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Internet of Underwater Things Infrastructure: An AI-Driven Hybrid Acoustic–Optical Framework for Real-World Underwater Communication

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Abstract- The Internet of Underwater Things (IoUT) is an emerging paradigm that extends IoT technology to underwater environments for applications such as environmental monitoring, ocean exploration, and disaster prevention. However, underwater communication remains a major challenge due to high latency, limited bandwidth, and the difficulty of conducting sea trials. This review paper presents a comprehensive analysis of recent research developments in underwater acoustic communication (UAC) technologies that support IoUT infrastructure. Various studies highlight advancements in shared communication frameworks, reconfigurable hardware systems, and adaptive signal processing algorithms aimed at enhancing data transmission reliability and synchronization accuracy. Techniques such as satellite-based timing synchronization, hybrid acoustic–optical models, and learning-based optimization have demonstrated potential to improve performance under dynamic underwater conditions. Building upon the Shared Underwater Acoustic Communication Layer (SUACL) concept, this paper proposes an AI-driven hybrid acoustic–optical framework that enhances adaptability, synchronization, and energy efficiency in IoUT environments. The study identifies key research trends, evaluates comparative performances of existing methods, and discusses open challenges including high energy consumption, complex channel modeling, and security issues. Finally, it outlines future research directions focused on developing scalable, intelligent, and interoperable communication layers for real-world IoUT deployment.

Keywords— Internet of Underwater Things (IoUT), Underwater Communication, Acoustic Systems, Artificial Intelligence, SUACL, Hybrid Communication, Energy Optimization.

I. INTRODUCTION

The Internet of Underwater Things (IoUT) extends the concept of the Internet of Things (IoT) into underwater environments, enabling intelligent sensing, monitoring, and communication for various marine applications such as environmental monitoring, ocean exploration, and disaster management [1], [2].

However, underwater communication presents several challenges including high propagation delay, limited bandwidth, multipath effects, and severe signal attenuation [1], [4]. Traditional radio frequency communication is ineffective underwater, while optical communication is limited by short range and environmental conditions. Therefore, acoustic communication remains the most reliable method for long-distance underwater communication [2], [3].

Recent advancements focus on hybrid communication models and artificial intelligence-based optimization techniques. Hybrid acoustic–optical systems enable adaptive switching between communication modes based on environmental conditions [2], [3]. Additionally, machine learning techniques improve signal processing and communication efficiency [4], [6].

This paper presents a comprehensive review of IoUT communication technologies and proposes an AI-driven hybrid acoustic–optical framework.

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II. LITERATURE REVIEW

The Internet of Underwater Things (IoUT) has emerged as a significant technological paradigm aimed at enabling intelligent underwater sensing, monitoring, and communica- tion. Zhou [1] reviewed the evolution of Underwater Wireless Sensor Networks (UWSNs), highlighting their layered archi- tecture, acoustic communication reliability, and challenges related to propagation delay and limited bandwidth. The study emphasized the importance of adaptive communication models and multi-node cooperation to achieve sustainable underwater connectivity.

Similarly, Li et al. [2] presented a comparative review of underwater communication meth- ods, concluding that hybrid multimodal systems integrating acoustic, optical, and electromagnetic channels can enhance data rates, reduce latency, and improve overall reliability in IoUT environments.

Youssef et al. [3] developed an energy- efficient hybrid optical–acoustic communication system that switches dynamically between optical and acoustic modes depending on environmental conditions.

This model significantly reduced energy consumption while maintaining stable throughput over variable underwater conditions. The research demonstrated that a combined approach can overcome the bandwidth limitations of acoustic systems and the short- range restrictions of optical links.

Wang et al. [4] later intro- duced a spatial–temporal fusion neural network that achieved high modulation recognition accuracy in low SNR conditions, improving underwater signal classification through deep learning-based feature extraction.

