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Design of a Conceptual Underwater Wireless Communication System Integrating Electromagnetic and Optical Technologies

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ABSTRACT

Underwater wireless communication is pivotal for advancing maritime technology, supporting applications such as underwater exploration, autonomous underwater vehicles (AUVs), diver communication, search-and-rescue operations, and military systems. Traditional acoustic communication systems, while effective over long distances, are constrained by low bandwidth and high latency, limiting their suitability for data-intensive operations. Electromagnetic (EM) and optical communication technologies offer promising alternatives, providing higher data rates, greater bandwidth, and lower latency, but face challenges such as signal attenuation, scattering, and environmental interference. To address these challenges, this paper explores the potential of an integrated wireless communication and navigation system combining EM and optical technologies. Initial experimental measurements of EM wave propagation in freshwater provided valuable insights into signal attenuation and frequency-dependent performance, demonstrating the feasibility of overcoming attenuation in such environments. Building on these observations, this paper proposes a conceptual system comprising three interconnected segments: a space segment utilizing the Galileo High Accuracy Service (HAS) for precise GNSS signals, a waterline segment processing and transmitting GNSS-like signals, and an underwater segment facilitating navigation and communication for divers and AUVs. Preliminary findings highlight the potential of combining EM and optical technologies for reliable, near real-time underwater wireless communication. Future work will focus on extending functionality, validating the system in saltwater environments, and refining the design for practical deployment.

1 Introduction

Recent advancements in maritime communication technologies have prioritized sustainable and efficient data transmission methods, addressing the growing demand for robust systems to support modern, data-intensive operations in challenging maritime environments [1-3]. Among these, underwater wireless communication has emerged as a cornerstone of modern maritime technology, with the potential to revolutionize applications such as underwater exploration, search-and-rescue operations, autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and enhanced diver communication [4,5]. These applications demand reliable, high-speed data transmission in challenging underwater environments characterized by high signal attenuation, the conductive properties of water, and unique environmental factors not encountered in terrestrial communication systems [4,6].

Acoustic technologies have been widely used for underwater wireless communication due to their ability to transmit signals over long distances in deep water. However, these systems suffer from low bandwidth, high latency, and susceptibility to environmental noise and multipath effects. Additionally, the slow propagation speed of sound in water limits their effectiveness in time-sensitive and data-intensive applications, such as coordinating AUVs, real-time diver communication, and transferring high-resolution data from underwater sensors [7].

To overcome these limitations, electromagnetic (EM) and optical communication technologies have emerged as viable alternatives. EM communication offers higher bandwidth and lower latency, making it more suitable for near real-time communication and medium-range data transmission. However, it is constrained by signal attenuation due to water's conductivity, particularly in saltwater environments, necessitating the use of specialized antennas and optimized frequency selection to achieve acceptable performance [4,7,8]. In contrast, underwater wireless optical communication (UWOC) enables extremely high data rates and robust security, with lower power consumption compared to acoustic or EM systems. Yet, optical systems are hindered by light absorption and scattering, requiring line-of-sight (LOS) alignment and clear water conditions for effective deployment [7,9,10]. Together, these complementary strengths suggest the potential for integrating EM and optical technologies into hybrid systems that address the shortcomings of traditional acoustic systems while meeting the unique demands of underwater environments.

This paper explores advancements in EM and optical communication technologies and their potential for enabling reliable underwater wireless communication and navigation. The proposed conceptual system combines three interconnected segments: a space segment utilizing GNSS signals, a waterline segment processing and transmitting GNSS-like signals, and an underwater segment designed to facilitate navigation and near real-time wireless communication. Experimental studies have been conducted to evaluate EM wave propagation in freshwater, providing insights into attenuation and frequency-dependent performance. The findings indicate the feasibility of integrating EM and optical technologies to create a robust underwater wireless communication system capable of near real-time operation.

The remainder of this paper is organized as follows: Section 2 discusses EM communication principles and their application in underwater environments, while Section 3 focuses on UWOC systems and their integration potential. Section 4 outlines the experimental setup and measurement procedures, including insights from freshwater EM wave propagation measurements. Section 5 presents the results and discussion, evaluating the feasibility of EM wireless communication underwater. Section 6 introduces the conceptual design of the integrated underwater wireless communication and navigation system, and Section 7 concludes with key findings and future research directions.

