A Systematic Review on Shallow-Water Internet of Things: Challenges, Architectures, and Emerging Technologies

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***Abstract*—This systematic literature review investigates technological advancements in underwater communication networks for shallow-water environments, which are critical for environmental monitoring, disaster response, and maritime security. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, over 200 peer-reviewed publications (1996–2025) were analysed. The review begins by identifying gaps in prior literature and classifies enabling Internet of Underwater Things (IoUT) technologies into two major domains: network management and modem development. Network-level developments are reviewed through deployment strategies, localisation methods, and routing protocols, with comparative analysis using delivery ratio, delay, energy use, and network lifetime. We examine progress in acoustic, optical, magnetic induction, and radio frequency (RF)-based modems. We discuss practical considerations of underwater system design and propose Modem Performance Index (MPI)—a unified metric for evaluating modem designs based on parameters such as range, bandwidth, energy efficiency, and cost. Through these analyses, this study identifies research gaps and provides guidelines for the development of efficient, robust, and cost-effective underwater communication systems tailored to various deployment scenarios.**

***Index Terms*—Acoustic, Optical, Communication, Internet of Underwater Things, Underwater Sensor Networks, Machine Learning**

I. Introduction

Underwater communication networks, composed of interconnected sensors and autonomous vehicles, are increasingly critical in marine ecosystem conservation, disaster mitigation, and maritime security. These networks enable a wide range of high-impact applications, including real-time seismic monitoring, marine biodiversity assessment, submerged infrastructure integrity analysis, and studies on the effects of climate change. The underwater environment is commonly classified into shallow and deep water based on both hypsometric and acoustic criteria. Hypsometrically, shallow waters are defined as regions with depths up to 200 metres, predominantly located along continental shelves [2]. The hypsometric definition aligns with the convention in most underwater communication research, where shallow water refers to depths less than 200 metres [3]. This zone comprises approximately 5% of the world's oceans and offers advantages such as reduced hydrostatic pressure, which simplifies the design, deployment, and maintenance of underwater communication equipment [4, 5]. Particularly, shallow water networks are invaluable due to their proximity to dense human populations and vital economic assets. Hybrid acoustic-optical systems, for example, offer high-resolution monitoring of coral reefs and fish populations, supporting real-time environmental assessments. Moreover, underwater networks are instrumental in early warning systems for natural disasters such as tsunamis and underwater earthquakes, as demonstrated by the transmission of seismic data during the 2022 Hunga Tonga-Hunga Ha'apai eruption [7], which enabled timely alerts for coastal communities [8]. These networks also play a pivotal role in maritime security, monitoring vast underwater infrastructures, such as over a million miles of gas pipelines, and ensuring safe navigation. These networks achieve near-real-time data transmission by deploying modems at varied depths, which is crucial for emergency evacuation and safety protocols.

An example of environmental monitoring is detecting gas pipeline leaks, which can cause severe harm to marine ecosystems and increase ocean pollution. Figure 1 shows the global underwater infrastructure and marine zones to emphasise the importance of vigilant monitoring systems for the extensive global gas pipeline network spanning over a million miles [6]. Deploying underwater networks for real-time pipeline inspection is essential for improving leak detection accuracy and enabling quick action to prevent environmental damage [9]. Moreover, these networks contribute to maritime security by monitoring protected marine areas and coral reefs [10, 11]. Integrating IoUT systems with autonomous monitoring solutions provides an efficient mechanism for ensuring the safety and sustainability of marine operations.

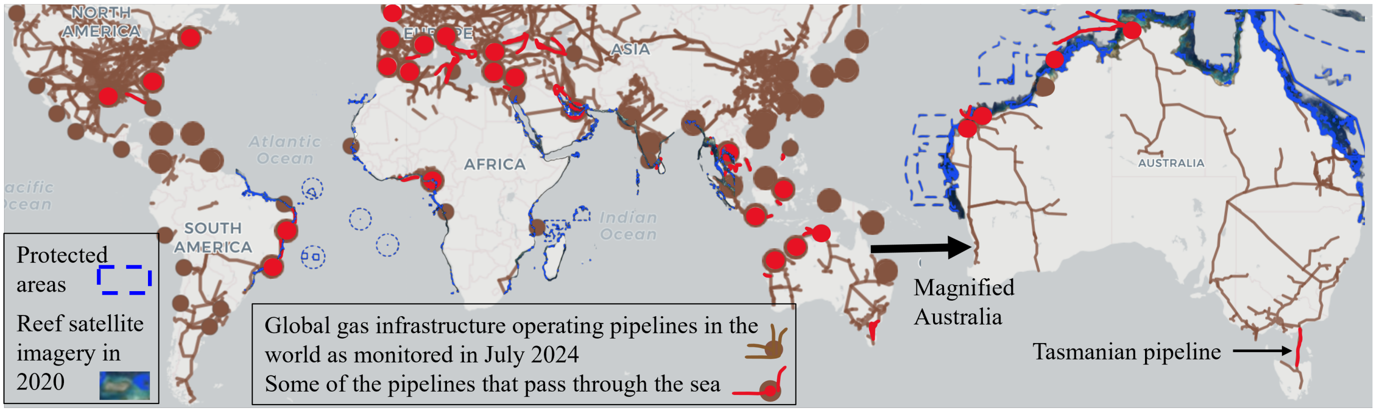

Fig. 1. Operating gas pipelines as captured on the 10th of July 2024 from [6]

Despite the operational advantages and the critical role of shallow water networks in environmental monitoring and maritime safety, shallow water environments present several acoustic challenges that hinder effective communication. Among these challenges is multipath propagation, where reflected signals from both the seabed and the surface lead to phase shifts and signal distortion, severely affecting data fidelity [12]. These conditions are exacerbated by high ambient noise levels resulting from maritime traffic, surface waves, and marine fauna, particularly within the 1–10 kHz frequency band widely used by acoustic modems [4]. Furthermore, signal reflections at the dynamic air-water interface introduce variable delays and additional interference, especially in coastal regions with fluctuating sea states. These factors collectively impair signal clarity, reduce communication range, and limit data throughput. Addressing these challenges requires innovative approaches in modem technology, adaptive signal processing, and network protocol design, specifically tailored to the complex propagation conditions of shallow water environments.

A. Contributions and Organisation

Driven by the distinct complexities of underwater communication in shallow waters, this review provides a systematic exploration of the technologies developed to mitigate these challenges. This review offers a comprehensive and methodologically robust synthesis of the current state-of-the-art of underwater communication networks in shallow water environments. It started by defining the scope, then developing a SCOPUS query to collect the recent work in this field. Over 200 selected research papers were reviewed to give a clear view of progress across both the physical and network layers. These studies address the fundamental underwater communication challenges and solutions, as shown in Figure 2.

Guided by the synthesis of the collected papers, this review is organised to include three core objectives as illustrated in Figure 2. The first objective is to assess the evolution of modern technologies, including acoustic, optical, and hybrid systems. The main focus is on their ability to mitigate multipath propagation, attenuation, and ambient noise. This includes recent innovations in flexible and software-defined modem (SDM) designs, particularly their applicability in dynamic and noise-prone coastal zones. The second objective is to explore advancements in network management, including adaptive routing protocols, localization techniques, and data transmission strategies. The main focus is on the methods designed to enhance reliability and efficiency in complex underwater environments.

The third objective is to examine hybrid IoUT systems that integrate various communication technologies and mobility. The mobility is achieved by combining mobile platforms such as autonomous underwater vehicles (AUVs) to expand network coverage and resilience. The detailed steps of the review workflow are elaborated in the Appendix A.

Developments in modem technology, network management, and hybrid IoUT architectures are critical to determining the performance, scalability, and resilience of underwater communication systems. Synthesising findings from the selected papers in these research areas has drawn our attention to other underwater system design aspects, including environmental impacts and cost. Therefore, this review aims to support the design of efficient, resilient, and adaptable communication networks that are tailored for the dynamic and complex nature of shallow water environments. To ensure clarity, Table I defines the symbols and units used throughout the study, while Table II provides a glossary of key IoUT-related terms.

The main contributions of this review are as follows:

- A systematic literature review that focuses on shallow water acoustic communication networks, offering a comprehensive methodology that can be extended to optical and deep-water communication systems.
- A detailed taxonomy and comparative analysis of key underwater communication technologies in both the physical and network layers, evaluating their performance in terms of range, data rate, power consumption, and commercial feasibility.
- A classification and analysis of underwater routing strategies and protocols assessing their strengths and limitations across various deployment contexts.

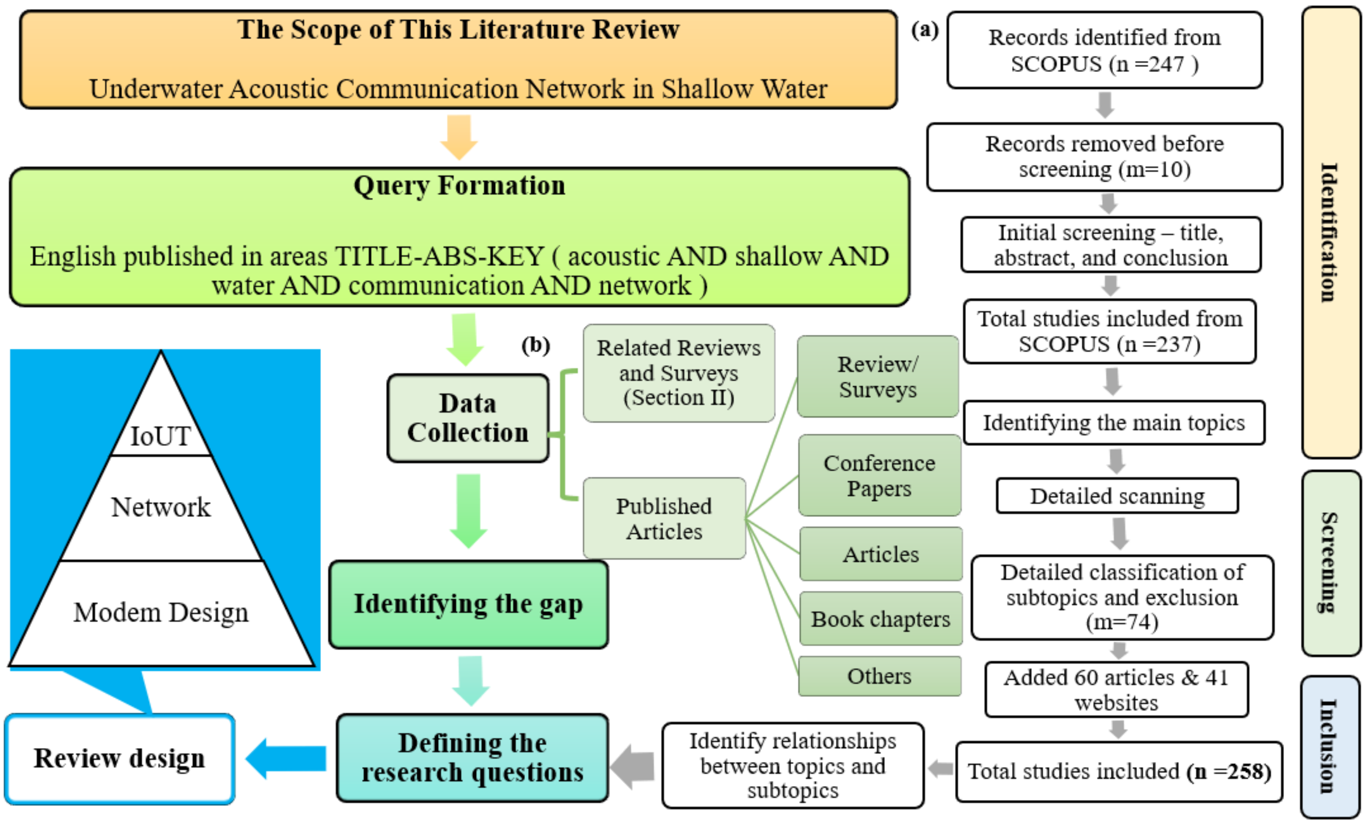

Fig. 2. PRISMA-inspired review workflow guiding the paper's organisation (Sections III- V) based on the data collected from the included 258 studies

- An exploration of the integration of machine learning (ML) in underwater networks and communication.
- Novel quantitative metrics, Logarithmic Modem Performance Index (log-MPI), and log-MPI-Extended introduced for evaluating both commercial and research-grade modems, considering key physical and economic indicators. These metrics offer a framework for comparative analysis.
- Identification of key research gaps and recommendations for future work, including the development of modular, reconfigurable modems, cross-layer design strategies, enhanced security frameworks, and the standardization of benchmarks and datasets.

The review is organised as follows: Section II identifies the gap in the existing literature reviews. Section III presents the categorisation of underwater network enabling technologies. Section IV presents the recent work in creating adaptive networking protocols for underwater transceivers. Section V presents the recent work developing underwater transceivers. Section VI summarises the environmental impact of underwater communication networks on the aquatic and marine environment. Section VII summarises the proposed research directions. Finally, Section VIII presents the conclusion.

II. Literature Review

This section analyses the papers retrieved from the SCOPUS query, specifically after applying the exclusion criteria. The prominent publishers in the specified domain during the last 30 years have been recognised as IEEE, ACM, Journal of the Acoustical Society of America, and ScienceDirect. All of these periodicals relate to the disciplines of engineering and computer science. The justification for this tendency is supported by the pie chart at the bottom of Figure 13. The chart reveals that the areas of engineering, computer science, and mathematics account for about 63% of the total publications within the specified scope.

To identify the area of engineering, computer science, and mathematics that this literature review aims to investigate, the contributions from seven reviews that were found via SCOPUS search are compared [21, 22, 24, 26, 27, 29, 33]. Then, four more literature reviews that examine broad characteristics of the IoUT system, which are closely relevant to our topic, are added to the comparison [28, 30, 31, 34]. The primary interconnected technology categories were identified to be similar to those in previous literature reviews published in this field of research.