Sabna et al. [5] implemented a deep neural network-based receiver for Orthogonal Fre- quency Division Multiplexing (OFDM) underwater acoustic communication. Real-world river trials confirmed higher data transmission reliability compared to conventional systems. This experiment established that AI-enhanced modulation and demodulation mechanisms significantly improve data recovery in highly dynamic underwater channels.

Omeke et al.[6] focused on sustainability, proposing a Reinforcement Learning (RL)-based framework combined with Simultaneous Wireless Information and Power Transfer (SWIPT) for Autonomous Underwater Vehicles (AUVs), which achieved a 207% increase in power efficiency and improved communication longevity.

Homaei et al. [7] proposed modifications to the Routing Pro- tocol for Low-Power and Lossy Networks (RPL), presenting UWRPL and UWMRPL tailored for underwater applications. These protocols enhanced packet delivery ratio and minimized latency under mobility conditions, contributing to more re- liable underwater network routing.

Unal et al. [8] designed SEANet, a software-defined networking (SDN) platform that uses FPGA-based reconfigurable hardware for high data-rate underwater networking. The system allowed dynamic protocol updates and demonstrated 150 kbit/s throughput with improved network control efficiency.

Mary et al. [9] conducted a study on energy-efficient designs and AI-based power management, emphasizing hybrid energy harvesting methods to extend operational lifetime.

Their results suggest that reinforcement learning-based optimization and intelligent energy scheduling are essential for large-scale underwater deployment.

Nkenyereye et al. [10] presented a survey of underwater network simulation tools such as Aqua-Sim, NS-3, and OMNeT++, discussing their integration with emerging 5G architectures. The study demonstrated that simulation environments play a crucial role in validating underwater communication protocols before costly sea trials.

Lin et al. [11] explored IoT applications in smart oceans and integrated federated learning for efficient data aggregation, enabling distributed intelligence across multiple underwater sensor nodes.

Kumar et al. [12] conducted a comprehensive analysis of IoUT architectures and identified security and privacy as emerging challenges. Their study discussed the integration of blockchain and AI for secure underwater data transmission.

III. COMPARATIVE ANALYSIS

Recent advancements in IoUT have resulted in diverse approaches such as hybrid communication models, AI-assisted signal processing, and energy-optimized networking. To eval- uate these contributions, a comparative analysis of major research works was conducted based on their methodology, innovations, and limitations.

Table1. Summary of Literature Survey

Author & Title (Year)	Methodology	Key Findings
Zhou (2025) – UWSN Evolution Review	Analytical survey of UWSN architectures	Identified layered design, acoustic reliability issues, bandwidth limitations, and need for adaptive communication models.
Li et al. (2025) – Underwater Communi- cation Review	Comparative study of acoustic, optical, and EM communication methods	Hybrid multimodal systems increase data rate, reduce latency, and improve reliability in IoUT.
Youssef et al. (2020) – Hybrid Opti- cal–Acoustic System	Dynamic switching model between acoustic and optical communication	Reduced energy consumption and overcame acoustic bandwidth limits and optical short-range issues.
Wang et al. (2024) – Spatial–Temporal Fusion NN	Deep learning–based neural network for modula- tion recognition	Achieved high modulation classification accuracy under low SNR conditions.
Sabna et al. (2024) – DNN-based OFDM Receiver	Real-world river trials using deep neural network receiver	Improved data transmission reliability compared to conven- tional OFDM systems.
Omeke et al. (2023) – RL + SWIPT Framework	Reinforcement learning integrated with wireless power transfer for AUVs	Achieved 207% improvement in power efficiency and better communication longevity.
Homaei et al. (2022) – UWRPL & UWM- RPL Protocols	Modified RPL routing protocols for underwater mobility	Increased packet delivery ratio and reduced latency in dynamic underwater scenarios.
Unal et al. (2024) – SEANet SDN Archi- tecture	FPGA-based software-defined networking plat- form	Enabled dynamic protocol updates and achieved 150 kbit/s throughput underwater.
Ansari & Vidyarthi (2025) – IoT Water Monitoring Framework	LoRaWAN + cloud analytics framework review	Provided insights applicable to IoUT data collection and envi- ronmental monitoring.
Mary et al. (2022) – Energy-Efficient De- signs	AI-based energy management and hybrid harvest- ing study	Highlighted that AI-driven power scheduling extends underwa- ter network lifetime.
Nkenyereye et al. (2024) – Underwater Simulation Tools	Review of Aqua-Sim, NS-3, OMNeT++ and 5G integrations	Emphasized simulators' importance before costly real-world sea trials.
Lin et al. (2020) – Federated Learning for Smart Oceans	Federated learning implementation on sensor net- works	Improved distributed data aggregation and privacy-preserving intelligence.
Kumar et al. (2025) – IoUT Security Re- view	Survey of IoUT threats, blockchain, and AI se- curity models	Identified security/privacy challenges; suggested secure blockchain-based underwater communication.