2 Electromagnetic Communication

EM wireless communication underwater has remained a largely underexplored field compared to optical and acoustic methods, primarily due to the high attenuation caused by the conductive properties of saltwater, as well as the relative permittivity, permeability, and underwater path loss. Typical system configurations for underwater EM wireless communication involve the use of two coils to generate and detect magnetic fields produced by transceivers, commonly implemented with loop antennas. These systems rely on matching networks to ensure impedance consistency between the transceivers. The impedance is further tuned using combinations of parallel and series LC circuits. Communication blocks are designed similarly to terrestrial systems but must be adapted to address the unique challenges of the underwater environment [11].

Attenuation in underwater EM wireless communication is predominantly influenced by the relative permittivity, permeability, and conductivity of the medium. Relative permittivity, or dielectric constant, represents a medium's ability to transmit an electric field. In water, this property is significantly affected by temperature, salinity, and carrier frequency, with an average value of approximately 81 used for rough calculations [5]. Permeability, which reflects a medium's ability to store magnetic fields, has minimal impact on underwater EM wave propagation, as both air and water are non-magnetic and share similar permeability values [7]. In contrast, conductivity plays a critical role in determining signal propagation. Higher conductivity, which corresponds to a greater concentration of ions in the medium, results in stronger reflection and higher attenuation of EM waves [9]. Conductivity values range from 0 to 1 S/m in freshwater, 1 to 2 S/m in river water, and exceed 2 S/m in saltwater. For reference, the average conductivity of the Mediterranean Sea is measured at 5.6 S/m [7].

Figure 1 illustrates the attenuation of EM waves at different frequencies underwater. A critical consideration in the design of underwater EM wireless communication systems is the choice of operating frequency.

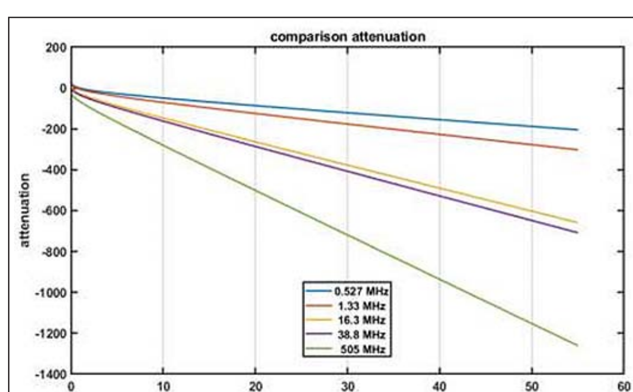

Figure 1 Frequency-dependent attenuation of EM waves in underwater environments. [4]

Higher frequencies experience greater attenuation, significantly limiting their effective range. Conversely, lower frequencies, while less affected by attenuation, often lack the transmission speed required for near real-time communication. Selecting an optimal frequency involves balancing these trade-offs to achieve reliable and efficient underwater wireless data transmission [4].

The velocity v of EM waves underwater is influenced by the relative permittivity ε_r, magnetic permeability μ_r, and conductivity δ of the water, as well as the angular frequency ω of the transmitted signal and the speed of light in a vacuum c. The relationship is given by [12]:

$$v = \frac{c}{\sqrt{(\varepsilon_r)(\mu_r)(\frac{1+\sqrt{1+\frac{\delta}{(\omega\varepsilon)^2}}}{2})}} \quad (1)$$

This formula highlights the interplay of these parameters in determining the propagation speed of EM waves. While the velocity in water is generally close to the speed of light in a vacuum, it is still affected by the medium's properties.

Attenuation is further influenced by underwater path loss, which represents the difference between the transmitted and received signal power. Path loss can be expressed as [13]:

$$P_r = P_t + G_t + G_r - L \quad (2)$$

where P_r and P_t are the received and transmitted power, respectively, G_t and G_r denote the transmitter and receiver gains, and L is the underwater path loss.

Figure 2 shows attenuation and velocity of EM waves in freshwater. Frequencies above 1 GHz are subject to excessive attenuation, making them impractical for underwater wireless communication. Frequencies below 1 GHz are more suitable for achieving proof-of-concept implementations, as they balance reduced attenuation with acceptable data rates for many underwater applications.

