work.

6.4.5 Optimization Problem Formulation

One of the primary objectives of this work is to maximize the ASE of the proposed H/LC-OSTAR-IRS-assisted multi-user UWOC system by optimizing the transmission coefficient (β^t) and reflection coefficient (β^r) of the OSTAR-IRS elements.

The power allocation coefficients for both NOMA and RSMA schemes are determined using the closed-form OPA strategy described earlier and are therefore treated as deterministic functions of the instantaneous CSI. Consequently, power allocation coefficients are not included as optimization variables in the following formulations.

Additionally, the yaw angle (ζ), roll angle (ϱ), and refractive index (η_{LC}) represent important physical parameters of the OSTAR-IRS. However, in this work, ζ , ϱ , and η_{LC} are assumed fixed and not directly optimized. Their constraints are included to reflect practical operational limits of the system.

The optimization problem is formulated for both power-domain NOMA and RSMA transmission schemes under two practical OSTAR-IRS operating configurations: ES and MS.

1) ES Configuration:

In the ES mode, each H/LC-OSTAR-IRS element can simultaneously reflect and transmit portions of the incident optical signal¹. The transmission and reflection coefficients ($\beta_{k,l}^t$ and $\beta_{k,l}^r$) are continuous variables satisfying:

$$0 \leq \beta_{k,l}^r, \beta_{k,l}^t \leq 1, \quad \beta_{k,l}^r + \beta_{k,l}^t = 1.$$

The ASE maximization problem under ES operation is formulated as:

¹While the ES case is theoretically analyzed for both H-OSTAR-IRS and LC-OSTAR-IRS architectures, in practice the ES mode is not feasible for H-OSTAR-IRS due to the static nature of its mirror elements. Consequently, only the MS case is practically realizable for H-OSTAR-IRS.

$$(\mathbf{P1}) : \max_{\{\beta^t, \beta^r\}} ASE^{\text{NOMA}} \text{ or } ASE^{\text{RSMA}} \quad (6.30)$$

$$\text{subject to } \beta_{k,l}^r, \beta_{k,l}^t \in [0, 1], \quad \forall k, l, \quad (6.31)$$

$$\beta_{k,l}^r + \beta_{k,l}^t = 1, \quad \forall k, l, \quad (6.32)$$

$$-\frac{\pi}{2} \leq \zeta \leq \frac{\pi}{2}, \quad (6.33)$$

$$-\frac{\pi}{2} \leq \varrho \leq \frac{\pi}{2}, \quad (6.34)$$

$$1.1 \leq \eta_{LC} \leq 1.7. \quad (6.35)$$

2) MS Configuration:

In the MS mode, each H/LC-OSTAR-IRS element operates either in a fully reflective or fully transmissive state. Thus,

$$\beta_{k,l}^r, \beta_{k,l}^t \in \{0, 1\}, \quad \beta_{k,l}^r + \beta_{k,l}^t = 1.$$

The corresponding ASE maximization problem is formulated as:

$$(\mathbf{P2}) : \max_{\{\beta^t, \beta^r\}} ASE^{\text{NOMA}} \text{ or } ASE^{\text{RSMA}} \quad (6.36)$$

$$\text{subject to } \beta_{k,l}^r, \beta_{k,l}^t \in \{0, 1\}, \quad \forall k, l, \quad (6.37)$$

$$\beta_{k,l}^r + \beta_{k,l}^t = 1, \quad \forall k, l, \quad (6.38)$$

$$-\frac{\pi}{2} \leq \zeta \leq \frac{\pi}{2}, \quad (6.39)$$

$$-\frac{\pi}{2} \leq \varrho \leq \frac{\pi}{2}, \quad (6.40)$$

$$1.1 \leq \eta_{LC} \leq 1.7. \quad (6.41)$$

The constraints ensure practical feasibility of the OSTAR-IRS operation. Constraints (6.31)–(6.32) and (6.37)–(6.38) enforce the transmission–reflection coefficient bounds and energy conservation. Constraints (6.33)–(6.34) and (6.39)–(6.40) restrict the yaw and roll angles within their physical steering limits. Constraint (6.35) and (6.41) bound the refractive index of the LC element according to its electro-optic tunability range.

The resulting optimization problems are nonlinear and non-convex due to the coupled SINR expressions in the ASE objective. In the MS configuration, the presence of binary variables leads to a mixed-integer nonlinear programming (MINLP) problem. For tractable

implementation, the problem can be efficiently solved using MILP-based approaches through suitable approximations or linearization techniques.

6.4.6 Computational Complexity Analysis

The computational complexity analysis follows standard principles of nonlinear programming and mixed-integer optimization theory [100–102]. The complexity scaling is characterized in terms of the number of optimization variables and interference coupling operations required for SINR evaluation.

The computational complexity of the ES and MS optimization schemes is analyzed in terms of the number of OSTAR-IRS elements (n_m^2), the number of users (N), and the number of solver iterations.

Let $K = n_m^2$ denote the total number of OSTAR-IRS elements.

6.4.6.1 ES Mode

In the ES configuration, each OSTAR-IRS element simultaneously supports transmission and reflection by splitting the incident optical energy into two portions.

In this configuration, each OSTAR-IRS element introduces a continuous variable $\beta_{k,l}^r$ (with $\beta_{k,l}^t = 1 - \beta_{k,l}^r$). Therefore, the number of optimization variables scales linearly with the number of elements, i.e., $O(K)$.

At each solver iteration, the ASE objective requires:

- 1) Computing the channel gains H_i for all N users, which scales as $O(KN)$ due to the interaction between OSTAR-IRS elements and users (since the channel gain computation involves contributions from each OSTAR-IRS element to each user),
- 2) Evaluating SINR expressions involving multi-user interference, which scales as $O(N^2)$,
- 3) Calculating SE terms for all users.

Therefore, the per-iteration computational cost becomes:

$$O(KN + N^2) \quad (6.42)$$

Let I_{ES} denote the number of iterations required by the nonlinear solver (fmincon). Since the optimization involves K continuous variables and gradient-based updates across all elements, the overall ES complexity is given by:

$$O(I_{\text{ES}} K(KN + N^2)) \quad (6.43)$$

For practical systems where $K \gg N$, this can be approximated as:

$$O(I_{\text{ES}} K^2 N) \quad (6.44)$$

6.4.6.2 MS Mode

In the MS configuration, each OSTAR-IRS element operates in either transmission or reflection mode, enabling discrete mode switching of the incident optical signal.

In this configuration, each OSTAR-IRS element operates in a binary state ($\beta_{k,l}^r, \beta_{k,l}^t \in \{0, 1\}$). Therefore, the optimization problem becomes a mixed-integer linear programming (MILP) problem with K binary decision variables.

Although the worst-case complexity of MILP grows exponentially with K , practical branch-and-bound implementations significantly reduce the search space.

At each node of the branch-and-bound tree, the ASE evaluation requires:

- 1) Channel gain computation with complexity $O(KN)$,
- 2) SINR evaluation involving multi-user interference with complexity $O(N^2)$.

Therefore, the per-node computational cost is given by:

$$O(KN + N^2) \quad (6.45)$$

Let I_{MS} denote the effective number of explored nodes during MILP convergence. The overall MS complexity can therefore be approximated as:

$$O(I_{\text{MS}}(KN + N^2)) \quad (6.46)$$

Although the worst-case complexity of the MILP formulation is exponential in K , practical branch-and-bound solvers significantly reduce the effective search space. As a result, the number of explored nodes I_{MS} remains substantially smaller than the number of iterations required for convergence in the ES scheme, i.e., $I_{\text{MS}} \ll I_{\text{ES}}$. Moreover, unlike the ES scheme, which requires continuous updates over all K variables, the MS formulation operates over a discrete decision space with efficient pruning. Consequently, the MS scheme exhibits lower computational complexity in practice, which is also reflected in the reduced runtime observed in the results section.

Convergence, Initialization, and Scalability: The convergence behavior of the proposed optimization framework depends on the nature of the underlying optimization problem. For the ES configuration, the transmission and reflection coefficients are continuous variables and the resulting problem is non-convex; therefore, the employed fmincon solver provides a locally optimal solution, and global optimality cannot in general be guaranteed. The obtained solution

can consequently depend on the initial values supplied to the solver. In the present analysis, a common initialization strategy and identical solver settings are adopted across the considered scenarios to ensure a consistent comparison.

The computational burden also increases with the number of OSTAR-IRS elements because the number of transmission/reflection coefficients to be optimized increases accordingly. This dependence is captured in the complexity expressions through the number of OSTAR-IRS elements K . For the MS configuration, the binary nature of the element-assignment variables leads to a discrete optimization problem whose worst-case search complexity can increase rapidly with the number of elements, although practical mixed-integer solvers can reduce the effective search space through their search and pruning procedures. Therefore, increasing the number of OSTAR-IRS elements provides additional resource-allocation flexibility but also introduces a corresponding computational-complexity trade-off.

The execution-time results (presented in Subsection 6.5.4) further demonstrates the practical difference between the two operating modes. The ES formulation requires substantially higher computational time because of its continuous non-convex optimization, whereas the MS formulation achieves lower execution time for the considered system configurations. Thus, the choice between ES and MS involves a trade-off between optimization flexibility, achievable communication performance, and computational cost.

6.4.7 Problem Characteristics and Solution Approach

The formulated ASE maximization problem is inherently non-convex. The non-convexity arises due to the coupled SINR expressions appearing inside the logarithmic objective function. Specifically, each SINR term contains interference components in the denominator that depend on the power allocation variables of other users. This leads to fractional and bilinear dependencies among optimization variables, preventing direct convex reformulation.

In the ES mode, the reflection and transmission coefficients $(\beta_{k,l}^r, \beta_{k,l}^t)$ are continuous variables subject to linear equality constraints. Therefore, the ES formulation constitutes a nonlinear non-convex programming (NLP) problem.

In contrast, the MS strategy imposes binary constraints on the OSTAR-IRS coefficients, resulting in a MINLP problem. Such problems are generally NP-hard due to the combinatorial nature of binary decision variables.

Since global optimality cannot be guaranteed for either ES or MS formulations, numerical optimization techniques are employed to obtain locally optimal solutions. The ES problem is solved using a nonlinear constrained optimization solver, while the MS formulation is addressed using mixed-integer programming techniques.

6.4.8 Optimization Methodology

The power allocation coefficients are first computed using the closed-form OPA strategy based on instantaneous CSI. Subsequently, the ASE maximization problems (P1) in (6.30) and (P2) in (6.36) are solved with respect to the OSTAR-IRS transmission and reflection coefficients.

ES Case: Since the ES configuration involves continuous decision variables ($\beta_{k,l}^t, \beta_{k,l}^r \in [0, 1]$), the resulting nonlinear constrained optimization problem is solved using MATLAB's `fmincon` solver. This solver is suitable for smooth nonlinear programming and efficiently converges to a locally optimal solution under practical initialization conditions.

MS Case: In the MS configuration, the transmission and reflection coefficients ($\beta_{k,l}^t, \beta_{k,l}^r \in \{0, 1\}$) are binary variables, resulting in a MINLP optimization problem. To handle this, a mixed-integer optimization approach is employed, where the binary decision variables determine the operational state of each OSTAR-IRS element. The solver iteratively searches the feasible binary space to determine the configuration that maximizes the ASE.

6.4.9 Optimization Algorithm

The unified optimization algorithm for both MS and ES operations is presented in Algorithm 6.1. The algorithm takes system parameters and user distributions as input and returns the optimized reflection/transmission coefficients along with the achievable ASE.

6.5 Numerical Results and Discussion

This section evaluates the performance of the H/LC-OSTAR-IRS-assisted multi-user UWOC system under ES and MS configurations. Both NOMA and RSMA schemes are analyzed using the OPA strategy. Unless otherwise specified, the simulation parameters follow Table 6.1, and all results are averaged over independent channel realizations.

6.5.1 Aggregate Spectral Efficiency (ASE) Analysis

6.5.1.1 ASE versus Transmit Power

Fig. 6.2 illustrates the ASE as a function of transmit power for different architectures and multiple access schemes.

For all configurations, ASE increases monotonically with transmit power. At low transmit power levels, improvements in signal strength significantly enhance the received SINR, resulting in rapid SE growth. As transmit power increases further, the ASE growth becomes gradual due to the logarithmic dependence of achievable rate on SINR.

