http://doi.org/10.35784/iapgos.8224

received: 10.08.2025 | revised: 10.12.2025 | accepted: 02.06.2026 | available online: 30.06.2026

ANALYSIS OF UNDERWATER COMMUNICATION SYSTEMS BASED ON HYBRID Li-Fi TECHNOLOGY

Nurzhigit Smailov[1,2], **Aizhan Urazgaliyeva**[1], **Akezhan Sabibolda**[1,2]

[1]Satbayev University, Department of Radio Engineering, Electronics and Space Technologies, Almaty, Kazakhstan, [2]Institute of Mechanics and Machine Science named by Academician U.A. Dzholdasbekov, Almaty, Kazakhstan

Abstract. *When humanity reaches a new phase in exploring the ocean floor, one of the most persistent technical challenges will still be maintaining dependable communication beneath the surface. The underwater environment introduces obstacles such as delayed signal transmission, fluctuating water conditions, significant signal loss, and the limited effectiveness of traditional communication methods. To address these issues, this work proposes a combined system that integrates both optical and acoustic channels, leveraging the strengths of each: the extensive range typical of acoustic links, and the fast, low-latency performance made possible by Li-Fi technology. The study compares existing approaches – acoustic, optical, and electromagnetic – with attention to the physical constraints imposed by the marine environment, including energy absorption, light scattering, refraction effects, and multipath propagation. It also considers the role of adaptive, intelligent signal-processing methods designed to maintain link stability as conditions change. From an engineering perspective, the discussion extends to laser wavelength choice, photodetector tuning, and the design of a network framework capable of enabling real-time data exchange between autonomous underwater vehicles and surface-level monitoring systems. The results suggest the potential for building a high-speed, large-scale underwater communication network with substantial capacity. This advancement could significantly accelerate deep-sea research, representing a major step forward in the evolution of marine communications.*

Keywords: Li-Fi, underwater, optics, acoustics, UOWC, attenuation

ANALIZA SYSTEMÓW ŁĄCZNOŚCI PODWODNEJ OPARTYCH NA HYBRYDOWEJ TECHNOLOGII Li-Fi

Streszczenie. *Gdy ludzkość wkroczy w nowy etap eksploracji dna oceanicznego, jednym z najtrudniejszych wyzwań technicznych nadal będzie zapewnienie niezawodnej łączności pod powierzchnią wody. Środowisko podwodne stwarza takie przeszkody, jak opóźnienia w transmisji sygnału, zmienne warunki wodne, znaczne straty sygnału oraz ograniczona skuteczność tradycyjnych metod komunikacji. Aby rozwiązać te problemy, w niniejszej pracy zaproponowano system łączony, który integruje zarówno kanały optyczne, jak i akustyczne, wykorzystując zalety każdego z nich: duży zasięg charakterystyczny dla łączy akustycznych oraz szybkość i niskie opóźnienia możliwe dzięki technologii Li-Fi. W badaniu porównano istniejące podejścia – akustyczne, optyczne i elektromagnetyczne – zwracając uwagę na ograniczenia fizyczne narzucone przez środowisko morskie, w tym pochłanianie energii, rozpraszanie światła, zjawiska refrakcji oraz propagację wielodrożną. W pracy uwzględniono również rolę adaptacyjnych, inteligentnych metod przetwarzania sygnałów, mających na celu utrzymanie stabilności łącza w miarę zmiany warunków. Z inżynieryjnego punktu widzenia dyskusja obejmuje wybór długości fali lasera, dostrajanie fotodetektorów oraz projekt struktury sieciowej umożliwiającej wymianę danych w czasie rzeczywistym między autonomicznymi pojazdami podwodnymi a systemami monitorowania na powierzchni. Wyniki sugerują, że istnieje potencjał do zbudowania szybkiej, wielkoskalowej podwodnej sieci komunikacyjnej o znacznej przepustowości. Postęp ten mógłby znacznie przyspieszyć badania głębinowe, stanowiąc znaczący krok naprzód w ewolucji komunikacji morskiej.*

Słowa kluczowe: Li-Fi, podwodny, akustyka, UOWC, tłumienie

Introduction

Water in its many forms – seas, rivers, oceans, and lakes – blankets close to three-quarters of our planet. Because of this vast coverage, my research naturally gravitated toward technologies that can operate beneath the surface [1]. Given that water is one of the most unpredictable environments in nature, developing robust communication systems for efficient data transfer [19], particularly in urgent or emergency scenarios, becomes essential.

While investigating underwater communication, I noted that technologies common in terrestrial and aerial contexts – such as Bluetooth, infrared, and high-frequency radio – have shown effectiveness in coordinating autonomous robot swarms [8]. However, all of these rely on electromagnetic waves, which face serious limitations when applied underwater [20].

My findings confirm that water, and seawater in particular, absorbs electromagnetic signals so effectively that stable, long-range communication using these methods is impractical. In underwater robotics, two wireless approaches show the most promise: acoustic communication and optical communication [6].

Acoustic channels are well-suited for long-distance transmission, as they can carry signals over many kilometres. The trade-off, however, is limited bandwidth, latency caused by the relatively slow speed of sound in water (about 1500 m/s), and susceptibility to multipath interference. Optical channels, in contrast, can deliver very low latency and high data rates [15], but only across short ranges, with performance dependent on water clarity and precise alignment between transmitter and receiver.

Considering these strengths and weaknesses, I propose a hybrid acoustic–optical system that combines both methods. Such an approach can leverage the range of acoustics with the speed of optics, creating a practical and effective framework for coordinated operations among teams of autonomous underwater robots [28].

Optical-acoustic communication (OAC) merges the use of light and sound waves to enable data exchange across significant underwater distances [11]. By employing infrared radiation, this method can enhance communication efficiency in various maritime operations, including ocean exploration, target monitoring, and signalling between vessels and submarines.

Although laser-based links can deliver high data rates, they are constrained by factors such as latency and interference. Some of these issues can be reduced through advanced modulation techniques and faster transmission speeds, but achieving this often requires multihop connections [22], which can increase overall system costs. Lasers also have deployment challenges and do not propagate acoustically, making them less suitable for certain underwater conditions where acoustic channels remain the more practical choice.