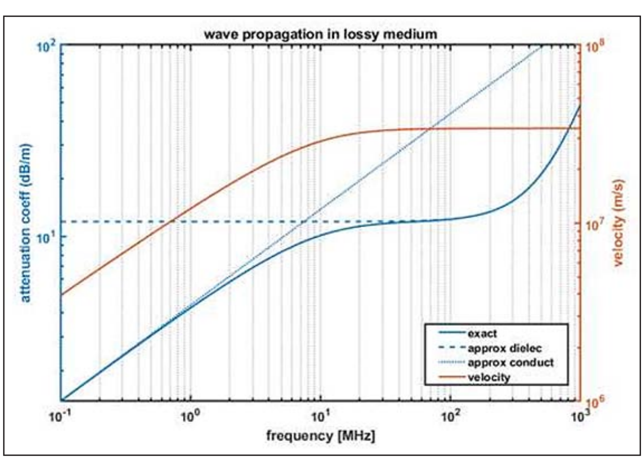

Figure 2 Attenuation and velocity of EM waves in freshwater across varying frequencies. [4]

3 Optical Communication

Given the goal of achieving a fully wireless underwater communication system, this paper exclusively considers UWOC, excluding any tethered variations. UWOC offers several advantages, including low latency, high data rates, reduced power consumption, and cost-effectiveness. Furthermore, it provides robust security against unauthorized access, data breaches, and cyberattacks, making it an attractive option for sensitive applications [4].

However, implementing UWOC for a purely wireless system presents significant challenges. The primary obstacles include light scattering and absorption in the underwater environment, mitigation of turbulence in seawater, and signal attenuation. Additionally, designing reliable optical transmitters and receivers that can endure harsh marine conditions is a critical requirement for practical deployment. Typical UWOC systems utilize light-emitting diodes (LEDs) and laser diodes (LDs) as transmitters, complemented by key components such as modulators and photodetectors that serve as receivers [14].

The two main sources of attenuation in UWOC systems are light scattering and absorption. Scattering occurs when light interacts with particles in the water, causing it to change direction. Reflection from underwater surfaces further compounds this challenge. Absorption, on the other hand, diminishes the intensity of light as it propagates through water [6, 15, 16]. Figure 3 illustrates the absorption and scattering of light through water, which can be modelled geometrically using the following formula [8]:

$$P_i(\lambda) = P_\alpha(\lambda) + P_s(\lambda) + P_t(\lambda) \quad (3)$$

where P_i represents the incident light power, P_α denotes the absorbed fraction of incident power, P_s accounts for the scattered fraction, and P_t is the remaining power that passes through the water medium. As shown in Equation (3), the light absorption and scattering is heavily dependent on the beam's wavelength [7].

The propagation of light underwater is also significantly influenced by various environmental conditions. Turbulence caused by currents, wind, or the movement of vessels and other objects can disrupt signal stability. Additionally, salinity and temperature variations alter the refractive index of water, potentially degrading signal propagation [7,17,18]. Figure 4 illustrates the attenuation of UWOC signals in different water types, each characterized by unique compositions of biological entities such as plankton and suspended particles [15]. These entities strongly impact the absorption and scattering of light. For example, open ocean water, which is relatively clear, exhibits the least attenuation, while turbid harbour water shows the highest levels of signal loss [15].

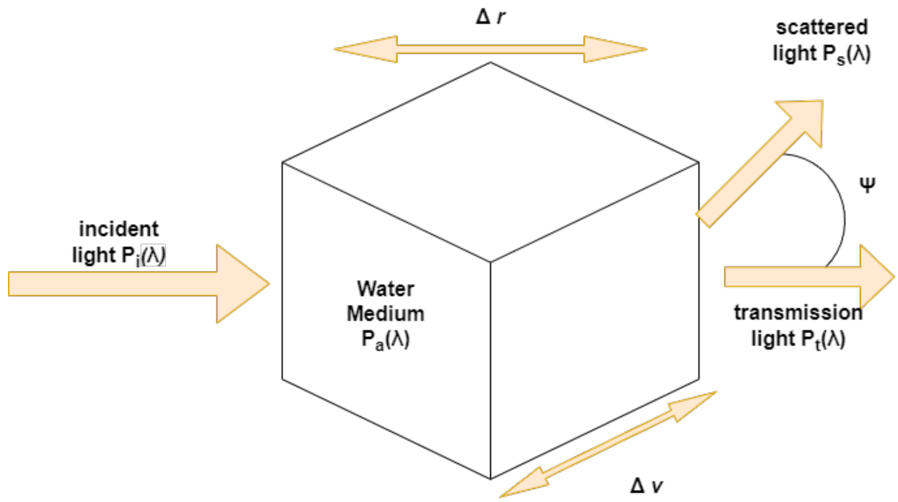

Figure 3 Graphical representation of light absorption and scattering mechanisms in underwater environments.