A. *Methodologies of Prior Reviews*

Table IIIsummarises each review and responds to the following questions:

TABLE I
NOTATIONS WITH DESCRIPTIONS AND UNITS

Symbol	Description
E_{tx}	Total energy consumed during transmission (Joules)
P_{laser}	Laser transmission power (Watts)
t	Duration of the transmission (Seconds)
E_{proc}	Energy consumed by processing during transmission (Joules)
E_{pulse}	Energy consumed per pulse in optical systems (Joules)
P_{peak}	Peak power of the optical pulse (Watts)
τ	Duration of the optical pulse (Seconds)
P_r	Received power in RF and acoustic systems (Watts)
P_t	Transmitted power (Watts)
α	Attenuation coefficient, depending on frequency and medium properties (dB/m)
d	Distance between transmitter and receiver (Metres)
I	Received intensity in optical and magnetic systems (Watts/m^2)
V_0	Initial transmitted intensity (Watts/m^2)
β	Attenuation coefficient for magnetic induction systems (dB/m)
TL	Transmission loss in acoustic systems (dB)
$N_a(f)$	Total ambient noise level as a function of frequency (dB re 1 μPa^2/Hz)
$N_{\text{turb}}(f)$	Noise contribution from turbulence (dB re 1 μPa^2/Hz)
$N_{\text{wave}}(f, w)$	Noise contribution from waves, depending on wind speed and frequency (dB re 1 μPa^2/Hz)
$N_{\text{traf}}(f, s)$	Noise contribution from traffic, depending on shipping factor and frequency (dB re 1 μPa^2/Hz)
$N_{\text{ther}}(f)$	Thermal noise, significant at high frequencies (dB re 1 μPa^2/Hz)
$N_{\text{abs}}(f, d)$	Attenuation noise based on Thorp's model [1], depending on frequency and depth (dB re 1 μPa^2/Hz)
h	Signal amplitude
σ^2	Variance of the received signal power
I_0	Modified Bessel function of the first kind
μ	Mean of the logarithmic signal amplitude
k	Shape parameter for Weibull distribution
$D(\theta)$	Angular distribution of energy
θ	Deviation from dominant wave direction (Radians)
θ_0	Dominant wave direction (Radians)
s	Spreading parameter in Mitsuyasu or Rician K-factor
p	Frequency-dependent parameter in Hasselmann
N_p	Normalisation constant in Hasselmann
f	Frequency of the signal (Hertz)
w	Wind speed (Metres/second)
A_1, A_2, A_3	Temperature-dependent coefficients
P_1, P_2, P_3	Pressure (depth)-dependent factors
f_1, f_2	Relaxation frequencies dependent on temperature and salinity

1) What methodology was used in making the review? It can be comprehensive, systematic, or targeted to a specific purpose.
2) Is the topic of underwater modem development addressed?
3) Are the development of networking protocols or network management techniques, including network link selection and scheduling, included?
4) Does the topic of discussion pertain to the development of a network including dynamic systems, namely AUVs?
5) Is the setup of a hybrid Internet of Things (IoT) network discussed?
6) Is the creation of a hybrid IoUT network discussed? If yes, does it involve hybrid communication technologies such as acoustic communication, optical communications, and radio frequency communication?
7) Is the advancement of the underwater communication system in a shallow water environment addressed?

Research on underwater acoustic networks (UANs) and underwater wireless sensor networks (UWSNs) has focused on addressing challenges in shallow water environments. These include limited bandwidth, high latency, and energy constraints [21, 33]. Advancements in acoustic modem technology have enabled higher-rate communications, but issues persist in network design, routing, and security [22, 24, 34]. The authors in [24] categorised the routing protocols in acoustic underwater networks into cross-layer ones and non-cross-layer ones by referring to a simplified version of the OSI model. Furthermore, low-cost and low-power acoustic systems are gaining momentum for shallow water applications, enabling new possibilities for environmental monitoring and AUV swarm coordination [29]. Thus, other reviews highlighted progress in essential services, localisation algorithms, and communication protocols [26]. However, there remains a need for robust and flexible solutions that can adapt to the evolving requirements of UWSNs, particularly in shallow water environments where traditional technologies may be less effective [27].

Existing surveys address separate aspects of underwater communication and leave practical shallow-water issues insufficiently covered. Simulation-centric work enables risk-free testing of underwater networks but remains tool-focused rather than integrative [31]. A broad technology overview spans RF, optical, and acoustic links across depths yet offers limited treatment of shallow-water constraints in [25]. Learning-based advances are documented, but typically in isolation from system design and deployment pipelines [28]. General system challenges are listed without translating them into shallow-water–specific design guidance in [30].

The most recent panoramic survey ranges from quantum and neutrino channels to biomimetic concepts, emphasizing physical-layer traits while giving scant attention to network-level integration, and context-specific practices for shallow water [32]. In contrast, this review provides a shallow-water–focused, end-to-end synthesis. It links channel physics to protocol design, learning-enabled adaptation, simulation-to-field validation, and deployment guidance. Therefore, it combines the strengths of prior surveys while directly addressing their gaps.

This review includes a specialised scope, systematic methodology, innovative technology integration, layered analysis, and a specific research agenda compared to other reviews. It systematically intertwines different technology components in a shallow water network to provide a comprehensive summary of the advanced research in this field. It is the first survey that focuses systematically on shallow water IoUT using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and highlights the advancements in hybrid systems.

TABLE II
TABLE OF TERMINOLOGIES

Term	Definition
A comprehensive literature review	An overview of the main research and scholarly articles on a specific subject, aiming to summarize and present a clear and broad understanding of the topic, without the strict methodology used in systematic reviews [13]
A systematic literature review	A review that follows a structured, predetermined methodology to identify, evaluate, and synthesize all relevant studies addressing a clearly formulated research question. This method minimizes bias by using explicit, reproducible criteria for the selection and analysis of studies [14]
Internet of Things (IoT)	A network of interconnected devices that can be underwater, on the surface, or above water surface
Hybrid Internet of Things (hybrid IoT)	A network of interconnected devices that are in different communication environments, which include devices underwater, water surface, or above water surface
Internet of Underwater Things (IoUT)	A network of interconnected underwater devices submerged beneath the water surface
Hybrid internet of underwater things (hybrid IoUT)	A network of interconnected underwater devices submerged under the water surface using different communication technologies, which may include acoustic, optical, and radio frequency that is used in terrestrial communication systems
Networked sensor	A sensor that is connected to a network, allowing it to transmit data to other devices or systems
Modem	A device that modulates and demodulates signals for data transmission in communication networks.
Node	A connection component in a network where data is created, received, or transmitted to another node or other nodes
Network node	A network node responsible for gathering and transmitting data from various sources or sensors.
Autonomous Underwater Vehicles (AUVs)	Dynamic nodes that are able to communicate with other static and dynamic nodes while moving; they are used as Underwater Autonomous Vehicles (UAVs) in some research papers too, but in this work, we use them as AUVs
Unmanned Surface Vehicles (USVs)	Autonomous vehicles that move on the water surface and can help in sending data from underwater to terrestrial networks.
Hydrophone	Underwater microphones
Passive Acoustic Monitoring (PAM)	Using acoustic signal analysis for monitoring the underwater environment, usually using hydrophones
NOAA	National Oceanic and Atmospheric Administration agency reporting environmental changes
Packet Delivery Ratio (PDR)	Percentage of packets received at the sink. We categorise it as high ($\geq$95%), moderate (90–94%), and low ($<$90%) [15–17]
Latency (end-to-end delay)	Time for packet to travel from source to sink in seconds (s). We categorise it as low ($<$0.5 s), moderate (0.5–1.0 s), and high ($>$1.0 s) [15–17]
Energy consumption	Mean energy per delivered packet (Joules/packet). We categorise it as low ($<$0.5), moderate (0.5–1.0), and high ($>$1.0) [15–17]
Network lifetime	Operational rounds until depletion threshold. We categorise it as short ($<$400), moderate (401–700), long (701–1000), and extended ($>$1000) [16, 17]
Composite Exponential–Generalized Gamma (EGG)	Fading model is a composite statistical model used in wireless communications to describe both multipath fading and shadowing effects [18]
Composite $\alpha - F$ fading model	A general statistical model used to characterise wireless channels subject to nonlinear multipath fading and shadowing simultaneously [19]
Direct Sequence Code Division Multiple Access (DS/CSMA)	A spread-spectrum communication technique used to allow multiple users to share the same frequency band simultaneously without interfering with each other
Inter-cluster link	The communication link between different clusters, usually connecting cluster heads to one another or to a sink (base station) [20]
Intra-cluster link	The communication link between nodes within the same cluster. These links are typically short-range and are used for local data aggregation, coordination, and routing inside a cluster [20]

III. UNDERWATER NETWORK TECHNOLOGIES

An underwater network consists of a number of underwater modems that act as network nodes to transfer data from the source to the destination. In a typical IoUT system scenario, the aim of the IoUT system is first identified, and then the network is designed to achieve this aim. Then, the selection of the modems, AUVs, and other networked nodes is guided by the network requirements to achieve the objective of deploying the IoUT system. This top-down approach [35] begins with application layer requirements, transport and network layer needs, and finally the physical layer to meet those requirements.

The research on underwater networks is divided into two main domains that are discussed in the following sections. The first domain is network management in Section IV, which focuses on managing the flow of information across the network. The second domain is modem development in Section V, which focuses on the physical layer. Finally, section VI examines the environmental impact of underwater wireless communication signals, and the economic aspects that affect real-world network sustainability.

Figure 3 shows that network management aspect was studied in only 26% of the selected papers (Section IV). It encompasses link scheduling in the MAC layer, link selection in the network layer, and data routing across different layers of the open systems interconnection (OSI) model. Routing across different OSI layers is classified as cross-layer routing according to [36]. Network management also includes enabling technologies that extend up to the application layer, such as localisation and security for specific use cases [37], as shown in the green hierarchy in Figure 3.

The holistic approach shown in the linking arrows in the

TABLE III
LITERATURE REVIEWS COMPARISON

Ref, Year	Summary	Method / Type	Modem	Net.	AUV	hybrid IoT	Hybrid IoUT	Shallow Water
[21], 2008	Energy-efficient networking algorithms that can be implemented on acoustic modem platforms	Comprehensive		✓				✓
[22], 2010	Comparative analysis of the existing MAC protocols	Comprehensive		✓			✓	✓
[23], 2021	Comparing RF waves propagation to acoustic and optical waves	Comprehensive						✓
[24], 2016	Analysed the state-of-the-art routing protocols for underwater networks	Comprehensive		✓	✓		✓	
[25], 2016	Physical layer characteristics of RF, optical, and acoustic systems in underwater environments	Comprehensive	✓	✓	✓		✓	
[26], 2017	Developing flexible, reprogrammable, and open-architecture underwater acoustic modems to enable interoperability and cognitive networking	Targeted- focused on the security aspects	✓	✓				✓
[27], 2021	Surveys the requirements and challenges for developing RF-based wireless networks in shallow water	Comprehensive	✓			✓		✓
[28], 2022	classification of neural network based methods and list of available datasets	Comprehensive					✓	✓
[29], 2023	Modem and positioning technology	Comprehensive			✓		✓	✓
[30], 2023	IoUT system architecture and applications, challenges and risks facing the IoUT, and potential solutions	Comprehensive		✓	✓	✓	✓	
[31],2024	Simulation tools for underwater networks and hybrid IoT and IoUT systems	Comprehensive		✓	✓	✓	✓	
[32], 2025	underwater communication methods, including acoustic, optical, and quantum technologies	Comprehensive	✓				✓	
This Review, 2025	Advancements in underwater acoustic network analytics including modem technology, network management, and hybrid systems	Comprehensive & systematic	✓	✓	✓	✓	✓	✓

modem technology development hierarchy in Figure 3 presents the current challenges and the future requirements of underwater communication systems. The interconnected nature of modem technology development phases, which are (A) channel modelling, (B) signal processing, and (C) modem development, highlights a comprehensive framework for enabling reliable underwater communication. This structured approach not only advances modem technology but also contributes to the broader field of IoUT.

Physical-layer improvements receive the most attention with around 74% participation in the total studied papers in this review, as illustrated in the pie chart in Figure 3 (Section V). This high percentage is due to the challenging underwater communication environment and its pivotal role in peer-to-peer communication in underwater networks. Modem technology development hierarchy in Figure 3 shows that modem development's pathway begins with foundational research on channel modelling and characterisation. Channel modelling studies the changing underwater environment to consider factors that affect communication system design. The percentage of work in channel modelling accounts for 50% of the selected work on modem development, which indicates its critical role in challenging shallow water environments.

The next step in the modem development process involves signal processing techniques, which account for 35% of the selected work on modem development. These techniques aim to optimise modulation and demodulation processes, reduce noise interference, and enhance data transmission reliability. By refining these processes, researchers lay the groundwork for robust communication systems that are capable of adapting to fluctuating underwater environments. Finally, modem development research that focuses on the hardware and SDMs constitutes only 15% of the selected work on modem development. These efforts include integrating advancements from channel modelling and signal processing into practical modem designs. SDMs, in particular, make this combination easier through modularity, which allows researchers to fine-tune communication parameters for specific underwater conditions.

The practical considerations in the beige hierarchy in Figure 3 demonstrate the integration of insights from both network management and modem technology development (Section VI). These considerations evaluate real-world deployment feasibility by considering the environmental impact and cost effectiveness. These aspects are covered in all the analysed research work since they bridge research and application. The considerations address how underwater communication systems interact with the marine environment. They aim to

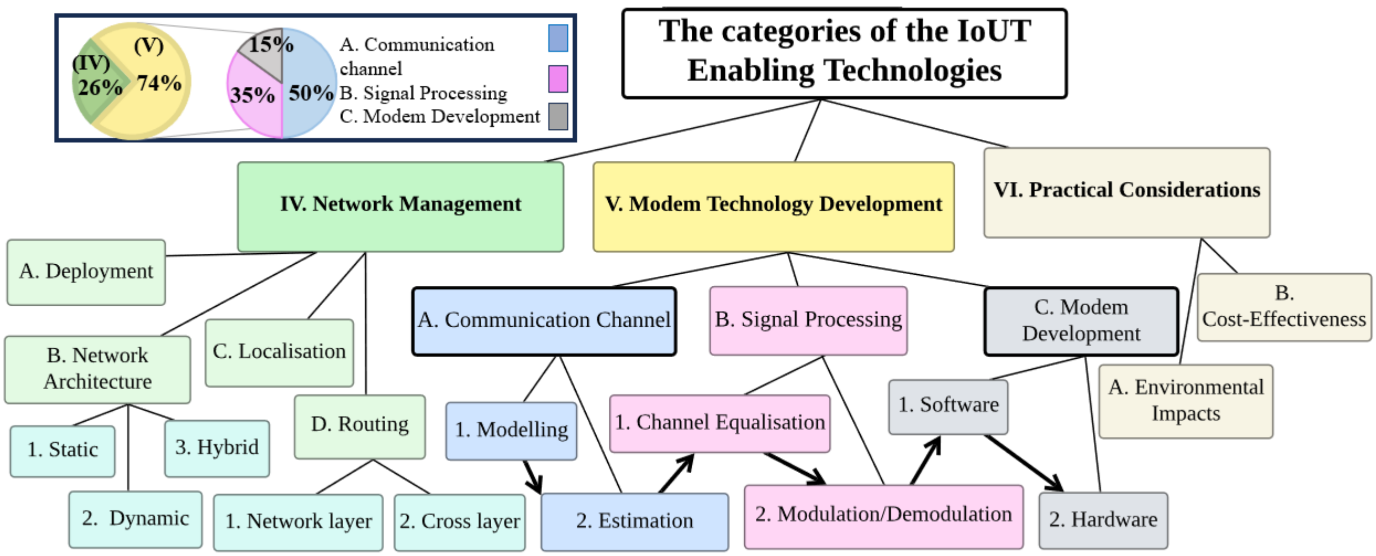

Fig. 3. IoUT technologies representing the sections of this review, where the arrows show the sequence of modem development steps that are identified by different colors. The colors also show the percentage of work studying each technology category in the pie graph on the top left

study the effects of signal propagation on marine life and sustainable deployment practices. Moreover, the considerations incorporate cost-related aspects, including equipment design, deployment logistics, and maintenance requirements. These factors collectively determine the long-term viability of IoUT systems. The practical consideration section completes the IoUT framework by translating the outcomes of network management and modem development into deployable eco-aware solutions from a structural perspective.