Algorithm 6.1 Unified Optimization for MS and ES in OSTAR-IRS Assisted UWOC

Require: System parameters ($P_t, n_m^2, c(\lambda)$, LC material constants, N)

Ensure: Optimal coefficients (β_r^*, β_t^*) and ASE

- 1: Initialize OSTAR-IRS geometry and LC parameters (η_{LC}, λ, D)
 - 2: **for** each transmit power level $P_T \in [0, 45]$ dBm **do**
 - 3: Generate N user positions in two circular clusters
 - 4: Compute geometric parameters (centroids, angles (ζ, ϱ))
 - 5: Compute path loss h_{att_i} and LC transmission term ψ_{LC}
 - 6: Compute composite channel coefficients H_i
 - 7: Allocate power coefficients κ_i using (Eq. 6.28)
 - 8: Normalize $\sum_{i=1}^N \kappa_i = 1$
 - 9: **if** Mode Switching (MS) **then**
 - 10: Formulate binary optimization problem for ASE maximization
 - 11: Subject to: $\beta_{k,l}^r + \beta_{k,l}^t = 1, \beta_{k,l}^r, \beta_{k,l}^t \in \{0, 1\}$
 - 12: Solve using `intlinprog()`
 - 13: **else if** Energy Splitting (ES) **then**
 - 14: Formulate continuous optimization problem for ASE maximization
 - 15: Subject to: $\beta_{k,l}^r + \beta_{k,l}^t = 1, 0 \leq \beta_{k,l}^r, \beta_{k,l}^t \leq 1$
 - 16: Solve using `fmincon()`
 - 17: **end if**
 - 18: Obtain optimal coefficients β_r^* and β_t^*
 - 19: Compute the achievable ASE using (Eqs. 6.18, 6.12) based on the adopted multiple access scheme
 - 20: **end for**
 - 21: Average ASE over Monte Carlo iterations
-

RSMA consistently outperforms NOMA across the entire transmit power range. This improvement is attributed to the rate-splitting mechanism, where part of the interference is decoded through the common stream before decoding private streams. Consequently, RSMA effectively reduces residual interference and achieves better throughput scaling in moderate-to-high SNR regimes.

Comparing OSTAR-IRS architectures, the H-OSTAR-IRS demonstrates superior ASE compared to the LC-OSTAR-IRS. This performance gain is attributed to the hybrid architecture, which provides improved signal control and reduced propagation losses, thereby enhancing the effective channel conditions.

Moreover, the ASE trends for the MS and ES modes are nearly identical over the considered transmit power range, indicating that both configurations achieve comparable SE under the given channel conditions. This similarity suggests that both discrete mode selection and continuous energy splitting provide comparable performance under the considered system parameters.

Table 6.1: Simulation Parameters

Parameter	Symbol	Value
Transmit power	P_t	0 to 45 dBm
Attenuation coefficient	$c(\lambda)$	0.056
Total OSTAR-IRS elements	n_m^2	36
Wavelength	λ	510 nm
Length of OSTAR-IRS element	ℓ_m	8 cm
Width of OSTAR-IRS element	w_m	8 cm
Number of users	N	6
Lambertian order	m	2
PD area	A_{PD}	0.0314 m ²
Current to light conversion efficiency	η	0.9
Responsivity	$\mathcal{R}$	1 A/W
Pointing parameter	ρ	1
Pointing parameter	A_0	0.0032
noise variance	$\sigma_{n_i}^2$	10 ⁻¹⁵
Power of the analog-to-digital converter	P_{ADC}	95 mWatt
Power of the LED driver	P_{Dvr}	2758 mWatt
Power of each mirror array-based reflector element	P_m	100 mWatt
Power of the receiver external circuit	P_{R-Crt}	1.9 mWatt
Power of each LC-based refractor element	P_{LC}	320 mWatt
Power of the digital-to-analog converter	P_{DAC}	175 mWatt
Power of the filter	P_{Ftr}	2.5 mWatt
Power of the trans-impedance amplifier	P_{TIA}	2500 mWatt
Power of the transmitter external circuit	P_{T-Crt}	3250 mWatt
Power of the power amplifier	P_{PA}	280 mWatt
Coordinates of transmitter/source	(x_s, y_s, z_s)	(0, 5m, 0)
Coordinates of OSTAR-IRS	(x_{kl}, y_{kl}, z_{kl})	(2m, 0, 15m)
Scintillation index	σ_I^2	{0.2178}
EGG distribution parameters corresponding to σ_I^2	$\{\omega\}$	{0.1665}
	$\{\Lambda\}$	{0.1207}
	$\{a\}$	{0.1559}
	$\{b\}$	{1.5216}
	$\{c\}$	{22.8754}

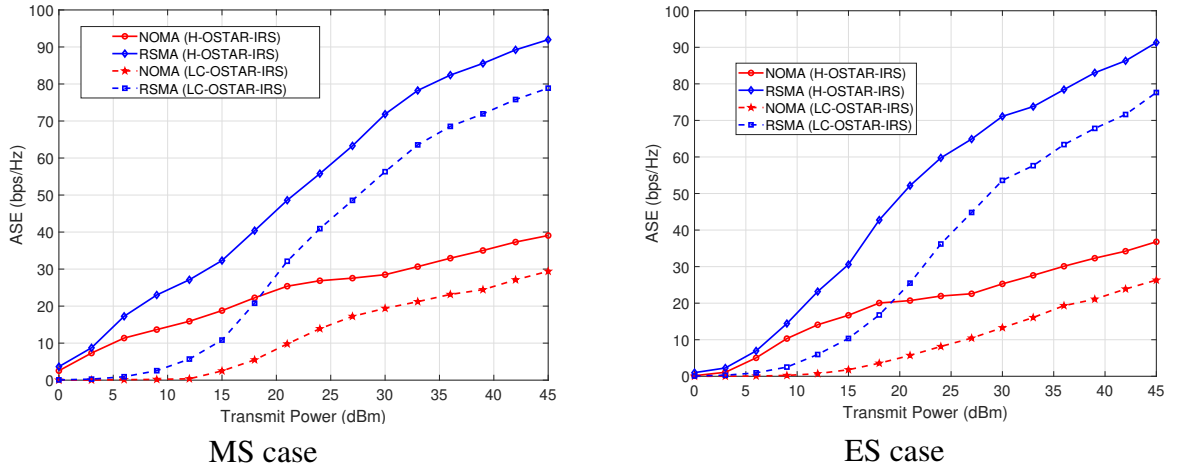


Figure 6.2: ASE versus transmit power for H/LC-OSTAR-IRS-assisted UWOC system under (a) MS and (b) ES operations.

6.5.1.2 ASE versus Number of Users

Fig. 6.3 presents the ASE of MS configuration as a function of the number of users (N) for $n_m^2 = 36$. It is observed that the ASE increases with the number of users, indicating improved utilization of system resources and enhanced multi-user diversity. Among the considered

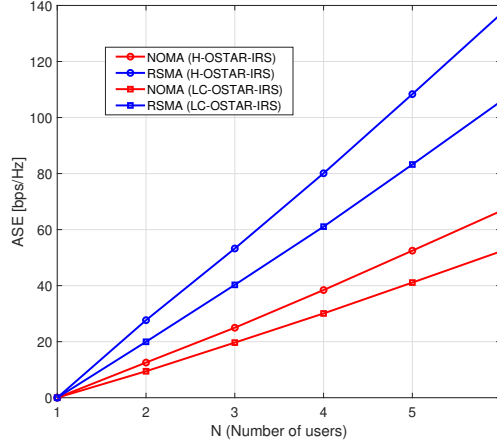


Figure 6.3: ASE versus number of users (N) for H/LC-OSTAR-IRS-assisted UWOC system (MS mode).

multiple access schemes, RSMA exhibits a more pronounced improvement compared to NOMA, highlighting its superior capability in managing multi-user interference and achieving higher SE.

Furthermore, the H-OSTAR-IRS architecture consistently outperforms the LC-OSTAR-IRS configuration across all user densities for both NOMA and RSMA schemes. This demonstrates the effectiveness of the hybrid architecture in enhancing system performance. Overall, for UWOC systems with a larger number of users, the combination of RSMA with H-OSTAR-IRS provides the most efficient solution in terms of ASE performance.

6.5.2 Energy Efficiency (EE) Analysis

Fig. 6.4 shows the EE performance as a function of transmit power.

At low transmit power levels, EE increases because improvements in SE outweigh the increase in total power consumption. In this region, SINR improvements translate directly into throughput gains.

At higher transmit powers, the rate of SE improvement slows down due to the logarithmic behavior of achievable rate, while total power consumption continues to increase linearly. As a result, EE saturates and may slightly decrease at very high transmit power levels.

RSMA achieves higher EE compared to NOMA in moderate SNR regions. Moreover, the EE performance of the ES and MS configurations remains comparable, as both modes exhibit similar ASE and incur comparable circuit power consumption under the considered system settings.

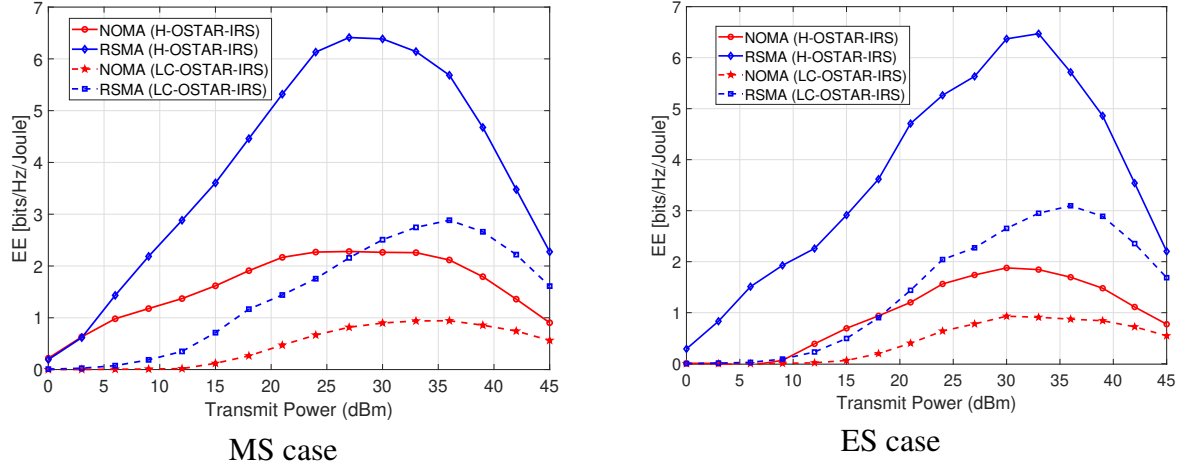


Figure 6.4: EE versus transmit power for H/LC-OSTAR-IRS-assisted UWOC system under (a) MS and (b) ES operations.

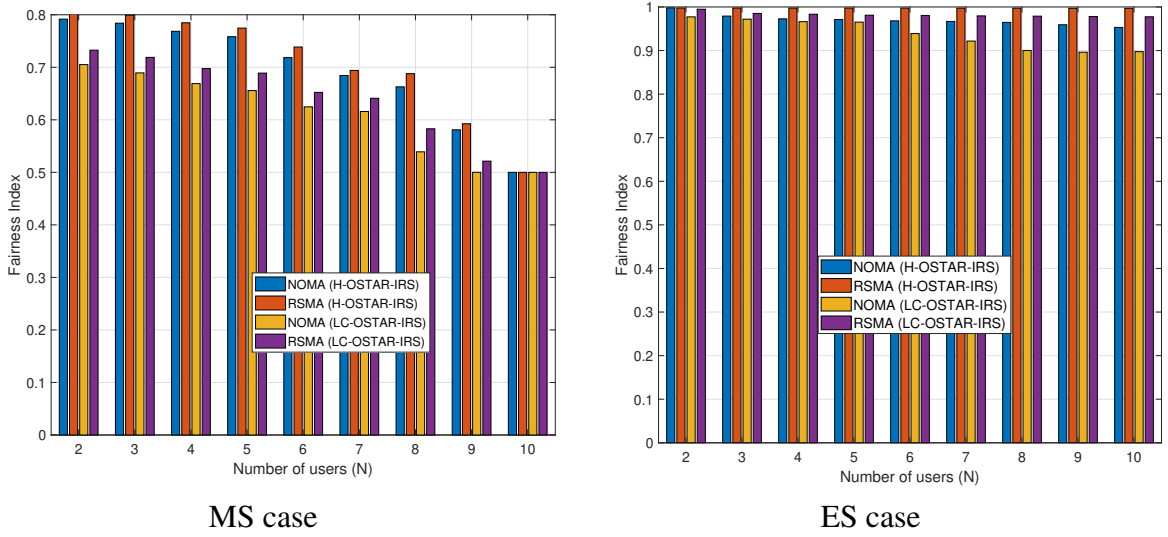


Figure 6.5: Fairness index versus number of users (N) for H/LC-OSTAR-IRS-assisted UWOC system under (a) MS and (b) ES operations.

6.5.3 Fairness Analysis

Fig. 6.5 illustrates Jain's fairness index for different configurations.

The ES configuration achieves better fairness compared to the MS configuration. Continuous transmission-reflection control enables smoother energy distribution among user clusters, allowing more balanced rate allocation under heterogeneous channel conditions.

RSMA further improves fairness relative to NOMA. By partially decoding interference through the common stream, RSMA reduces the rate disparity between strong and weak users, leading to a more uniform distribution of user rates.