Another essential consideration in the design of UWOC systems is the configuration of optical links between communication nodes. These configurations include point-to-point line-of-sight (LOS), diffused line-of-sight (DLOS), retro-reflector-based line-of-sight (RLOS), and non-line-of-sight (NLOS) systems [10,19].

1) *Point-to-Point Line-of-Sight (LOS):* This configuration establishes a direct optical link between two devices, achieved by aligning their transmitters and receivers. LOS systems provide higher bandwidth, low latency, and enhanced security due to the narrow beamwidth of the transmitted signal. However, they are highly dependent on maintaining a clear LOS, which can be disrupted by environmental factors, the movement of underwater vehicles, or marine life. This setup is most effective when the devices are fixed on a stable platform and mounted on precisely controlled underwater vehicles [10,19].

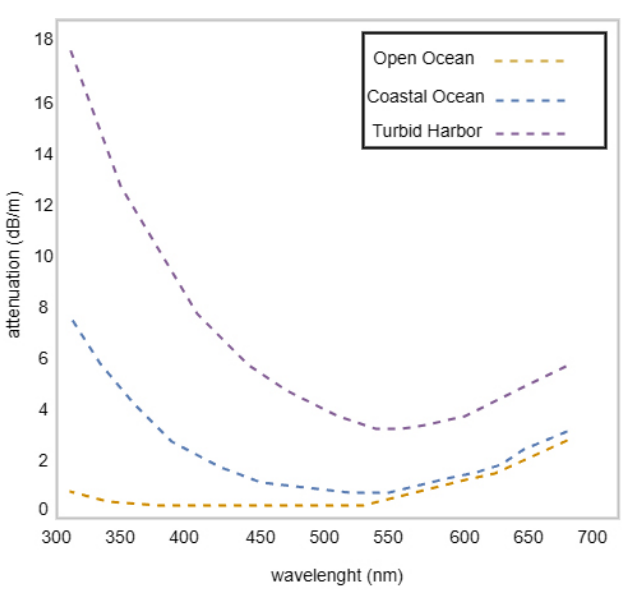

Figure 4 Comparison of UWOC signal attenuation in different water types. [15]

2) *Diffused Line-of-Sight (DLOS):* DLOS systems use non-directional optical signal for short- to medium-range communication. The transmitter emits a widely diffused light beam, allowing multiple receivers to detect the signal without requiring precise alignment. This configuration is cost-effective and simple to construct, as it does not rely on strict LOS alignment. However, it suffers from high attenuation, severe multipath propagation, and low energy efficiency, making it less suitable for long-range applications [10,19].

3) *Retro-Reflector-Based Line-of-Sight (RLOS):* RLOS systems employ retro-reflectors to create a communication link. A low-power receiver reflects the transmitted light back to the source, enabling full-duplex communication for short ranges. This configuration can be optimized for photon-limited or contrast-limited conditions, depending on whether it operates in clear ocean waters or murky harbour environments. Advantages include high efficiency, a compact and lightweight receiver design, and duplex communication capability. However, RLOS systems face challenges such as signal interference from backscatter, degradation of the signal-to-noise ratio (SNR), increased bit-error rates, and attenuation due to the signal traveling the channel path twice during transmission and reflection [10,19].

4) *Non-Line-of-Sight (NLOS):* NLOS configurations enable communication when direct LOS is obstructed by natural or artificial obstacles. Signals are reflected off surfaces such as the seawater surface, seabed, or underwater objects to reach the receiver. This reduces the need for precise alignment and tracking, making NLOS systems versatile in complex underwater environments.

However, they are susceptible to significant path loss, background radiation interference, and disruptions caused by environmental factors like wind-induced surface tilts. Such conditions can lead to increased signal dispersion and reduced reliability [10,19].

4 Experimental Setup and Measurement Procedures

The measurements were conducted in a lake near Graz, Austria by 1st-Relief GmbH [4,20]. Table 1 summarizes the water parameters which fell in their respective ranges during the experiments.

The experimental setup utilized two identical units, each comprising a transmitter and a receiver. Each unit consisted of two main components: a signal processing component positioned above the water and an underwater component designed for signal transmission and reception. The signal processing component was connected to a computer for data evaluation, while the underwater components, including a signal transmission or reception antenna, were housed within protective enclosures to ensure durability in submerged conditions.

