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AI-Enabled Hybrid Optical–Acoustic Communication for UUVs Using WDM-OOK: Design and Real-Time Performance Evaluation

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Abstract: One of the key challenges is reliable communication for Unmanned Underwater Vehicles (UUVs) since underwater environments are dynamic and challenging for signal transmission. The traditional acoustic communication systems allow long-distance communication but are limited by the low bandwidth, high latency, and doppler effect. Optical wireless, on the other hand, provides high data rates with water absorption and scattering occurring within the transmission distance, but has a short range of communication. To overcome these drawbacks, a smart hybrid optical-acoustic communication system is proposed that is a combination of Wavelength Division Multiplexing and On-Off Keying (WDM-OOK) to transmit a high-speed signal over optical and acoustic channels to achieve high reliability of long-range communication. The design of an intelligent hybrid optical–acoustic communications network to improve the continuity, reliability, and throughput of the communication between a UUV system is the focus of this research. It is a combination of a simple model of Multilayer Perceptron (MLP), a real-time communication mode switch, an optical subsystem (Wavelength Division Multiplexing On–Off Keying (WDM-OOK)), and an acoustic communication subsystem. The system has been modelled and simulated in MATLAB/Simulink and synthesized in HDL Coder as it will be implemented on an FPGA (Kintex-7 325T). The results of the simulations validate the superiority of the proposed hybrid method (hybrid with AI) over the purely optical method, the purely acoustic method, and the hybrid method without AI. The minimum BER recorded on this platform was (10^{-7}), the average throughput was 152 Mbps, and the end-to-end latency time was 12.7ms with good water clarity. The FPGA synthesis results also show that the model was appropriate for real-time implementation with only 18.1% of the LUTs, 10.5% of the flip-flops, 23.6% of the BRAMs, and 17.4% of the DSPs utilized for the Kintex-7 325T FPGA. The results verified the feasibility of the proposed hybrid optical–acoustic communication system, where the high-speed feature of using the optical communication WDM-OOK system and the robustness of the acoustic communication system are provided by the intelligent adaptive switching. The proposed framework is feasible and is scalable for underwater reliable real-time communication between unmanned optical vehicles (UOVs) in underwater unmanned vehicle networks (UUVnets) in the near future.

Keywords: Underwater communication, Unmanned Underwater Vehicle, Wavelength Division Multiplexing On–Off Keying, Hybrid optical acoustic communication, Adaptive systems, Artificial Intelligence.

1. Introduction

Unmanned Underwater Vehicles (UUVs) in underwater applications such as ocean monitoring, environmental sensing, offshore exploration, and military surveillance have made underwater communication a vital research area [1], [2]. The existing methods of underwater communication are mainly based on acoustic methods, and optical methods have many drawbacks such as low bandwidth, high latency, and limited data transmission capabilities are among the drawbacks of acoustic communication, which is characterized by long-range connectivity. In contrast, optical communication will have high data rates and low latency, but will quickly start to degrade with absorption, scattering, and water turbidity [3].

Hybrid optical–acoustic communication systems have been proposed to take advantage of both techniques [4]. The proposed systems are based on a fixed threshold switching scheme that is not able to efficiently adapt to changing channel conditions in the ocean environment. Moreover, real-time hardware implementation and communication management with AI have not yet been completely investigated. To overcome these limitations, an optical subsystem based on WDM-OOK and an acoustic communication subsystem are introduced into the system, and the lightweight MLP-based intelligent switching mechanism is implemented on an FPGA platform [5]. The proposed system can dynamically adjust the communication mode based on the channel conditions to enhance communication reliability, speed, and adaptability for UUV applications.

The main contributions of this study are:

- A novel hybrid optical–acoustic communication architecture for UUVs, which is enabled by an artificial intelligence (AI) system.
- An intelligent adaptive link-switching mechanism based on the real-time channel conditions.
- FPGA implementation using MATLAB HDL Coder and Kintex-7 325T, and
- Comprehensive performance evaluation that shows the superior BER, throughput, and communication reliability in dynamic underwater scenarios. The combination of the AI-based adaptive link selection and the hybrid WDM-OOK optical–acoustic communication system on a Kintex-7 FPGA platform is the main novelty of this work. To realize high-speed optical transmission, reliable acoustic communication, and real-time intelligent mode switching in underwater communication, the proposed framework adopts these three methods.

The remainder of this paper is organized as follows: Section 2 reviews the related work, Section 3 presents the methodology, Section 4 discusses the results, and Section 5 concludes the paper.

2. Related Works

The most recent research work on underwater communication systems has been on the improvement of the drawbacks of the classical acoustic communication, such as low bandwidth, high latency, and strong multipath effects. Underwater optical wireless communication (UOWC) has been studied by several researchers due to its low latency and high-speed data transmission capabilities [6], [7]. Optical communication systems are very susceptible to one or more of these factors: absorption, scattering, alignment error, and water turbidity, which also limit the range and reliability of transmission [8]. To address these challenges, hybrid optical–acoustic communication architectures have been proposed that leverage the strengths of both link types, namely high-data-rate optical links and robustness and long-range acoustic links [9], [10]. In addition, recent developments in artificial intelligence (AI) and FPGA-based communication systems have made it possible to implement adaptive underwater communication techniques that support real-time channel estimation and dynamic mode selection [11]. Research into underwater communications has recently concentrated on five main topics: underwater optical communication, acoustic communication, hybrid optical–acoustic systems, AI-based adaptive communication, and FPGA-based real-time implementation. The underwater optical communication attracts a lot of interest for its capabilities of high data rate and low latency for the transmission of a large volume of sensor and multimedia data [12], [13].