IV. Network Management

This section presents IoUT network management from a system-engineering perspective across static and dynamic settings. Static networks strengthen simplicity and longevity of network design; whereas dynamic networks with AUV/USV add control overhead for the sake of agility and extended coverage of the network [38]. Accordingly, the following subsections address deployment, network architecture, localisation, and routing.

Deployment addresses node placement and maintenance to show the effect of shallow or deep water deployment on its cost and access trade-offs. It compares static, dynamic (AUV/USV), and hybrid layouts in terms of energy, reliability, and coverage implications. Network architecture discusses network data communication protocols with all static, dynamic, or hybrid nodes. Furthermore, localisation as a data routing requirement and as a network objective to localise external targets are addressed. These aspects explain the complexity of data routing in the presence and absence of mobility under time-varying links.

A. Deployment

The deployment and maintenance of underwater sensor network nodes pose substantial logistical challenges that shape long-term sustainability [4]. At shallow depths, deployments are more accessible and cost-effective. Moreover, node placement and routine servicing are easier while engineering requirements (e.g., pressure resistance) are more relaxed [4]. In contrast, deep-water sites face higher pressure, harder access, and longer servicing intervals, which raise cost and complexity [39]. These depth-driven factors motivate careful deployment strategies to optimise performance and reliability.

Nonetheless, shallow water adds some communication burdens. In [40, 41], it was demonstrated that cluster-based RF links deliver high data rates only over short distances, which requires closer spacing to meet reliability and energy objectives. Similarly, in [23, 25], the authors showed that optical links offer very high data rates but over short ranges due to absorption, scattering, and alignment sensitivity. Although blue–green wavelengths mitigate loss, practical coastal ranges are limited to a few tens of metres.

In light of practical experiments of deployments, it has been observed that optical communication in shallow waters is best used for dense short-hop relays (e.g., docking links and controlled uplinks). In [42], the authors used docking links in hybrid designs. Their proposed design consists of short optical hops toward a surface vessel for high-rate bursts, and acoustic links for control signals over long-range communication links.

These static networks are foundational for environmental sensing and surveillance, where fixed nodes are used for long-term observation [43]. NetALS [44], for example, demonstrated low-power, bottom-mounted nodes in a surveillance setting, showing the practicality of static layouts in controlled environments. At scale, however, adaptability and coverage are limited in such static meshes. In the literature, channel- or distance-aware relay selection algorithms were used to improve reliability–energy trade-offs in static sustainable networks [45, 46]. It is worth noting that accurate placement is vital for improving the network performance with the help of relay selection algorithms [47].

On the other hand, dynamic deployments enhance coverage and responsiveness by integrating mobile platforms (AUVs/USVs) that support data muling and network management. Integrating AUVs with surface or aerial platforms can also provide localisation support in hybrid designs [43, 48]. Mobility can be optimised explicitly to enhance data delivery. For example, the authors of [49] conducted field trials in the Charles River Basin (Boston, MA; $\sim$2–12 m depth) with a fixed source and destination and a USV relay. The USV relays data between the source and destination by visiting discrete candidate locations. The placement was approached as a learning problem to maximise overall communication efficiency, while avoiding too-frequent repositioning. Signal-to-noise ratio (SNR), packet delivery ratio (PDR), and cumulative bytes were recorded to show strong spatial variability and improved throughput under this switching-cost–aware policy [49].

Deployment choices also tie directly to operating conditions and protocol behaviour. To avoid routing voids, local energy-balancing rules guide node placement for balanced consumption [50]. MAC throughput and error models measurements are used to characterise links for realistic performance assumptions [10, 51]. As a result, low-power bottom-mounted arrays demonstrate feasible servicing and energy profiles for persistent surveillance [44, 52].

Similar measurements were used in two-tier architectures, where the impact of relay geometry was observed. For example, USV/AUV positions are optimised while considering different data routing metrics. The commonly used metrics in the optimisation of relay node placement are frame-error constraints, linking placement density, and surface–underwater partitioning. Hence, improving network reliability is the primary objective of this optimisation process, as proposed in [5]. Field and simulation evidence also constrain the connectivity capabilities of the network. For example, AUV networks at tens of metres depth may adopt mobile-sink relay policies to harvest data from static sensors [49, 53].

B. Network Architecture

We distinguish two ad-hoc patterns that recur in UWSNs: (a) tiered or hierarchical architecture, and (b) clustered architecture, as surveyed in [54]. This subsection defines their patterns and contrasts their topology, role assignment, control scope, and the way they include different communication technologies (e.g., acoustic, optical, and RF). Then, it discusses the design trade-offs that they induce in energy balance, reliability, scalability, and maintenance. We also indicate when each pattern is preferable in static, dynamic, and hybrid networks. Finally, it highlights how these architectural choices interface with the routing strategies that are covered in subsection IV-D.

Tiered networks have distinct roles defined in the network layers. These roles can be a seabed sensing tier, a relay tier that is considered the network backbone, and surface gateways. Tiered networks often use different communication technologies per tier, where acoustic is used for long haul, and optical or RF are used for short-hop relays. This multi-tier design yields a structured route to a sink, as studied in [42, 48]. The separation creates a relatively stable backbone of gateways acting as relay nodes above a denser sensing tier. This 2-tier design enables scheduling (e.g., time division multiple access (TDMA)) at the sensing tier and more predictable scaling with area rather than node count [55].

Mobility is commonly deployed in the relay tier in static networks to improve the network performance. For example, two-tier architectures place USV/AUV relays to meet frame-error requirements that explicitly couple geometry to reliability [5]. The strengths of this multi-tier network architecture with mobile nodes include predictable aggregation and scalability across large areas. However, its weaknesses include gateway bottlenecks, which can be considered single points of failure.

Additionally, tiered networks need placement, localisation, and role assignment when tiers combine mobile and static nodes [42, 48]. Tiered designs add explicit infrastructure and roles, including relays and gateways. It is observed that combining different communication technologies provides backbone stability and coverage at scale at the cost of higher planning and placement costs.

In clustered networks, nodes are partitioned into clusters with one or more cluster-heads (CHs) controlling local coordination, aggregation, and relaying. Intra-cluster links remain peer-to-peer while inter-cluster traffic hops via CHs. The goal is to keep contention local and balance energy through CH election on the basis of residual-energy and link-quality metrics [45, 50, 56]. In shallow water, RF cluster-head selection shows how the clustered pattern can raise throughput while saving energy in short-range communication links [40].

The advantages of clustered network architecture include reduced control scope that is limited within clusters, short intra-cluster hops, and flexibility to re-elect CHs as energy depletes [45, 50]. However, its drawbacks include re-clustering overhead, hotspot formation near CHs, and sensitivity to cluster geometry under channel variability. CHs emerge from peers and confine coordination locally, which is effective for energy balancing and short-hop operation with manageable overhead [40, 45, 50].

1) Static Network: Static UWSN architectures involve placing fixed nodes on the seabed or structures in 2D/3D area. The deployment is guided by sensing depth and coverage requirements [57, 58]. Network stability simplifies management while constraining lifetime, although energy-aware scheduling and low-duty operation are common to extend its lifetime [59]. The limited network lifetime of static networks mandates a fault-tolerant design to ensure cost-effectiveness. The work in [45] showed that robustness is addressed with fault-tolerant layouts and conservative link budgets.

2) Dynamic Network: Dynamic architectures integrate mobile nodes (AUV/USV) for data muling, on-demand relaying, and adaptive coverage. Mobile nodes are often arranged in hybrid tiers linking seabed nodes, surface gateways, and mobile relays. This improves spatial reach and responsiveness at the cost of control overhead for mobility and hand-off. Mobility-aware routing and relay selection are typically employed together (see IV-D). For example, channel or distance-aware relays that improve reliability-energy trade-offs are commonly mobile relay nodes [47, 60].

3) Hybrid Architecture: Hybrid architectures couple a dense, clustered sensing tier with a tiered relay backbone architecture. Combining acoustic and optical communication links aligns with balanced link ranges, data rate, and network energy consumption. Acoustic links provide long-haul connectivity and control, while optical or RF short-hops deliver high-rate bursts within clusters and to nearby gateways.

In practical hybrid networks [42], decode-and-forward acoustic–optical relays funnel traffic toward a surface vessel. In [48], low-cost Manta gateway devices aggregate traffic through surface RF and optical docks while providing an acoustic interface to underwater nodes. In this network, the key design aspects include (a) cluster size, (b) spacing, (c) relay placement, (d) depth, and (d) gateway layout. These design aspects jointly guide node density, alignment requirements, and energy budget.

C. Localisation

While localisation schemes are often used as a means for data forwarding, localization itself can also be the primary objective of the network. With the help of surface, airborne, and underwater references, anchors, and gateways, nodes within the network and external targets can be localised [48, 55]. Buoys and gateways use anchor-based localisation methods such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), and Angle of Arrival (AoA).

For localisation, array-based and range-free schemes have been employed in cooperative designs of clustered or relay-centric networks. However, most of these networks assume accurate node positioning to reduce problem complexity. Under such assumptions, reliable and energy-efficient vector-based forwarding (REE-VBF) schemes have been proposed [64]. VBF schemes reduce transmissions and delay by selecting forwarding nodes based on relative distance. The simulation in [61] showed that hierarchical geographic-based routing with anchor nodes improves delivery under long delay and low bandwidth. The reliance on reference infrastructure in shallow water environments was proven in [61]. It can be noted that long-lived modem-based observatories provide the infrastructure context in which positioning and networking coexist at scale [43].

Beyond enabling the network, UWSNs provide localisation for external assets and targets as a network objective. Array-based acoustic source localisation with vertical receivers and Bayesian inference were proposed in [63] to identify the position range and depth of a stationary tonal source. The methods use sequential updates, quantifying uncertainty and information gain [63] in a static shallow-water. Furthermore, network-assisted AUV localisation using energy-aware acoustic routing has been validated in two field trials in [62]. Additionally, localisation of moving targets in maritime surveillance of watercraft using tele-sonar repeaters and shore gateways has been demonstrated in [65].

Furthermore, hybrid networks of multi-tier architecture have been tested in moving target localisation tasks. In [48], the REP-AUV10 trials in Portugal demonstrated shallow-water operations involving heterogeneous autonomous vehicles supported by hybrid communication and localisation networks. Low-cost AUVs were localised through the global system for mobile (GSM) links using gateway nodes that were carried by airborne and surface platforms within the hybrid network architecture. While infrastructure-based networks support localisation, buoy-based hybrid networks that combine TDMA scheduling with localisation enable persistent surveillance [55].

D. Routing

Some methods depend on node positions as described in Subsection IV-C, while others are localisation-agnostic. We organise the discussion of this section into network-layer control that can be centralised or distributed and cross-layer designs that couple routing with data-link/physical (MAC/PHY) adaptation.

1) Network Layer Routing: Energy-efficient multi-hop routing depends on rigorous coordination of relay selection across the network. Distributed protocols, including VBF and DBR, eliminate reliance on central controllers, thereby enhancing resilience and scalability. Centralised coordination through surface buoys and AUVs yields globally optimised paths at the expense of additional control latency, while hybrid architectures integrate decentralised autonomy with periodic global guidance to balance these effects. Channel-aware and distance-aware relay selection methods further improve the energy–reliability trade-off in static meshes and shallow environments [47]. In addition, localisation-assisted geographic forwarding and angle-based forwarding increase delivery performance when anchors are available [61].

On the other hand, hybrid networks that include mobile assets balance workload by assigning relays across static and mobile nodes to address energy–reliability tradeoff [46, 64]. For example, real-world deployments in lake trials [68] showed that source routing protocol for underwater acoustic networks (SUN) is capable of self-reconfiguration. Similarly, Q-learning-based energy-efficient routing (QELAR) used learning to extend lifetime [69]. Additionally, in [16] trust-based secure and aided path repairing (T-SAPR) protocol was proposed by combining AUV mobility with trust-based repair in hostile settings.

2) Cross-Layer Routing: Shallow-water UWSNs are characterised by strong multipath, high ambient noise, short coherence times, and tight energy budgets. Channel-aware schemes such as directional flooding routing (DFR) and location-aware routing protocol (LARP) adapt forwarding to measured link quality [17]. In contrast, the hydraulic-pressure-based anycast (HydroCast) routing protocol exploits hydrostatic pressure

TABLE IV
SUMMARY OF PAPERS ON NETWORKING THAT CONSIDER LOCALISATION

Ref, Year	Network architecture	Energy	Relay nodes	Routing layer	Channel model	Simulation / Trial	Localisation	Proposed solution
[46], 2023	AUVs, ROVs, static, & USV as sink	relay selection	static	network, physical, & application	Thorp model	MATLAB	required, acoustic	Energy aware routing protocol through energy efficient relay node selection
[61], 2021	hybrid IoUT,	Routing protocol	all nodes	MAC & Application		NS3-AquaSim	anchor nodes	Geographic and angle-based energy-efficient routing protocol that is based on hierarchical architecture in the presence of high propagation delay, low bandwidth, and high packet loss ratio
[45], 2018	cluster-based static	Balanced topology	residual energy & network metrics based dynamic selection	network, physical, application	cylindrical spreading model	Matlab R2013a & Atarraya	game-theoretic model	Overcoming time-delay and interference and achieving balanced energy consumption across the network through a non-cooperative game-based cluster-head selection scheme and optimised relay node selection in the intra-cluster and inter-cluster topology construction.
[62], 2016	hybrid IoUT		static and dynamic nodes			2 field trials	required	Energy-efficient data routing scheme supporting the localisation of autonomous underwater vehicles through networked acoustic communication
[63], 2015	5-element vertical receiver array				nonlinear channel		acoustic source	Information theory to quantify the performance of iterated Bayesian localisation of a narrowband acoustic source in an acoustic waveguide
[64], 2013	hybrid	relay election	dynamically selected	network	Thorp model	MATLAB	required & assumed accurate	The REE-VBF protocol proposed two aspects for reliable and energy-efficient data transmission by minimising the number of transmitted packets, and the time of transmitting packets.
[48], 2011	hybrid IoUT, optical,RF		Static Manta Gateway devices	network		Setúbal, Portugal	GSM & ariel vehicles	Hybrid network architecture capabilities and limitations of low-cost, man-portable autonomous underwater vehicles for improving safety and emergency strategies
[65], 2010	hybrid IoUT		tele-sonar repeater	network		Morehead City, NC, USA	maritime targets-port facility	Localisation through the deployment and recovery of sensor nodes network routes for maritime surveillance system to detect and report the passage of watercraft, including asymmetric threats, to a regional command center
[55], 2006	hybrid IoT	control information	fixed buoys	network, DSR reactive	various effects	Both, Opnet	required	Minimise control information transfer using TDMA in hybrid IoUT with localisation methods to achieve surveillance through energy-efficient scheduling mechanism
[43], 2004	hybrid IoUT static, AUV		seaweb nodes (AUVs)	network, application		Theoretical	acoustic modems	U.S. Navy autonomous, modem-based underwater observatories for environmental and threat sensing over extended areas and time through system architecture hypothesis for network sustainability
[66], 1997	hybrid IoT			MAC layer	multipath and noise	offshore Boca Raton		Communication protocol for underwater platforms that enables reliable, timely, and flexible communication between multiple nodes through link sharing methods for reliable communication