Table 1 Water parameters during the experiments.

Parameter	Measuring range
Conductivity	1.0 µS/cm – 100.0 mS/cm
Salinity	0 g/kg – 50 g/kg
Dissolved Particles (TDS)	0 mg/l – 2000 mg/l
Temperature	-5.0°C – +10.5°C

For the custom-designed loop antenna, the electronic components were shielded by a dedicated housing. Alternatively, in the "MLA-MC-20" loop antenna, the components were protected by a robust plastic cover. The two components of each unit were interconnected via a coaxial cable. The underwater units were further secured with additional linkages to enhance stability during deployment. The computing units relied on external power supplies, while the measurement units were powered through USB connections to the computers.

The transmitter and receiver units were deployed at separate locations, with the coaxial cable allowing the underwater components to be positioned up to 10 meters away from the signal processing units. Both antennas were fully submerged at a water depth of 2 meters to mitigate environmental interference, such as substrate noise. To minimize electromagnetic leakage and prevent unintended signal transmission through the air, the transmitter unit was enclosed in an aluminium radio-frequency (RF) shielding box.

Figure 5 provides a graphical representation of the experimental setup. An adapted Global Positioning System (GPS) signal was employed as the pilot signal, with the frequency adjustable via the connected computer. The signal was transmitted in a loop and recorded by the receiving unit across various experimental scenarios. Preliminary data analyses were conducted in the field, while more detailed analyses were carried out during post-processing.

Signal strength was dynamically adjusted to match experimental conditions, and precise measurements of the distance between the transmitter and receiver units, as well as the depth of deployment were recorded. Dis-

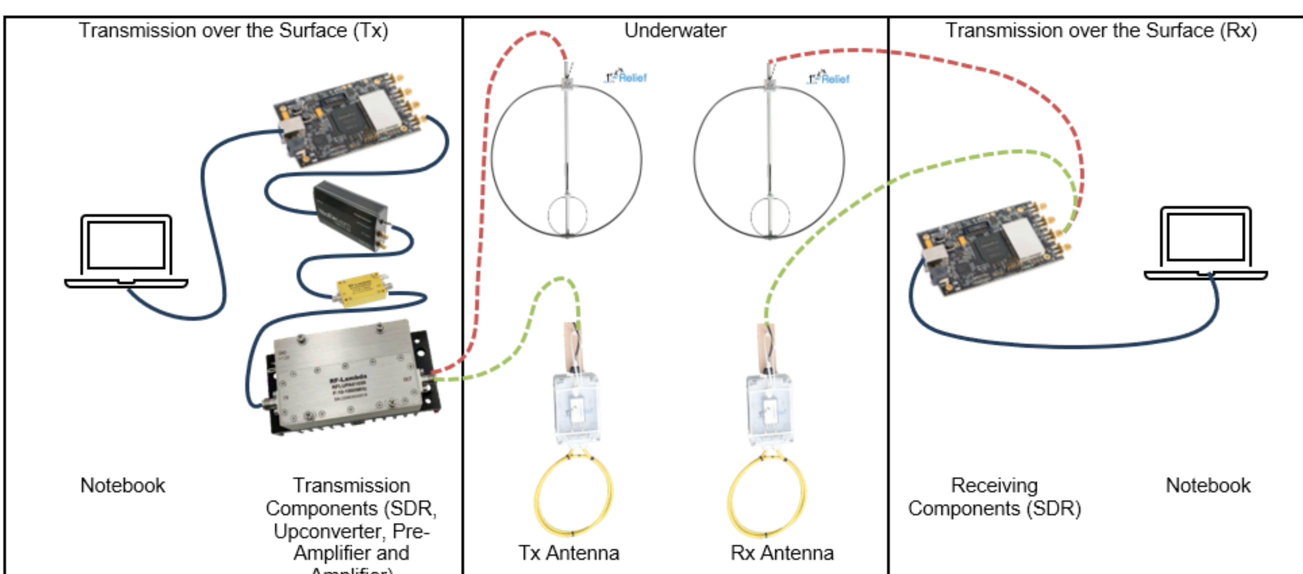

Figure 5 Overview of the experimental setup used to evaluate EM wave propagation in freshwater environments. [4]

tance measurements were taken using bridge-mounted markings and a roller meter, and post-processing incorporated coordinate data for improved accuracy. The separation distance began at 2 meters and was incrementally increased by 1 meter up to 8 meters. For a long-range performance evaluation, an additional measurement was conducted at a distance of 52 meters.