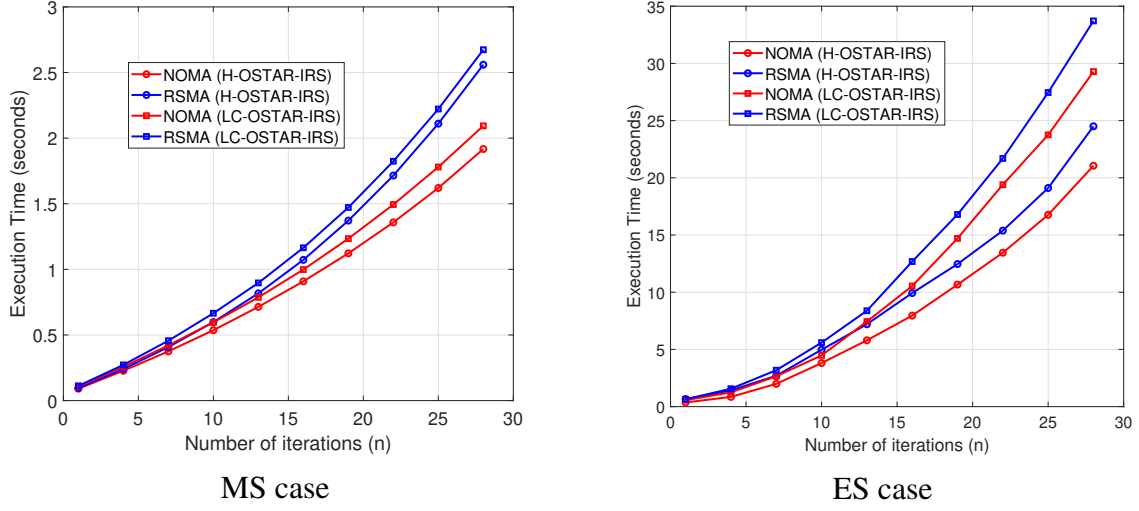


Figure 6.6: Execution time versus number of iterations (n) for H/LC-OSTAR-IRS-assisted UWOC system under (a) MS and (b) ES operations.

6.5.4 Computational Complexity Analysis

Fig. 6.6 presents the execution time versus the number of iterations for ES and MS configurations.

The ES mode involves solving a continuous nonlinear optimization problem and therefore exhibits higher computational complexity. In contrast, the MS configuration operates under binary constraints, resulting in reduced effective search dimensionality and lower execution time in practical implementation.

RSMA incurs higher computational burden compared to NOMA due to additional processing associated with common stream handling and increased optimization dimensionality.

These results demonstrate a clear trade-off between fairness and computational complexity. While RSMA combined with ES achieves the highest fairness, the MS configuration offers a more efficient alternative by maintaining comparable SE with lower computational cost.

The performance evaluation of different metrics is crucial for understanding the comparative advantages of the different modes of H/LC-OSTAR-IRS. Table 6.2 provides a comprehensive comparison of various performance metrics for H-OSTAR-IRS aided UWOC system. This comparison highlights the strengths and trade-offs of each mode and scheme, offering valuable insights into their suitability for different application scenarios.

Table 6.2: Comparison of NOMA and RSMA under Energy Splitting and Mode Switching cases for H-OSTAR-IRS.

Metric	Energy Splitting		Mode Switching	
	NOMA	RSMA	NOMA	RSMA
Aggregate SE vs. P_t	★	★★★	★	★★★
EE vs. P_t	★★	★★★	★★	★★★
Fairness Index	★★★	★★★	★★	★★
Time Complexity (s)	★	★	★★★	★★

Rating criterion: ★★★: $ASE > 80$ bps/Hz, $EE > 5$ bits/HZ/Joule, Fairness index > 0.9 , complexity < 2 second, ★★: $50 < ASE < 80$ bps/Hz, $2 < EE < 5$ bits/HZ/Joule, $0.5 < \text{Fairness index} < 0.9$, $2 < \text{complexity} < 10$ second, ★: $ASE < 50$ bps/Hz, $EE < 2$ bits/HZ/Joule, Fairness index < 0.5 , complexity > 10 second.

6.6 Conclusion

In this chapter, a unified optimization framework for OSTAR-IRS-assisted multi-user UWOC systems has been developed and analyzed. Building upon the channel modeling and element-level analysis presented in the previous chapters, this chapter extended the study to a system-level perspective by jointly considering OSTAR-IRS architecture, advanced multiple access techniques, and practical operational strategies.

Two practical OSTAR-IRS architectures were investigated, namely the LC-OSTAR-IRS and the H-OSTAR-IRS. While the H-OSTAR-IRS provides structured reflection and transmission through hybrid elements, the LC-OSTAR-IRS enables dynamic transmission–reflection control and refractive-index tuning, offering enhanced flexibility for adaptive underwater communication scenarios.

A comprehensive signal and channel model incorporating attenuation loss, oceanic turbulence modeled through the EGG distribution, and misalignment fading was employed to characterize realistic underwater propagation conditions. Based on this composite channel formulation, SINR expressions and achievable rate metrics were derived for both NOMA and RSMA transmission schemes under OPA.

To maximize ASE, two practical operating strategies were formulated: ES and MS. The ES configuration allows continuous adjustment of transmission and reflection coefficients, resulting in a nonlinear non-convex optimization problem, whereas the MS strategy imposes binary constraints leading to a mixed-integer formulation. Numerical optimization techniques were employed to obtain locally optimal solutions for both configurations.

The numerical results demonstrate that RSMA consistently outperforms NOMA in terms of SE and fairness due to its enhanced interference management capability. Furthermore, the H-OSTAR-IRS architecture achieves superior performance compared to the LC-OSTAR-IRS, owing to improved signal control and reduced propagation losses.

The ASE performance of the ES and MS modes is observed to be nearly identical under the considered system settings, indicating comparable efficiency of both configurations. While the ES scheme enables continuous energy allocation, the MS scheme provides reduced computational complexity with comparable performance, making it a practical and efficient alternative.

Overall, this chapter establishes that the joint integration of optimized power allocation, rate-splitting transmission, and adaptive OSTAR-IRS control effectively enhances the performance of multi-user UWOC systems in practical underwater environments. The proposed framework provides a scalable foundation for future research on intelligent underwater surface design, adaptive control mechanisms, and low-complexity optimization strategies for next-generation underwater communication networks.

LC-OSTAR-IRS: Geometry-Driven Performance Analysis for UWOC

This chapter complements the system-level optimization framework developed in Chapter 6 by investigating the intrinsic geometry-dependent behavior of liquid crystal (LC) elements. While Chapter 6 focused on operational mode optimization, the present analysis isolates the physical reflection–refraction dynamics governed by refractive-index contrast and incidence angle.

7.1 Chapter Overview

This chapter investigates a LC-based optical simultaneously transmitting and reflecting intelligent reflecting surface (LC-OSTAR-IRS) for underwater wireless optical communication (UWOC). The proposed framework focuses on the geometric principles governing optical wave propagation, explicitly incorporating angular-dependent reflection, refraction, and transmission characteristics of LC elements into the system analysis.

The motivation for this study is aligned with the vision of next-generation (sixth generation (6G)) networks, which aim to enable seamless integration across air, ground, and underwater domains [2]. In this context, UWOC has emerged as a promising communication technology due to its ability to provide high data rates and low latency compared to conventional radio frequency (RF) and acoustic systems. However, UWOC performance remains fundamentally constrained by underwater channel impairments such as turbulence-induced fading, pointing errors, and environmental obstructions [29], which limit link reliability and coverage.

To address these challenges, optical intelligent reflecting surfaces (OIRS) have recently been explored to enhance signal propagation in underwater environments. Mirror-array (MA)-based OIRSs provide strong reflectivity but are inherently limited to fixed 180° coverage [10],

whereas metasurface-based OIRSs enable flexible beam manipulation but suffer from high fabrication complexity and slower reconfiguration [95].

In contrast, the proposed LC-OSTAR-IRS leverages the refractive-index contrast between water and voltage-controlled LC elements, enabling each element to dynamically switch between reflective and transmissive modes. This dual functionality allows simultaneous coverage of multiple spatial regions without requiring separate hardware components, thereby improving system flexibility and resource utilization.

Building upon this architecture, this chapter develops a geometry-driven analytical framework to characterize the interaction between optical propagation and LC surface behavior. The analysis explicitly accounts for total internal reflection (TIR), angular-dependent transmittance, underwater turbulence, and pointing errors, enabling a realistic evaluation of system performance under practical underwater conditions.

Furthermore, the integration of advanced multiple access schemes, including non-orthogonal multiple access (NOMA) and rate-splitting multiple access (RSMA), is investigated to enhance multi-user communication efficiency. The performance is evaluated in terms of key metrics such as aggregate spectral efficiency (ASE) and fairness index under varying geometric configurations and system parameters.

The main contributions of this chapter can be summarized as follows:

- A geometry-driven LC-OSTAR-IRS framework is developed for UWOC systems, incorporating angular-dependent reflection, refraction, and transmission characteristics of LC elements.
- The impact of refractive-index contrast and LC tunability on dynamic switching between reflective and transmissive modes is analyzed, enabling dual-region coverage within a single intelligent surface.
- A comprehensive performance analysis is conducted by incorporating TIR conditions, underwater turbulence, and pointing errors, providing a realistic characterization of underwater optical channels.
- The integration of NOMA and RSMA schemes with LC-OSTAR-IRS is investigated to evaluate multi-user performance under practical deployment scenarios.
- The effects of geometric parameters, such as incident angle and vertical distance, on ASE and fairness are systematically analyzed, highlighting key performance trade-offs.
- Design insights and deployment guidelines are established for LC-OSTAR-IRS-assisted UWOC systems, enabling efficient and flexible underwater communication in future 6G-enabled networks.

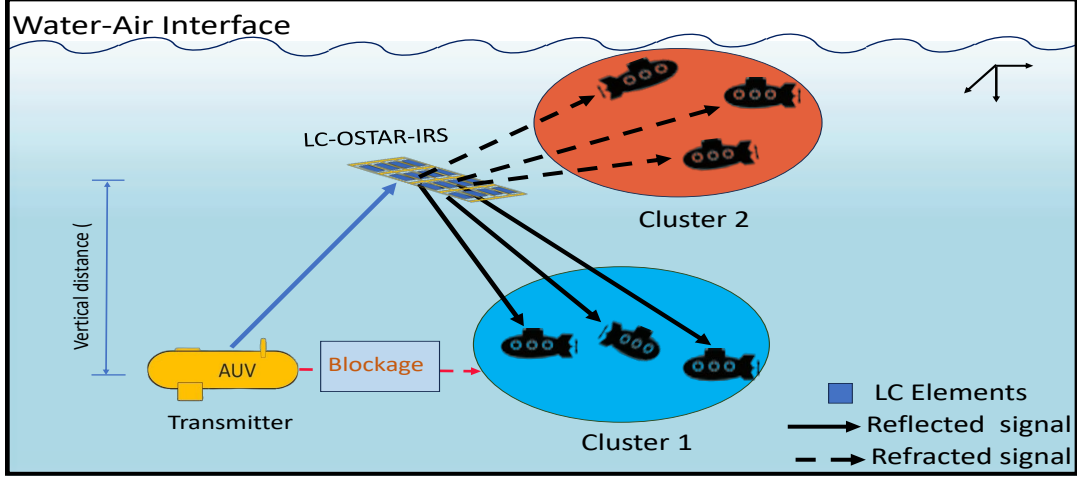


Figure 7.1: System model for LC-OSTAR-IRS-assisted UWOC system.

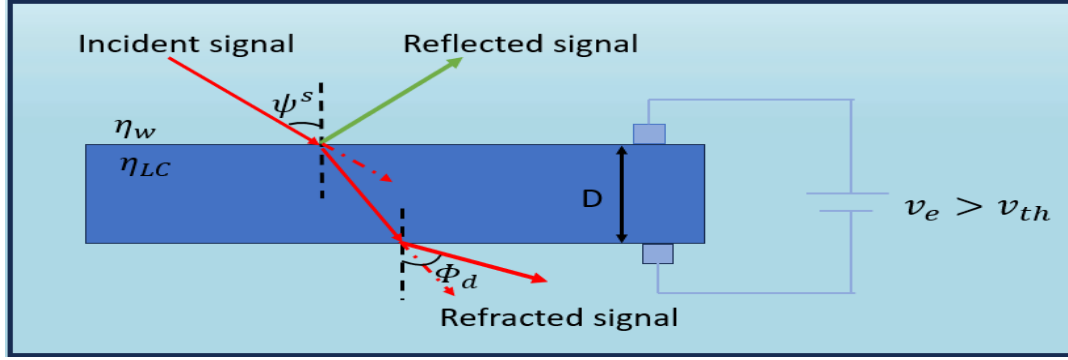


Figure 7.2: Signal propagation geometry for a single LC element in underwater medium.