Electromagnetic signals, meanwhile, lose strength rapidly in water, severely limiting their transmission range. Optical communication stands out for its low power requirements, high potential throughput, and resistance to many forms of interference. However, its performance can deteriorate due to scattering and absorption of light [29], both of which depend heavily on the clarity and composition of the surrounding water.

This study supports the adoption of a hybrid optical-acoustic approach to facilitate communication among divers, autonomous underwater vehicles, and other submerged systems [3]. The findings can inform future enhancements in underwater communication networks, helping improve both performance and reliability in real-world marine environments. By evaluating the strengths and weaknesses of each method and considering emerging technologies, the work aims to outline a balanced solution that optimizes data transfer efficiency, cost-effectiveness, and operational dependability under aquatic conditions.

1. Literature review

This study examines how light fidelity (Li-Fi) technology can be applied to transmit data in underwater optical-acoustic communication systems. Li-Fi uses light waves as the transmission medium, enabling much higher data speeds [5] than many traditional wireless approaches. Research by Ali A. and Kumar R. reports that Wi-Fi can reach speeds of up to 9.6 Gbit/s, while Li-Fi can surpass 100 Gbit/s [4]. Similarly, Saleha A., Nada M., and Bedaiwi note that Li-Fi's ability to overcome the bandwidth limitations of radio-frequency links makes it particularly valuable for domains such as aviation and subsea operations [12].

The urgency for rapid environmental monitoring and disaster prediction has been underlined by recent ecological incidents, including a major oil spill in the Black Sea [26]. These events highlight the strategic advantage of implementing Li-Fi systems in regions such as the Caspian Sea. Real-time tracking of pollutants could prevent crises like those experienced in the Black Sea and Aral Sea, enabling faster responses to environmental threats. Beyond safeguarding ecosystems, such capabilities could reduce long-term economic losses associated with ecological emergencies by enabling continuous monitoring of water conditions.

Li-Fi's relevance extends beyond technical innovation. In controlled aquatic environments such as swimming pools or coastal recreation areas, it could support safety systems to help prevent drowning [7]. In Kazakhstan, for instance, persistent monitoring of water levels via Li-Fi-enabled systems could contribute to flood risk reduction.

Military, industrial, and scientific sectors all stand to benefit from advances in underwater wireless communication. Potential uses include oceanography, environmental data collection, climate research, and maritime operations. In such applications, autonomous underwater vehicles (AUVs) [10] and robotics equipped with high-capacity communication modules could reliably handle the required data exchange [24].

Looking ahead, integrating Li-Fi technology into offshore oil and gas operations could create new possibilities for continuous pipeline monitoring and rapid incident prevention [13]. Such measures would not only improve safety across the shipping industry but also support responsible management of natural resources in response to the rising global demand for energy products.

Beyond its operational benefits, a Li-Fi-enabled infrastructure could stimulate economic growth by creating skilled jobs, attracting foreign investment, and strengthening national security. The system's capacity for advanced underwater surveillance would give Kazakhstan a stronger ability to protect its maritime borders and to manage marine resources more effectively.

The lessons from the Black Sea disaster underscore the importance of proactive engagement in natural resource stewardship. By introducing Li-Fi into underwater communication systems, this research identifies the technology as a transformative innovation – one that holds clear benefits for Kazakhstan while also contributing to progress in global technological capabilities [21].

2. Materials and methods

This research focuses on examining the characteristics of underwater optical-acoustic communication, developing simulation models, and refining methods for efficient data transfer. Key aspects under consideration include channel behaviour, modulation techniques, coding strategies, and noise factors specific to Underwater Optical Wireless Communication (UOWC) [27]. The system's reliability and performance were assessed through computer-based modelling and prototype-level functional verification.

The proposed optical-acoustic communication setup was first designed using the OptiSystem software environment [9], followed by the development of a working physical model. The overall architecture consists of two main components. The transmitter sends data signals into the water medium, while the receiver captures these signals and converts them into a form usable for further processing. Together, these stages maintain consistent and effective communication between different parts of the system.

To identify the most suitable design, existing underwater communication methods were reviewed, with a focus on their advantages and limitations [18]. From the wide range of available approaches, three were selected for detailed comparison: acoustic, electromagnetic, and optical communication [14]. Their characteristics are summarized in Table 1.

Fig. 1 presents the functional layout of the proposed audio signal transmission unit, which can operate either from an external power source or via a solar panel serving as the primary energy supply.

Table 1. Overview of underwater communication types

Parameters	Acoustic communication	Electromagnetic communication	Optical communication	Optical-acoustic communication
Attenuation	For low frequencies (e.g., ~100 Hz), attenuation ranges from 0.1 to 0.2 dB/km. For medium frequencies (~1 kHz), it is 1–3 dB/km. For high frequencies (~10 kHz), it reaches 10–20 dB/km or higher [20].	For radio frequencies (10–1000 MHz) in seawater, attenuation ranges from 20 to 50 dB/km, increasing with frequency [20]. At ultra-low frequencies (3–30 Hz), it is 0.1–0.2 dB/km, suitable for long-range links but requiring large antennas. Above 1000 MHz, attenuation exceeds 100 dB/km, making them unsuitable for underwater use.	Optical signal attenuation in water is much higher than in fibre. In fresh water, it is about 100 dB/km, significantly limiting underwater optical communication range [14]. Li-Fi in clear water: ≈ 100 dB/km, limiting range to tens of meters. Acoustic: lower attenuation and longer range but lower data rate than optics.	
Propagation Speed (m/s)	1500 m/s	≈ 2.3×10^8 m/s	≈ 2.3×10^8 m/s	1500 m/s
Data Rate	1–150 kbps	Up to 100 Mbps at short distances	Up to several Gbps at ≤ 10 m; Mbps at up to 150 m	1–10 Mbps
Latency	High	Medium	Low	Low
Range	Several km	Up to 10 m	≈ 10–100 m	Limited to line-of-sight deployment
Bandwidth	Depends on range: < 1 kHz at 1000 km; < 10 kHz at 1–10 km; ≈ 1 kHz at < 100 m.	Several MHz	10–150 MHz	10–100 Mbps at 1–10 m; 1–10 Mbps at 100 m; 1–5 Mbps at 1 km; 1 Mbps at 10 km.
Frequency Range	10–15 kHz	30–300 Hz (ELF) for stationary direct underwater links	10^{12}–10^{15} Hz	1–10 kHz
Transmission Power	10 W	Several MW to 100 W depending on range	Several W	10 mW–100 W
Energy Efficiency	≈ 100 bit/J	LF (30–300 kHz): 2–100 bit/J	≈ 30,000 bit/J	10^6–10^7 bit/J
Operational Factors	Temperature, salinity, pressure	Conductivity and dielectric properties	Absorption, scattering, turbidity	Scattering, absorption