5 Results and Discussion

The recorded signal files were thoroughly re-examined to evaluate signal strength and SNR. For comparative analysis, data from the main measurement at an 8-meter distance were used, focusing on frequencies of 12.5 MHz, 25 MHz, and 50 MHz. Throughout the measurements, water parameters were assumed to remain stable, ensuring consistent environmental conditions. A modified sampling frequency was employed during control measurements to minimize aliasing effects. To quantify performance, channel power (PWR) and maximum peak amplitude were analysed, as shown in Figure 6. Both metrics demonstrated consistent trends across measurements.

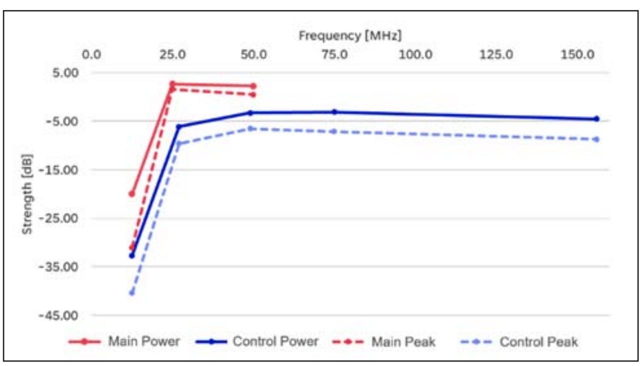

Figure 6 Channel power and peak amplitude measurements at an 8-meter distance for selected frequencies. [4]

The results indicate that the control measurements yielded slightly lower signal strengths at the receiver compared to the main measurements, with an approximate offset of 10 dB. Despite this offset, the frequency-dependent trends were comparable across the measurements. At 12.5 MHz, signal reception was minimal, whereas higher frequencies of 25 MHz and 50 MHz exhibited significantly improved performance. When the frequency was increased beyond 50 MHz during control measurements, no further gains in signal reception were observed. Notably, for frequencies above 60 MHz, the upconverter—which typically introduces a ~10 dB loss per side—was deactivated. This deactivation eliminated a cumulative 20 dB loss, positively influencing results at higher frequencies but complicating direct comparisons.

The differences in signal strength between the main and control measurements can be attributed to two primary factors: aliasing effects due to the modified sampling rate and enhanced equipment shielding. The additional shielding effectively prevented electromagnetic leakage and ensured that the measured signals were exclusively transmitted through the water medium. However, some reliability issues arose due to water ingress into the underwater housing, which caused unintended contact with the equipment housing. This compromised the validity of certain measurements, limiting the ability to draw definitive conclusions beyond frequency-specific trends.

6 Conceptual Underwater Wireless Communication and Navigation System Design

The proposed conceptual system design for underwater wireless communication and navigation consists of three interconnected segments: the space segment, the waterline segment, and the underwater segment [4]. Each segment is envisioned to perform a specific function, collectively enabling reliable wireless communication and navigation in underwater environments. This system is currently at a development stage and has not been fully implemented or validated in practical settings. Figure 7 provides an overview of the proposed system design, illustrating its envisioned components and functionality.