Optical links, severely degraded by absorption, scattering, beam divergence, and water turbidity, greatly reduce the distance over which they can successfully transmit signals and the quality of the communication [14]. On the other hand, acoustic communication is the major technology for long-range underwater communication due to its robustness in an adverse environment. However, the bandwidth, throughput, and propagation delay are low in acoustic systems, making them ineffective in real-time applications [15], [16]. Based on the complementary benefits of both approaches, several hybrid optical–acoustic communication systems have been proposed. Typically, these systems enhance the availability of communication links by automatically changing between optical and acoustic modes based on channel conditions. However, the current hybrid methods mostly use threshold-based switching strategies, which do not have the ability to adapt in an efficient way to fast-changing underwater conditions. More recently, the use of artificial intelligence and machine learning has been championed to improve the ability to adapt communication and make decisions. While these methods show good results, there are numerous already established AI models that are computationally heavy and challenging to use in resource-constrained applications on real-time hardware. Moreover, the reported FPGA communication module-based implementations from the literature are limited to a single communication module but not to complete AI-enabled hybrid architectures. Thus, there is a significant research gap in designing an intelligent, lightweight, and hardware-efficient hybrid communication framework with adaptive communication management and real-time implementation.

To overcome this, the proposed system uses a WDM-OOK optical communication subsystem, an acoustic communication subsystem, and a lightweight MLP-based intelligent switching mechanism in a Kintex-7 FPGA platform. The proposed framework keeps a continuous track of the channel-state parameters such as SNR, BER, communication distance, and water turbidity, dynamically switching the communication mode to maximize throughput, communication reliability, adaptability, and practical deployment feasibility for UUV.

3. Methodology

The hybrid optical-acoustic communication system proposed for adoption in Unmanned Underwater Vehicles (UUVs) is going to be a two-layer communication system of Wavelength Division Multiplexing (WDM) and On-Off Keying (WDM-OOK) model. Under this architecture, the underwater channels can dynamically change according to the intelligent decision module, which will be based on AI. The general system model will be broken down into three interdependent subsystems: the environmental subsystem, the optical communication subsystem, the other being the acoustic communication subsystem, and the AI-assisted adaptive control subsystem [17]. Furthermore, the optical subsystem enables high-speed data transmission when channel conditions are favorable, allowing efficient, low-latency transmission over short distances [18]. The acoustic subsystem is used for long-range sound connection in situations where the optical system is not working due to absorption, scattering, turbidity, and/or transmission distance [19]. The critical environmental and channel data that are captured, such as distance to the link, water clarity, signal-to-noise ratio (SNR), and vehicle speed, are all continuously captured by the control subsystem, which is driven by AI [20]. Based on these inputs, it makes decisions on the most appropriate mode of communication to adopt in real time, whether it would be the optical link in real time, the acoustic link in real time, or it would adopt an integrated hybrid operation mode. It is an adaptive technique that makes it possible for the system to be reliable for communication and achieve maximum throughput and minimum delay in different underwater scenarios.

The proposed model may enable the realization of a scalable and smart communication system for next-generation UUV operations in a complex marine environment by combining three subsystems in one model. The optical channel is mainly affected by phenomena of absorption and scattering and significantly limits propagation distance [21]. The Beer-Lambert law can be used to model the optical power received as in Eq(1) below:

$$P_r = P_t\, e^{cd} \qquad (1)$$

The optical power transmitted is denoted by (P_t), and the optical power received is denoted by (P_r). The attenuation coefficient of water is denoted by (c), and the transmission distance is denoted by (d), which is dependent on the wavelength.

In the proposed WDM-OOK architecture, in which the transmitted signal is divided into several wavelength channels, as described in Eq.(2) :

$$S_{\mathrm{WDM}}(t) = \sum_{i=1}^{N} \mathrm{b}_i(\mathrm{t}) P_i \cos(2\pi \mathrm{f}_i \mathrm{t}) \qquad (2)$$

N: Number of WDM channels, $\mathrm{b}_i(\mathrm{t}) \in \{0,1\}$ represents the OOK-modulated binary data sequence, P_i is the optical power associated with the i^{th} wavelength channel, f_i denotes the optical carrier frequency corresponding to wavelength λ_i

The attenuation coefficient can be expressed as in Eq.(3).

$$c = a + b \qquad (3)$$

a: absorption coefficient, b: scattering coefficient

The acoustic channel is a multipath fading model that is modeled based on propagation delays, Doppler shifts, and additive Gaussian noise [22]. Several delayed versions of the signal may reach the receiver due to reflections from the ocean bottom, ocean waters, or other obstacles. The acoustical received signal that can be retrieved as shown in Eq(4) :

$$r_a(\mathrm{t}) = \sum_{i=1}^{L} \alpha_i s_a(t - \tau_i)\, e^{j2\pi f_{d,i} t} + n_a(t) \quad (4)$$

We have $r_a(t)$: The received acoustic signal, $s_a(t)$: Transmitted signal,α_i attenuation coefficient of the i^{th} propagation path, τ_i: propagation delay, and $f_{d,i}$ is the Doppler frequency, L Number of multipath components, and $n_a(t)$ is the additive white Gaussian noise. These are the inter-symbol interference from delayed versions of the signal, and Doppler shifts that can cause distortion to the carrier frequency and timing synchronism, and thus cause noise to impair the accuracy of detecting a signal. In spite of such difficulties, acoustic communication is still useful since it can be reliable for communicating over larger distances compared to optical links [23].