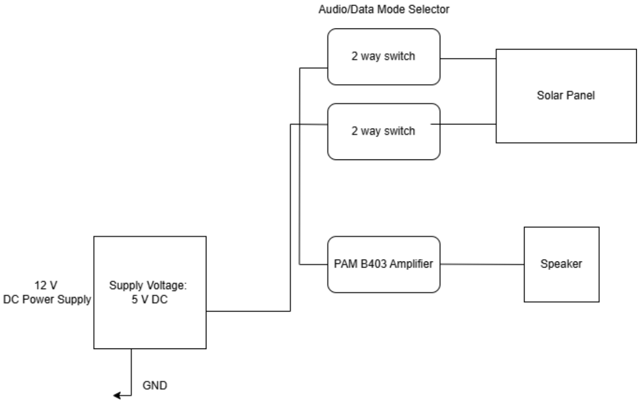


Fig. 1. Block diagram of the transmitter

In this design, the module is powered by a 5 V input from either a conventional supply or a compact solar panel. A two-way switch enables seamless selection between these power sources. The selected input drives a PAM8403 amplifier, which boosts the audio signal before sending it to the loudspeaker for playback. This arrangement creates an energy-conscious transmitter capable of solar-powered operation.

The configuration and operation of the receiver module are shown in Fig. 2. The circuit is managed by an Arduino Uno, which processes incoming signals in either audio or digital mode. Power is supplied from an external 12 V source, stepped down to 5 V through a dedicated power conversion unit. A mode-selection switch allows the user to direct the processed signal toward either a laser module for digital transmission or a voice recording module for audio relay.

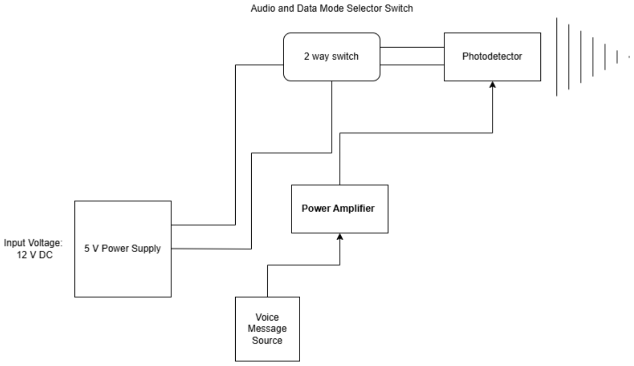


Fig. 2. Block diagram of the receiver

In digital mode, the laser conveys encoded data, while in audio mode, the voice recording module accepts input from an external source–such as a microphone–via an AUX connection. The resulting system supports a hybrid communication method capable of sending both audio and digital content through a laser beam.

Fig. 3 presents the system architecture developed in OptiSystem, demonstrating a hybrid optical communication setup that integrates a fibre-optic link with a free-space optical (FSO) channel.

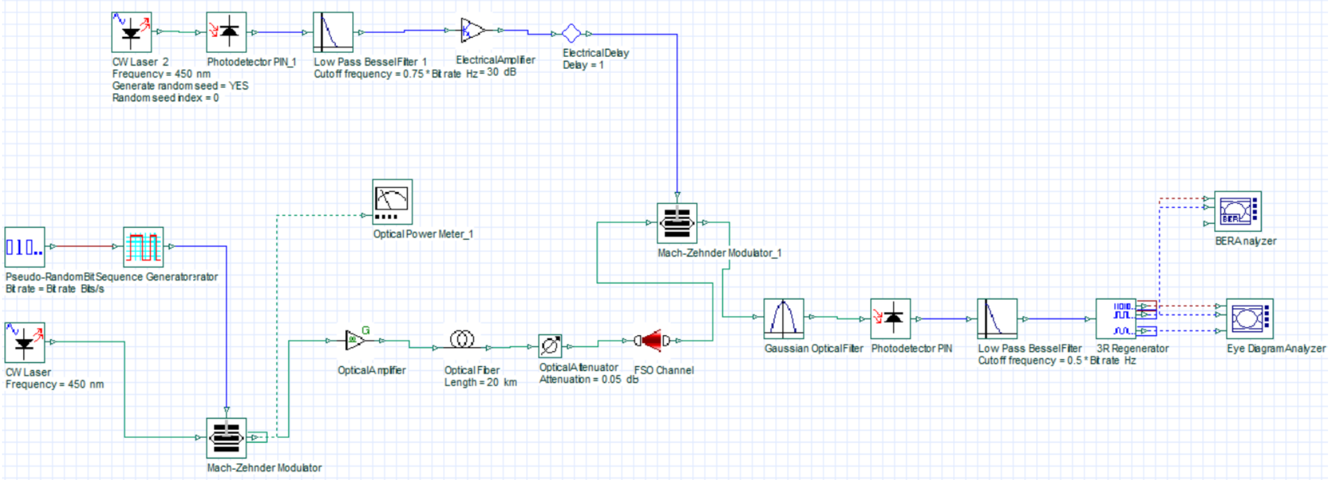


Fig. 3. System structure in the OptiSystem software

The model simulates data transfer within an optical communication framework, allowing for detailed analysis of transmission performance. At the transmitter end, a random bit sequence generator produces the digital input signal. This is then modulated using a coherent laser source operating at 450 nm through a Mach-Zehnder modulator. In addition, an LED operating in the red visible spectrum is incorporated. The Li-Fi optical frequency is determined by the relationship between the speed of light and the chosen wavelength:

$$f = \frac{c}{\lambda} \tag{1}$$

where c is the speed of light in vacuum; λ – the wavelength of the light wave.