7.2 System Model

In this work, we consider a downlink UWOC system in which a fixed light-emitting diode (LED) transmitter mounted on an autonomous underwater vehicle (AUV) communicates with multiple photodetector equipped users through an LC-OSTAR-IRS, as illustrated in Fig. 7.1. The LC-OSTAR-IRS is deployed as a planar structure consisting of n_m^2 uniformly distributed LC elements arranged in a square grid configuration.

Each LC element can independently operate in either reflection or transmission mode depending on its electrically controlled refractive index state, thereby enabling flexible non-line-of-sight (NLoS) connectivity. This dual-mode capability allows simultaneous service to users located on both sides of the surface without requiring separate reflective and transmissive components, significantly enhancing spatial coverage and system efficiency.

7.2.1 Operational Principle of LC-OSTAR-IRS

The operating principle of the LC-OSTAR-IRS is governed by the refractive-index contrast between water and the LC material, as illustrated in Fig. 7.2. To characterize the dual-mode behavior, two representative LC states are considered:

- Low refractive index state: $\eta_{LC} = 1.1$ (reflective mode),
- High refractive index state: $\eta_{LC} = 1.5$ (transmissive mode).

The refractive index of water is approximately $\eta_w \approx 1.33$ [41]. When $\eta_{LC} < \eta_w$, light propagating from water to the LC interface undergoes total internal reflection (TIR), depending on the incidence angle. This enables mirror-less reflection purely due to refractive-index contrast.

The critical angle governing TIR is given by:

$$\sin(\theta_c) = \frac{\eta_{LC}}{\eta_w}. \quad (7.1)$$

For $\eta_{LC} = 1.1$ and $\eta_w = 1.33$, the critical angle is approximately $\theta_c \approx 55.8^\circ$. When the incidence angle ψ^s on the LC-OSTAR-IRS satisfies $\psi^s > \theta_c$, efficient reflection occurs due to TIR. Conversely, when $\psi^s < \theta_c$, partial refraction takes place, reducing reflective efficiency and resulting in power leakage through the LC element.

In contrast, when the LC element operates in the high refractive index state ($\eta_{LC} = 1.5 > \eta_w$), efficient transmission is achieved via refraction, enabling signal propagation toward users located behind the surface. Thus, reflective elements redirect the incident optical beam, whereas transmissive elements forward it through the surface.

Although the refractive index of LC elements can be continuously tuned via applied voltage, two discrete steady-state values are adopted to ensure analytical tractability while capturing the essential dual-mode operation of the LC-OSTAR-IRS [103].

7.2.2 Multi-User Connectivity and Element Assignment

To support multi-user communication, users are grouped into two spatial clusters as shown in Fig. 7.1:

- Cluster 1: users served via reflected signals,
- Cluster 2: users served via transmitted signals.

The total n_m^2 LC elements are first partitioned between the two clusters. The elements assigned to each cluster are then equally and randomly distributed among the users within that cluster. This equal-per-user allocation serves as a baseline configuration for evaluating system performance in terms of spectral efficiency (SE) and fairness.

The resulting per-user LC-OSTAR-IRS gain is determined by the aggregate contribution of all assigned elements, forming the effective channel component used in subsequent performance analysis. While this simple allocation strategy provides analytical clarity, more advanced schemes such as angle-based or distance-based assignment [104] can be employed for non-uniform user distributions.

Unlike the optimization-driven framework presented in Chapter 6, the present chapter focuses exclusively on geometry-driven performance behavior and does not involve optimization of transmission or reflection coefficients. This allows isolating the impact of geometric parameters, such as incidence angle and spatial configuration, on system performance.

7.2.3 Channel Model

The channel modeling framework adopted in this chapter follows the composite UWOC channel formulation introduced in Chapter 2. Specifically, the channel incorporates geometric propagation loss, underwater attenuation, oceanic turbulence, and pointing error effects. Rather than re-deriving these well-established models, this section briefly summarizes their expressions and focuses on the additional geometry-dependent characteristics introduced by the LC-OSTAR-IRS.

The composite channel gain from the LED transmitter to the i^{th} user via its assigned LC-OSTAR-IRS elements is expressed as [96]:

$$H_i = \sum_{(k,l) \in \mathcal{A}_i} G_{i_{k,l}}^{\text{LC}} h_{att_i} h_{\alpha_i} h_{m_i} \exp(AD) \xi^{\text{LC}}, \quad (7.2)$$

where $\mathcal{A}_i$ denotes the set of LC-OSTAR-IRS elements assigned to user i . The term $G_{i_{k,l}}^{\text{LC}}$ represents the geometric gain of the $(k,l)^{\text{th}}$ LC element, h_{att_i} denotes the attenuation loss, h_{α_i} represents turbulence-induced fading, and h_{m_i} models pointing errors. The term $\exp(AD)$ captures the LC-induced field-dependent gain, where A is the gain coefficient and D is the effective optical interaction depth, while ξ^{LC} denotes the LC transition coefficient.

The individual components of the composite channel are described in the following subsections.

7.2.3.1 Geometric Gain

The geometric gain for the $(k, l)^{\text{th}}$ LC element serving user i follows the OIRS channel model introduced in Chapter 2 and is expressed as [52]:

$$G_{ik,l}^{\text{LC}} = \begin{cases} \frac{\beta_{k,l}\eta(m+1)A_{PD}}{2\pi(d_{sr}+d_{rd}^i)^2} \cos^m(\Phi^s) \cos(\psi^s) \\ \quad \times \cos(\Phi_d) \cos(\psi_d) T(\psi) G(\psi), & 0 \leq \psi_d \leq \psi_{FoV}, \\ 0, & \text{otherwise,} \end{cases} \quad (7.3)$$

where $\beta_{k,l}$ denotes the reflection or transmission coefficient of the LC element, η is the LED electro-optical conversion efficiency, m is the Lambertian order, and A_{PD} is the photodetector area. The distances d_{sr} and d_{rd}^i represent the transmitter-to-IRS and IRS-to-user links, respectively. The angles Φ^s and ψ^s denote the irradiance and incidence angles at the transmitter-to-IRS link, while Φ_d and ψ_d represent the corresponding angles at the IRS-to-user link. The terms $T(\psi)$ and $G(\psi)$ denote the optical filter and concentrator gains, respectively, and ψ_{FoV} represents the receiver field-of-view (FoV).

7.2.3.2 Channel Impairments

(A) Underwater Attenuation: The underwater attenuation follows the Beer–Lambert law and is given by:

$$h_{att_i} = e^{-c(\lambda)(d_{sr}+d_{rd}^i)}, \quad (7.4)$$

where $c(\lambda)$ denotes the wavelength-dependent attenuation coefficient that captures absorption and scattering effects in the underwater medium.

(B) Oceanic Turbulence Fading: Oceanic turbulence arising from temperature and salinity variations is modeled using the mixture Exponential–Generalized Gamma (EGG) distribution [104], expressed as:

$$h_\alpha(\alpha) = \omega f(\alpha; \Lambda) + (1 - \omega) g(\alpha; [a, b, c]), \quad (7.5)$$

where $\omega \in (0, 1)$ is the mixture parameter, $f(\cdot)$ denotes the exponential component representing weak turbulence, and $g(\cdot)$ denotes the generalized gamma component capturing moderate-to-strong turbulence effects.

(C) Pointing Error: The pointing error due to misalignment between the optical beam and the receiver aperture is modeled using a Beta distribution given by [104]:

$$f_{h_{m_i}}(h_m) = \frac{\rho_i^2}{A_0^{\rho_i^2}} h_m^{\rho_i^2-1}, \quad 0 \leq h_m \leq A_0, \quad (7.6)$$

where A_0 represents the maximum collected optical power under perfect alignment and ρ_i denotes the pointing error coefficient.

7.2.3.3 LC Transition Characteristics

The LC transition coefficient is defined as [90, 97]:

$$\xi^{LC} = \begin{cases} T_{wc}(\psi^s)T_{cw}(\Phi_d), & \text{if LC operates in transmission mode,} \\ R_{wc}(\psi^s), & \text{if LC operates in reflection mode,} \end{cases} \quad (7.7)$$

where $T_{wc}(\psi^s)$ denotes the transmittance from water to LC at incidence angle ψ^s , $T_{cw}(\Phi_d)$ denotes the transmittance from LC to water at angle Φ_d , and $R_{wc}(\psi^s)$ represents the reflectance at the water–LC interface. These coefficients are obtained from Fresnel equations and depend on the incidence angle as well as the refractive-index contrast between water and the LC material. Consequently, in transmission mode, the optical signal propagates through both interfaces, whereas in reflection mode, it is reflected at the LC interface.

Unlike conventional MA OIRS architectures, where reflectivity remains largely independent of the incidence angle, the LC-OSTAR-IRS introduces an inherently geometry-dependent transition mechanism at the LC–water interface. As a result, system performance becomes strongly dependent on the incident angle and refractive-index contrast, which forms the central focus of the analysis in this chapter.

7.2.4 Multiple Access Schemes for UWOC

To evaluate the multi-user performance of the developed LC-OSTAR-IRS-assisted UWOC system, two advanced power-domain multiple access schemes are considered, namely non-orthogonal multiple access (NOMA) and rate-splitting multiple access (RSMA). These schemes enable simultaneous transmission to multiple users over the same time–frequency resources, thereby improving SE.

The effective channel gain H_i derived in the previous section directly determines the received signal-to-interference-plus-noise ratio (SINR) under both schemes. Unlike the optimization-driven framework in Chapter 6, where optimized power allocation (OPA) was employed, this chapter adopts a fixed power allocation strategy in order to isolate and analyze the impact of geometry-dependent channel variations introduced by the LC-OSTAR-IRS.

7.2.4.1 NOMA Scheme

In the NOMA-based LC-OSTAR-IRS-assisted UWOC system, users share identical resource blocks through power-domain multiplexing. Superposition coding is employed at the transmitter, while successive interference cancellation (SIC) is performed at the receiver.

The power allocation coefficient κ_i for the i^{th} user follows [90]:

$$\kappa_i = \begin{cases} \mu^{\text{NOMA}} (1 - \mu^{\text{NOMA}})^{i-1}, & 1 \leq i < N, \\ (1 - \mu^{\text{NOMA}})^{i-1}, & i = N, \end{cases} \quad (7.8)$$

where $\mu^{\text{NOMA}} \in (0.5, 1]$, and the normalization condition $\sum_{i=1}^N \kappa_i = 1$ ensures that the total transmit power is conserved.

The instantaneous electrical signal-to-noise ratio (SNR) for user i is defined as:

$$\gamma_i = \frac{\mathcal{R}^2 P_t^2 |H_i|^2}{\sigma_{n_i}^2}, \quad (7.9)$$

where $\mathcal{R}$ denotes the photodetector responsivity, P_t is the transmit optical power, and $\sigma_{n_i}^2$ represents the additive white Gaussian noise (AWGN) variance at the i^{th} user.

Assuming ideal SIC and perfect channel state information (CSI), the SINR of the i^{th} user is given by:

$$\gamma_i^{\text{NOMA}} = \frac{\kappa_i \gamma_i}{\gamma_i \sum_{j=1}^{i-1} \kappa_j + 1}. \quad (7.10)$$

This SINR expression reflects the hierarchical decoding structure of NOMA, where users with stronger channel gains successively cancel interference from weaker users. However, in practical underwater environments characterized by turbulence, pointing errors, and geometry-dependent channel variations, imperfect SIC may degrade system performance. Nevertheless, ideal SIC is assumed here to provide a baseline performance evaluation consistent with prior UWOC studies [41, 104].

7.2.4.2 RSMA Scheme

RSMA enhances interference management by splitting each user's message into common and private components, thereby enabling partial interference decoding and improved robustness.

The transmitted signal under RSMA is expressed as [18]:

$$x^{\text{RSMA}} = \sqrt{a_c P_t} x_c + \sum_{i=1}^N \sqrt{\kappa_i P_t} x_i, \quad (7.11)$$

where a_c denotes the power allocation for the common message, and κ_i represents the power allocation for the i^{th} private stream. In this work, the private message power allocation follows the same exponential structure adopted in NOMA for consistency, while satisfying $\sum_{i=1}^N \kappa_i = a_p$.

The SINR for decoding the common message at the i^{th} user is given by:

$$\gamma_i^{\text{RSMA}_C} = \frac{a_c \gamma_i}{1 + \gamma_i(1 - a_c)}, \quad (7.12)$$

while the SINR for decoding the private message is expressed as:

$$\gamma_i^{\text{RSMA}_P} = \frac{\kappa_i \gamma_i}{1 + \gamma_i \sum_{j=1, j \neq i}^N \kappa_j}. \quad (7.13)$$

Unlike NOMA, RSMA relaxes the strict decoding order imposed by SIC by enabling partial interference decoding through the common message. This property makes RSMA more robust to channel variations arising from underwater turbulence, pointing errors, and the geometry-dependent behavior of LC-OSTAR-IRS elements. Consequently, RSMA is expected to achieve improved ASE and enhanced user fairness in multi-user UWOC systems.