This model mimics the main challenges involved in underwater acoustics. Inter-symbol interference, Doppler shifts that distort carrier frequency and timing synchronism, and noise are caused by the delayed copies of the signal [24]. Despite these problems, acoustic communication has proven to be useful because it can be accurate and also offers longer-range connectivity between these points than optical communication. The acoustic subsystem contains adaptive equalization and Forward Error Correction (FEC) to minimize the impairments on the channels [25], [26]. FEC enhances reliability by identifying and correcting the transmission errors, and adaptive equalization corrects the multipath distortion and the time-varying channel effects. These are the techniques that improve the strength of communication in demanding underwater conditions. The acoustic channel signal-to-noise ratio (SNR) is given as

$$\mathrm{SNR} = \frac{P_s}{P_n} \quad (5)$$

and P_s: signal power received, P_n: power of noise at the receiver. The SNR may also be expressed in Decibels as:

$$\mathrm{SNR_{dB}}=10\log_{10}(P_s/P_n) \quad (6)$$

An increased SNR corresponds to an improved channel quality, resulting in reduced bit error rates and increased dependability of channel acoustic communication.

The BER for OOK modulation can be expressed as Eq (7)

$$BER = \frac{1}{2} erfc\,\left(\sqrt{\frac{SNR}{2}}\right) \quad (7)$$

erfc: Complementary error function

An artificial intelligence (AI) module is proposed to enable real-time selection between optical and acoustic communication modes, ensuring optimal communication performance under dynamically varying underwater conditions. The proposed MLP has three layers: an input layer, a hidden layer, and an output layer. The input layer has four neurons, representing each communication state parameter, such as (SNR, BER, Distance, and Turbidity). Low computational complexity and FPGA compatibility require using a single hidden layer with 8 neurons. The output layer includes three neurons, which correspond to the communication modes: optical, acoustic, and hybrid mode. The input feature vector of the MLP can be defined as Eq (8):

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$$X=[SNR_{opt}, SNR_{ac}, BER_{opt}, BER_{ac}, d, T, v]^T \quad (8)$$

SNR_{opt}: optical signal-to-noise ratio, SNR_{ac}, acoustic signal-to-noise ratio, d: transmission distance, T: water turbidity level,v: UUV velocity, $BER_{opt:}$ bit error rate optical, BER_{ac}: bit error rate acoustic.

The hidden layer output is expressed as in Eq.(9):

$$h = f(W_1x) + b_1) \quad (9)$$

(W) : weight matrices of the hidden layer, b: bias vector, f(.): is a nonlinear activation function, h: hidden layer output vector. identifies which mode of communication should be active, with 0 being optical WDM-OOK transmission and 1 being acoustic fallback communication.

The AI-based decision-making is applied with a lightweight multilayer perceptron (MLP) as Eq.(10)

$$y = g(W_2h) + b_2) \quad (10)$$

W: output layer weight matrix, b: output layer bias vector, g(.) activation function, y: decision output.

The communication mode selection is described as Eq.(11)

$$M= \text{argMax}\ (Y_{opt}, Y_{ac}) \quad (11)$$

Where M=0 for optical WDM-OOK Link.

M=1, Acoustic Link.

Y_{opt}, $Y_{ac:}$ Optical and acoustic link score.

The lightweight MLP decision function is used for the implementation of the Kintex-7 FPGA described in Eq. (12)

$$M = F\ (SNR_{opt}, SNR_{ac}, d, T, v) \quad (12)$$

F(.): Trained MLP model for optimal communication mode.
A lightweight Multilayer Perceptron (MLP) is adopted to select the optimal communication mode of the optical WDM-OOK link and the acoustic communication link in real time, to enable adaptive communication in the dynamic underwater environment. The main goal of the AI module is to optimize the effective throughput while ensuring reliable communication under different channel conditions. The system will be in a position to utilize smart decision-making to dynamically select the optimal transmission mode on the basis of real-time conditions by collaborating to model complementary properties of optical and acoustic channels and approach the problem. The framework facilitates capable, low-latency, and high-throughput communication of Unmanned Underwater Vehicles (UUVs), which factors in its applicability to real-time hardware platforms based on FPGAs. The parameters of the MLP's are optimized using the categorical cross-entropy loss and the Adam optimizer:

$$L = -\frac{1}{N}\sum_{i=0}^{nN}\sum_{j=0}^{C} y_{ij} \log(\hat{y}_{ji}) \quad (13)$$

y_{ij} : true class label, $\hat{y}_{ij}$: predicted probability generated by the MLP model, N: number of training samples, C: Output classes