Then, using (1), we obtain:

$$f = \frac{c}{\lambda} = \frac{3 \cdot 10^{8}}{450 \cdot 10^{-9}} = 667\ \text{THz}$$

Following modulation, the optical signal passes through an amplifier to compensate for power losses before traveling through a 20 km segment of optical fibre [2]. It then encounters an attenuator designed to simulate environmental effects in the free-space channel. On the receiving side, a Gaussian optical filter removes noise, and a PIN photodiode converts the optical signal into an electrical form [30]. The output is processed by a Bessel low-pass filter to further reduce noise, then restored in amplitude, waveform, and timing by a 3R regenerator.

To evaluate transmission quality, the setup includes a Bit Error Rate (BER) analyser and an Eye Diagram analyser. These tools provide both quantitative and visual assessments of signal integrity. Through this modelling, it becomes possible to evaluate the stability of hybrid optical systems, understand how various parameters impact performance, and determine the conditions under which signal quality can be maintained.

The research methodology was based on a combined simulation-and-prototype approach. At the first stage, the general feasibility of hybrid underwater communication was evaluated through a comparative analysis of acoustic, electromagnetic, optical and optical-acoustic communication methods. At the second stage, a simulation model of the optical Li-Fi channel was developed in the OptiSystem environment. The model included a random bit sequence generator, a coherent optical source with a wavelength of 450 nm, a Mach-Zehnder modulator, an optical amplifier, a 20 km fibre segment, an attenuator for simulating channel losses, a Gaussian optical filter, a PIN photodiode, a Bessel low-pass filter and a 3R regenerator. At the third stage, the quality of signal transmission was assessed using the BER Analyser and Eye Diagram Analyser. The main evaluation parameters were the Q-factor, minimum bit error rate, eye height, decision threshold and optimal decision instant. At the fourth stage, a laboratory transmitter-receiver prototype was assembled to verify the functional feasibility of the proposed Li-Fi-based communication concept.

Table 2. Research criteria and expected behaviour of the hybrid Li-Fi communication model

Research criterion	Evaluation parameter	Expected behaviour	Evaluation tool
Signal integrity	Q-factor	A higher Q-factor should indicate better separation between logical signal levels and lower probability of transmission errors	BER Analyser
Transmission reliability	Minimum BER	A lower bit error rate should confirm more reliable data transmission through the modelled optical channel	BER Analyser
Noise tolerance	Eye height	A larger eye opening should indicate better resistance to noise and more stable signal recovery at the receiver	Eye Diagram Analyser
Decision stability	Decision threshold	A stable decision threshold should support correct recognition of transmitted bits after optical-to-electrical conversion	BER Analyser
Timing stability	Optimal decision instant	The optimal decision instant should correspond to the time interval where the bit error probability is minimal	BER Analyser
Functional feasibility	Transmitter–receiver operation	The prototype should confirm the practical possibility of transmitting an audio-modulated optical signal between the laser source and the photoresistor-based receiver	Laboratory prototype verification

These criteria were selected because they directly characterize the quality of the optical Li-Fi transmission link. The Q-factor and BER were used as the main quantitative indicators of signal quality and reliability, while the eye height, decision threshold and optimal decision instant were used to assess the stability of signal recovery at the receiver. Prototype verification was used as an additional criterion to confirm the practical feasibility of the proposed transmitter–receiver configuration.

3. Research results

3.1. Simulation results of the hybrid optical communication model

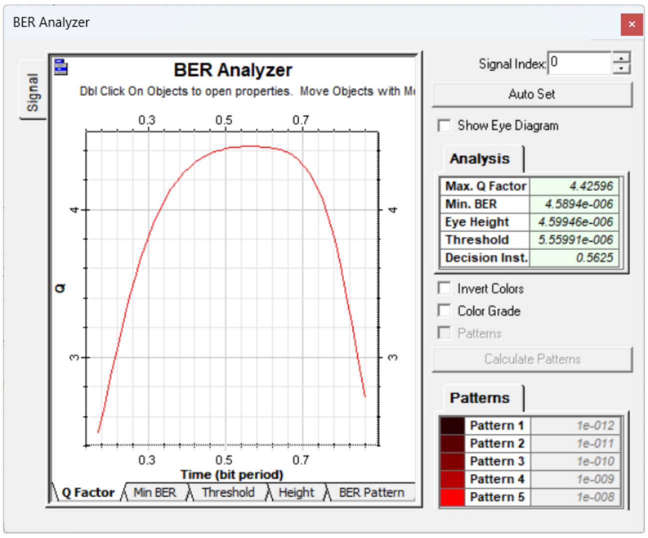
The simulation and subsequent verification of the hybrid optical-acoustic communication system in OptiSystem produced a set of measurable performance indicators. The assessment focused on signal integrity, bit error rate (BER), modulation effectiveness, and stability of the transmission channels. Particular attention was paid to Q-factor measurements, BER statistics, and eye diagram characteristics, as these parameters directly reflect both the robustness of the link and the clarity of data transfer.

Fig. 4 displays the variation in Q-factor obtained through the BER Analyser tool in OptiSystem, offering a visual representation of the signal quality within the modelled system.

From the BER Analyser output, the key evaluation parameters included the Q-factor, BER, eye height, and decision threshold. The maximum recorded Q-factor was 4.42596, indicating strong signal quality, while the minimum BER value of 4.5894×10^{-6} confirmed a low error probability. The eye height measurement of approximately 4.59946×10^{-6} suggests an adequate signal level for demodulation, though in challenging channel conditions, some information loss could still occur.

These findings imply that the link quality is within acceptable limits but could be further enhanced. Possible improvements include increasing transmitter power, refining noise filtering, or employing higher-sensitivity detectors to boost reception performance.