Practical Considerations and Experimental Validation: The performance analysis presented in this chapter assumes perfect instantaneous CSI at the centralized network controller for OSTAR-IRS configuration. In practical UWOC deployments, channel estimation errors, feedback latency, and residual SIC may degrade system performance. Therefore, the results presented herein should be interpreted as upper performance bounds under ideal CSI conditions. Robust resource allocation and adaptive algorithm design under imperfect CSI constitute important directions for future investigation.

Furthermore, the analysis in this chapter provides a geometry-driven analytical benchmark for the proposed LC-OSTAR-IRS architecture based on geometrical-optics principles, Fresnel reflection/refraction, and TIR. However, direct experimental validation using a fabricated LC-OSTAR-IRS prototype is beyond the scope of the present study. In a practical implementation, the angular reflection and transmission characteristics may be influenced by LC material properties, birefringence, polarization, interface imperfections, fabrication tolerances, and temperature-dependent variations. Experimental characterization of the LC element under controlled underwater conditions would therefore be valuable for quantifying the angular optical response, beam-steering accuracy, optical coupling efficiency, and voltage-dependent transition between reflection and transmission. Such measurements can subsequently be used to calibrate and validate the geometry-dependent analytical model developed in this chapter. Experimental

Table 7.1: Simulation Parameters

Parameter	Symbol	Value
Transmit power	P_t	0–45 dBm
Mirror reflectivity	R^m	0.9
Attenuation coefficient	$c(\lambda)$	0.056
Total OSTAR-IRS elements	n_m^2	36
Wavelength	λ	510 nm
Element length	l_m	8 cm
Element width	w_m	8 cm
Number of users	N	6
Lambertian order	m	2
PD area	A_{PD}	0.0314 m ²
Conversion efficiency	η	0.9
Responsivity	$\mathcal{R}$	1 A/W
Pointing parameter	ρ	1
Pointing coefficient	A_0	0.0032
Noise variance	$\sigma_{n_i}^2$	10 ⁻¹⁵
Tx coordinates	(x_s, y_s, z_s)	(0, 2 m, 0)
OSTAR-IRS coordinates	(x_{kl}, y_{kl}, z_{kl})	(2 m, 0, 15 m)
Scintillation index	σ_I^2	0.2178
EGG parameters	$\{\omega, \Lambda, a, b, c\}$	{0.1665, 0.1207, 0.1559, 1.5216, 22.8754}
Critical angle	$\theta_c \approx \sin^{-1}\left(\frac{1.10}{1.33}\right)$	$\approx 55.8^\circ$

prototype development and validation are therefore identified as important directions for future work.

7.3 Performance Analysis and Metrics

This section evaluates the performance of the LC-OSTAR-IRS-assisted UWOC system using two key metrics, namely ASE and Jain's fairness index. These metrics jointly characterize the system throughput and the distribution of user rates under geometry-dependent channel conditions.

7.3.1 Aggregate Spectral Efficiency (ASE)

ASE quantifies the total achievable data rate across all users per unit bandwidth.

For the NOMA scheme, the ASE is expressed as:

$$\text{ASE}^{\text{NOMA}} = \sum_{i=1}^N \log_2 \left(1 + \tau \gamma_i^{\text{NOMA}} \right), \quad (7.14)$$

where τ represents the modulation-dependent scaling factor and γ_i^{NOMA} denotes the SINR derived in the previous subsection.

For the RSMA scheme, the ASE is given by:

$$\text{ASE}^{\text{RSMA}} = R_c + \sum_{i=1}^N \log_2 \left(1 + \tau \gamma_i^{\text{RSMA}_P} \right), \quad (7.15)$$

where the common rate is defined as:

$$R_c = \min_i \log_2 \left(1 + \tau \gamma_i^{\text{RSMA}_C} \right). \quad (7.16)$$

The ASE explicitly depends on the composite channel gain H_i , which is strongly influenced by geometric parameters such as the incidence angle and the transmitter vertical distance. Consequently, variations in spatial configuration directly impact the achievable SE of the LC-OSTAR-IRS-assisted system.

In particular, when the incidence angle satisfies the TIR condition, the reflective efficiency of LC elements increases, resulting in enhanced effective channel gain and higher ASE. In contrast, when the incidence angle falls below the critical angle, partial refraction reduces the reflected power, leading to a degradation in spectral performance.

7.3.2 Fairness Index

User fairness is quantified using Jain's fairness index [104], defined as:

$$J = \frac{\left(\sum_{i=1}^N \overline{SE}_i \right)^2}{N \sum_{i=1}^N \overline{SE}_i^2}, \quad (7.17)$$

where $\overline{SE}_i = \mathbb{E} [\log_2(1 + \tau \gamma_i)]$ denotes the average SE of the i^{th} user and N represents the total number of users.

The fairness index satisfies:

$$\frac{1}{N} \leq J \leq 1,$$

where $J = 1$ indicates perfect fairness among users.

In LC-OSTAR-IRS-assisted UWOC systems, fairness is influenced not only by power allocation but also by geometry-dependent channel variations. Users located in regions satisfying TIR conditions experience stronger effective channel gains, which may lead to rate imbalance compared to users outside the TIR region.

RSMA mitigates this imbalance through its common message decoding mechanism, which ensures a baseline rate for all users, including those experiencing weaker channel conditions.

As a result, RSMA achieves improved fairness compared to NOMA, particularly in scenarios with significant geometric disparities.

7.4 Numerical Results

This section evaluates the LC-OSTAR-IRS against the hybrid OSTAR-IRS (H-OSTAR-IRS) benchmark under ideal CSI and perfect SIC assumptions.

The H-OSTAR-IRS employs mirror elements (with reflectivity $R^{OIRS} = 0.9$) for reflection toward Cluster 1 and LC elements ($\eta_{LC} = 1.5$) for transmission toward Cluster 2. This configuration represents a performance upper bound for hybrid architectures under perfect alignment. Simulation parameters are summarized in Table 7.1.

7.4.1 Aggregate Spectral Efficiency (ASE) versus Transmit Power

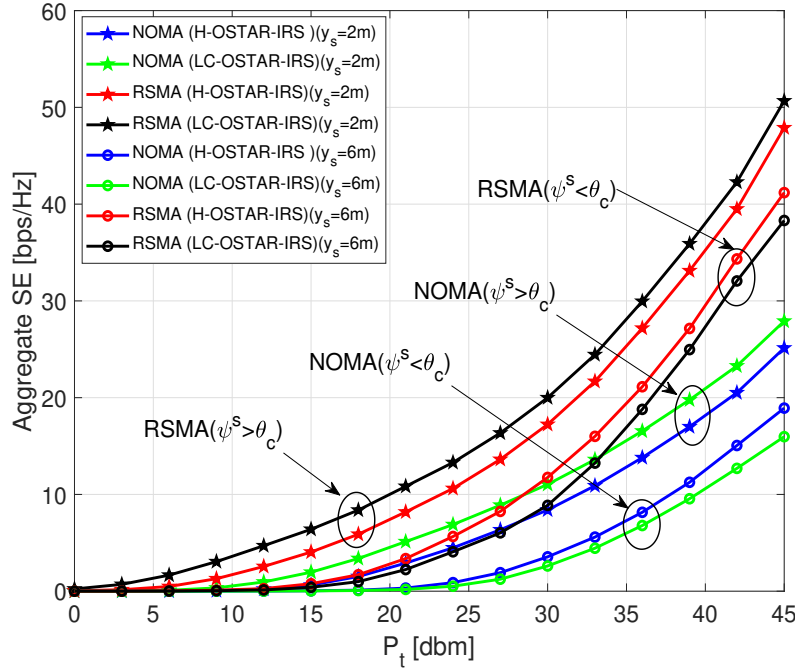


Figure 7.3: ASE vs. transmit power for different OSTAR-IRS assisted UWOC systems.

Fig. 7.3 illustrates the ASE as a function of transmit power P_t for $N = 6$ users under two geometric configurations.

When the transmitter vertical position is set to $y_s = 2$ m, the incidence angle at the LC-OSTAR-IRS satisfies $\psi^s > \theta_c$, thereby fulfilling the TIR condition. Under this configuration, LC

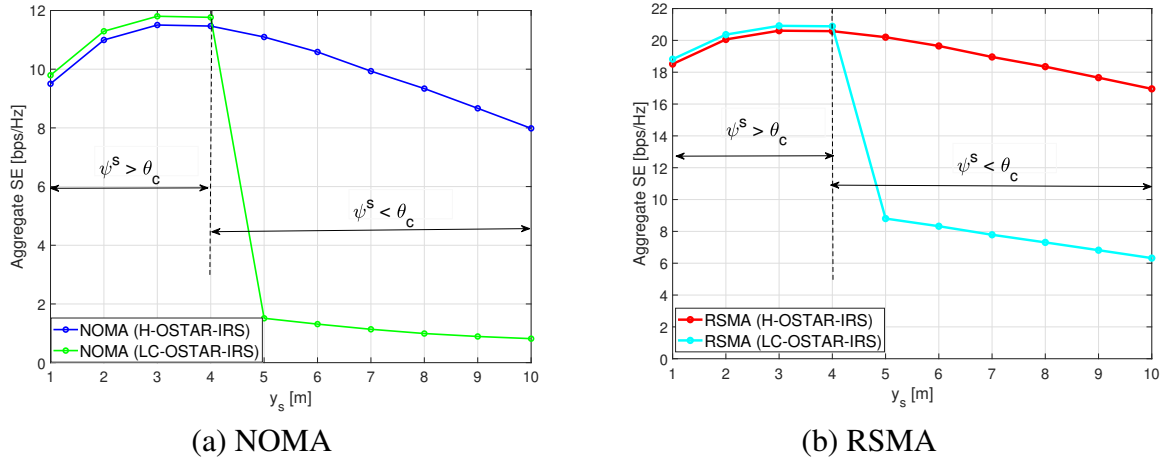


Figure 7.4: ASE vs. vertical distance (y_s) for different OSTAR-IRS assisted UWOC systems under (a) NOMA and (b) RSMA schemes.

elements operating in reflective mode exhibit high reflection efficiency, resulting in enhanced effective channel gains.

In this TIR-dominant regime, LC-OSTAR-IRS combined with RSMA achieves the highest ASE, outperforming both its NOMA counterpart and the H-OSTAR-IRS benchmark. This performance improvement arises from two complementary factors:

- Efficient light steering due to TIR-enabled reflection,
- Superior interference management provided by RSMA.

Conversely, when the transmitter height increases to $y_s = 6$ m, the incidence angle becomes $\psi^s < \theta_c$, and the TIR condition is no longer satisfied. In this region, reflection efficiency of LC elements decreases because a significant portion of optical power undergoes refraction instead of reflection.

As a result, H-OSTAR-IRS exhibits higher ASE under both NOMA and RSMA schemes in this configuration. This performance crossover highlights a key geometric design insight:

LC-OSTAR-IRS achieves maximum performance when deployed in configurations where the incidence angle exceeds the critical angle required for TIR.

7.4.2 ASE versus Vertical Distance

Fig. 7.4(a) and Fig. 7.4(b) present ASE as a function of the transmitter vertical distance y_s for NOMA and RSMA, respectively.

The ASE of LC-OSTAR-IRS peaks in the region $y_s \leq 4$ m, where $\psi^s > \theta_c$. In this region, LC elements configured as reflectors leverage TIR to redirect optical power efficiently toward users in Cluster 1.

As y_s increases beyond 4 m, the incidence angle decreases below the critical angle. Consequently, reflective LC elements suffer reduced efficiency due to partial refraction. This results in a noticeable ASE degradation.

Importantly, under the mode switching (MS) protocol, refracted optical power does not contribute to Cluster 2 users when the LC element is configured for reflection. Therefore, power leakage due to sub-critical incidence angles leads directly to SE loss.

In contrast, H-OSTAR-IRS exhibits a more gradual ASE decline, as its mirror elements maintain angle-independent reflectivity. The performance degradation in H-OSTAR-IRS is primarily governed by path loss rather than angular sensitivity.