TABLE V
SUMMARY OF PAPERS ON NETWORKING

Ref, Year	Network architecture	Energy	Relay nodes	Routing layers	Channel model	Simulation / Trial	Proposed solution
[42], 2022	AUVs acoustic, static optical	optimising the number of hops	Optical nodes	network, physical	acoustic, composite $\alpha - F$ fading, optical: EGG fading	Theoretical	Hybrid network of acoustic and optical relay nodes that decode-and-forward data from the underwater sensor nodes to a floating vessel for broad coverage
[5], 2023	hybrid IoUT		USV (sink) & AUV (node)	network, mobility	Thorp model & ambient noise	MATLAB	Optimal location finding for USV and AUVs in a two-tier network given frame error rate constraint
[47], 2021	static	relay node selection	channel condition based selection	network, physical	Rayleigh fading, distance-dependent path loss	Matlab	Energy-efficient with acceptable data rates that improve communication reliability and energy usage under the constraints of limited bandwidth and long propagation delays
[40], 2020	cluster-based	cluster head selection		network, physical	Ambient noise	MATLAB	Energy-efficient and high data rate cluster-based RF underwater network in shallow water environment
[60], 2023	Static & AUVs	packet size, modulation & next-hop selection	all nearest-neighbour nodes	network, physical	Rayleigh fading channel model	NS3	ARQ-based performance analytical model for packet size and modulation level optimisation to maximise the energy efficiency of long distance communication between the source and destination nodes
[41], 2019	hybrid static IoUT,				exponential decay, Gaussian noise, & Rayleigh fading	both, MATLAB	Data analysis of static nodes in Bay of Bengal & Arabian Sea – 10 & 20 m depths, respectively, that proved the feasibility of RF-based multihop wireless communication at high data rates in shallow water
[53], 2017	AUVs, static					both, Matlab	Real-life data analysis of data collected from a network in METU Yalıncak Pond at 80 metres depth to study the factors that affect the connectivity of AUV networks
[49], 2013	static, AUVs, USV		USV	network, mobility	data-driven model	Charles River Basin, Boston	MAB algorithm to maximise the total data transmission from the static source and the destination nodes through adaptive mobility of USV relay
[50] ,2009	static	balanced consumption	energy metrics	physical	Thorp model	Both	Local decision making by nodes to achieve balanced energy consumption
[10], 2021	AUVs			MAC	data-driven model from measurements	Simulation	Bernoulli error model leading to two-state Markov chain channel model for an existing AUV network
[67], 2009	static, AUV	energy-throughput trade-off	static, anchored in the sea bottom	network, MAC	Rayleigh & Urick for deep ocean	C++ customised	Data link algorithm that dynamically finds the optimal trade-off among network objectives in shallow water communications in hybrid network architecture
[44], 2007	static	low-power nodes	all	network, application	time-varying FIR filter	Simulation	Low-cost low-power bottom mounted nodes; e.g. NetALS system, for surveillance application
[51], 2006	static			network, MAC	Rayleigh fading & ambient noise	Both, GlomoSim	Real-life data analysis of MAC throughput of Ad hoc On-Demand Distance Vector network with asynchronous half-duplex DS/CSMA Access
[52], 2005	Staic, AUVs, control vessel				spherical spreading model, AWGN	Omnet++	Enabling multi-user communication in underwater acoustic networks

gradients and opportunistic detouring to avoid network routing voids [70].

Cross-layer designs directly connect location-based routing algorithms with the physical properties of the system. Next-hop selection is co-optimised with MAC/PHY layer metrics. These metrics include SNR, bit error rate (BER), link asymmetry, contention, queue occupancy, duty-cycle state coordinated with transmit power and rate, coding, and wake-up/sleep schedules. The joint adaptation improves network routing void avoidance, reliability, latency, and often energy efficiency, at the cost of stability, overhead, or portability in shallow-water deployments.

Channel models provide the foundation for these cross-layer methods. In shallow-water RF studies, exponential-decay and Rayleigh-fading analysis were used to determine when high data rates are feasible at short ranges [41]. In hybrid IoUT architectures, composite fading in the acoustic tier and the optical tier was modelled to inform power control, rate adaptation, coding, and relay selection [42]. Furthermore, the authors in [36] leveraged empirical channel measurements to derive design rules that relate SNR and delay spread to specific configurations of power control, rate adaptation, and relay selection throughout the network stack.

3) Performance Comparison: Tables IV and V summarise the papers in this review, highlighting the assumptions and energy–latency trade-offs of the proposed methods. Table IV covers the methods that require node localisation as well as studies that are focused on localisation as the network objective. Table V shows localisation-agnostic methods and compares architectural choices alongside their network efficiency.

Drawing on reported results in [15, 71], Table VI compares routing protocols in terms of PDR, energy consumption, end-to-end delay, and network lifetime (definitions in Table II). It can be noticed that baselines VBF [72] and DBR [73] achieve moderate PDR and delay at relatively high energy cost, while cooperative DBR (CoDBR) improves the delay at the same energy cost.

Energy-efficient routing based on clustering and relay nodes (EERBCR), and topology control with energy balance (TCEB) clustering protocol reduce energy consumption and extend lifetime through topology control and cooperative region-aware forwarding [45, 74]. Reliability and adaptive cooperation for efficient use of sink mobility (RACE-SM) protocol attains high PDR with low delay and long lifetime by combining adaptive cooperation with sink mobility [15]. Hybrid automatic repeat request with chase combining (HARQ-CC) routing protocol lowers delay and energy per delivered packet by designing cooperative retransmissions and adaptive settings. These features made HARQ-CC suitable in noisy shallow waters [60].

In [40], the authors proposed a cluster-based RF realistic shallow underwater energy (RSU-energy) model to estimate energy consumption for RF transmission underwater. Accordingly, they proposed a cluster-based communication architecture in shallow water (E-CRUSE) to organise underwater nodes into clusters for efficient RF communication. This RF-centric nature of E-CRUSE prioritises throughput with higher energy per packet to cope with the RF attenuation in shallow seawater.

Network aspects, including localisation availability, node mobility, and physical-layer, jointly determine how effective the cross-layer strategies are [23, 25]. This was investigated in measurement-driven MAC/link studies [10, 51, 67]. For example, static environmental monitoring tends to favour energy-efficient distributed schemes. In contrast, dynamic or tactical missions benefit from mobility-aware or centrally coordinated strategies. The direct implications of underwater environment constraints for protocol choice and control design are studied in [40–42]. Guided by similar network design aspects, the following subsection foregrounds physical layer specifics. It reviews acoustic spreading, fading, and noise in shallow-water, optical propagations, and RF constraints.

V. Underwater Modem Development

Underwater communication systems face significant environmental and technological challenges. Signal attenuation, interference, and the inherent characteristics of the acoustic waves used for communication all complicate signal transmission in underwater environments. These challenges significantly constrain the operating range and reliability of underwater communications [78]. For example, the authors of [79] highlighted the sensitivity of underwater acoustic channels to environmental noise.

In the physical layer, there are multiple wireless underwater communication technologies that can be deployed on ships, buoyancy units, or in the harbour. These technologies can be briefly summarised into five main categories: (a) terrestrial radio frequency (RF), (b) acoustic signal, (c) sonar, (d) optical, and (e) magnetic induction (MI). Although sonar operates using acoustic waves, it is typically classified separately in this context due to its distinct functional role—focused on environmental sensing, ranging, and detection—rather than continuous digital communication. In contrast, acoustic communication refers specifically to the use of modulated sound waves to transmit information (e.g., sensor data) over long distances in underwater sensor networks. Each of these technologies provides an edge over the other in one of the main wireless communication aspects, including the range of coverage, data rate, directivity, and resistance to interference or noise from different underwater environments. These diverse ways of communicating possess unique advantages and limits. Table VII presents a comparative analysis of different underwater communication technologies, emphasising their data rates, operational ranges, and other relevant features given the existing modes in the market.

A. Communication Channel

Optical communication, typically operating in the visible light spectrum (˜400–750 nm), provides extremely high data rates (up to Gbps), making it attractive for short-range underwater links. However, it is significantly limited by environmental factors such as turbidity, scattering, and absorption,

TABLE VI
PERFORMANCE COMPARISON OF UWSN ROUTING PROTOCOLS

Protocol	PDR	Energy Consumption	End-to-End Delay	Network Lifetime	Simulation
VBF [72]	85%	High (>1.0 J/packet)	Moderate (0.5-1.0 s)	Short (<400 rounds)	NS2, MATLAB
DBR [73]	90%	Moderate (0.5-1.0 J/packet)	Moderate (0.5-1.0 s)	Moderate (400-700 rounds)	MATLAB, NS2
CoDBR [75]	92%	Moderate (0.5-1.0 J/packet)	Low (<0.5 s)	Long (700-1000 rounds)	Aqua-Sim, NS3
AURP [76]	95%	Low (<0.5 J/packet)	High (>1.0 s)	Long (700-1000 rounds)	MATLAB
RACE-SM [15]	98%	Low (<0.5 J/packet)	Low (<0.5 s)	Extended (>1000 rounds)	NS2, MATLAB
EERBCR [74]	96%	Low (<0.5 J/packet)	Low (<0.5 s)	Extended (>1000 rounds)	NS3
L2-ABF [76]	93%	Moderate (0.5-1.0 J/packet)	Low (<0.5 s)	Moderate (400-700 rounds)	Aqua-Sim, NS2
DVRP [76]	90%	Moderate (0.5-1.0 J/packet)	Moderate (0.5-1.0 s)	Moderate (400-700 rounds)	MATLAB
HARQ-CC [60]	N/A	Low (<0.5 J/packet)	Low (<0.5 s)	Extended (¿1000 rounds)	NS3
E-CRUSE [40]	N/A	High (>1.0 J/packet)	Moderate (0.5-1.0 s)	Moderate (<700 rounds)	RSU-Energy, CRUSE
TCEB [45]	95%	Low (<0.5 J/packet)	Low (<0.5 s)	Long (700-1000 rounds)	MATLAB
UOASN [42]	90%	Moderate (0.5-1.0 J/packet)	Low (<0.5 s)	Extended (>1000 rounds)	MATLAB

TABLE VII
COMPARISON OF UNDERWATER COMMUNICATION TECHNOLOGIES

Parameter	**RF**	**Acoustic - Digital comms**	**Acoustic- Sonar**	**Optical - Visible light**	**Optical - Other**	**MI**
Operating Frequency	MHz–GHz range	10–100 kHz	30 kHz–1 MHz	$4\times10^{14} - 7.5\times10^{14}$	IR: $3 \times 10^{11} - 4 \times 10^{14}$Hz, UV: $8 \times 10^{14} - 3 \times 10^{16}$Hz	Hz–kHz range
Average Propagation Speed	2.25×10^8 m/s	$\sim$ 1500 m/s	$\sim$ 1500 m/s	2.25×10^8 m/s	2.25×10^8 m/s	Near-instantaneous field propagation
Average Bit Rate	10 kbps–1 Mbps	100 bps–10 kbps	N/A (detection-focused)	10 Mbps–1 Gbps	1–100 Mbps (varies)	Tens to hundreds of bps
Average Area Coverage	1–10 m	1–20 km	Detection over kilometres	10–100 m	1–50 m	1–5 m
Operating Depth	Shallow depths only	Any depth	Any depth	$\leq$ 200 m (clear)	Shallow to moderate depths	Any depth
Environmental Effects	Strongly affected by salinity and bubbles	Moderately affected by salinity; minimally impacted by turbidity	Sensitive to object density and geometry	Strongly affected by turbidity and scattering	Highly sensitive to turbidity and scattering	Affected by water properties including conductivity [77]
Modem Size (cm^2)	100–400	50–200	300–1000	30–150	30–150	100–400
Existing Modems	Seatooth	WHOI Micro-Modem, Evologics S2C	Side-scan sonar systems	BlueComm (Sonardyne)	Experimental IR/UV modems	Experimental prototypes
Directivity	Omni-directional	Omni or directional (60–120°)	Directional (5–20°)	Low directional (1–5°)	Directional (5–15°)	Omni-directional
Communication Range	1–10 m	1–20 km	Kilometres (detection)	10–200 m	1–50 m	1–5 m
Power Consumption	Moderate to high	Low to moderate	High	Moderate to high	Moderate to high	High
Energy Consumption Equation	$E_{tx} = P_t \cdot t$	$E_{tx} = P_t \cdot t + E_{proc}$	$E_{pulse} = P_{peak} \cdot \tau$	$E_{tx} = P_{laser} \cdot t$	$E_{tx} = P_{laser} \cdot t$	$E_{tx} = P_t \cdot t$
Attenuation Equation	$P_r = P_t \cdot e^{-\alpha d}$	$TL = 10 \log_{10}(d) + \alpha d$	$TL = 20 \log_{10}(d) + \alpha d$	$I = I_0 e^{-\alpha d}$	$I = I_0 e^{-\alpha d}$	$H = H_0 e^{-\beta d}$
Multipath Fading Effect	Minimal	Significant; requires equalisation	Minimal	Dominated by scattering	Strong multipath effects	Minimal
Average Price per Modem	\$3,720 – \$7,100	\$1,000 – \$20,000	\$10,000 – \$100,000+	\$10,000 – \$30,000	\$5,000 – \$25,000	Not commercial

particularly in coastal and harbour waters [80, 81]. These impairments restrict the effective optical transmission range to tens of metres under realistic conditions. Furthermore, visible-range optical modems such as BlueComm (Sonardyne) may suffer performance degradation under ambient lighting conditions, including direct sunlight. Experimental systems using infrared (IR) or ultraviolet (UV) wavelengths—referred to here as "Optical (Other)"—have also been investigated to improve robustness, although they remain sensitive to medium conditions and strong multipath effects.