Proposed Framework

As shown in Fig. 1, the proposed system architecture is designed using a three-layer structure comprising the Application and Fusion Layer, the SUACL Node Layer, and the Underwater Acoustic Network (UAN) Research Layer. This layered design improves system modularity and flexibility while ensuring precise synchronization, adaptive communication, and support for real-world underwater experimentation. Each layer performs a specific role and works closely with the others to enable efficient and intelligent underwater communication.

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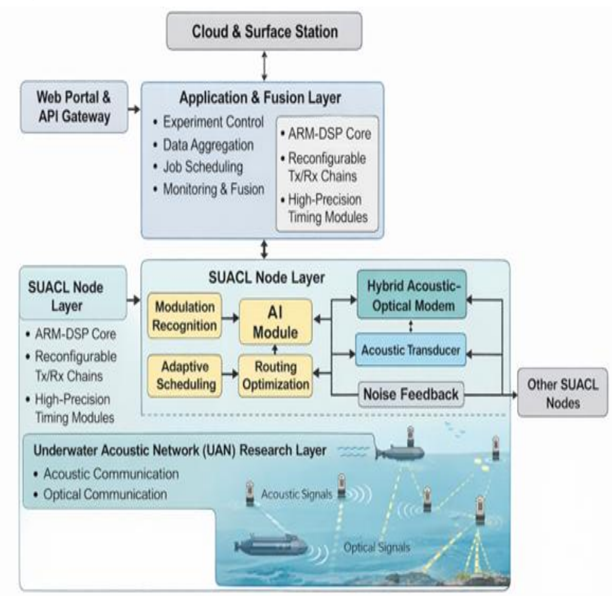

Fig.1 Simplified SUACL-Based Underwater Communication Framework showing Application and Fusion Layer, SUACL Node, and UAN Research Layer.

Application and Fusion Layer

The Application and Fusion Layer functions at the cloud and surface station level and acts as the main coordination and control unit of the proposed framework. It provides a centralized interface through which researchers and system operators can remotely configure experiments, submit communication tasks, and observe system performance in real time.

This layer includes a web-based portal and API gateway that allow users to define experimental parameters such as modulation schemes, transmission power, communication mode (acoustic or optical), and scheduling strategies. It also manages the execution of experiments by distributing tasks to appropriate SUACL nodes.

The major responsibilities of this layer include remote experiment control, aggregation and storage of experimental data received from underwater nodes, efficient job scheduling across distributed resources, and visualization of collected data for analysis and performance assessment. Communication between the cloud and SUACL nodes takes place through surface stations using reliable terrestrial links such as Wi-Fi or 4G/5G, enabling low-latency feedback and control.

SUACL Node Layer

The SUACL Node Layer forms the core processing component of the framework and serves as an intelligent bridge between the cloud infrastructure and the underwater network. Each SUACL node is equipped with an ARM–DSP-based processing unit, which supports real-time signal processing, protocol execution, and intelligent decision-making. The nodes incorporate reconfigurable transmit and receive chains, allowing them to adapt dynamically to different modulation techniques and channel conditions. Additionally, high-precision timing modules are integrated to maintain accurate synchronization among distributed nodes, which is essential for reliable underwater acoustic communication experiments.