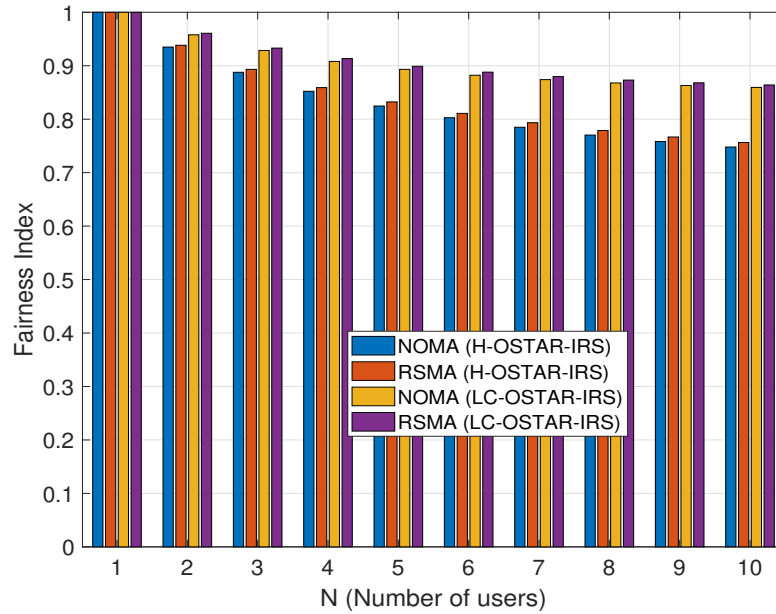


Figure 7.5: Fairness index vs. number of users (N) for different OSTAR-IRS assisted UWOC systems.

7.4.3 Fairness versus Number of Users

Fig. 7.5 shows Jain's fairness index as a function of the number of users N for $y_s = 2$ m (TIR condition satisfied).

For $N = 1$, all schemes achieve perfect fairness ($J = 1$). As the number of users increases, fairness gradually decreases due to increased interference and unequal power allocation.

RSMA combined with LC-OSTAR-IRS maintains superior fairness compared to NOMA. This improvement arises from the message-splitting mechanism of RSMA, which guarantees a baseline rate to users with weaker channels through common message decoding.

The fairness advantage of RSMA becomes particularly evident under turbulence and geometry-sensitive channel variations. While NOMA relies heavily on accurate channel ordering for efficient SIC, RSMA reduces strict decoding hierarchy, making it more robust to channel disparities induced by angular-dependent LC behavior.

These results confirm that LC-OSTAR-IRS combined with RSMA provides a favorable balance between SE and fairness under optimal geometric deployment.

7.5 Conclusion

This chapter presented a geometry-driven analytical framework for LC-OSTAR-IRS-assisted multi-user UWOC systems. By exploiting the refractive-index contrast between water and LC elements, the proposed LC-OSTAR-IRS enables dynamic switching between reflective and transmissive modes within a single reconfigurable element, thereby supporting dual-region coverage.

A detailed system and channel model incorporating geometric gain, underwater attenuation, oceanic turbulence, pointing errors, and LC transition characteristics was developed. Unlike conventional MA architectures, the reflection efficiency of LC elements was shown to depend explicitly on the incidence angle at the water–LC interface. In particular, the TIR condition plays a decisive role in determining spectral performance.

Numerical results demonstrated that when the incidence angle exceeds the critical angle, LC-OSTAR-IRS achieves superior ASE compared to the H-OSTAR-IRS benchmark. However, when the geometric configuration violates the TIR condition, performance degradation occurs due to refraction-induced power leakage. This establishes an important deployment guideline: LC-OSTAR-IRS provides maximum performance benefits when operated under geometric configurations satisfying TIR.

Furthermore, integration with RSMA consistently achieved higher SE and improved fairness compared to NOMA, particularly in turbulence-prone and geometry-sensitive scenarios.

Overall, this chapter demonstrates that LC-OSTAR-IRS is not merely a hardware alternative to H-OSTAR architectures but introduces a fundamentally geometry-dependent communication paradigm. Unlike MA systems whose reflectivity remains largely invariant with respect to incidence angle, the performance of LC-based elements is strongly governed by refractive-index contrast and TIR conditions.

These findings highlight that the effectiveness of LC-OSTAR-IRS deployments is intrinsically linked to geometric configuration and incidence-angle management. Consequently, geometry-aware placement and adaptive LC control emerge as key design considerations for future UWOC networks. The insights developed in this chapter provide an important foundation for the design of next-generation intelligent optical surfaces capable of supporting reliable and high-capacity underwater 6G communication systems.

While the analytical framework developed in this chapter provides valuable insights into the geometry-driven performance of LC-OSTAR-IRS-assisted UWOC systems, experimental validation using a fabricated prototype remains an important direction for future research. Such experimental studies would enable direct measurement and calibration of the angular optical response, beam-steering accuracy, and voltage-dependent LC behavior, thereby bridging the gap between theoretical modeling and practical deployment.

Conclusion and Future Research Directions

8.1 Summary of the Dissertation

This dissertation has developed unified analytical models and optimization methodologies for intelligent reflecting surface (IRS) and optical intelligent reflecting surface (OIRS) assisted underwater wireless optical communication (UWOC) systems under realistic channel impairments. The work systematically progressed from hybrid radio frequency (RF)–UWOC architectures to fully optical intelligent surface–enabled underwater networks.

First, a hybrid RF–UWOC system incorporating a programmable RF-based IRS in the terrestrial link was investigated. Closed-form expressions for spectral efficiency (SE), energy efficiency (EE), outage probability (OP), and bit error rate (BER) were derived. Comparative analysis demonstrated that IRS-assisted transmission enhances end-to-end performance compared to conventional decode-and-forward relaying while maintaining superior EE.

Subsequently, the focus transitioned to submerged mirror-array (MA)-based OIRS architectures for direct enhancement of underwater optical links. A comprehensive channel model incorporating absorption–scattering effects, Exponential-Generalized Gamma (EGG) turbulence, and pointing errors was developed. Analytical expressions for SE, EE, OP, and BER were derived under non-line-of-sight (NLoS) conditions. The results demonstrated that MA-based OIRS significantly outperforms planar mirror surfaces (PMS) and total internal reflection (TIR)-based conventional techniques, particularly in deep-sea deployments.

The dissertation further extended MA-based OIRS systems to multi-user environments. Two intelligent mirror allocation strategies, namely equal mirror assignment (EMA) and distance-based mirror assignment (DMA), were proposed to enhance fairness and maximize aggregate

spectral efficiency (ASE). Integration with orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA), and rate-splitting multiple access (RSMA) schemes revealed that DMA-based allocation combined with RSMA provides improved robustness under severe turbulence and depth-dependent attenuation.

Advanced optical surface architectures were then introduced. The optical simultaneously transmitting and reflecting IRS (OSTAR-IRS) enabled concurrent reflection and transmission for serving spatially separated user clusters. A joint transmission–reflection coefficient optimization framework was formulated under energy splitting (ES) and mode switching (MS) operations. The resulting non-convex optimization problems were solved using constrained nonlinear programming and mixed-integer linear programming (MILP) techniques. Complexity–performance trade-offs were rigorously analyzed.

Finally, a liquid-crystal-based OSTAR-IRS (LC-OSTAR-IRS) architecture was proposed to enable tunable refractive-index control and dynamic beam steering in underwater environments. Two complementary analytical perspectives were developed: (i) optimization-driven performance analysis and (ii) geometry-driven modeling incorporating Fresnel reflection, refraction, and TIR conditions. The results establish important deployment guidelines, demonstrating that LC-OSTAR-IRS achieves superior SE and fairness when operated under TIR-satisfying geometric configurations.

Overall, this dissertation establishes RF-based IRS, MA-based OIRS, intelligent mirror allocation strategies, OSTAR-IRS optimization methodologies, and LC-OSTAR-IRS architectures as promising and energy-efficient technologies for enabling reliable and high-capacity underwater communication in future 6G-integrated ocean networks.

While the proposed architectures and analytical models provide significant insights into IRS-assisted UWOC systems, several open challenges and research opportunities remain for advancing intelligent underwater communication technologies.

8.2 Key Contributions of the Dissertation

The principal contributions of this dissertation can be summarized as follows:

- Development of a unified analytical framework for IRS-assisted hybrid RF–UWOC systems, including closed-form performance expressions for SE, EE, OP, and BER under realistic channel impairments.
- Design and performance analysis of submerged MA-OIRS for NLoS UWOC, incorporating absorption–scattering effects, oceanic turbulence, and pointing errors.

- Proposal of intelligent mirror allocation strategies, namely EMA and DMA, for multi-user MA-OIRS-assisted UWOC systems, enabling improved fairness and ASE.
- Development of an OSTAR-IRS architecture with joint transmission–reflection coefficient optimization under ES and MS protocols.
- Introduction of a LC-OSTAR-IRS architecture enabling refractive-index-controlled beam steering and dynamic optical surface reconfiguration for underwater environments.
- Establishment of geometry-driven performance analysis for LC-OSTAR-IRS systems, demonstrating the critical role of TIR conditions in determining SE and fairness performance.

8.3 Future Research Directions

While this dissertation provides comprehensive analytical and optimization frameworks for IRS and OIRS-assisted UWOC systems, several promising research directions remain open.

- **Robust Optimization under Imperfect CSI:** The optimization frameworks developed in this dissertation primarily consider the availability of channel state information (CSI) at the network controller. In practical UWOC systems, however, CSI acquisition can be affected by channel-estimation errors, feedback delay, and channel uncertainty. Future research will therefore investigate robust resource-allocation and beam/mirror-control strategies under imperfect CSI. The impact of CSI uncertainty on power allocation, mirror orientation, transmission and reflection coefficients, and achievable SE will be analyzed.
- **Prism-Based IRS for UWOC:** A promising future direction is the development of prism-based intelligent reflecting surfaces (Prism-IRS) for UWOC. Unlike MA or LC-based surfaces, Prism-IRS architectures can exploit controlled geometric refraction and angular beam shaping to achieve enhanced spatial coverage and reduced power leakage. Future work will focus on deriving analytical channel models that incorporate prism-induced beam steering under underwater turbulence and attenuation constraints.
- **Energy Efficiency (EE) Optimization for UWOC Systems:** Although SE has been extensively analyzed, a comprehensive EE framework for OIRS and LC-OSTAR-IRS-assisted UWOC systems remains an open challenge. Future research will investigate joint optimization of optical transmit power, mirror orientation, LC-state control, and multiple access parameters to maximize EE under practical power consumption models.

The trade-off between optical power efficiency, ASE performance, and achievable rate will be rigorously characterized.

- **Hybrid Acoustic–Optical Underwater Communication:** A fundamental limitation of UWOC systems is restricted communication range due to severe absorption and scattering. To overcome this constraint, future research will explore hybrid acoustic–optical architectures in which long-range acoustic links provide reliability and control signaling, while short-range optical links deliver ultra-high data rates. Joint resource allocation, adaptive mode switching, and cross-layer optimization for hybrid underwater networks will be investigated.
- **Integrated Active–Passive Relaying Frameworks:** The combination of active full-duplex relaying and passive intelligent reflecting surfaces presents an opportunity to exploit both amplification and intelligent beam steering. Future work will analyze joint active–passive underwater relaying architectures under realistic hardware impairments and oceanic channel dynamics.
- **Experimental Validation and Prototype Development:** Translating the proposed OIRS and LC-OSTAR-IRS frameworks into experimental prototypes constitutes an important next step. Hardware validation under controlled water tank environments and field deployment studies will bridge the gap between theoretical modeling and practical realization.

Overall, this dissertation provides a comprehensive foundation for the design and analysis of intelligent surface-assisted UWOC systems and paves the way for next-generation 6G-enabled underwater communication networks.

Author's Publications

Journals (Published)

1. **R. Salam**, A. Srivastava, V. A. Bohara and A. Ashok, "An Optical Intelligent Reflecting Surface-Assisted Underwater Wireless Communication System," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 1774-1786, 2023.
2. **R. Salam**, V. A. Bohara and A. Srivastava, "Smart Element Allocation Strategies for Dynamic Optical IRS in Underwater Wireless Communication," *IEEE Transactions on Vehicular Technology*, vol. 74, no. 3, pp. 4349-4361, March 2025.
3. **R. Salam** and V. A. Bohara, "LC-OSTAR-IRS: Tunable Liquid Crystal Surfaces for High-Performance UWOC," *IEEE Wireless Communications Letters*, vol. 15, pp. 1305-1309, 2026.
4. **R. Salam**, V. A. Bohara, and A. Srivastava, "Optical Multi-STAR-IRS Assisted Underwater Wireless Communication System," *IEEE Transactions on Green Communications and Networking*, vol. 10, pp. 3312–3323, 2026.

Journals (Under Review)

1. K. Joshi, **R. Salam**, and V. A. Bohara, "Experimental Validation for a Circular Optical Reflective Intelligent Surface Aided Indoor Visible Light Communication," under review in *IEEE Wireless Communications Letters*, 2026.
2. **R. Salam** and V. A. Bohara, "OSTAR-IRS Assisted Underwater Wireless Optical Communication Systems: NOMA, RSMA, and Duplexing Perspectives," under review in *IEEE Wireless Communications Magazine*, 2026.
3. **R. Salam** and V. A. Bohara, "Adaptive LC-Assisted Hybrid Prism–Metasurface OSTAR-IRS for Underwater Wireless Optical Communication," under review in *IEEE Transactions on Wireless Communications*, 2026.