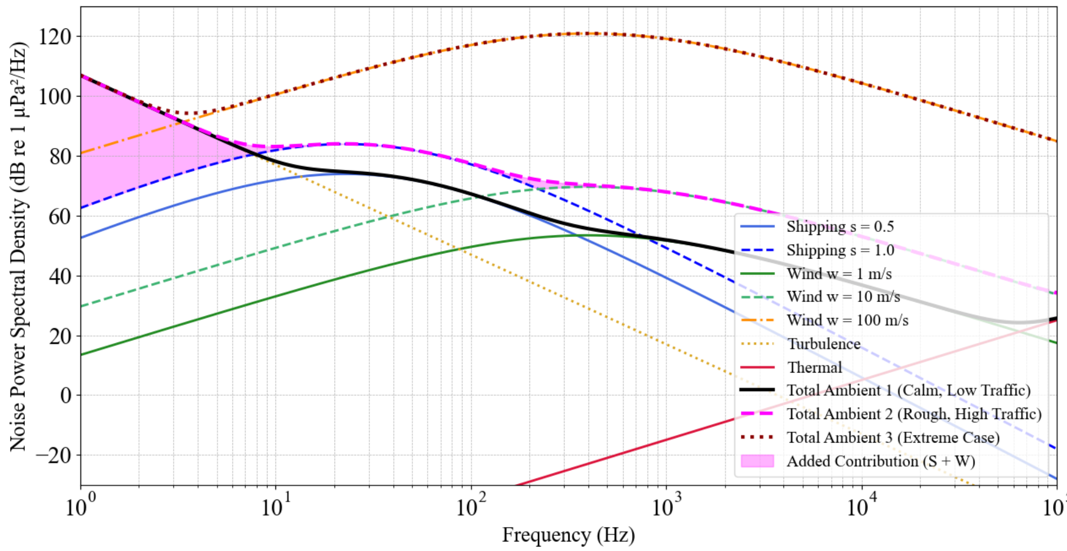

Fig. 4. PSD of ambient noise model from 1 Hz to 100 kHz

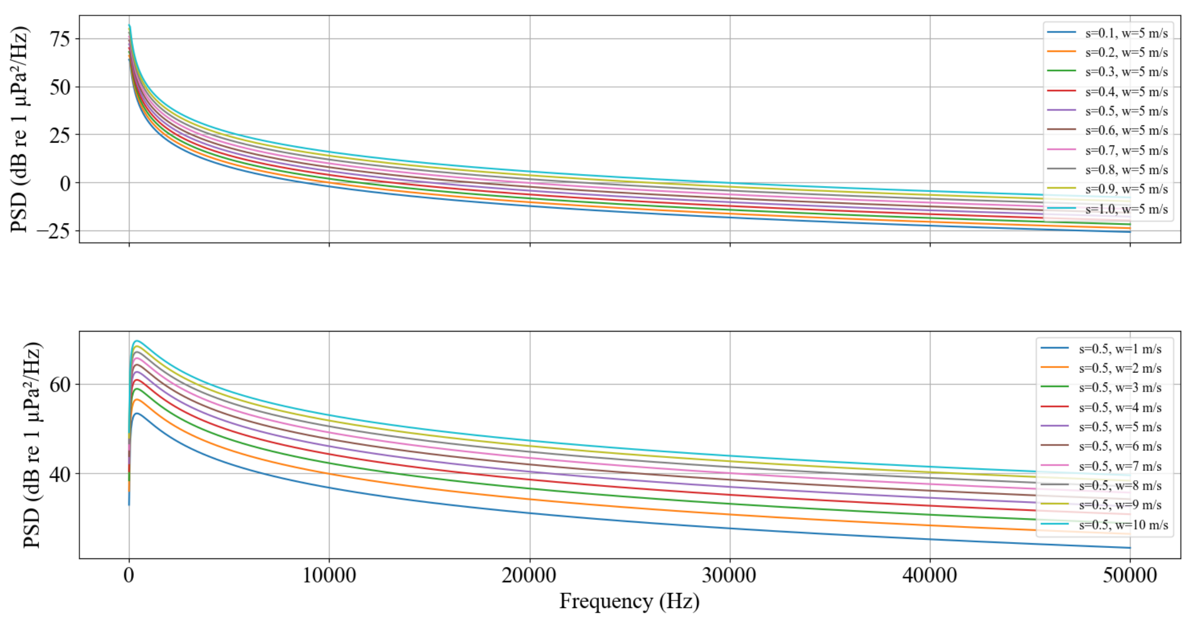

Fig. 5. PSD of underwater ambient noise over 1 Hz to 50 kHz under varying shipping activity levels ($s = 0.1$ to 1.0) and a fixed wind speed ($w = 5$ m/s) and increasing wind speed (w from 1 to 10 m/s) with a fixed shipping factor ($s = 0.5$)

In contrast, magnetic induction (MI) communication has gained attention as a robust alternative for short-range underwater communication. MI was developed particularly for turbid and conductive environments where optical and acoustic signals face many challenges. MI relies on near-field magnetic coupling between coils. It is inherently resilient to acoustic reverberation, salinity, and turbidity. However, MI performance is constrained by field dispersion and conductive losses in seawater, typically limiting its effective range to less than 5 m [82].

Wireless For Subsea (WFS) Technologies' Seatooth modems are commercial subsea RF systems that use electromagnetic (EM) waves with magnetically coupled antennas to provide short-range through-water communication links. It is often mischaracterised as MI due to its near-field behaviour [83, 84]. In practice, Seatooth systems operate via

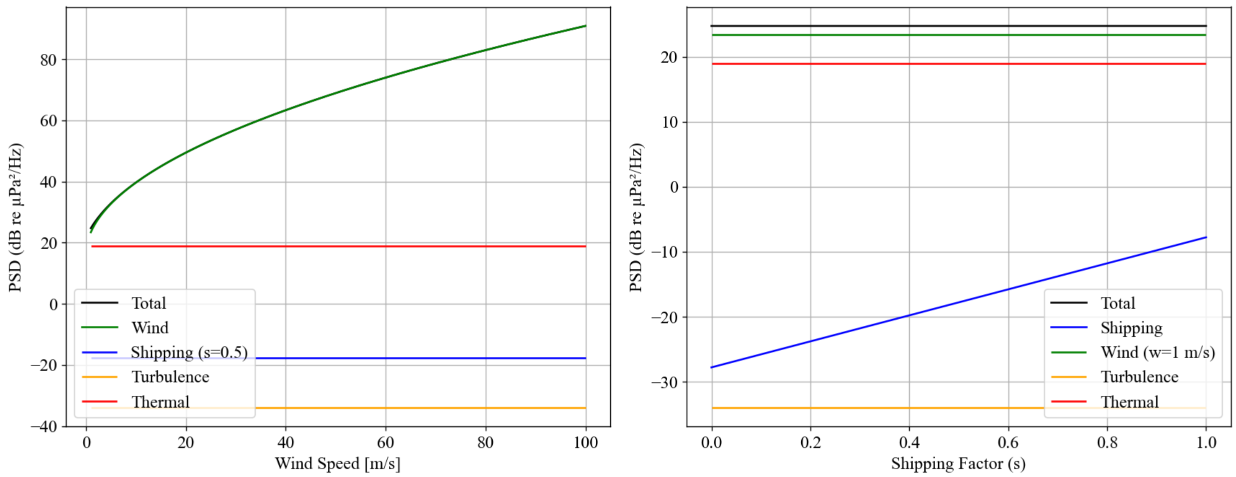

Fig. 6. PSD of underwater ambient noise at a fixed frequency of 50 kHz shown in linear scale (µPa²/Hz) due to wind, shipping, turbulence, and thermal noises. The effect of varying wind speed $w \in [1, 100]$ m/s with a fixed shipping activity factor $s = 0.5$ (left). The effect of varying shipping activity factor $s \in [0, 1]$ with a fixed wind speed $w = 1$ m/s (right)

EM coupling rather than true MI, enabling short-range ($<$ 5 m) data transmission through seawater, ground, and metal. Several Seatooth models have been successfully demonstrated in subsea environments, including deep-water pipeline and ROV operations. They have also been tested in shallow and confined environments such as laboratory tanks and harbours [85]. Therefore, Seatooth is best regarded as a short-range, environment-agnostic EM solution rather than a dedicated shallow-water technology.

True MI-based systems remain primarily within the research domain. Prototypes developed at institutions such as Massachusetts Institute of Technology (MIT) and the University at Buffalo have demonstrated the feasibility of MI communication in underwater environments. For instance, the MIT Sea Grant project demonstrated reliable bottom-to-surface communication using MI for ocean-temperature monitoring [86]. Also, University of Buffalo researchers analysed the reliability and spatial diversity of MI links using tri-axis coils [87].

RF communication in the MHz–GHz range has also been explored for underwater use, particularly in shallow water conditions. Research initiatives [88, 89] have examined the use of the 2.4 GHz industrial, scientific, and medical (ISM) band, where high-speed links are feasible over very short distances. Dash et al. [90] and others [91, 92] have proposed RF-based physical-layer designs tailored for the underwater environment. However, due to extreme signal attenuation—exceeding hundreds of dB/km even at 1 MHz [25]—current systems remain limited to a few metres. No commercial RF modem is currently available aside from Seatooth, and shallow deployments remain constrained by reflective surfaces and lossy propagation paths.

Sonar systems operate primarily in the 30 kHz–1 MHz range and are designed for marine object detection, navigation, and mapping. These systems use ultrasonic pulses and are not suitable for digital data transmission. They typically exhibit high directionality and long-range detection but do not support the modulation or bandwidth requirements of communication systems.

In contrast, underwater acoustic communication systems for digital data exchange operate in the 10–100 kHz range. These systems offer longer ranges (up to 20 km in ideal conditions) and are widely used in underwater sensor networks and robotic operations. Acoustic signals in this band are more resilient to attenuation but are strongly affected by ambient noise, Doppler shift, and multipath fading, especially in dynamic underwater environments. Modem designs often include complex equalisation and synchronisation mechanisms, with power consumption distributed across transmission and signal processing components.

The RF ISM band is generally considered unsuitable for underwater communication due to high absorption in conductive media such as seawater. For example, attenuation at 1 MHz can exceed 400 dB/km, severely limiting transmission range [93]. As a result, acoustic waves in the kilohertz range are preferred, despite their own limitations. In particular, these low-frequency signals are vulnerable to ambient noise sources, including shipping noise and turbulence, as illustrated in Figure 4.

Moreover, underwater acoustic noise is frequently impulsive in nature, characterised by sudden bursts of high-energy interference that deviate from traditional Gaussian assumptions. This impulsiveness can severely degrade communication performance, particularly in systems based on orthogonal frequency-division multiplexing (OFDM), where channel and noise estimation are critical. Chen et al. [94] have demonstrated the need for joint channel-noise estimation to counteract impulsive noise effects. To mitigate these issues, ultrasound frequencies (above 21 kHz) are often adopted, as they lie beyond the energy range of most anthropogenic and environmental noise sources. This allows communication to occur in relatively clean spectral bands, improving performance for short- to mid-range applications.

1) Channel Modelling: According to [95], ambient noise, turbulence and wind noise, and human activities, including maritime shipping traffic. These parameters influence the wave speed and contribute to ambient noise levels. The combined effects of these sources can be modelled using the power spectral density (PSD) of ambient noise in Equation (1)

$$N_a(f,w,s,d) = N_{\text{turb}}(f) + N_{\text{wave}}(f,w) + N_{\text{traf}}(f,s) + N_{\text{ther}}(f) \quad (1)$$

where each term represents a specific noise component. Turbulence noise is described by:

$$N_{\text{turb}}(f) = 17 - 30 \cdot \log_{10}(f),$$

which dominates at low frequencies. Wave noise depends on wind speed (w) and frequency:

$$N_{\text{wave}}(f,w) = 50 + 7.5 \cdot \sqrt{w} + 20 \cdot \log_{10}(f) - 40 \cdot \log_{10}(f + 0.4).$$

Shipping noise, which is prominent in the low-frequency range (typically below 1 kHz), is influenced by the shipping factor (s) and frequency:

$$N_{\text{traf}}(f,s) = 40 + 20 \cdot (s - 0.5) + 26 \cdot \log_{10}(f) - 60 \cdot \log_{10}(f + 0.03).$$

Thermal noise becomes significant at high frequencies:

$$N_{\text{ther}}(f) = -15 + 20 \cdot \log_{10}(f).$$

Attenuation of low-frequency acoustic signals in seawater is commonly modelled using Thorp's empirical formula [1], where the absorption coefficient $\alpha(f)$ depends on the frequency f (in kHz) as

$$\alpha(f) = \frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 \quad \text{(dB/km)} \quad (2)$$

This model is valid primarily for frequencies between approximately 100 Hz and 1 MHz in deep ocean conditions and includes contributions from boric acid, magnesium sulphate, and pure water absorption. For more accurate estimation across a wider range of frequencies and oceanographic conditions (e.g., pressure, temperature, salinity), the Francois and Garrison model provides a more detailed Equation (3) as modelled in [96]

$$\alpha(f) = A_1 P_1 \frac{f^2}{f_1^2 + f^2} + A_2 P_2 \frac{f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \quad (3)$$

where each term represents a distinct absorption mechanism, and the coefficients A_i, P_i, and f_i are determined based on salinity, temperature, pH, and depth. Notably, Thorp's model can be seen as a simplified special case of the Francois–Garrison formulation, using constant parameter values for standard deep-sea conditions.

The PSD of ambient noise in underwater environments is influenced by environmental factors such as wind speed and shipping activity, as illustrated in Figure 4. As wind speed increases, ambient noise in the low- to mid-frequency range (e.g., below 10 kHz) rises significantly [97]. Shipping noise is concentrated in the low-frequency range and increases as the shipping factor (s) grows, exacerbating noise levels in maritime traffic zones [98]. Frequencies above 100 kHz are often selected for short-range underwater communication systems, where higher data rates are prioritised over range [99], and the effects of thermal noise are more tolerable. The selection of modulation techniques and frequency bands in underwater systems is ultimately guided by the need to achieve an acceptable signal-to-noise ratio (SNR) at the receiver while addressing the challenges posed by noise and attenuation.

TABLE VIII
DEFINITIONS OF AMBIENT NOISE CASES

Ambient Case	**Shipping (s)**	**Wind (w)**
Ambient 1	0.5 (low)	1 m/s (calm)
Ambient 2	1.0 (high)	10 m/s (moderate to strong)
Ambient 3	1.0 (high)	100 m/s (extreme)

To effectively model underwater ambient noise for acoustic communication systems, we define three ambient profiles based on combinations of shipping activity and wind speed, categorised in Table VIII. **Ambient 1** represents a quiet underwater environment with low ship traffic and calm sea conditions. Suitable for best-case communication performance analysis. **Ambient 2** models a realistic, noisy underwater environment with heavy shipping activity and typical rough sea surface agitation. Useful for evaluating practical system robustness. **Ambient 3**, in contrast, is a synthetic extreme-case scenario using exaggerated wind speed to examine the system's resilience under extreme surface agitation. These profiles help assess system performance across a wide range of operating environments.

The 50 kHz band is particularly well-suited for underwater communication systems because it balances noise resilience and reduced attenuation. It is ideal for medium-range communication, as demonstrated in Figure 4. This frequency band minimises the impact of shipping and thermal noise while allowing for practical signal propagation over extended distances. It has been widely used in commercial modems, including Evologics and WHOI [100] modems. Thus, we further analyse the PSD of underwater ambient noise over the 0–50 kHz frequency band in Figure 5, which shows the PSD of underwater ambient noise over a frequency range of 0 to 50 kHz. The top subplot illustrates the effect of varying shipping activity levels (s from 0.1 to 1.0) at a fixed wind speed ($w = 5$ m/s). The bottom subplot shows the impact of increasing wind speed (w from 1 to 10 m/s) with a fixed shipping factor ($s = 0.5$). The PSD values highlight that shipping noise dominates low-frequency regions (<1 kHz), while wind-induced noise first rises with frequency and then reduces in mid-frequency ranges.