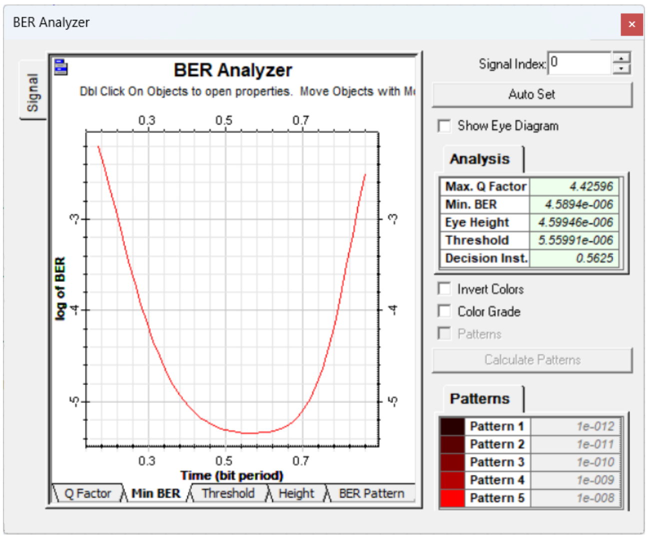
Fig. 5 illustrates how the logarithmic BER varies over time, based on BER Analyser data, providing insight into system reliability across different bit periods.



Max. Q Factor	4.42596
Min. BER	4.5894e-006
Eye Height	4.59946e-006
Threshold	5.55991e-006
Decision Inst.	0.5625

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 4. Q-factor signal graph from the BER Analyser



Max. Q Factor	4.42596
Min. BER	4.5894e-006
Eye Height	4.59946e-006
Threshold	5.55991e-006
Decision Inst.	0.5625

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 5. Dependence of the logarithm of bit error probability on time

This graph, generated from BER Analyser measurements in OptiSystem, depicts how the logarithmic bit error rate (log-BER) changes over time per bit. The U-shaped curve highlights a central segment of the time scale where BER reaches its minimum, indicating the most dependable period for signal transmission, while error probability rises toward the edges of the scale. Numerical analysis confirms the system's strong reliability: the maximum Q-factor is 4.42596, and the minimum BER is 4.5894×10^{-6}, demonstrating high-quality data transfer. Additional measured values include an eye height of 4.59946×10^{-6}, interference resistance, a decision threshold of 5.55991×10^{-6}, and an optimal decision instant of 0.5625. Error pattern visualization at the bottom of the analysis window shows the relationship between bit errors and signal level, ranging from a very low 1×10^{12} at the start to 1×10^{8}, enabling assessment of the system's tolerance to distortion. This evaluation not only identifies the most effective operating parameters but also guides adjustments to improve transmission efficiency and reduce errors.

3.2. Prototype design and functional verification

In addition to the OptiSystem simulation, a laboratory prototype of the hybrid Li-Fi communication system was assembled to verify the functional feasibility of the proposed transmitter–receiver configuration. This stage focused on checking the interaction between the audio input, PAM amplifier, laser module, photoresistor-based receiver, PAM8403 amplifier and output speaker. Therefore, the following figures present the prototype structure and its functional verification rather than a complete underwater field experiment.

Fig. 6 and 7 present the principal elements of the transmitter design: the PAM amplifier module (Fig. 6) and its incorporation into the full hybrid Li-Fi transmitter configuration, which comprises seven modules in total (Fig. 7).

Fig. 6. PAM amplifier module

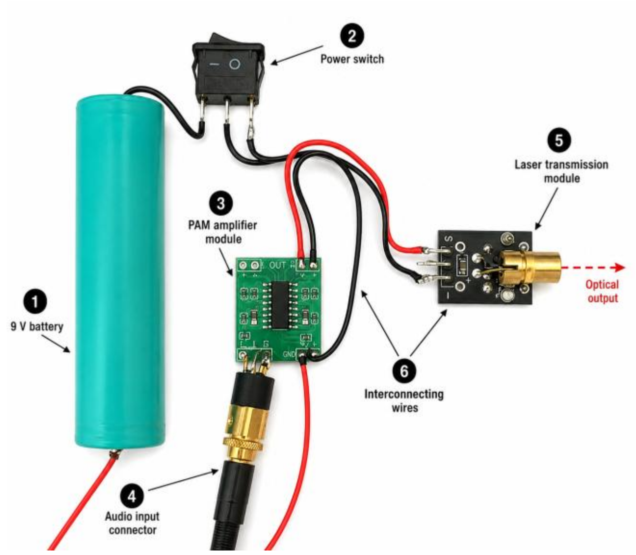


Fig. 7. Labelled transmitter module based on hybrid Li-Fi technology: 1 – 9 V battery, 2 – power switch, 3 – PAM amplifier module, 4 – audio input connector, 5 – laser transmission module, 6 – interconnecting wires

The labelled transmitter module shown in Fig. 7 clarifies the physical arrangement of the main hardware elements used for optical audio transmission. Its main components include a 9 V battery for circuit power, a PAM amplifier module to process the input signal before modulation, a power-selection switch, a connector for an external audio source, and the laser module that serves as the transmission carrier. Pulse Amplitude Modulation (PAM) was chosen for this setup because it can represent data with multiple amplitude levels, making it more efficient than simple On–Off Keying (OOK) [17]. In comparison, OOK operates in a binary format, transmitting information through the presence ("1") or absence ("0") of a signal. While OOK is straightforward, it is typically less energy-efficient and more susceptible to noise.

Although PAM was selected in this prototype due to its simple implementation and suitability for amplitude-based optical audio transmission, the choice of modulation format can significantly affect the parameters of an underwater Li-Fi communication system. Other modulation schemes, such as OOK, PPM, OFDM and QAM-based approaches, may provide different trade-offs between energy efficiency, spectral efficiency, noise immunity, implementation complexity and receiver sensitivity. Therefore, future research should include a comparative analysis of modulation formats under varying underwater conditions, including turbidity, optical alignment, transmission distance and ambient light interference.

In operation, the audio signal is modulated onto the light beam, enabling transmission over greater distances to the receiving unit. The amplified audio signal drives the laser module, altering its light intensity according to the input waveform. This approach is favoured in many optical communication systems because the laser provides a highly directional beam, allowing information to travel farther with minimal signal loss.