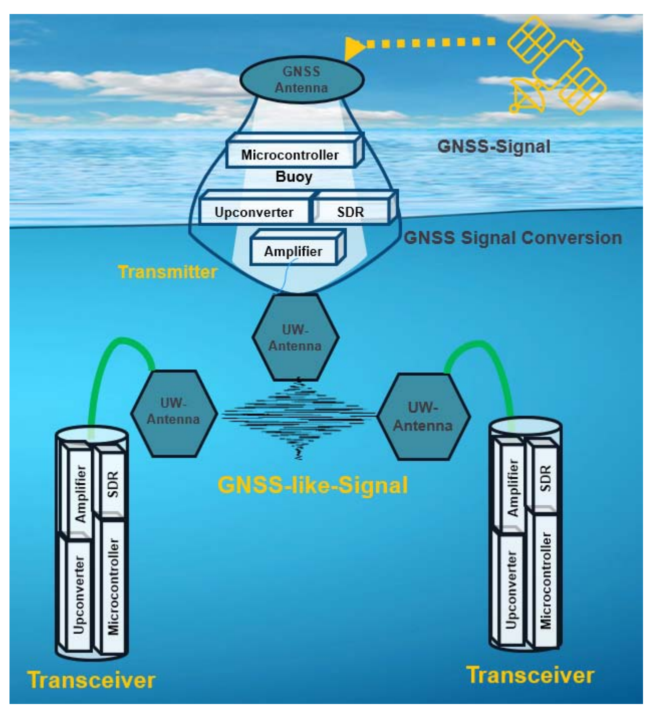

Figure 7 Conceptual representation of the proposed underwater wireless communication and navigation system with space, waterline, and underwater segments. [4]

1) *Space Segment:* The space segment is proposed to leverage existing infrastructure, specifically the Galileo High Accuracy Service (HAS), to provide Global Navigation Satellite System (GNSS) signals. These signals, conforming to the National Maritime Electronics Association (NMEA) protocol, are intended to deliver near real-time, high-precision positioning data to the waterline segment.

2) *Waterline Segment:* The waterline segment is envisioned to feature a buoy-based infrastructure designed to protect critical electronic components, including a power amplifier, microcontroller, software-defined radio (SDR), and upconverter. This segment is conceptualized to serve as the intermediary between the space and underwater segments. It would process GNSS signals received via a standard GNSS antenna and convert them into GNSS-like signals optimized for underwater transmission. To address environmental attenuation, the design proposes the use of an underwater antenna with a directional radiation pattern to maximize transmission range. However, stabilizing the buoy and antenna in dynamic environmental conditions, such as wind, waves, and currents, presents a significant challenge.

3) *Underwater Segment:* The underwater segment represents the most complex and challenging part of the proposed conceptual design. It is envisioned to utilize a protective cylindrical housing to encase essential electronic components, ensuring durability and functionality in harsh underwater conditions [21]. Real-world deployments will need to consider factors such as biofouling, which can affect the performance of optical and antenna components, and exposure to environmental stressors like salinity and temperature fluctuations. The primary objective of this segment is to facilitate wireless communication using EM signals while providing reliable navigation capabilities. This segment is conceptualized to support interaction between divers, ROVs, and AUVs. It is designed to allow the transmission of pre-prepared textual messages or near real-time inputs from diving computers to the surface. To enhance versatility, the housing is intended to be adaptable for deployment on divers, ROVs, and AUVs. An independent battery power supply is incorporated into the design to ensure operational autonomy. While the primary focus of this segment is on navigation and intercommunication, surface communication is included as a secondary function to increase system versatility. Figure 7 illustrates the conceptual design and the envisioned implementation of this segment.

4) *Component Integration and Housing Design:* The housing design incorporates six proposed components: batteries, a microcontroller, SDR, upconverter, power amplifier, and transceiver. The microcontroller (e.g., Raspberry Pi) is conceptualized to process GNSS-like signals received from the waterline segment, store the processed data locally, and present positioning, navigation, and timing (PNT) information to users (e.g., divers, ROVs, or AUVs). The signal would then be forwarded to the SDR for preparation and transmission. The upconverter and power amplifier are designed to enhance signal strength to mitigate underwater attenuation. These components are outlined in Figure 8.

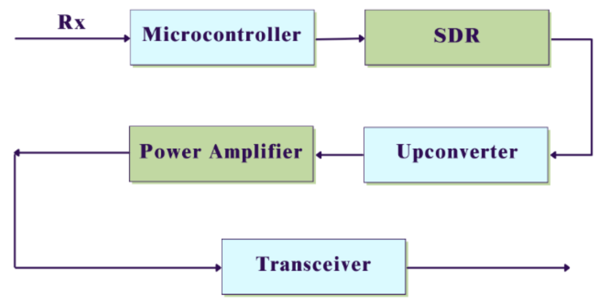

Figure 8 Conceptual design of the integrated components for the underwater segment.

5) Antenna Design: Antenna design is critical for the system's success. Both the waterline and underwater antennas must be designed to withstand the harsh marine environment, with a protection rating of IP69K to ensure durability and consistent functionality over extended periods. Key design parameters, such as gain, frequency, and bandwidth, will be tested and specified during development to optimize performance. The waterline antenna requires a directional radiation pattern to maximize underwater signal transmission. In contrast, the transceiver antenna for the underwater segment should have a spherical radiation pattern. This design minimizes the effects of buoy movement on the surface and mitigates multipath propagation loss, improving the likelihood of receiving the GNSS-like signal effectively.