The proposed methodology is based on the design and implementation of an AI-enabled hybrid optical–acoustic communication system for Unmanned Underwater Vehicles (UUVs). The system is based on high-speed optical communication, with wavelength division multiplexing and on–off keying (WDM-OOK), and includes a reliable acoustic communication link for the long-range underwater transmission. The data set was obtained through MATLAB simulations under various underwater channel situations. The optical and sound subsystems are tested under different SNR levels. Transmission distances, Water turbidity conditions, Channel attenuation. The average latency of inference of the Kintex-7 FPGA is less than 1ms, suitable for real-time adaptive communication. Figure 1 describes the flow process chart of the proposed model using MATLAB, HDL coder, and Kintex-7 FPGA. Firstly, the data are encoded and split into several parallel optical channels, with each channel of the wavelength channels being modulated by employing OOK modulation techniques. The optical signals pass through an underwater optical channel where they experience water turbidity, scattering, and attenuation. At the same time, the acoustic communication subsystem serves as a backup communication link with a reliable connection when the optical communication link is degraded.

At the receiver side, both optical and acoustic signals are processed to estimate important communication parameters such as signal-to-noise ratio (SNR), bit error rate (BER), and channel quality. A real-time channel condition analyzer based on artificial intelligence (AI) is then used to analyze real-time channel conditions and dynamically determine the optimal communication mode between optical and acoustic links. The entire system is modeled and simulated in MATLAB/Simulink, and HDL Coder is used to achieve hardware compatibility and to generate the VHDL/Verilog code for deployment on the FPGA. Lastly, the proposed architecture is realized on a Kintex-7 325T FPGA board, and its performance is measured at the real-time application level with various underwater environments in terms of BER, throughput, latency, and adaptive mode switching efficiency.

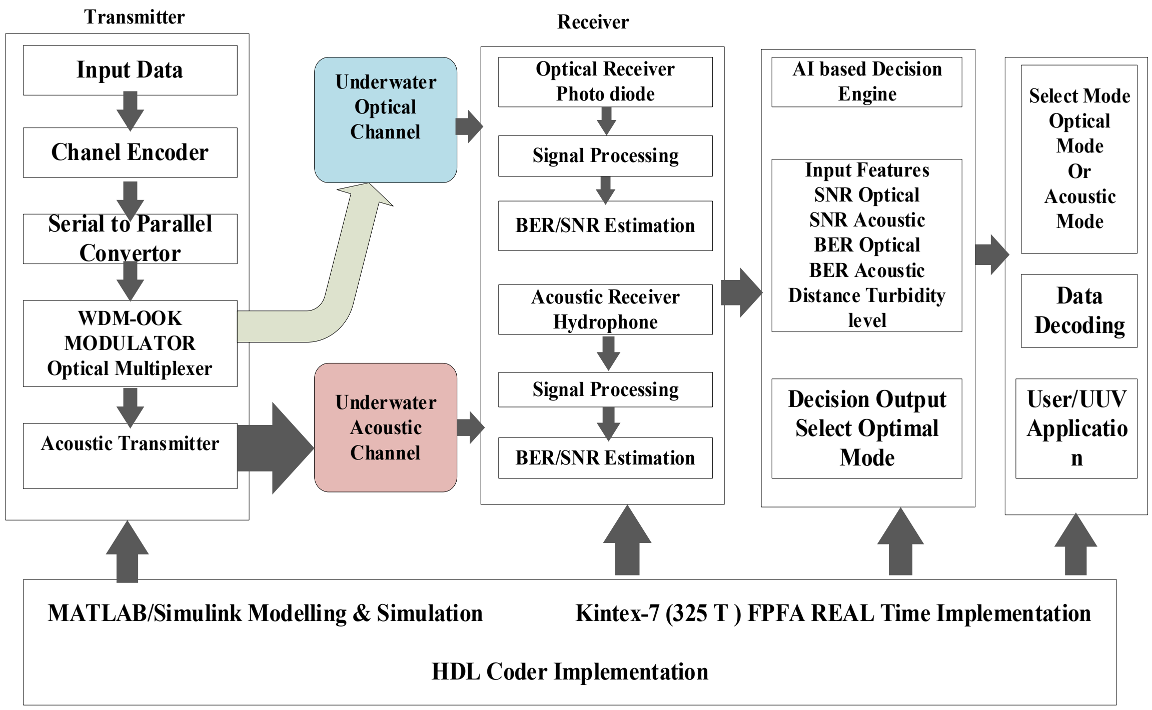

Figure 1. Proposed AI-enabled hybrid optical acoustic communication system.

The proposed MLP was designed with 4 input neurons related to channel-state features (SNR, BER, transmission distance, and water turbidity); a hidden layer having 12 ReLU activation neurons; and an output layer having 3 neurons corresponding to the types of optical, acoustic, and hybrid communication modes. The network has been trained with the Adam optimizer with a learning rate of 0.001 and categorical cross-entropy loss. A batch size of 32 samples and a max number of training epochs of 100 were used.
The dataset was split into a training set of 70% of the data, a validation set of 15% of the data, and a test set of 15% of the data. The SoftMax activation function was employed in the output layer to

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obtain class probabilities, and the class with the highest probability was chosen as the final decision. The training parameters of the MLP are summarized in Table 1. Thus, this setup offers a lightweight structure that can be implemented in real time on FPGAs and still achieves high classification accuracy when selecting the communication mode.