Laser-based communication systems have become important tools in both telecommunications and scientific applications [16, 25]. Research published in IEEE Xplore highlights that free-space optical (FSO) links can deliver extremely high bandwidth while remaining unaffected by electromagnetic interference. These systems are deployed in both civilian and defence contexts, including satellite data networks and underwater links. Such transmission methods are particularly valuable when conventional radio-frequency channels are congested or impractical, as in urban areas or subsea environments. Selecting an optimal wavelength can further enhance performance, and future upgrades-such as beam stabilization and adaptive modulation–could substantially improve signal quality and resilience to environmental fluctuations [23].

Fig. 8 depicts the receiver section of the hybrid Li-Fi communication system, showing its physical construction and integration stage for audio signal recovery.

Fig. 8. Receiver module based on hybrid Li-Fi technology

In this design, the receiver incorporates a PAM8403 stereo amplifier, 9 V battery, speaker, and photoresistor. The optical signal from the transmitter is detected by the photoresistor, whose resistance changes in proportion to the incoming light intensity. These variations are fed into the PAM8403 amplifier, which strengthens the signal before sending it to the speaker for playback. A built-in potentiometer provides volume adjustment, while an LED indicator displays operational status. By using light as the transmission medium, the Li-Fi-based system avoids radio-frequency interference and operates with high energy efficiency.

The laboratory prototype was tested at the functional level to verify the basic operation of the proposed Li-Fi transmitter-receiver chain. The verification focused on whether the audio signal supplied to the transmitter could be amplified, converted into optical intensity modulation by the laser module, detected by the photoresistor at the receiver side, amplified again and reproduced through the output speaker. The test confirmed the functional continuity of the transmission chain and demonstrated that the proposed configuration can be used as a low-cost prototype for optical audio transmission. However, this verification was limited to laboratory conditions and did not include full-scale underwater testing with controlled variation of distance, turbidity, alignment angle or water depth.

Table 3. Functional verification results of the laboratory prototype

Prototype element	Verification criterion	Observed result
Audio input and PAM amplifier	The input audio signal should be amplified before optical modulation	The audio signal was successfully supplied to the amplification stage
Laser transmission module	The amplified signal should modulate the laser intensity	Optical intensity modulation was achieved through the laser module
Photoresistor-based receiver	The receiver should respond to changes in incident light intensity	The photoresistor detected optical signal variations from the transmitter
PAM8403 receiver amplifier	The detected signal should be amplified for acoustic output	The received signal was amplified before reproduction
Output speaker	The transmitted signal should be reproduced as an audible output	The prototype confirmed functional audio recovery at the receiver side
Overall prototype chain	The transmitter and receiver should operate as a complete Li-Fi communication link	Functional feasibility of the proposed transmitter-receiver configuration was confirmed under laboratory conditions

These prototype-level results complement the OptiSystem simulation results by confirming that the proposed architecture is not limited to a theoretical model. At the same time, the obtained verification should be interpreted as a functional laboratory test rather than a complete assessment of underwater communication performance. Further experiments are required to quantify the influence of water turbidity, transmission distance, optical alignment and modulation format on the stability of the hybrid Li-Fi link.

4. Prospects for building a hybrid optical-acoustic system in the Caspian Sea

Designing a hybrid optical-acoustic monitoring network for the Caspian Sea requires accounting for the region's unique characteristics – an area of roughly 371,000 km^2, an average depth of 211 m, and variable water properties that influence signal behaviour. Combining optical and acoustic links can balance transmission range with data rate, ensuring robust performance under diverse environmental conditions. Optical systems are particularly useful for short-range links within the 450–550 nm spectrum, where water absorption is relatively low.

Light intensity over distance can be described using the Beer-Lambert-Bouguer law:

$$I = I_0 e^{-(c \cdot d)} \qquad (2)$$

where c represents the absorption coefficient, which in the Caspian Sea typically falls between 0.2 and 0.4 m^{-4} depending on particulate content and pollution levels. This means that over a distance of 10 m, the optical signal loses more than half its strength, limiting effective communication range between system nodes.

For greater distances, acoustic channels are more suitable, as sound travels through water at approximately 1480 m/s and can carry signals over many kilometres. Power loss for acoustic waves is expressed by:

$$L = L_0 - 20\log_{10}(r) - ar \qquad (3)$$

where r is the distance, and the absorption coefficient α depends on signal frequency and water temperature. In the 1–10 kHz range, acoustic waves can propagate up to 50 km, making them effective for communication between distant nodes in the system.

It is proposed that the monitoring network include a coastal control station serving as the central hub for data analysis, with mid-depth underwater nodes (50–200 m) equipped with both optical and acoustic transceivers. Deeper nodes, positioned at depths reaching 1000 m, would rely primarily on acoustic links for communication. Reliable power is critical for uninterrupted operation, which could be ensured by outfitting surface buoys with solar panels and pairing them with low-consumption lithium-ion batteries capable of functioning in harsh marine conditions.

By combining optical and acoustic transmission methods, such a system could provide continuous monitoring of the Caspian Sea's environmental state, including real-time measurements of temperature, salinity, and pollutant concentrations. Data would be transmitted directly to the coastal station for further processing and assessment.

5. Conclusions

This work has explored the feasibility of a hybrid underwater communication approach that merges the advantages of conventional acoustic channels with the speed and low latency of optical Li-Fi links. The findings indicate that relying solely on one technology is insufficient for achieving consistent, high-quality data exchange in marine environments. While acoustic systems excel at covering long distances, Li-Fi can deliver rapid transmission rates with minimal delay. Integrating these methods produces not only a viable engineering solution but also a strategic framework for advancing research, enhancing environmental monitoring, and improving maritime safety and emergency response capabilities.

The practical value of this concept is reinforced by simulation results, channel modelling, and the integration of adaptive signal processing techniques. Examples such as the environmental crises in the Black Sea and Caspian Sea highlight the relevance of such systems for applications like flood prediction, oil spill detection, and border surveillance. Overall, this hybrid design represents both a scientific contribution and a forward-looking technological opportunity that aligns with Kazakhstan's objectives for water resource management, environmental stewardship, and the expansion of its digital infrastructure.