Furthermore, Figure 6 illustrates the dependence of underwater ambient noise power on wind speed and shipping activity at a fixed frequency of 50 kHz. The left sub-figure shows the effect of varying wind speed $w \in [1, 100]$ m/s on noise level, with the shipping activity factor fixed at $s = 0.5$. The right sub-figure shows the effect of varying shipping activity factor $s \in [0, 1]$ on noise level, with wind speed fixed at $w = 1$ m/s. These results demonstrate that both higher wind speeds and increased shipping activity contribute significantly to the overall noise power. The visualisation supports the design of robust underwater communication systems by highlighting environmental impacts on the acoustic channel.

2) Channel Estimation: Accurate channel estimation (CE) underpins reliable underwater acoustic (UWA) communication. This is because multipath, Doppler, and time variability distort phase-coherent links. Foundational surveys outline the channel causes and estimator families for UWA systems [101]. Additionally, measurements taken over communication-relevant time scales provide a quantitative characterization of channel coherence and variability in shallow-water environments [33]. For example, in multi-carrier systems, pilot-assisted CE for time-varying channels is commonly formulated in basis-expansion models and related estimators [102, 103]. In these studies, performance is often reported as pilot SNR or effective SNR metrics alongside sparse orthogonal matching pursuit estimators [104].

In shallow water specifically, several studies make CE requirements and methods explicit. For example, pilot-aided OFDM CE with least squares was evaluated on time-varying shallow channels [105]. Moreover, adaptive CE that couples Doppler prediction with time smoothing demonstrated gains on real shallow-water data. At 10–15 kHz over 0.5–2 m/s with 64–1024 carriers, the system could achieve ≈2 dB mean square error improvement and significant BER reduction when configured optimally [106].

Beyond pilots, sparse approaches have been tailored to shallow water. Bahrami studied CE sensitivity to node placement in shallow water [107]. Also, Naushad proposed energy-efficient dictionary-based CE for shallow-water links [108]. Meanwhile, Doppler estimation and correction have been demonstrated in shallow-water channels using joint Doppler tracking and equalisation [109].

Recently, deep-learning-assisted CE has been explored for shallow-water systems using orthogonal chirp division multiplexing (OCDM). The system is proposed as a super-resolution networks that improve channel-state recovery under multipath and Doppler [110]. These results motivate shallow-water CE designs that combine Doppler-aware tracking, pilot, sparse, dictionary estimation, and learning-based refinement. The following subsection details how the underwater channel affects the received signal.

B. Signal Processing

Acoustic communication, widely used for long-range underwater transmission, suffers from low data rates and interference, as noted by Theocharidis and Kavallieratou [32]. Reflection and multipath fading are the primary causes of acoustic signal attenuation during propagation in water. Multipath propagation leads to the spread of signal power, resulting

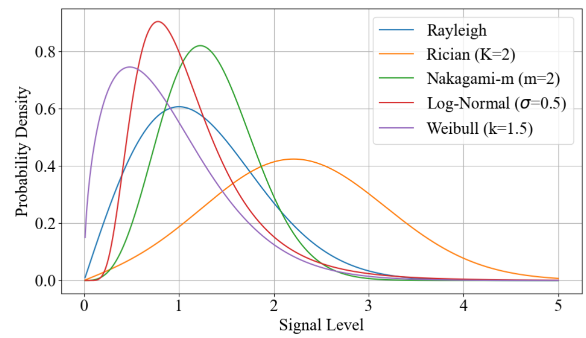

Fig. 7. Comparison of fading models

in constructive and destructive interferences among signal components. It also introduces phase shifts in the signal due to different delays across propagation paths. These issues become more complex in dynamic communication scenarios due to the Doppler shift, as investigated in [111, 112].

Figure 7 illustrates the impact of multipath fading, where signal amplitudes fluctuate due to scattering, reflections, and interference caused by environmental irregularities. It compares five fading models (Rayleigh, Rician, Nakagami-m, Log-Normal, and Weibull) based on their probability density functions (PDFs). The Rayleigh fading model, described by [113]:

$$p_R(h) = \frac{h}{\sigma^2} e^{-h^2/(2\sigma^2)},$$

applies to environments with no dominant line-of-sight (LOS) component, leading to significant signal degradation under scattered conditions. In contrast, the Rician fading model, suitable for scenarios with a direct LOS component (s), is given by [114]

$$p_{Ri}(h) = \frac{h}{\sigma^2} e^{-(h^2+s^2)/(2\sigma^2)} I_0\left(\frac{hs}{\sigma^2}\right),$$

where I_0 is the modified Bessel function of the first kind. Additional models, such as the log-normal fading model,

$$p_L(h) = \frac{1}{h\sigma\sqrt{2\pi}} e^{-(\ln h - \mu)^2/(2\sigma^2)},$$

account for shadowing effects, while the Weibull fading model generalises fading severity with a shape parameter (k).

Complementing these fading models, Figure 8 demonstrates how sea surface conditions influence the angular distribution of acoustic energy [115]. It compares three spreading functions—Cosine-squared, Mitsuyasu, and Hasselmann—using the angle theta (θ) as the deviation from the dominant wave direction (θ_0). The Cosine-squared spreading function

$$D(\theta) = \begin{cases} \frac{2}{\pi}\cos^2(\theta - \theta_0), & \text{for } -\frac{\pi}{2} + \theta_0 < \theta < \frac{\pi}{2} + \theta_0, \\ 0, & \text{otherwise}, \end{cases}$$

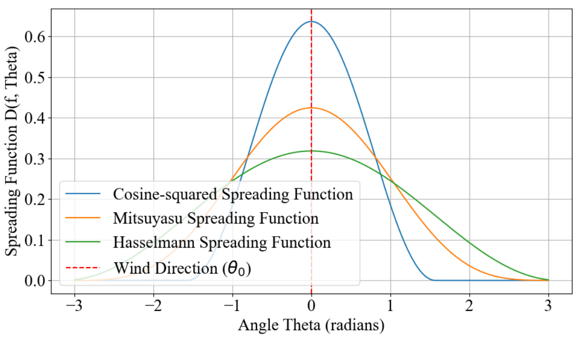

Fig. 8. Comparison of sea surface spreading functions

is isotropic and suitable for calm conditions. The Mitsuyasu spreading function extends this with frequency dependency

$$D(f, \theta) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\Gamma(s+\frac{1}{2})} \cos^{2s}\left(\frac{\theta-\theta_0}{2}\right),$$

where s varies with frequency, while the Hasselmann spreading function incorporates wave spectra,

$$D(f, \theta) = \frac{1}{N_p} \cos^2\left(\frac{\theta-\theta_0}{2}\right)^p,$$

highlighting how environmental variability affects energy dispersion.

1) Channel Equalisation: Effective channel modelling is crucial for designing robust underwater communication systems. Deterministic tools like Bellhop [111] provide precise models but often overlook random variations. Stochastic models using Rayleigh, Rician, or Log-Normal distributions account for these uncertainties [112]. Advanced modulation and demodulation techniques [116, 117] further optimise signal processing to mitigate channel effects, with ML and optimisation methods providing adaptive solutions [118–120].

Underwater acoustic communication channels are characterised by time-varying multipath propagation, leading to intersymbol interference (ISI) and signal distortion. To mitigate these effects, various equalisation techniques have been developed. Adaptive equalisation methods, such as the least mean squares and recursive least squares algorithms, adjust filter coefficients in real-time to counteract channel variations [121]. Non-linear equalisation approaches, including decision feedback equalisers and turbo equalisers, have shown improved performance in handling severe ISI by leveraging past decisions and iterative processing [122].

Recent advancements have introduced ML-based equalisation techniques, which utilise neural networks to model complex channel behaviours and adapt to dynamic environments [123]. These data-driven methods offer promising results in scenarios where traditional algorithms may struggle, particularly in highly non-stationary underwater channels.

2) Modulation and Demodulation: Modulation schemes in underwater acoustic communications must contend with limited bandwidth, high latency, and significant multipath effects. Traditional schemes like frequency shift keying (FSK) and phase shift keying (PSK) are commonly used due to their robustness and simplicity [137]. However, these methods often suffer from low spectral efficiency.

To enhance data rates and reliability, advanced modulation techniques such as orthogonal frequency division multiplexing (OFDM) have been adopted. OFDM divides the available bandwidth into multiple orthogonal sub-carriers, allowing for parallel data transmission and improved resilience to frequency-selective fading [138]. Additionally, continuous phase modulation (CPM) offers benefits in power efficiency and reduced out-of-band emissions, making it suitable for power-constrained underwater applications [139].

Demodulation strategies must complement the chosen modulation scheme and account for channel impairments. Coherent demodulation requires accurate channel estimation and synchronisation, while non-coherent methods offer simplicity at the cost of performance. Emerging techniques employ ML algorithms to classify and demodulate signals adaptively, providing robustness against channel uncertainties [140].

C. Modem Development

1) Software-Defined Modems: The NILUS methodology highlights the significance of adaptive modem designs that encompass various open systems interconnection (OSI) layers, such as the physical, network access, and network layers, to improve underwater communication networks [26]. The adaptability of contemporary architecture, especially concerning software-defined acoustic modems (SDAMs), is essential for responding to evolving environmental conditions, communication requirements, and technological advancements. These modems allow for greater flexibility and interoperability, enabling researchers to customise communication protocols according to specific mission requirements.

2) Hardware Modems: Modem development plays a pivotal role in enhancing the performance and reliability of data transmission in challenging underwater environments. The evolution of acoustic modems has been marked by significant advancements in modulation techniques, signal processing capabilities, and hardware design. Table IX presents a comparative analysis of some acoustic modems currently available in the market, highlighting their data rates, operational ranges, and modulation methods. Acoustic modems offer communication ranges of up to 8 km at costs under 10,000 USD, while other modular modems focus on high customisability at relatively low prices.

The modular modems include BlueBuzz [141] and AHOI [142], which exemplify compact, energy-efficient, and versatile designs for various applications. These modems offer reliable communication over distances exceeding 150 metres while keeping costs under 600 USD [142, 143]. Open-source designs facilitate customisation and integration with other platforms, opening new avenues for research in underwater acoustics and networking protocols. For instance, the WHOI Micro-Modem [144] is engineered for use with platforms such

TABLE IX
COMPARISON OF ACOUSTIC MODEMS

Modem Model	Price (USD)	Data Rate (bps)	Range (m)	Frequency Band (kHz)	Modulation Method	Manufacturer
WNC-M25MRS4	18,740	15,000	1,000	25–45	PSK, FSK	Subnero [124]
HAM.NODE	14,990	7,000	760	18–34	PSK, QPSK	Develogic [125]
Modem 6	$> 30{,}000$	9000	5000	20-34	QPSK	Sonardyne [126]
HAM.Base	9,900	10,000	1,000	18–34	QPSK	Develogic [125]
S1000-N	6,750	80	3,000	10–25	BPSK	PopotoModem [127]
M2000	7,250	80	8,000	10–25	BPSK	PopotoModem [127]
Aquacomm	2,085	480	8,000	25–50	FSK, PSK	DSPComm [128]
S2C M 18/34	9,990	13,900	3,500	18–34	DPSK, QPSK	Evologics [129]
Aquanet	4,077	1,000	3,000	10–30	FSK	DSPComm [128]
MM2	4,250	5,000	5,000	25–50	PSK, QPSK	WHOI [100]
Delphis Nanomodem V3 (NM3)	620	640	3,500	25	FSK, MFSK	Succorfish [130]
Ahoi	890	2,350	200	30–50	FSK, GFSK	Labmaker [131]
S2C R 42/65	12,500	10,000	2,000	42–65	DSSS, QPSK	Evologics [129]
ATM-900	8,500	7,200	1,500	10–15	FSK	Teledyne Benthos [132]
AQUAmodem 1000	5,000	3,000	1,000	10–40	FSK, QPSK	Aquatec [133]

TABLE X
COMPARISON OF UNDERWATER OPTICAL MODEMS

Modem Model	Data Rate	Operational Range	Environmental Conditions	Minimum Operating Depth	Approximate Price (USD)	Suitability for Coastal Environments	Directivity
Hydromea LUMA X-UV [134]	Up to 10 Mbps	Up to 50 m	Effective in high ambient light and turbidity	Surface level	$10,000 – 20,000	High; optimised for turbid conditions	120°
LUMA 100 [134]	115 kbps	2 m	bottom to surface	$1-6$ km	N/A	works best at night	120°
Sonardyne BlueComm 200 [135]	Up to 10 Mbps	Up to 150 m	Low turbidity; deep or nighttime	200 m	$20,000 – 30,000	Moderate; best in clear waters	$\approx 1°$
Shimadzu MC500 [136]	Up to 20 Mbps	Up to 80 m	Effective in clear water; performance may vary in turbid conditions	Surface level	$15,000 – 25,000	Moderate; optimal in clear waters	Beam angle of 40°
BlueLink LUMA Series	Up to 10 Mbps	Up to 50 m	Compact design for various conditions	Surface level	$10,000 – 20,000	High; designed for versatile conditions	120°

as AUVs and static nodes, enabling robust communication even in challenging conditions.

Similarly, optical modems offer significant potential for underwater communications. Table X compares the existing optical modems, focusing on their data rates, operational ranges, environmental suitability, and approximate costs. The rating of environment suitability is done based on the work in [145]. Optical modems, including the Hydromea LUMA series, provide high data rates but are effective mainly in low turbidity or clear water conditions. However, their limited range and dependency on environmental factors restrict their application compared to acoustic modems.

While both acoustic and optical modems present promising features, acoustic modems are typically more suitable for long-range communication, albeit at lower data rates. By leveraging adaptive signal processing techniques and modular physical designs, modern modems can dynamically adjust their parameters to overcome fluctuating underwater conditions, such as varying salinity, temperature, and ambient noise levels. Despite the advancements, the relatively high cost of commercial acoustic and optical modems underscores the ongoing need for cost-effective yet efficient communication solutions for underwater applications.

Table XI provides a detailed categorisation of research work in the IoUT systems, particularly modem technology development, communication channels, and signal processing. Specifically, the table delves deeper into the modem development aspects, detailing key technological areas such as channel modelling, signal processing techniques, and modem hardware and software. Each row in the table represents a distinct development aspect, summarising the focus of research, related published works, and key findings. This detailed overview enhances the understanding of specific advancements and trends in the modem technology development within the IoUT domain.