Table 1. MLP algorithm parameters

No.	Parameter	Value
1	Input Features	SNR, BER, Distance, Turbidity
2	Number of Input Neurons	4
3	Hidden Layers	1
4	Hidden Neurons	12
5	Hidden Activation Function	ReLU
6	Output Neurons	3
7	Output Classes	Optical, Acoustic, Hybrid
8	Output Activation Function	Softmax
9	Optimizer	Adam
10	Learning Rate	0.001
11	Loss Function	Categorical Cross-Entropy
12	Batch Size	32
13	Epochs	100
14	Training Split	70%
15	Validation Split	15%
16	Testing Split	15%

4. Results and Discussion

The acoustic subsystem can be ensured to work reliably with a higher latency in long-range conditions. AI-powered switching mechanism makes the system stronger because the switching mode is dynamically determined according to the suitable mode to communicate.

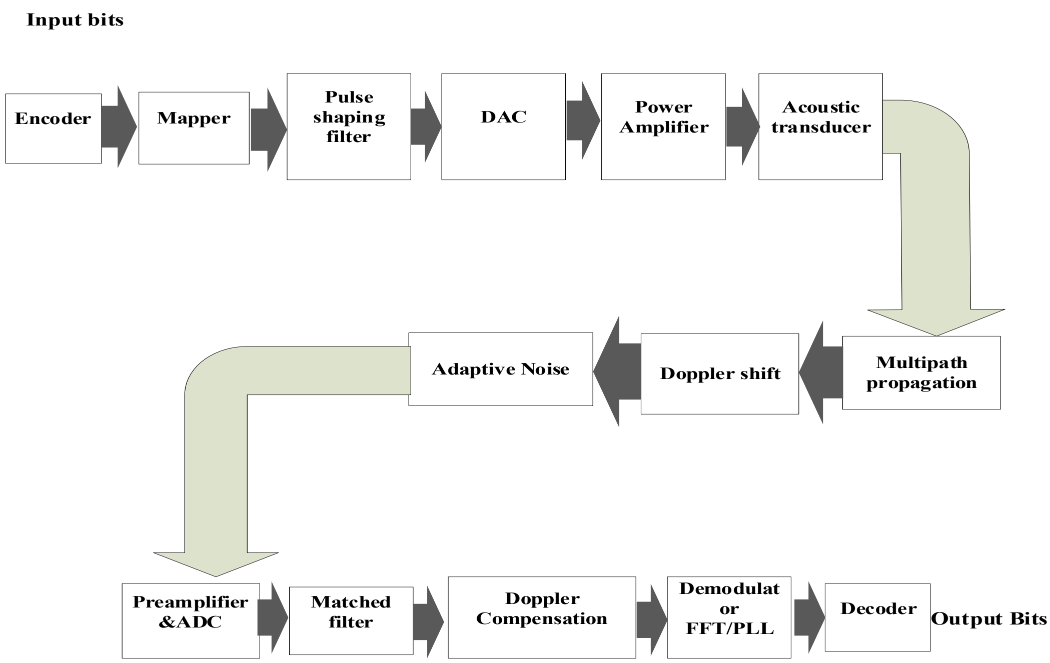

Figure 2. The acoustic communication subsystem

The acoustic communication subsystem is shown in Figure 2, and its stability in the harsh underwater environment is indicated. Forward error correction and Doppler compensation make the signal stronger by reducing the impact of multipath fading and distortion due to the movement of the platform. These processing steps are particularly important in dynamic underwater environments where the variability in the channels may play a significant role in the quality of the communication process. Despite the fact that the subsystem has lower data rates than optical communication, it has a stable and reliable transmission over longer distances. This experiment has proved its worth as an alternative means of communication in the hybrid system proposed and as a continuity at times when optical connections fail.