AI Module and Intelligent Processing

An integrated AI module within each SUACL node enables adaptive and autonomous system operation. This module continuously evaluates channel characteristics, ambient noise levels, and network feedback to optimize communication performance.

The AI-driven functions include automatic recognition of suitable modulation schemes under varying signal-to-noise ratios, adaptive scheduling of transmissions to reduce collisions and delay, intelligent routing decisions to enhance packet delivery reliability, and real-time analysis of noise feedback to fine-tune transmission parameters.

These capabilities allow the system to respond effectively to changing underwater conditions without requiring manual adjustments.

Hybrid Acoustic–Optical Communication Module

The framework employs a hybrid acoustic–optical communication module that supports dynamic switching between acoustic and optical transmission modes. Acoustic communication is primarily used for long-distance and non-line-of-sight communication where robustness is critical, while optical communication is utilized for short-range, high-data-rate transmission in clear water environments.
Electrical signals are converted into acoustic waves through acoustic transducers, whereas optical transmitters handle high-speed optical data transfer. The AI module determines the most appropriate communication mode by considering factors such as node distance, channel quality, energy availability, and application latency requirements.

Underwater Acoustic Network (UAN) Research Layer

The UAN Research Layer represents the actual underwater deployment environment, consisting of sensor nodes, autonomous underwater vehicles (AUVs), and relay devices. This layer supports both acoustic and optical signal exchange among underwater nodes.The proposed framework enables experimental evaluation of small-scale and large-scale underwater acoustic networks, including testing of MAC protocols, routing strategies, synchronization mechanisms, and cross-layer performance analysis. Real-time interaction between SUACL nodes and the UAN layer allows realistic testing of underwater communication protocols under practical conditions.

Inter-Node Communication and Scalability

Multiple SUACL nodes can communicate with one another as well as with underwater devices to form a scalable and distributed network. The modular architecture allows new nodes to be added easily, making the framework suitable for collaborative research and large-scale IoUT deployments.

Advantages of Proposed Methodology

The proposed methodology offers several benefits, including:

- Intelligent adaptability through AI integration
- Improved synchronization accuracy
- Energy-efficient communication
- Support for real-world experimentation
- Scalability and interoperability across IoUT environments

CHALLENGES AND RESEARCH GAPS

Despite notable progress in the development of IoUT communication technologies, several technical and practical challenges continue to limit large-scale and long-term underwater deployments. One of the most significant challenges is limited bandwidth, particularly in underwater acoustic communication. Acoustic channels inherently support low data rates due to narrow available frequency bands and high attenuation at higher frequencies. This limitation restricts real-time data transmission, especially for applications involving high-resolution sensing, video streaming, or large-scale data aggregation.

Energy constraints represent another critical challenge in IoUT systems. Underwater sensor nodes and autonomous vehicles typically rely on batteries with limited recharging opportunities. Acoustic transmission, signal processing, and frequent communication significantly increase energy consumption, reducing network lifetime. Although energy harvesting techniques and power-aware protocols have been proposed, their effectiveness remains constrained by environmental conditions and hardware limitations. Consequently, there is a strong need for intelligent energy management strategies that balance communication performance with power efficiency.

IV. CONCLUSION

This paper presented a comprehensive analysis of recent advancements in the Internet of Underwater Things (IoUT), with a particular focus on underwater communication technologies, hybrid transmission models, and AI-driven optimization techniques. The study highlighted the critical role of underwater acoustic communication as the primary enabler of long-range connectivity, while also emphasizing its inherent limitations in terms of bandwidth, latency, energy consumption, and channel variability. By examining a wide range of contemporary research works, this paper identified key trends that demonstrate a shift from static communication designs toward intelligent, adaptive, and hybrid architectures capable of addressing the dynamic nature of underwater environments.

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