To facilitate a robust and quantitative evaluation of underwater communication technologies, we propose the *Log-MPI* as a foundational performance metric. This index integrates key performance dimensions—data rate, communication range, and power consumption—into a unified and interpretable score that aids in deployment planning and trade-off analysis. The mathematical definition of Log-MPI is provided in Equa-

TABLE XI
MODEM TECHNOLOGY AND DEVELOPMENT ASPECTS SUMMARY

Tech.	Development aspect	Published work	Summary
Channel V-A	Modelling	[10, 29, 42, 91, 97, 98, 105–107, 110, 112, 116, 117, 117–120, 146–170, 170–213]	Studies focus on the impact of shallow water conditions on signal propagation, including variations in sound speed profiles, ambient noise, and channel dynamics. Robust modelling techniques are used to predict signal behaviour in these fluctuating environments
	Dynamics	[10, 29, 42, 91, 97, 98, 105–107, 112, 116, 117, 117–120, 146–157, 157–170, 170–176, 179, 180, 183, 185–193, 195–200, 202–205, 208–210, 212, 212–220]	Exploration of channel dynamics in shallow waters, addressing the effects of temperature, salinity, and pressure on signal propagation. Research emphasises the need for adaptive signal processing techniques
	Simulation	[10, 29, 97, 98, 105–107, 110, 112, 117, 119, 120, 149–154, 157, 159, 161–165, 167–170, 172–175, 178–183, 185–203, 205–212, 215, 216, 221]	Simulation studies validate channel models and predict performance under varying environmental conditions, supporting the development of reliable communication protocols for shallow water networks
	Estimation	[97, 98, 105–107, 110, 112, 116, 117, 117–120, 149–154, 156, 157, 157, 159, 160, 163–166, 169, 170, 170, 173, 175, 176, 179, 180, 189, 195, 196, 200, 203, 205–207, 211, 212, 212, 213, 215, 216, 218, 222]	Techniques focus on estimating channel state information for optimal signal processing, enhancing data integrity in the challenging shallow water environment
Signal Processing V-B	Modulation/ Demodulation	[29, 97, 98, 105, 106, 110, 112, 116, 117, 119, 146–148, 150, 151, 153, 156, 157, 160, 163, 165, 166, 168–170, 170–174, 176, 177, 185, 187, 194, 195, 200, 202–204, 209, 210, 213, 215, 218–220]	Advanced modulation techniques are tailored to the shallow water acoustic environment to improve data transmission reliability despite high noise levels
	Information sharing	[42, 98, 105–107, 112, 117–119, 150, 151, 153, 157, 157, 161–165, 167, 175, 182, 183, 190, 195, 203, 205, 213, 215–218]	Studies on optimising information sharing between network nodes to improve overall communication efficiency and data throughput in underwater networks
	Optimisation & ML	[112, 116–120, 207, 209, 222]	Application of ML techniques to optimise network operations, enhance signal processing, and adapt communication strategies to the dynamic shallow water environment
ModemV-C	Software	[29, 97, 112, 116, 119, 149, 152, 169, 170, 170–172, 176, 185, 218, 220]	Software advancements focus on the adaptability of modems to variable underwater conditions, facilitating efficient communication
	Hardware	[97, 112, 118, 146, 149, 150, 156, 171, 172, 174, 176, 177, 204, 220, 221]	Hardware improvements emphasise the need for durable, low-power modems capable of reliable performance in harsh, shallow water conditions

tion (4).

$$\text{Log-MPI} = \frac{\log_{10}(\text{Data Rate} + 1) + \log_{10}(\text{Range} + 1)}{\text{Power Consumption (W)}} \quad (4)$$

This formulation captures the relative efficiency of underwater modems and reflects critical trade-offs relevant to both environmental and defence-related missions [223, 224]. The selected parameters are (a) data rate (bps) which reflects the throughput capability crucial for sensor data transmission, particularly in high-bandwidth applications, (b) range (m) which determines spatial coverage and influences network topology and redundancy; and (c) power consumption (W) which represents energy cost, which is pivotal for long-duration or battery-constrained deployments. Figure 9 visualises Log-MPI values across a subset of commercially available acoustic and optical modems for which data-sheet information was obtainable. However, due to incomplete data in public documentation, only a representative subset of modems was used.

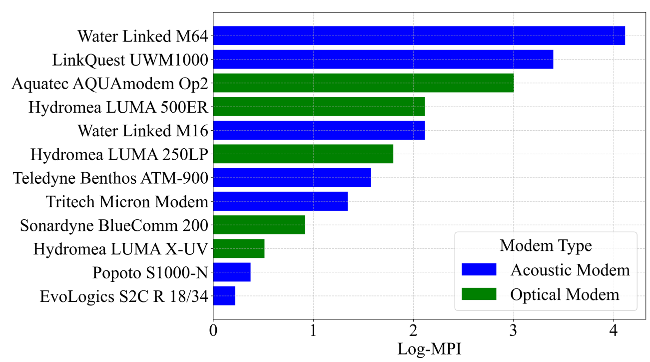

Fig. 9. Log-MPI for the modems that have the power consumption stated in their datasheets

VI. PRACTICAL CONSIDERATIONS

Underwater communication networks are critical for marine environmental monitoring, disaster early-warning systems, and maritime security. However, their deployment must balance functionality with ethical considerations to minimise ecological harm and practical strategies to ensure economic viability. This section examines the environmental impacts of acoustic and optical communication systems, focusing on their effects on marine mammals like dolphins and broader aquatic ecosystems, alongside cost-effective solutions to enhance accessibility.

A. Environmental Impacts

Environmental impacts add practical constraints to the network management strategies reviewed in Section IV. For example, acoustic communication systems, operating across 10 Hz to over 100 kHz, pose risks to marine ecosystems due to noise pollution. These frequencies overlap with those used by dolphins, which rely on 0.2–150 kHz for communication and echolocation, including signature whistles at 7–15 kHz and clicks at 40–150 kHz for navigation [225]. For example, Commerson's dolphins emit pulses in the 125–135 kHz range for navigation. Exposure to anthropogenic sounds within these ranges can cause disorientation, stress, and hearing damage, disrupting essential behaviours like navigation, communication, and feeding [226–228]. In [226], the effect of vessel approach on the Burrunan dolphin and other cetaceans has been studied by analysing their behaviour in the Gippsland Lakes region in Australia. Furthermore, recent studies highlight developmental issues and reduced reproductive success in marine species due to persistent noise exposure [229].

Optical systems, while quieter, contribute to light pollution through blue and white LED emissions, which disrupt the photic environment. Artificial lighting in these wavelengths of blue and white LEDs alters the photic environment, disturbing circadian rhythms and biological processes such as spawning and migration in fish and plankton [230, 231]. Excess light also affects photosynthetic organisms such as algae and corals, impacting ecosystem productivity and resilience in shallow coastal zones, exacerbating climate change impacts on coastal ecosystems [232]. For instance, excessive light can stress corals, threatening reef resilience.

Furthermore, the physical deployment of underwater network infrastructure, such as cables and sensors, can disturb benthic ecosystems, especially in coral reefs. Non-biodegradable components introduce long-term risks of marine pollution [229, 233]. To address these environmental challenges, the following strategies are proposed:

- **Frequency Management:** Selecting acoustic frequencies outside the 0.2–150 kHz dolphin range or using spread spectrum modulation to reduce signal intensity [234].
- **Light Emission Control:** Employing narrow-spectrum or infrared lighting to minimise biological disruption [230].
- **Eco-friendly Materials:** Designing modems and sensors using biodegradable polymers, which reduce pollution risks compared to traditional plastics [235].
- **Passive Monitoring:** Employing passive acoustic systems to monitor marine habitats without adding anthropogenic noise [236].
- **Regulatory Compliance:** Adhering to guidelines from the International Maritime Organisation and the United Nations Convention on the Law of the Sea [237, 238].

B. Cost-Effectiveness

Economic feasibility is vital for scaling underwater networks. Modems—both optical and acoustic—range from \$10,000 to \$30,000, making widespread deployment cost-prohibitive [6]. Modular and software-defined modem architectures can significantly reduce lifecycle costs by allowing partial upgrades and maintenance [239]. Standardising communication protocols and hardware platforms further enhances cost efficiency by fostering interoperability and enabling mass production [240]. Additionally, integrating renewable energy sources such as tidal and solar power can lower operational costs and environmental impact, particularly for long-term remote monitoring stations.

To provide a broader and more inclusive comparison, particularly in scenarios where complete specifications are unavailable, we augment Log-MPI metric to introduce the *Log-MPI-Extended*. This version integrates a discretized Power Index to account for qualitative estimates of energy efficiency and incorporates modem cost into the performance denominator, as shown in Equation (5)

$$\text{Log-MPI-Extended} = \frac{\log_{10}(\text{Data Rate}+1)+\log_{10}(\text{Range}+1)}{\text{Power Index}\cdot\log_{10}(\text{Price (USD)}+1)} \quad (5)$$

Here, the Power Index is assigned values in $\{1,2,3\}$ based on manufacturer-reported or inferred energy efficiency, and Price reflects approximate market cost. This formulation compresses variability in parameters across several orders of magnitude using logarithms, highlights diminishing returns in overly expensive or high-power systems, and enables inclusion of modems with partial specifications.

As demonstrated in Figure 10, Log-MPI-Extended offers a practical yet theoretically grounded way to assess modem suitability across diverse mission requirements. It aligns with multi-objective selection strategies in underwater networks, as discussed in [241, 242], and provides actionable insights for cost-effective system design.

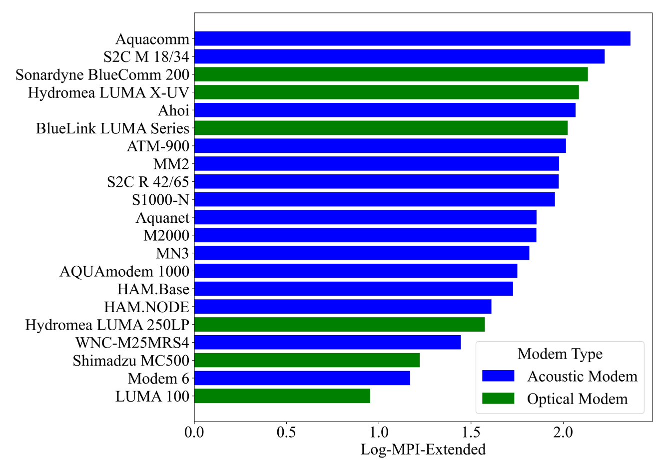

Fig. 10. Extended log-MPI for the modems that are stated in Tables (IX, X)

VII. Future Research Directions

This section outlines pivotal research directions to advance underwater acoustic network systems, including hybrid environments, bridging simulations with real-world applications, and enhancing autonomous operations and collective intelligence.

A. Benchmarking and Datasets

Real-world testing of medium- or large-scale underwater networks is cost-intensive, driving reliance on simulations that may inadequately reflect real-world challenges. Ocean

Networks Canada (ONC) provides data for ocean management, such as tsunami alerts and enhanced shipping routes, but lacks a focus on submerged communication datasets [243]. Conversely, NOAA offers annotated datasets capturing biological, anthropogenic, and ecophysical sounds, yet their application in underwater communication remains underexplored [244].

Marine test beds, such as Taiwan's Sizihwan coastline, provide invaluable insights into shallow-water sound propagation [217]. Experiments conducted there have informed transmission characteristics in shallow environments. Deep learning approaches, including those by Domingos et al. [28], classify underwater acoustic data for coastal surveillance and vessel categorisation, underscoring the need for uniform datasets and benchmarks to expedite technological advancements [245].

Additionally, systematic benchmarking frameworks like WATERMARK simulate real-world challenges, including Doppler shift and time-varying impulse responses [246]. Open-source platforms, such as Monterey Bay Aquarium Research Institute's (MBARI's) soundscape explorer. The project offers datasets to validate algorithms under realistic conditions [247], complementing efforts by NOAA's PAM programs [248]. While such resources contribute to algorithm evaluation, dedicated and standardised datasets specifically designed for underwater acoustic communication remain limited. Notable exceptions include the publicly available dataset introduced in [249], which contains recorded underwater acoustic channels from diverse geographical locations such as Singapore and Norway. This dataset encourages real-world testing reports to validate simulation results, improve the practical applicability of findings, and explore new challenges [144, 250].

B. Cooperative Network Optimisation and Machine Learning

Incorporating ML techniques into underwater networks promises enhanced efficiency and adaptability. Benchmarks, including IEEE DataPort [251, 252], provide a foundation for testing modem designs. ML algorithms have been employed to improve localisation accuracy [222], reduce noise in biological signals [79], and optimise resource allocation [253]. Due to the lack of datasets in this field, designing and training ML techniques is hindered.

Another promising research direction would be combining data routing and transmission scheduling with advanced signal processing for improving the quality of the communication links. For example, protocols investigated in [253] dynamically select communication technologies based on environmental conditions. Further strategies that leverage swarm intelligence for cooperative routing and resource management have shown promise in improving network throughput and reducing energy consumption [39, 203]. In the physical layer, ML-based adaptive modulation techniques enhance data transmission reliability in challenging environments [207, 209]. Thus, combining these methods with energy consumption optimisation in data transmission is crucial for prolonging the operational lifespan of IoUT systems [64]. These techniques that combine energy-efficient routing and adaptive signal processing can reduce network power demands [27, 203].

C. Adaptability of Modem Design

The future of modem development lies in creating modular systems that can be easily upgraded or reconfigured, ensuring that they remain relevant in the rapidly evolving field of underwater communication. Low-cost, efficient modems like WHOI's Micro-Modem and the open-source AHOI have introduced significant advancements for medium to short-range communications [216, 253]. However, creating modular, full-stack modems capable of reacting to environmental changes remains an unmet goal in the market [254]. Advancements in modulation schemes, signal processing, and hardware flexibility are critical for overcoming underwater challenges. Studies such as Su's emphasise addressing multipath propagation and Doppler effects for robust broadband communication [118]. Modular designs, including SDAMs, enable dynamic adaptability to environmental conditions, promoting interoperability and longevity [255].

Despite the large number of market players and various research efforts for improving the modularity of acoustic modems, see Table IX, a full-stack modem that can be modular and reactive to environmental changes is not available in the market. The only modem that can be considered highly modular for further research and development is the one produced by Subnero, which is relatively expensive. Moreover, the available data rates for acoustic communications are limited due to the limited operational frequency ranges, which limit the overall network throughput and make the acoustic modems used mostly in point-to-point communication rather than multi-hop networks.

This intensive use in point-to-point communication has encouraged researchers and market players to focus on improving the signal processing techniques, hence the majority of the surveyed work covers the modem development progress. A major direction in communication link improvement is including ML-based methods in modulation methods. Research on OFDM transceivers further illustrates how optimised modulation can mitigate multipath interference in complex channels [42, 256]. Guerrero-Chilabert et al. [255] also highlighted the use of ML to enhance modulation and signal processing for field-programmable gate array (FPGA)-based underwater modems. More research in the modularity of modern design and adoption of advanced ML-based signal processing will contribute to the advancement in modem development.