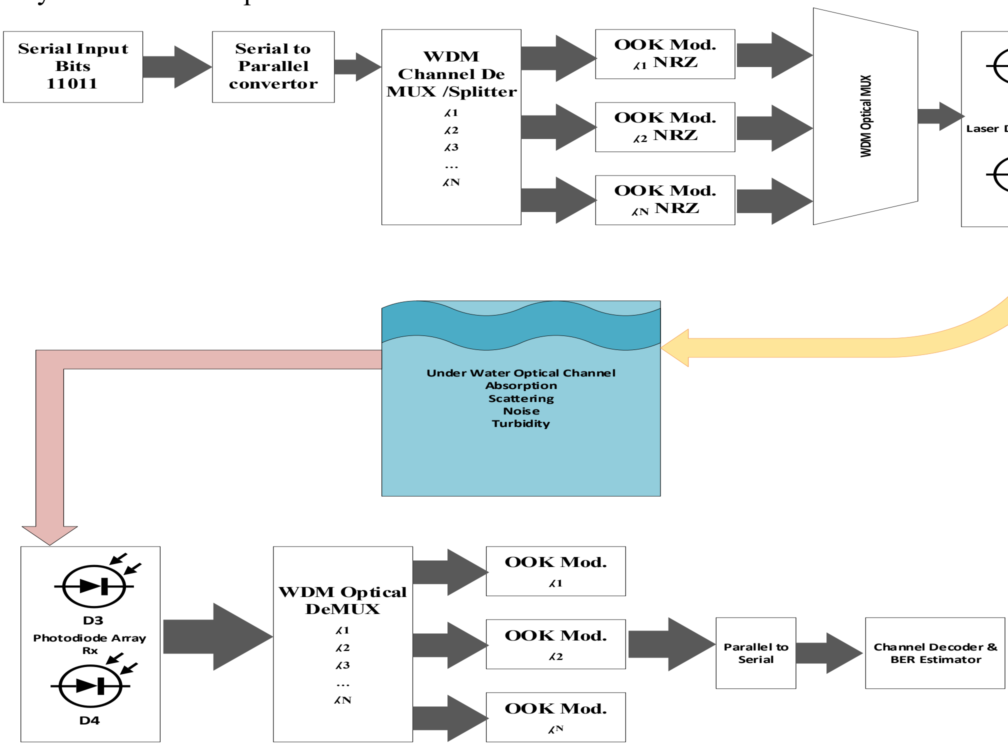

Figure 3. WDM optical subsystem

Figure 3: Using a combination of wavelength division multiplexing (WDM) and on–off keying (OOK) modulation techniques, the goal of the WDM-OOK optical subsystem is to achieve high-speed underwater data transmission. In this subsystem, an input data stream is segmented into several parallel data streams, each of which is transmitted at a different optical wavelength. The modulation technique used is OOK because of its low complexity, low-power requirement, and ease of implementation on an FPGA. Laser diodes are used for optical transmission in underwater optical channels and the optical reception is carried out at the receiver by means of photodetectors and optical demultiplexers. Due to limitations of underwater attenuation, scattering, absorption, and water turbidity, the optical subsystem has a high data rate and low latency. Thus, the proposed system includes adaptive switching based on artificial intelligence for communication reliability in different environmental conditions. Figure 4 displays the input feature vector, consisting of optical SNR, acoustic SNR, transmission distance, water turbidity, and UUV velocity, and the multilayer perceptron (MLP)- based real-time communication mode selection. The findings suggest that the selected input features are effective in reflecting the dynamic nature of underwater communication channels. The model will allow measuring the actual conditions with the help of the environmental and link-quality parameters, thus identifying the most appropriate transmission mode. The MLP architecture is lightweight because of the tradeoff between the precision of the decision and computation speed, and, hence, is very practical to implement in an FPGA. It is relatively simple in

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complexity, which reduces processing latency and hardware resource consumption and does not affect processing reliability. The figure confirms that the implementation of real-time adaptive control can be achieved with minimal hardware overhead, where efficient real-time implementation can be performed in a resource-constrained UUV platform.

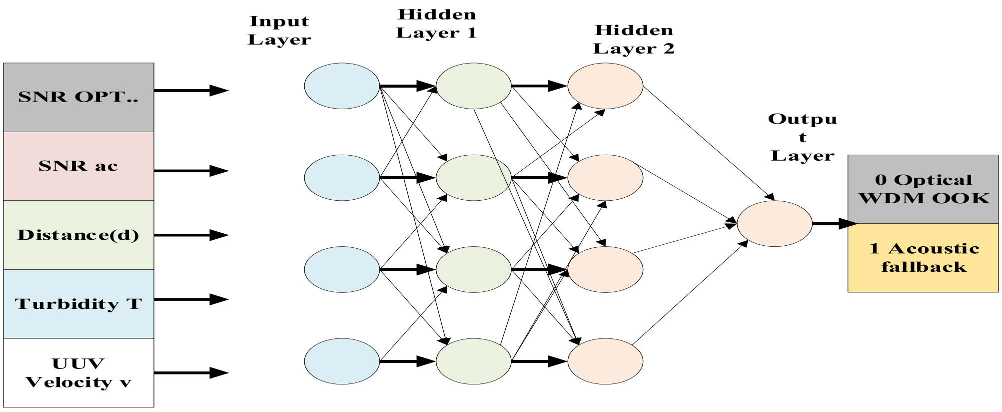

Figure 4. Presents the architecture of the AI-based adaptive link selection module

The performance of the optical WDM-OOK link with respect to the distance of transmission, as in Figure 5, according to the bit error rate (BER). The results show that the BER values are extremely low in the short-range transmission under different water conditions, showing that it is suitable for transmitting high-speed communication in this unfriendly underwater environment. A steep decline in BER is witnessed as the transmission distance increases since the attenuation of optical signals in water is exponential. The scattering effects also make a contribution to this degradation, because of the attenuation of the signal and the degradation of the receiver accuracy. The behavior observed is consistent with the theoretical underwater optical channel model and emphasizes the fundamental limitation of optical communication in the underwater environment.