Conferences

1. **R. Salam**, A. Srivastava, V. A. Bohara, and A. Ashok, "Performance Comparison of IRS and DF Relay Assisted Mixed RF–Underwater Optical Communication System," *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, Gandhinagar, India, 2022, pp. 129-134.
2. **R. Salam**, A. Srivastava, V. A. Bohara and A. Ashok, "Dynamic Element Allocation for Optical IRS-Assisted Underwater Wireless Communication System," *IEEE Global Communications Conference (GLOBECOM)*, Kuala Lumpur, Malaysia, 2023, pp. 4692-4697.
3. **R. Salam**, V. A. Bohara, and K. Joshi, "Circular Optical Intelligent Reflecting Surface Assisted Underwater Wireless Communication System," *IEEE Future Networks World Forum (FNWF)*, Bangalore, India, 2025, pp. 1-6.
4. **R. Salam** and V. A. Bohara, "Footprint-Aware OIRS Design for Enhanced NLoS UWOC Systems," under review in *IEEE ANTS*, 2026.
5. **R. Salam** and V. A. Bohara, "LC-Prism-OSTAR-IRS for UWOC: Beam Steering with RSMA-Based Multi-User Communication," under review in *IEEE GLOBECOM Workshops*, 2026.

Patents

1. **R. Salam**, K. Joshi and V. A. Bohara, “Circular Optical Intelligent Reflective Surface (C-OIRS): Apparatus and System Thereof,” Indian Patent Application No. 202411100855, Application Date: 19/12/2024.
2. **R. Salam** and V. A. Bohara, “Liquid-Crystal-Based OSTAR-IRS Assisted Underwater Wireless Optical Communication System and Method Thereof,” Indian Patent Application No. 202511100371, Application Date: 16/10/2025.
3. **R. Salam** and V. A. Bohara, “Hexagonal Optical Intelligent Reflecting Surface with Circular Grid Pattern for Non-Line-of Sight Optical Wireless Communication,” Indian Patent Application No. 202611028169, Application Date: 10/03/2026.
4. **R. Salam** and V. A. Bohara, “A Prism-based Optical Simultaneously Transmitting and Reflecting Intelligent Reflecting Surface for Underwater Wireless Optical Communication Systems,” Indian Patent Application No. 202611055545, Application Date: 30/04/2026.

References

- [1] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, “Underwater optical wireless communications, networking, and localization: A survey,” *Ad Hoc Networks*, vol. 94, p. 101935, 2019.
- [2] W. Long, R. Chen, M. Moretti, W. Zhang, and J. Li, “A promising technology for 6G wireless networks: Intelligent reflecting surface,” *Journal of Communications and Information Networks*, vol. 6, no. 1, pp. 1–16, 2021.
- [3] E. M. Sozer, M. Stojanovic, and J. G. Proakis, “Underwater acoustic networks,” *IEEE Journal of Oceanic Engineering*, vol. 25, no. 1, pp. 72–83, Jan 2000.
- [4] D. Pompili, T. Melodia, and I. F. Akyildiz, “Three-dimensional and two-dimensional deployment analysis for underwater acoustic sensor networks,” *Ad Hoc Networks*, vol. 7, no. 4, pp. 778–790, 2009.
- [5] H. Kaushal and G. Kaddoum, “Underwater optical wireless communication,” *IEEE Access*, vol. 4, pp. 1518–1547, 2016.
- [6] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, “A survey of underwater optical wireless communications,” *IEEE Communications Surveys and Tutorials*, vol. 19, no. 1, pp. 204–238, 2017.
- [7] S. Q. Duntley, “Light in the sea,” *Journal of the Optical Society of America*, vol. 53, pp. 214–233, 1963.
- [8] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, “A survey of underwater optical wireless communications,” *IEEE Communications Surveys and Tutorials*, vol. 19, no. 1, pp. 204–238, 2016.
- [9] V. Jamali, R. Schober *et al.*, “Intelligent reflecting surface-aided wireless communications: A tutorial,” *IEEE Communications Surveys and Tutorials*, vol. 23, no. 3, pp. 1643–1692, 2021.
- [10] V. Jamali, H. Ajam, M. Najafi, B. Schmauss, R. Schober, and H. V. Poor, “Intelligent reflecting surface assisted free-space optical communications,” *IEEE Communications Magazine*, vol. 59, no. 10, pp. 57–63, 2021.

- [11] E. Basar, M. Di Renzo, J. de Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116 753–116 773, 2019.
- [12] S. Li, L. Yang, D. B. da Costa, M. Di Renzo, and M.-S. Alouini, "On the performance of RIS-assisted dual-hop mixed RF-UWOC systems," *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 2, pp. 340–353, 2021.
- [13] S. Aboagye, A. R. Ndjiongue, T. Ngatched, O. Dobre, and H. V. Poor, "RIS-assisted visible light communication systems: A Tutorial," *arXiv preprint arXiv:2204.07198*, 2022.
- [14] M. D. Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, H. Gacanin *et al.*, "Smart radio environments empowered by reconfigurable AI Meta-surfaces: An Idea whose time has come," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, pp. 1–20, 2019.
- [15] Y. Li *et al.*, "Hybrid rf and underwater wireless optical communication systems: A survey," *IEEE Communications Surveys & Tutorials*, 2021.
- [16] S. Arnon and D. Kedar, "Non-line-of-sight underwater optical wireless communication network," *J. Opt. Soc. Amer. A, Opt. Image Sci.*, vol. 26, no. 3, pp. 530–539, 2009.
- [17] S. Tang, Y. Dong, and X. Zhang, "On path loss of NLOS underwater wireless optical communication links," in *2013 MTS/IEEE OCEANS-Bergen*. IEEE, 2013, pp. 1–3.
- [18] B. Clerckx, Y. Mao, E. A. Jorswieck, J. Yuan, D. J. Love, E. Erkip, and D. Niyato, "A primer on rate-splitting multiple access: Tutorial, myths, and frequently asked questions," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 5, pp. 1265–1308, 2023.
- [19] M. Elamassie, L. Bariah, M. Uysal, S. Muhaidat, and P. C. Sofotasios, "Capacity analysis of noma-enabled underwater vlc networks," *IEEE Access*, vol. 9, pp. 153 305–153 315, 2021.
- [20] M. Jain, N. Sharma, A. Gupta, D. Rawal, and P. Garg, "Performance analysis of NOMA assisted underwater visible light communication system," *IEEE Wireless Communications Letters*, vol. 9, no. 8, pp. 1291–1294, 2020.
- [21] F. Xing, S. He, Y. Yue, and H. Yin, "Ergodic rate characterization for rate-splitting multiple access based underwater wireless optical communications," in *2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring)*. IEEE, 2022, pp. 1–7.
- [22] Z. Rahman, I. Romdhane, and G. Kaddoum, "Performance of RSMA-based UOWC systems over oceanic turbulence channel with pointing errors," *IEEE Open Journal of the Communications Society*, 2023.
- [23] X. Mu, Y. Liu, L. Guo, J. Lin, and R. Schober, "Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications," *IEEE Transactions on Wireless Communications*, vol. 21, no. 5, pp. 3083–3098, 2022.

- [24] R. P. Naik, M. Salman, J. Bolboli, S. Shetty, and W.-Y. Chung, "Multiuser data transmission aided by simultaneous transmit and reflect reconfigurable intelligent surface in underwater wireless optical communications," *IEEE Transactions on Vehicular Technology*, 2024.
- [25] M. Jain, N. Sharma, A. Gupta, D. Rawal, and P. Garg, "NOMA assisted underwater visible light communication system with full-duplex cooperative relaying," *Vehicular Communications*, vol. 31, p. 100359, 2021.
- [26] S. Al-Zhrani, N. M. Bedaiwi, I. F. El-Ramli, A. Z. Barasheed, A. Abduldaiem, Y. Al-Hadeethi, and A. Umar, "Underwater optical communications: A brief overview and recent developments," *Engineered Science*, vol. 16, pp. 146–186, 2021.
- [27] X. Sun, C. H. Kang, M. Kong, O. Alkhazragi, Y. Guo, M. Ouhssain, Y. Weng, B. H. Jones, T. K. Ng, and B. S. Ooi, "A review on practical considerations and solutions in underwater wireless optical communication," *Journal of Lightwave Technology*, vol. 38, no. 2, pp. 421–431, Jan. 2020.
- [28] M. A. Khalighi, C. Gabriel, T. Hamza, S. Bourennane, P. Léon, and V. Rigaud, "Underwater wireless optical communication: Recent advances and remaining challenges," in *Proceedings of the IEEE International Conference on Transparent Optical Networks (ICTON)*, Graz, Austria, Jul. 2014, pp. 1–4, invited Paper.
- [29] P. K. Sajmath, R. V. Ravi, and K. A. Majeed, "Underwater wireless optical communication systems: A survey," in *2020 7th International Conference on Smart Structures and Systems (ICSSS)*, 2020, pp. 1–7.
- [30] C. D. Mobley, *Light and Water: Radiative Transfer in Natural Waters*. Academic Press, 1994.
- [31] C. Gabriel, M. A. Khalighi, S. Bourennane, P. Léon, and V. Rigaud, "Monte-carlo-based channel characterization for underwater optical communication systems," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 5, no. 1, pp. 1–12, Jan. 2013.
- [32] E. Zedini, H. M. Oubei, A. Kammoun, M. Hamdi, B. S. Ooi, and M.-S. Alouini, "Unified statistical channel model for turbulence-induced fading in underwater wireless optical communication systems," *IEEE Trans. Commun.*, vol. 67, no. 4, pp. 2893–2907, 2019.
- [33] M. V. Jamali, A. Mirani, A. Parsay, B. Abolhassani, P. Nabavi, A. Chizari, P. Khorramshahi, S. Abdollahramezani, and J. A. Salehi, "Statistical studies of fading in underwater wireless optical channels in the presence of air bubbles, temperature, and salinity random variations," *IEEE Transactions on Communications*, vol. 66, no. 10, pp. 4706–4723, Oct. 2018.
- [34] M. Elamassie and M. Uysal, "Vertical underwater visible light communication links: Channel modeling and performance analysis," *IEEE Transactions on Communications*, vol. 68, no. 10, pp. 6948–6959, Oct. 2020.
- [35] W. Liu, W. Jiang, N. Huang, and Z. Xu, "Experimental investigation of underwater optical wireless communication for correlated simo channel under temperature-induced turbulence," *IEEE Photonics Journal*, vol. 15, no. 4, pp. 1–7, 2023.

- [36] C. Gabriel, M. A. Khalighi, S. Bourennane, P. Léon, and V. Rigaud, "Misalignment considerations on point-to-point underwater wireless optical links," in *Proceedings of the IEEE OCEANS Conference*, Bergen, Norway, Jun. 2013, pp. 1–5.
- [37] A. S. Ghazy, S. Hranilovic, and M. A. Khalighi, "Angular mimo for underwater wireless optical communications: Link modelling and tracking," *IEEE Journal of Oceanic Engineering*, vol. 46, no. 4, pp. 1391–1407, Oct. 2021.
- [38] I. C. Ijeh, M. A. Khalighi, M. Elamassie, S. Hranilovic, and M. Uysal, "Outage probability analysis of a vertical underwater wireless optical link subject to oceanic turbulence and pointing errors," *Journal of Optical Communications and Networking*, vol. 14, no. 6, pp. 439–453, Jun. 2022.
- [39] R. P. Naik and W.-Y. Chung, "Evaluation of reconfigurable intelligent surface-assisted underwater wireless optical communication system," *Journal of Lightwave Technology*, vol. 40, no. 13, pp. 4257–4267, 2022.
- [40] Y. Ata, H. Abumarshoud, L. Bariah, S. Muhaidat, and M. A. Imran, "Intelligent reflecting surfaces for underwater visible light communications," *IEEE Photonics Journal*, vol. 15, no. 1, pp. 1–10, 2023.
- [41] R. Salam, A. Srivastava, V. A. Bohara, and A. Ashok, "Dynamic element allocation for optical irs-assisted underwater wireless communication system," in *GLOBECOM 2023-2023 IEEE Global Communications Conference*. IEEE, 2023, pp. 4692–4697.
- [42] D. Anguita, D. Brizzolara, and G. Parodi, "Building an underwater wireless optical communication link: A monte carlo simulation based approach," *IEEE Journal of Oceanic Engineering*, vol. 34, no. 4, pp. 547–560, Oct. 2009.
- [43] E. Zedini, H. M. Oubei, A. Kammoun, M.-S. Hamdi, B. S. Ooi, and M.-S. Alouini, "Unified statistical channel model for turbulence-induced fading in underwater wireless optical communication systems," *IEEE Transactions on Communications*, vol. 67, no. 4, pp. 2893–2907, Apr. 2019.
- [44] H. Zhang and Y. Dong, "General stochastic channel model and performance evaluation for underwater wireless optical links," *IEEE Transactions on Wireless Communications*, vol. 15, no. 2, pp. 1162–1173, Feb. 2016.
- [45] S. Yildiz, İ. Bağlica, B. Kebapçı, M. Elamassie, and M. Uysal, "Reflector-aided underwater optical channel modeling," *Optics Letters*, vol. 47, no. 20, pp. 5321–5324, 2022.
- [46] L. Yang, Q. Zhu, S. Li, I. S. Ansari, and S. Yu, "On the performance of mixed FSO-UWOC dual-hop transmission systems," *IEEE Wireless Communications Letters*, vol. 10, no. 9, pp. 2041–2045, 2021.
- [47] S. Li, L. Yang, D. B. d. Costa, M. D. Renzo, and M.-S. Alouini, "On the performance of RIS-assisted dual-hop mixed RF-UWOC systems," *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 2, pp. 340–353, 2021.