The revised analysis also clarified the measurable outcomes of the study. The OptiSystem simulation showed a maximum Q-factor of 4.42596 and a minimum BER of 4.5894×10^{-6}, confirming acceptable signal quality for the selected set of modelling parameters. The laboratory prototype additionally confirmed the functional continuity of the transmitter–receiver chain, including audio input amplification, optical intensity modulation, photoresistor-based detection and output signal reproduction. However, the obtained prototype results should be interpreted as functional laboratory verification rather than full underwater field testing. Future work should therefore focus on controlled underwater experiments involving transmission distance, turbidity, optical alignment, water depth and comparative modulation analysis.

References

[1] Abdykadyrov, A., Smailov, N., Sabibolda, A., Tolen, G., Dosbayev, Z., Ualiyev, Z., & Kadyrova, R. (2024). Optimization of distributed acoustic sensors based on fiber optic technologies. *Eastern-European Journal of Enterprise Technologies*, *5*(5 (131)), 50–59. https://doi.org/10.15587/1729-4061.2024.313455

[2] Abdykadyrov, A., Yerishova, M., Kuttybayeva, A., Yermekbayev, M., & Amanzholov, A. (2025). Mechanisms of signal loss and reflection in optical fibers and their impact on radio direction finding efficiency in bent cable routes. *International Journal of Innovative Research and Scientific Studies*, *8*(3), 5056–5069. https://doi.org/10.53894/ijirss.v8i3.7706

[3] Ahmed, M., Alam, Md. M., & Arefin, M. S. (2023). An Experimental Study to Operate Underwater Vehicle Using Li-Fi: Advantages and Challenges. *2023 1st International Conference on Circuits, Power and Intelligent Systems (CCPIS)*, 1–4. https://doi.org/10.1109/CCPIS59145.2023.10291476

[4] Ali, A. A., Kumar, R. H., R. Dheenathalayan, N. Prasanth, V. Parthasaradi, S. Senthilkumar, & Kumar, T. S. (2023). Audio Streaming Using Li-FI Communication. *Irish Interdisciplinary Journal of Science & Research*, *07*(01), 01–07. https://doi.org/10.46759/IIJSR.2023.7101

[5] Ali, M. F., Jayakody, D. N. K., & Li, Y. (2022). Recent Trends in Underwater Visible Light Communication (UVLC) Systems. *IEEE Access*, *10*, 22169–22225. https://doi.org/10.1109/ACCESS.2022.3150093

[6] Al-Zhrani, S., Bedaiwi, N. M., El-Ramli, I. F., Barasheed, A. Z., Abduldaiem, A., Al-Hadeethi, Y., & Umar, A. (2021). Underwater Optical Communications: A Brief Overview and Recent Developments. *Engineered Science*, *16*, 146–186. https://doi.org/10.30919/es8d574

[7] Apoorva, N., Pragati, R. M., Impana, B., Anusha, K., & Siddalingappagouda, B. (2024). Underwater audio and data transmission system using Li-Fi technology. *International Research Journal of Modernization in Engineering Technology and Science*, *6*(5), 5713–5722. https://doi.org/10.56726/IRJMETS57039

[8] Campagnaro, F., Favaro, F., Casari, P., & Zorzi, M. (2014). On the feasibility of fully wireless remote control for underwater vehicles. *2014 48th Asilomar Conference on Signals, Systems and Computers*, 33–38. https://doi.org/10.1109/ACSSC.2014.7094391

[9] Chen, Y., Zhang, L., & Ling, Y. (2022). New approach for designing an underwater free-space optical communication system. *Frontiers in Marine Science*, *9*, 971559. https://doi.org/10.3389/fmars.2022.971559

[10] Codd-Downey, R., & Jenkin, M. (2018). Wireless Teleoperation of an Underwater Robot using Li-Fi. *2018 IEEE International Conference on Information and Automation (ICIA)*, 859–864. https://doi.org/10.1109/ICInfA.2018.8812544

[11] He, J., Li, J., Zhu, X., Xiong, S., & Chen, F. (2022). Design and Analysis of an Optical–Acoustic Cooperative Communication System for an Underwater Remote-Operated Vehicle. *Applied Sciences*, *12*(11), 5533. https://doi.org/10.3390/app12115533

[12] Intaniawati, L. S. J., Pantjawati, A. B., Saripudin, A., & Nurhidayatulloh. (2022). Underwater Wireless Optical Communication Using Li-Fi Technology In Data Transmission. *2022 5th International Seminar on Research of Information Technology and Intelligent Systems (ISRITI)*, 430–433. https://doi.org/10.1109/ISRITI56927.2022.10053033

[13] Jayaweera, V. L., Peiris, C., Darshani, D., Edirisinghe, S., Dharmaweera, N., & Wijewardhana, U. (2025). Visible Light Communication for Underwater Applications: Principles, Challenges, and Future Prospects. *Photonics*, *12*(6), 593. https://doi.org/10.3390/photonics12060593

[14] Johnson, L. J., Green, R. J., & Leeson, M. S. (2013). Underwater optical wireless communications: Depth dependent variations in attenuation. *Applied Optics*, *52*(33), 7867. https://doi.org/10.1364/AO.52.007867

[15] Kaushal, H., & Kaddoum, G. (2016). Underwater Optical Wireless Communication. *IEEE Access*, *4*, 1518–1547. https://doi.org/10.1109/ACCESS.2016.2552538

[16] Kiesewetter, D., Krivosheev, S., Magazinov, S., Malyugin, V., Koshkinbayev, S., & Smailov, N. (2022). Measurement of High-Speed Deformations Using Fiber Bragg Gratings. *2022 International Conference on Electrical Engineering and Photonics (EExPolytech)*, 324–327. https://doi.org/10.1109/EExPolytech56308.2022.9950795

[17] Kuttybayeva, A., Sabibolda, A., Kengesbayeva, S., Baigulbayeva, M., Amir, A., & Sekenov, B. (2024). Investigation of a Fiber Optic Laser Sensor with Grating Resonator Using Mirrors. *2024 Conference of Young Researchers in Electrical and Electronic Engineering (ElCon)*, 709–711. https://doi.org/10.1109/ElCon61730.2024.10468264