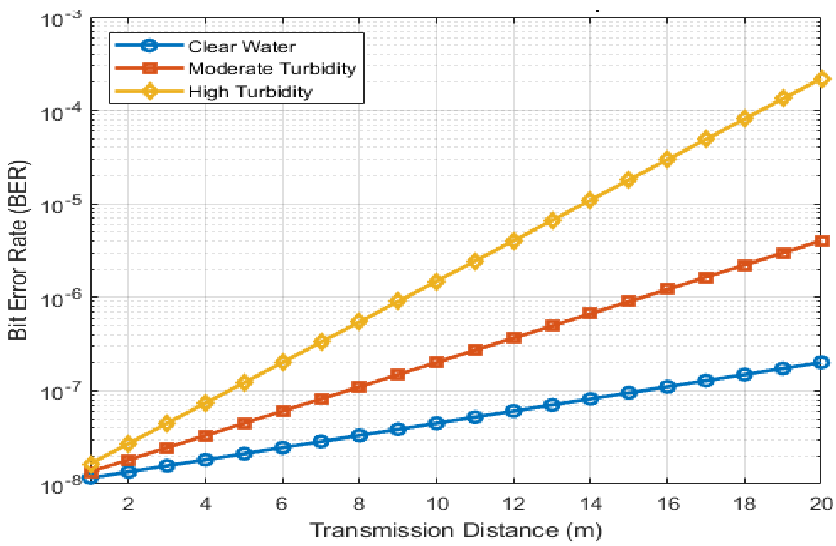

Figure 5. BER performance of transmission distance

The BER performance of the proposed WDM-OOK optical link is depicted in Figure 6 for different water conditions. Optical attenuation, absorption, and scattering make the BER worse with transmission distance. Progressively higher values of BER are found in water of increasingly high turbidity, while clear water has the lowest value of BER. The results show that the turbidity of water has a significant impact on the reliability of optical communication and transmission distance. Therefore, the proposed hybrid communication system with the use of an acoustic link when the quality of the optical channel is degraded provides reliable communication in various underwater environments.

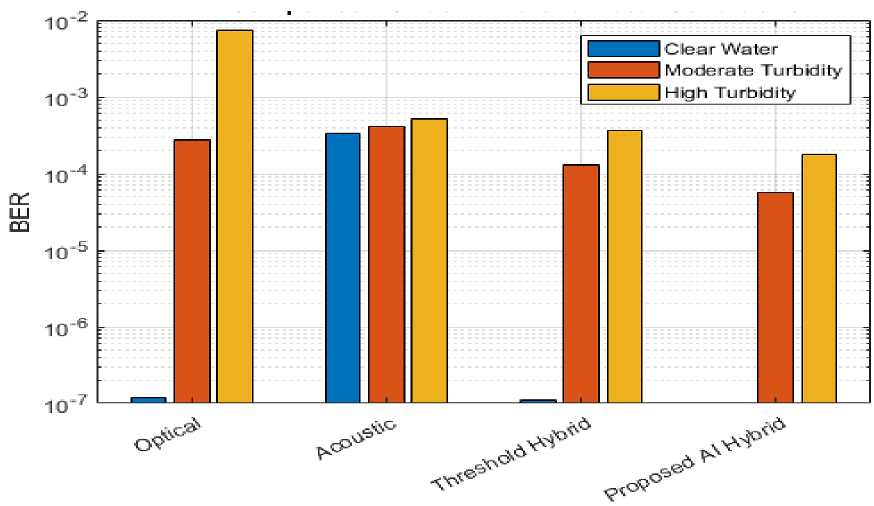

Figure 6. BER under different water conditions

Figure 7 illustrates the throughput of optical, acoustic, and hybrid communication modes for different transmission distances. The optical WDM-OOK link has the characteristics of large bandwidth and low latency and can realize the highest speed over short distances. But, as the transmission distance increases, optical throughput reduces due to the effects of attenuation, absorption and scattering in the water. The acoustic link, though, has a relatively stable throughput across the entire range, but has a low bandwidth. The proposed hybrid communication system with the combination of both technologies has the benefit of using the optical link when performance is satisfactory and switching to the acoustic link when the optical link's performance is not satisfactory. The hybrid system thus has a higher average throughput and better communication continuity than standalone optical or acoustic communication systems.

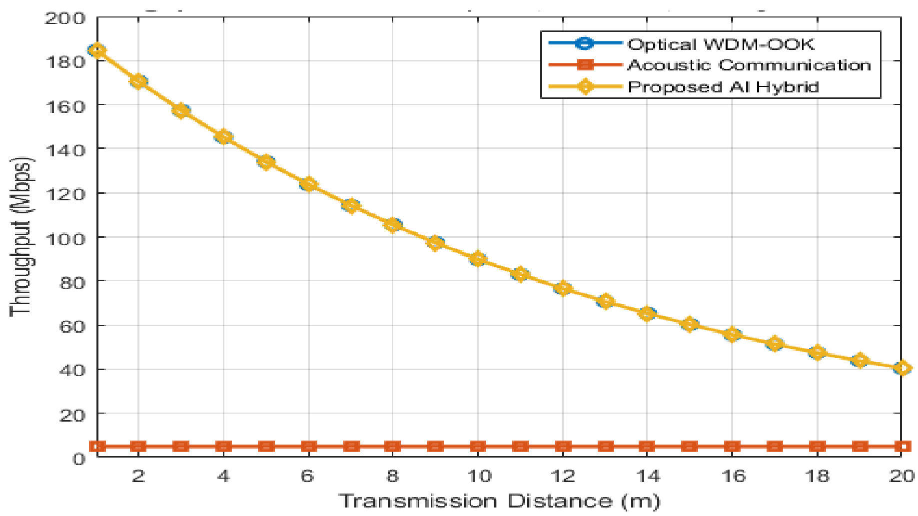

Figure 7. Throughput performance of the optical, acoustic, and proposed AI hybrid communication

The FPGA synthesis results, as in Figure 8, confirm that the proposed AI-based hybrid communication system consumes more hardware resources than optical-only, acoustic-only, and

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the conventional proposed architecture is suitable for supporting real-time communication processing systems with sufficient resources for future enhancements, such as deploying additional hybrid communication systems because of the incorporation of an MLP-based switching engine and the dual communication subsystems. However, the utilization is still relatively low, using 10.5% of LUTs, 6.9% of flip-flops, 15.3% of BRAM resources, and 11.2% of the platform's available DSP48 slices on the Kintex-7 325T platform. The findings show that the architecture proposed can be suitable for supporting real-time communication processing systems with a sufficient amount of resources for future enhancements, such as deploying further WDM channels, implementing advanced channel coding schemes, or integrating more complex AI models. This validates the feasibility and scalability of the proposed FPGA implementation of UUV communication applications.