- [48] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A Tutorial," *IEEE Transactions on Communications*, vol. 69, no. 5, pp. 3313–3351, 2021.
- [49] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6G wireless networks: Vision, requirements, architecture, and key technologies," *IEEE vehicular technology magazine*, vol. 14, no. 3, pp. 28–41, 2019.
- [50] S. Dang, O. Amin, B. Shihada, and M.-S. Alouini, "What should 6G be?" *Nature Electronics*, vol. 3, no. 1, pp. 20–29, 2020.
- [51] E. Björnson, Ö. Özdogan, and E. G. Larsson, "Intelligent reflecting surface versus decode-and-forward: How large surfaces are needed to beat relaying?" *IEEE Wireless Communications Letters*, vol. 9, no. 2, pp. 244–248, 2019.
- [52] A. M. A. Abdelhady, A. S. Salem, O. Amin, B. Shihada, and M.-S. Alouini, "Visible light communications via intelligent reflecting surfaces: Metasurfaces vs mirror arrays," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1–20, 2021.
- [53] V. Jamali, H. Ajam, M. Najafi, B. Schmauss, R. Schober, and H. V. Poor, "Intelligent reflecting surface assisted free-space optical communications," *IEEE Communications Magazine*, vol. 59, no. 10, pp. 57–63, 2021.
- [54] S. Aboagye, T. M. N. Ngatched, O. A. Dobre, and A. R. Ndjiongue, "Intelligent reflecting surface-aided indoor visible light communication systems," *IEEE Communications Letters*, vol. 25, no. 12, pp. 3913–3917, 2021.
- [55] A. M. Abdelhady, A. K. S. Salem, O. Amin, B. Shihada, and M.-S. Alouini, "Visible light communications via intelligent reflecting surfaces: Metasurfaces vs Mirror arrays," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1–20, 2021.
- [56] T. G. Waduge, Y. Yang, and B.-C. Seet, "A review of reconfigurable intelligent surfaces in underwater wireless communication: Challenges and future directions," *Journal of Sensor and Actuator Networks*, vol. 14, no. 5, p. 97, 2025.
- [57] X.-H. Huang, C.-Y. Li, H.-H. Lu, C.-W. Su, Y.-R. Wu, Z.-H. Wang, and Y.-N. Chen, "6-m/10-gbps underwater wireless red-light laser transmission system," *Optical Engineering*, vol. 57, no. 6, p. 066110, 2018.
- [58] S. A. H. Mohsan, A. Mazinani, N. Q. H. Othman, and H. Amjad, "Towards the internet of underwater things: A comprehensive survey," *Earth Science Informatics*, pp. 1–30, 2022.
- [59] S. Kisseleff, S. Chatzinotas, and B. Ottersten, "Reconfigurable intelligent surfaces in challenging environments: Underwater, underground, industrial and disaster," *IEEE Access*, vol. 9, pp. 150 214–150 233, 2021.
- [60] H. Jiang, H. Qiu, N. He, W. Popoola, Z. Ahmad, and S. Rajbhandari, "Performance of spatial diversity dco-ofdm in a weak turbulence underwater visible light communication channel," *Journal of Lightwave Technology*, vol. 38, no. 8, pp. 2271–2277, 2020.

- [61] Z. Zeng, "A survey of underwater wireless optical communication," Ph.D. dissertation, University of British Columbia, 2015.
- [62] L. J. Johnson, F. Jasman, R. J. Green, and M. S. Leeson, "Recent advances in underwater optical wireless communications," *Underwater Technology*, vol. 32, no. 3, pp. 167–175, 2014.
- [63] F. Miramirkhani and M. Uysal, "Visible light communication channel modeling for underwater environments with blocking and shadowing," *IEEE Access*, vol. 6, pp. 1082–1090, 2017.
- [64] N. Anous, M. Abdallah, M. Uysal, and K. Qaraqe, "Performance evaluation of LOS and NLOS vertical inhomogeneous links in underwater visible light communications," *IEEE Access*, vol. 6, pp. 22 408–22 420, 2018.
- [65] I. C. Ijeh, M. A. Khalighi, and S. Hranilovic, "Parameter optimization for an underwater optical wireless vertical link subject to link misalignments," *IEEE Journal of Oceanic Engineering*, vol. 46, no. 4, pp. 1424–1437, 2021.
- [66] M. W. Eltokhey, M. S. Bashir, O. I. Younus, Z. Ghassemloooy, H. Haas, G. K. Karagianidis, S. R. Teli, S. Zvanovec, M.-A. Khalighi, Z. C. Zhang, S. Hranilovic, M. Brandt-Pearce, J.-P. Linnartz, A. Trichili, H. Chun, D. O'Brien, M. Uysal, J. Song, M. Yuksel, H. Elgala, Z. Xu, N. Chi, T. Yamazato, C.-W. Chow, B. S. Ooi, and M.-S. Alouini, "Optical wireless communications: Illuminating the path for cooper's law," *IEEE Open Journal of the Communications Society*, 2024.
- [67] I. C. Ijeh, M. A. Khalighi, and S. Hranilovic, "Parameter optimization for an underwater optical wireless vertical link subject to link misalignments," *IEEE Journal of Oceanic Engineering*, vol. 46, no. 4, pp. 1424–1437, 2021.
- [68] M.-A. Khalighi, T. Hamza, S. Bourennane, P. Léon, and J. Opderbecke, "Underwater wireless optical communications using silicon photo-multipliers," *IEEE Photonics Journal*, vol. 9, no. 4, pp. 1–10, 2017.
- [69] E. Sarbazi, M. Safari, and H. Haas, "Statistical modeling of single-photon avalanche diode receivers for optical wireless communications," *IEEE Transactions on Communications*, vol. 66, no. 9, pp. 4043–4058, 2018.
- [70] F. Miramirkhani and M. Uysal, "Visible light communication channel modeling for underwater environments with blocking and shadowing," *IEEE Access*, vol. 6, pp. 1082–1090, 2018.
- [71] H. E. Nistazakis, E. A. Karagianni, A. D. Tsigopoulos, M. E. Fafalios, and G. S. Tombras, "Average capacity of optical wireless communication systems over atmospheric turbulence channels," *Journal of Lightwave Technology*, vol. 27, no. 8, pp. 974–979, 2009.
- [72] A. Lapidoth, S. M. Moser, and M. A. Wigger, "On the capacity of free-space optical intensity channels," *IEEE Transactions on Information Theory*, vol. 55, no. 10, pp. 4449–4461, 2009.

- [73] Y. B. A. Prudnikov and O. Marichev, *Integrals and Series: More Special Functions*. Boca Raton, FL, USA: CRC Press, 1999.
- [74] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*, New York, NY, USA: Academic, 2000.
- [75] L. Zhan, H. Zhao, W. Zhang, and J. Lin, “An optimal scheme for the number of mirrors in vehicular visible light communication via mirror array-based intelligent reflecting surfaces,” in *Photonics*, vol. 9, no. 3. MDPI, 2022, p. 129.
- [76] E. Zedini, H. Soury, and M.-S. Alouini, “Dual-hop FSO transmission systems over gamma–gamma turbulence with pointing errors,” *IEEE Transactions on Wireless Communications*, vol. 16, no. 2, pp. 784–796, 2016.
- [77] A. Kilbas and M. Saigo, *H-Transforms: Theory and Applications (Analytical Methods and Special Functions)*. 1st ed. Boca Raton, FL, USA: CRC Press, 2004.
- [78] Z. Rahman, N. V. Tailor, S. M. Zafaruddin, and V. K. Chaubey, “Unified performance assessment of optical wireless communication over multi-layer underwater channels,” *IEEE Photonics Journal*, vol. 14, no. 5, pp. 1–14, 2022.
- [79] M. F. Ali, D. N. K. Jayakody, Y. A. Chursin, S. Affes, and S. Dmitry, “Recent advances and future directions on underwater wireless communications,” *Archives of Computational Methods in Engineering*, vol. 27, no. 5, pp. 1379–1412, 2020.
- [80] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, “Reconfigurable intelligent surfaces for energy efficiency in wireless communication,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 8, pp. 4157–4170, 2019.
- [81] V. I. Haltrin, “Chlorophyll-based model of seawater optical properties,” *Applied Optics*, vol. 38, no. 33, pp. 6826–6832, 1999.
- [82] R. M. Pope and E. S. Fry, “Absorption spectrum (380–700 nm) of pure water. ii. integrating cavity measurements,” *Applied optics*, vol. 36, no. 33, pp. 8710–8723, 1997.
- [83] A. M. A. Bricaud, M. Babin and H. Claustre, “Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: analysis and parameterization,” *J. Geophys.*, no. 100, 13321–13332, (1995).
- [84] A. Morel and L. Prieur, “Analysis of variations in ocean color 1,” *Limnology and oceanography*, vol. 22, no. 4, pp. 709–722, 1977.
- [85] O. Kopelevich, “Small-parameter model of optical properties of sea water,” *Ocean optics*, vol. 1, pp. 208–234, 1983.
- [86] V. I. Haltrin and V. Khalturin, “Propagation of light in sea depth,” *Optical Remote Sensing of the Sea and the Influence of the Atmosphere*, pp. 20–62, 1985.
- [87] L. J. Johnson, R. J. Green, and M. S. Leeson, “Underwater optical wireless communications: depth dependent variations in attenuation,” *Applied optics*, vol. 52, no. 33, pp. 7867–7873, 2013.

- [88] A. Alqahtani, "Non-orthogonal multiple access: a comprehensive analytical study and optimisation in fading channels," Ph.D. dissertation, University of Manchester, 2022.
- [89] O. Maraqa and T. M. N. Ngatched, "Optimized design of joint mirror array and liquid crystal-based RIS-aided VLC systems," *IEEE Photonics Journal*, vol. 15, no. 4, pp. 1–11, 2023.
- [90] O. Maraqa, S. Aboagye, and T. M. N. Ngatched, "Optical STAR-RIS-aided VLC systems: RSMA versus NOMA," *IEEE Open Journal of the Communications Society*, vol. 5, pp. 430–441, 2024.
- [91] A. El Gamal and Y.-H. Kim, *Network information theory*. Cambridge university press, 2011.
- [92] R. K. Jain, D.-M. W. Chiu, W. R. Hawe *et al.*, "A quantitative measure of fairness and discrimination," *Eastern Research Laboratory, Digital Equipment Corporation, Hudson, MA*, vol. 21, 1984.
- [93] M. A. Chancey *et al.*, "Short range underwater optical communication links," 2005.
- [94] X. Quan and E. S. Fry, "Empirical equation for the index of refraction of seawater," *Applied optics*, vol. 34, no. 18, pp. 3477–3480, 1995.
- [95] C. Fang, S. Li, Y. Wang, and K. Wang, "Optical wireless communication with intelligent reflecting surfaces," 2024.
- [96] O. Maraqa, S. Aboagye, and T. M. Ngatched, "Optical star-ris-aided vlc systems: Rsma versus noma," *IEEE Open Journal of the Communications Society*, 2023.
- [97] S. Aboagye, A. R. Ndjiongue, T. M. Ngatched, and O. A. Dobre, "Design and optimization of liquid crystal RIS-based visible light communication receivers," *IEEE Photonics Journal*, vol. 14, no. 6, pp. 1–7, 2022.
- [98] I. C. Khoo and S. T. Wu, "Liquid crystals for lasercom applications," *Optics & Photonics News*, vol. 12, no. 10, pp. 28–33, 2001.
- [99] R. A. Soref and D. H. McMahon, "Liquid crystal variable optical attenuator," *Applied Optics*, vol. 18, no. 10, pp. 1580–1584, 1979.
- [100] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.
- [101] J. Nocedal and S. Wright, *Numerical Optimization*. Springer, 2006.
- [102] L. A. Wolsey, *Integer Programming*. Wiley, 1998.
- [103] R. Salam and V. Ashok Bohara, "LC-OSTAR-IRS: Tunable liquid crystal surfaces for high-performance UWOC," *IEEE Wireless Communications Letters*, vol. 15, pp. 1305–1309, 2026.
- [104] R. Salam, V. A. Bohara, and A. Srivastava, "Smart element allocation strategies for dynamic optical IRS in underwater wireless communication," *IEEE Transactions on Vehicular Technology*, vol. 74, no. 3, pp. 4349–4361, 2025.