Recent design considerations propose implementing a RLOS configuration utilizing a telecentric lens, as illustrated in Figure 9. Positioned on top of the protective housing, this component is envisioned as a key part of the UWOC system. The RLOS configuration enables the

Figure 9 RLOS telecentric lens for UWOC. [22]

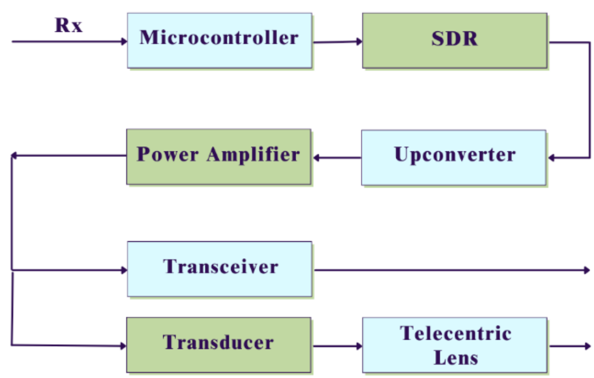

Figure 10 Proposed implementation of the UWOC components within the underwater housing.

reception of signals via a photodetector and the transmission of processed GNSS-like signals from other system components through the telecentric lens. This approach leverages the adaptability of RLOS configurations to varying environmental conditions, as they do not require a direct LOS between the transmitter and receiver.

In this proposed system, the RLOS configuration is designed to enable full-duplex communication between divers. This includes the capability to transmit textual messages, either as pre-prepared messages for quick communication or custom-typed inputs via diving computers. Additionally, the system is envisioned to support voice communication, potentially integrated into divers' masks. Figure 10 illustrates the proposed implementation of the UWOC components within the housing.

The overarching goal of the system is to create a solution that operates independently of extensive external processing or resource-intensive setups. This conceptual design aims to provide reliable navigation and communication capabilities in underwater environments at depths of up to 200 meters. By enabling both local and global localization, the system will support critical applications such as mapping underwater infrastructure (e.g., hydropower plants), assisting in underwater cable laying, and, most importantly, enabling precise tracking of divers and other points of interest. This capability is expected to significantly reduce the time required for search-and-rescue operations while enhancing overall operational efficiency in underwater environments.

7 Conclusion

This paper proposes an innovative conceptual system for underwater wireless communication and navigation, integrating EM and optical technologies to overcome the limitations of traditional acoustic methods. Preliminary experimental evaluations in freshwater environments provided valuable insights into the frequency-dependent performance of EM wave propagation, demonstrating the feasibility of achieving reliable communication despite attenuation challenges.

The findings indicate that EM communication is well-suited for medium-range, near real-time underwater applications, while optical communication delivers exceptional data rates for short-range scenarios. By leveraging these complementary strengths, the proposed system incorporates three interconnected segments—space, waterline, and underwater—designed to facilitate precise navigation and robust wireless communication.

While promising, the system remains at a conceptual stage and requires further development and validation. Key priorities include conducting field trials in saltwater environments to evaluate performance across varying salinity and conductivity levels and optimizing frequency selection to balance data rates with signal attenuation. Deployment in real-world conditions will also require addressing challenges such as biofouling and ensuring the durability of hardware under prolonged exposure to harsh underwater environments. Additionally, integrating advanced voice and data communication capabilities for deployment in AUVs, divers, and ROVs will further enhance the system's adaptability and practical applications.

The proposed system has the potential to significantly enhance underwater operations by supporting precise mapping of marine infrastructure, advancing underwater exploration, enabling accurate diver tracking, and reducing response times in search-and-rescue missions. By addressing the challenges of achieving reliable, near real-time wireless communication in underwater environments, this research establishes a foundation for developing a practical, market-ready solution that advances maritime exploration, safety, and innovation.

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Jurdana; research, Damir Brdar; writing—original draft preparation, Damir Brdar; writing—review and editing, Damir Brdar, Nikola Lopac, Andreas Lesch, and Irena Jurdana; visualization, Damir Brdar; validation, Nikola Lopac, Andreas Lesch, and Irena Jurdana; supervision, Nikola Lopac, Andreas Lesch, and Irena Jurdana; funding acquisition, Nikola Lopac, Andreas Lesch, and Irena Jurdana.

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