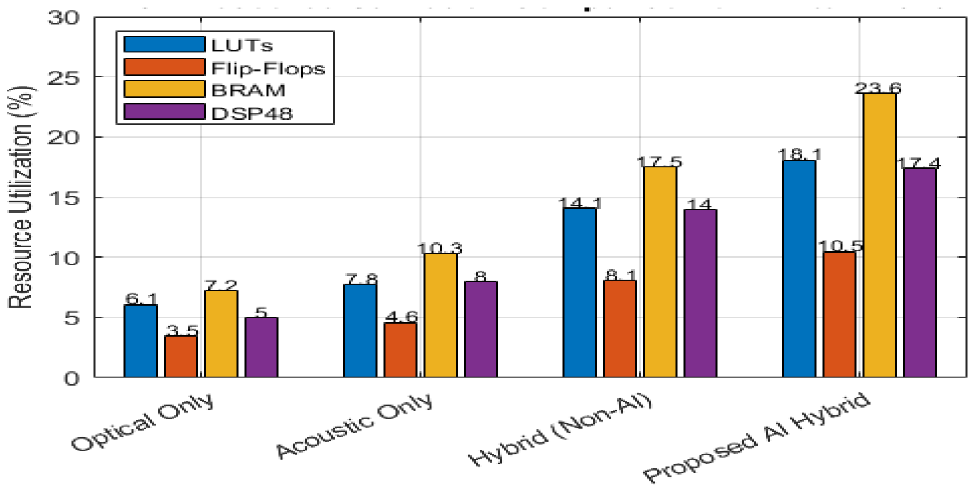

Figure 8. FPGA resource utilization of the proposed system implemented on the Kintex-7 325T platform

Table 2 shows that the proposed hybrid communication system with the aid of artificial intelligence possesses good performance characteristics in both optical and acoustic communication and avoids their shortcomings. The proposed framework offers intelligent AI-based switching that can adaptively select links, reduce BER, increase the throughput, and enhance the reliability compared with the optical-only and acoustic-only schemes. The results show that underwater UUV communication is effective and efficient using these.

Table 1. Comparative performance evaluation

Feature	**Optical Only**	**Acoustic Only**	**Hybrid (Non-AI)**	**Proposed AI Hybrid**
High Throughput	✓	×	✓	✓
Long-Range Communication	×	✓	✓	✓
Adaptive Switching	×	×	Limited	✓
AI-Based Decision-Making	×	×	×	✓
FPGA Implementation	Partial	Partial	Partial	✓
Lowest BER	×	×	Moderate	✓
Highest Throughput	Moderate	low	Hiigh	✓

The proposed study has several limitations; however, the results of this study appear to be promising. While the system evaluation was done mostly through MATLAB/Simulink simulations and FPGA synthesis, it should be noted that this was not necessarily representative of actual testing with the system in water, and other factors, including currents, fluctuations in noise, and fluctuations in link orientation, could not be reproduced. Further, the MLP model was chosen as it is a lightweight model to enable real-time FPGA implementation, which might restrict the adaptability of the model when more sophisticated AI methods are applied. Also, this work is limited to a single UUV communication scenario, neglecting large-scale multi-UUV networks. The challenges underscore avenues for further research, such as experimental validation, development of more sophisticated AI models, and implementation of scalable underwater communication networks.

5. Conclusion

Finally, a hybrid optical–acoustic communication system with WDM-OOK and a real-time FPGA-oriented implementation technique is introduced for UUV applications. The proposed architecture combines high-speed optical communication with reliable acoustic fallback transmission to improve underwater communication performance across different channel conditions. The simulation and evaluation results showed that the AI-based switching mechanism successfully enhanced communication reliability, decreased the BER, optimized throughput, and enabled adaptive mode selection in dynamic underwater environments. Moreover, the practical implementation of the system on real-time hardware using MATLAB/Simulink, HDL Coder, and the Kintex-7 325T FPGA platform further demonstrated the feasibility of implementing the system in real-time hardware. The proposed system is a scalable and efficient solution for the next-generation intelligent underwater communication network.

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Authors' Contributions: [Sameer Sami Hassan]: Conceptualization, methodology, data collection, writing – original draft. [Yusor Rafid Bahar Al-Mayouf], Data analysis, visualization, writing, review & editing. [Omar Adil Mahdi] & [Marcel Ambroze]: writing – review & editing, Supervision, project administration, validation. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Ethical Approval: This study did not involve human or animal subjects, and ethical approval was not required.

Data Availability Statements: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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