[18] Oubei, H. M., Shen, C., Kammoun, A., Zedini, E., Park, K.-H., Sun, X., Liu, G., Kang, C. H., Ng, T. K., Alouini, M.-S., & Ooi, B. S. (2018). Light based underwater wireless communications. *Japanese Journal of Applied Physics*, *57*(8S2), 08PA06. https://doi.org/10.7567/JJAP.57.08PA06

[19] Pal, A., Campagnaro, F., Ashraf, K., Rahman, M. R., Ashok, A., & Guo, H. (2023). Communication for Underwater Sensor Networks: A Comprehensive Summary. *ACM Transactions on Sensor Networks*, *19*(1), 1–44. https://doi.org/10.1145/3546827

[20] Qu, Z., & Lai, M. (2024). A Review on Electromagnetic, Acoustic, and New Emerging Technologies for Submarine Communication. *IEEE Access*, *12*, 12110–12125. https://doi.org/10.1109/ACCESS.2024.3353623

[21] Rajan, S., C, Nagaraj., B.S, V. Murthy., Srivastava, A., M R, V., & Karadi, D. S. (2024). Development of Underwater Communication System Using Li-Fi Technology. *2024 5th International Conference on Circuits, Control, Communication and Computing (I4C)*, 509–514. https://doi.org/10.1109/I4C62240.2024.10748501

[22] Saeed, N., Celik, A., Al-Naffouri, T. Y., & Alouini, M.-S. (2019). Underwater optical wireless communications, networking, and localization: A survey. *Ad Hoc Networks*, *94*, 101935. https://doi.org/10.1016/j.adhoc.2019.101935

[23] Smailov, N., Koshkinbayev, S., Yssyraiyl, K., Kuttybayeva, A., Yussupova, G., Batyrgaliyev, A., & Sabibolda, A. (2026). Fiber Bragg Grating-Based Deformation Monitoring in Space Infrastructure: A Comprehensive Review. *Journal of Sensor and Actuator Networks*, *15*(3), 38. https://doi.org/10.3390/jsan15030038

[24] Smailov, N., Tsyporenko, V., Ualiyev, Z., Issova, A., Dosbayev, Z., Tashtay, Y., Zhekambayeva, M., Alimbekov, T., Kadyrova, R., & Sabibolda, A. (2025). Improving accuracy of the spectral-correlation direction finding and delay estimation using machine learning. *Eastern-European Journal of Enterprise Technologies*, *2*(5 (134)), 15–24. https://doi.org/10.15587/1729-4061.2025.327021

[25] Smailov, N., Zhadiger, T., Tashtay, Y., Abdykadyrov, A., & Amir, A. (2024). Fiber laser-based two-wavelength sensors for detecting temperature and strain on concrete structures. *International Journal of Innovative Research and Scientific Studies*, *7*(4), 1693–1710. https://doi.org/10.53894/ijirss.v7i4.3481

[26] Taissariyeva, K., Abdykadyrov, A., Mussilimov, K., Jobalayeva, G., & Marxuly, S. (2025). Analysis and Modeling of Environmental Monitoring Using Multicopters. *International Journal of Innovative Research and Scientific Studies*, *8*(3), 2947–2960. https://doi.org/10.53894/ijirss.v8i3.7119

[27] Zeng, Z., Fu, S., Zhang, H., Dong, Y., & Cheng, J. (2017). A Survey of Underwater Optical Wireless Communications. *IEEE Communications Surveys & Tutorials*, *19*(1), 204–238. https://doi.org/10.1109/COMST.2016.2618841

[28] Zhang, H., Liu, L., Yang, C., Yang, Z., Wang, Q., Yao, B., Zhang, Z., Wang, X., Shi, X., Liu, D., & Xue, C. (2023). Cooperative Control of Multiple Underwater Robots Based on Brief Binary Optical-Acoustic Dual Signals. *IEEE Access*, *11*, 136924–136933. https://doi.org/10.1109/ACCESS.2023.3338630

[29] Zhu, S., Chen, X., Liu, X., Zhang, G., & Tian, P. (2020). Recent progress in and perspectives of underwater wireless optical communication. *Progress in Quantum Electronics*, *73*, 100274. https://doi.org/10.1016/j.pquantelec.2020.100274

[30] Zilgarayeva, A., Smailov, N., Pavlov, S., Mirzakulova, S., Alimova, M., Kulambayev, B., & Nurpeissova, D. (2024). Optical sensor to improve the accuracy of non-invasive blood sugar monitoring. *Indonesian Journal of Electrical Engineering and Computer Science*, *34*(3), 1489. https://doi.org/10.11591/ijeecs.v34.i3.pp1489-1498

Ph.D. Nurzhigit Smailov
e-mail: n.smailov@satbayev.university

Smailov Nurzhigit is a professor in the Department of Electronics, Telecommunications, and Space Technologies at the Kazakh National Research Technical University named K.I. Satbayev (KazNRTU), Almaty, Kazakhstan. He received his B.Eng., M.Eng., and Ph.D. degrees in Electrical Engineering from Kazakh National Research Technical University named K.I. Satbayev, in 2010, 2011, and 2016, respectively.
Research interests: electronics, radio engineering, optical sensors.

https://orcid.org/0000-0002-7264-2390

M.Sc. Aizhan Urazgaliyeva
e-mail: a.urazgaliyeva@satbayev.university

Aizhan Urazgaliyeva is a Master's student in the Department of Electronics, Telecommunications, and Space Technologies at the Kazakh National Research Technical University named after K.I. Satbayev (KazNRTU), Almaty, Kazakhstan. She received her B.Eng. degree in Electrical Engineering from Kazakh National Research Technical University named after K.I. Satbayev in 2024.
Research interests: Internet of Things (IoT), electronics, radio engineering.

https://orcid.org/0009-0004-0594-9327

Ph.D. Akezhan Sabibolda
e-mail: sabibolda98@gmail.com

Akezhan Sabibolda holds a Ph.D. in Telecommunications from the Kazakh National Research Technical University named after K.I. Satbayev. He received his master’s degree in Telecommunications and Radio Engineering from the State University "Zhytomyr Polytechnic", Ukraine, in 2021. His research interests include radio monitoring, direction finding, digital signal processing, cybersecurity, and telecommunications.

https://orcid.org/ 0000-0002-1186-7940