D. Hybrid Networks

Large-scale networks face challenges such as limited throughput due to bandwidth constraints [101]. A feasible solution is a hybrid network combining acoustic, optical, and RF communication technologies that offers the flexibility needed to navigate diverse underwater environments. This is because acoustic communication provides long-range coverage, while optical systems enable high data rates in clear conditions [135]. The commercial modems in Tables (IX,

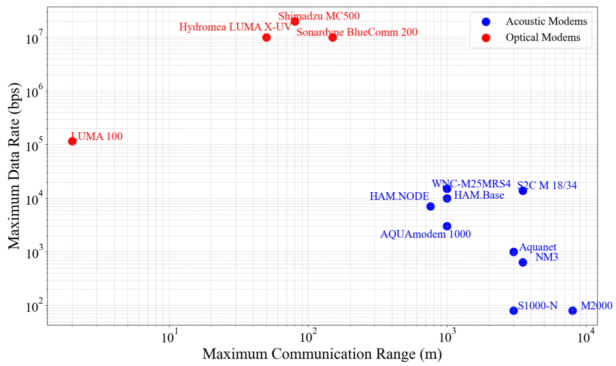

Fig. 11. Data rate vs. communication range for acoustic (blue) and optical (red) modems

X) demonstrate significant differences between acoustic and optical modems in terms of their data rate, communication range, and operating depth. Figure 11 illustrates the relationship between data rate and communication range for the acoustic and optical modems. Acoustic modems (in blue) dominate the long-range, low-data-rate spectrum, making them ideal for deep and shallow water backbone communication. Optical modems (in red) excel in providing high data rates but are constrained to short distances, making them suitable for localised, high-speed applications. Therefore, integrating these modalities could overcome the limitations of individual systems [257]. These complementary characteristics suggest the feasibility of hybrid networks where both technologies are combined. The network setup can be as follows:

- Acoustic modems are deployed as core nodes to establish a reliable underwater backbone network, ensure connectivity over long distances, and serve as reliable links in challenging underwater conditions.
- Optical modems are used as edge devices, providing localised high-speed data transfers in localised areas, such as during data aggregation from sensor nodes or high-throughput relay operations between AUVs.
- Dynamic switching mechanisms can enable seamless transitions between acoustic and optical communication modes, adapting to environmental changes such as turbidity or distance requirements.

Joint Uplink and Downlink Relay Selection (JUDRS) scheme [47] proposed to minimise the total energy consumption per information bit in cooperative cellular networks with asymmetric traffic. Inspired by such strategies, energy-efficient underwater networks can maintain acceptable data rates by selecting relay nodes based on channel conditions, thereby improving communication reliability and energy usage under the constraints of limited bandwidth and long propagation delays. However, while relay selection enhances performance, it may face scalability limitations in large-scale or highly dynamic underwater environments where rapidly changing channel conditions, node mobility, or environmental variability challenge the accuracy and responsiveness of relay decisions. Additionally, the computational and sensing overhead required to evaluate channel metrics in real time may introduce latency, especially in time-sensitive missions.

Combining these complementary features allows hybrid networks to overcome stand-alone systems' limitations, ensuring enhanced coverage, reliability, and throughput. The hybrid network scenario integrates both modem types, leveraging acoustic modems to provide long-range connectivity and optical modems for high-throughput data bursts in shallow, clear water environments. Accordingly, the network reliability is enhanced by ensuring robust, long-distance communication and maintaining high throughput where environmental conditions permit. This design is particularly advantageous for applications such as environmental monitoring, search and rescue, and underwater data collection, where both range and speed are critical. Hybrid IoUT systems should also address issues of synchronisation across technologies, as highlighted in [250].

E. Swarm Networks in Shallow Waters

Swarm networks of interconnected AUVs, USVs, and static nodes offer a scalable solution for shallow water monitoring. These systems improve adaptability and reduce deployment costs compared to deep-water alternatives [221]. However, environmental factors such as fluctuating sound profiles and ambient noise present unique challenges [33, 201]. Thus, adaptive signal processing techniques and ML algorithms can enhance swarm performance by dynamically adjusting communication parameters in response to channel variations [207, 209].

Swarm networking necessitates energy-efficient protocols, including the ones proposed in [163, 203]. Despite the potential of swarm underwater networks, it has been shown that only limited research on underwater swarm networks [258] has been done. This highlights the need for increased exploration of the challenges and development directions of swarm underwater networks.

F. Data Communication Security

The integration of advanced security protocols in underwater networks is paramount. Pelekanakis et al. leveraged physical-layer cryptography to ensure robust communication even in hostile environments [11]. CDMA-based methods [217] and secure protocol designs [34] further emphasise the importance of protecting IoUT systems. Additionally, systematic reviews indicate vulnerabilities in IoUT, necessitating robust cryptographic solutions [10, 34].

VIII. Conclusion

This review underscored the critical importance of both physical and network layers in shallow water networks. By narrowing down the scope of the review, we delved deeply into a specialised area often overlooked in broader surveys, providing targeted insights for shallow water applications. This review also employs the PRISMA framework for a systematic literature review, analysing over 180 peer-reviewed articles from 1996 to 2025. This structured approach ensures transparency and reproducibility. In this review, the physical layer focuses on ensuring reliable signal transmission through advancements in modulation, propagation modelling, and adaptive modem designs, directly addressing challenges such as signal attenuation, multipath fading, and noise interference. Meanwhile, the network layer enhances overall communication efficiency by optimising data routing, resource allocation, and error correction. The interplay between these layers forms the foundation of modern underwater networks.

The review also highlights the potential of hybrid communication systems integrating acoustic, optical, and RF technologies. Acoustic communication is well-suited for long-range transmissions, albeit at lower data rates, whereas optical communication offers higher throughput but is limited in range and susceptible to environmental interference. By combining these modalities, hybrid systems can balance communication range, data rate, and energy efficiency, addressing diverse application requirements in underwater environments. However, a notable gap remains: while theoretical models for hybrid networks are well-established, their real-world integration into practical systems remains limited, particularly in addressing inter-technology switching for dynamic environmental conditions.

An additional dimension explored is associated with the integration of static and dynamic nodes within hybrid networks. Static nodes, often deployed across wide areas, are fixed for environmental monitoring or communication. In contrast, dynamic nodes, such as AUVs or USVs, can act as relay nodes, extending network coverage while reducing deployment costs. This approach enables large-scale coverage without incurring the extensive infrastructure costs associated with deploying only static nodes. However, a critical gap persists: the dynamic allocation of relay nodes based on real-time network requirements and environmental changes remains underexplored, limiting the scalability of such systems in practical deployments.

Energy efficiency remains a concern for underwater networks, particularly given the reliance on battery-powered nodes with limited capacity. Despite advances in energy-efficient routing and adaptive signal processing techniques, a key gap lies in the lack of comprehensive strategies that integrate energy-efficient protocols across physical and network layers. Such an integrated approach ensures prolonged network operation in energy-constrained environments.

Furthermore, ML has emerged as a promising tool for addressing several challenges in underwater networks, including channel prediction, resource optimisation, and fault management. ML can enhance network resilience and adaptability by enabling dynamic network optimisation and real-time decision-making. However, the lack of standardised and annotated datasets for underwater environments hinders the widespread application of ML techniques in this domain.

While simulators like WATERMARK and datasets from organisations such as NOAA provide valuable resources, they often lack the specificity required for evaluating underwater communication systems comprehensively. The need for standardised benchmarks and testing frameworks remains an overarching challenge. Addressing this gap will require concerted efforts to develop datasets and benchmarks tailored to the unique challenges of underwater communication, including hybrid networks and dynamic node configurations. Hybrid networks that combine static and dynamic nodes, supported by multi-modal communication technologies, represent a critical avenue for achieving reliable, scalable, and cost-effective underwater communication. By leveraging dynamic nodes as relay points, such networks can achieve extensive coverage with minimised infrastructure costs, enabling environmental monitoring, disaster management, and maritime security applications.

However, realising the full potential of these systems requires addressing the outlined research gaps: practical integration of hybrid communication technologies, real-time allocation of relay nodes, comprehensive energy-efficient protocols, and standardised benchmarks. Bridging these gaps will significantly advance the field, enabling the design of intelligent, resilient, and efficient underwater networks capable of supporting a wide range of critical applications. Furthermore, environmental stewardship and economic practicality should be considered. By mitigating acoustic and optical impacts on marine life and adopting cost-effective designs, these technologies can support sustainable marine conservation and disaster mitigation, ensuring a positive contribution to human needs and ocean health.

Appendix A
Review Workflow

The process for conducting this literature review started with an investigation of the work done in underwater acoustic communication. By considering the environmental benefits of deploying underwater networks around the world, the query ”Q0: acoustic AND water AND communication AND network” was used in SCOPUS database to find the published articles in English with ”TITLE”, ”ABSTRACT”, or ”KEYWORDS” that have the words in the query. Furthermore, the economic benefits of deploying these networks in shallow water are considered, which defines the scope of this review: ”Underwater Acoustic Communication Network in Shallow Water”. The scope is then used to update the query to ”Q: acoustic AND shallow AND water AND communication AND network”. The number of published articles and the publishing countries in underwater acoustic communication networks were then obtained for queries Q0 and Q in October 2025.

Figure 12(left) presents the number of published articles from 1996 to 2025 obtained from SCOPUS using Q0 and Q in black and blue labels, respectively. It is worth noting that work in shallow water is specifically part of work in underwater communication networks. It can be observed in Figure 12(left) that the work in underwater communication, specifically in shallow water environments, has gained more interest owing to the ease of deployment and the recent technological advancement in underwater sensors and data management technologies. A comparison between the accu-

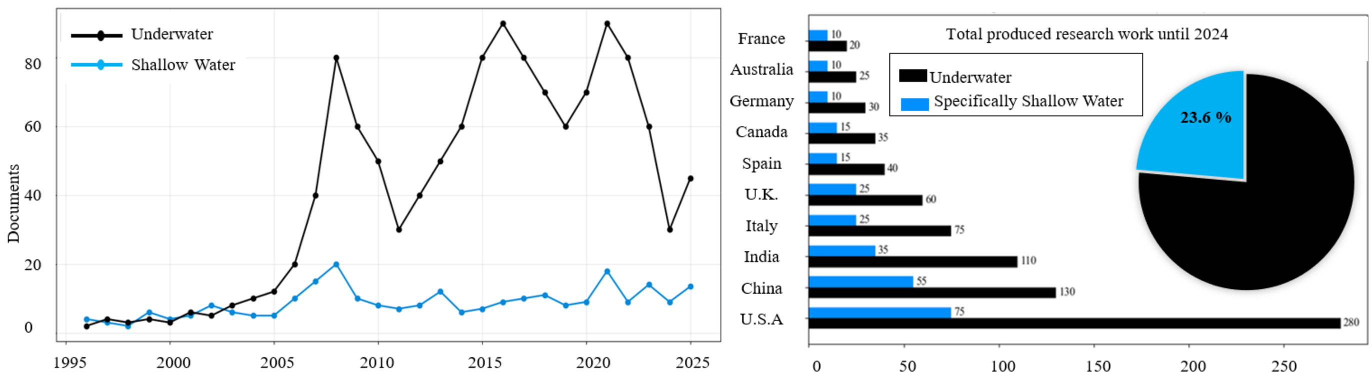

Fig. 12. Publication trends in underwater communication in the last 3 decades (left) and publications by countries (right), blue for studies with a focus on shallow water communication

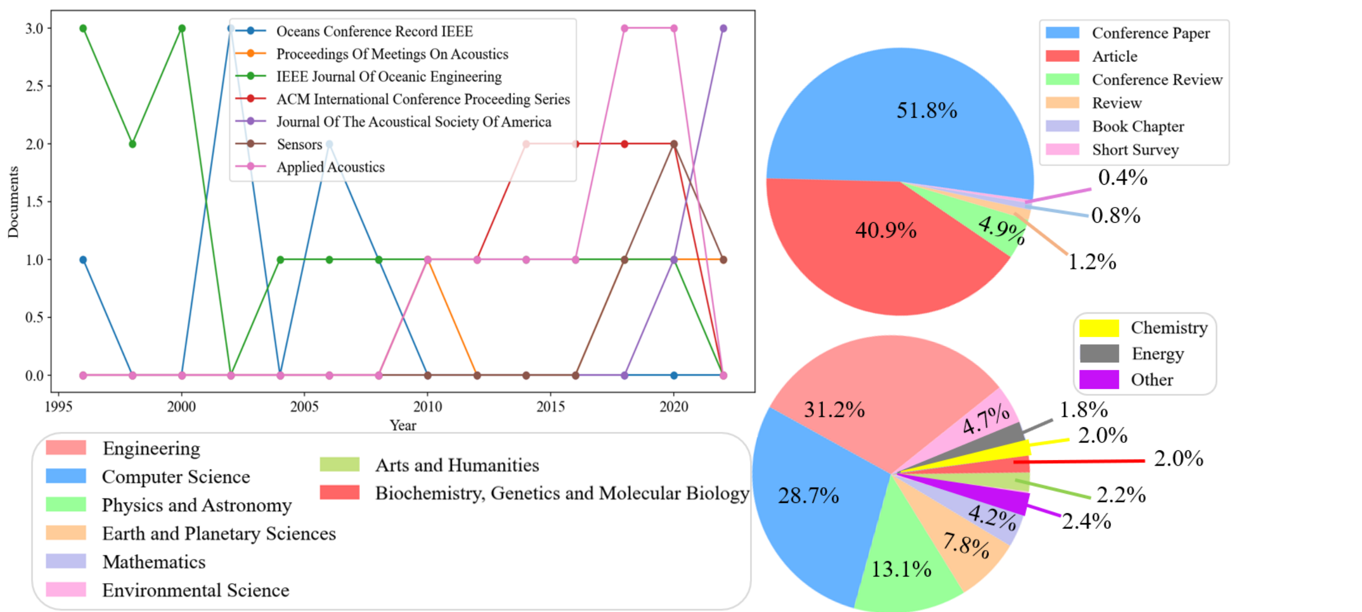

Fig. 13. Categories of published articles according to publishers through the years 1996 to 2025 in the line chart (left), and the accumulated categorisation of the published work according to the type in the pie chart at the top and field of study in the pie chart at the bottom (right)

mulated publications since 1996 that are coming from different countries is shown in Figure 12(right).

The USA and China have the highest publication numbers in this field, which justifies the number of acoustic modems produced by American companies, as shown in Section V. Australia is ranked 9th and 6th in terms of the number of publications in underwater communication networks and specifically for shallow water, respectively. The pie chart in Figure 12(right) shows that only 23.6% of the work is focused on shallow water despite the ease of networked sensor deployments and the variety of challenges in shallow water environments.

Motivated by the scope defined and guided by query ”Q”, the review protocol is designed using PRISMA as illustrated in Figure 2. The collected data from SCOPUS were compiled as titles in an Excel sheet for scanning. Thus, the first reason for exclusion was identified as ”R1: record is not a research article”. Then, the record were downloaded to be scanned. In this scanning phase, the articles were categorised by type: reviews, books, conference papers, and journal articles, as shown in Figure 2 (flow-chart (a)). Then, the review and survey papers are screened separately to identify the gaps in the literature as discussed in Section II. Furthermore, the conference and journal articles were used to specify further the central research questions that were addressed, which guided the design of this literature, as shown in Figure 2 (taxonomy (b)). The significant intertwined contributions in the state of the art noted in the screening phase have been used to identify the second reason for exclusion, which is ”R2: the topic is not closely related to communication networking in a shallow water environment.” Then, the third reason for exclusion was identified as ”R3: the article is not accessible, its results are not clear, or its references are not accurate.” Figure 2 shows the query, total number of obtained results, and number of articles excluded ($m = 74$) out of the most relevant 237 results after considering the reasons for exclusion following the PRISMA flow chart. Then, 60 more reported research papers and reports, and 41 websites were included for further details about the commercial modems and current IoUT applications.

In the screening and inclusion phases in Figure 2, the significant intertwined contributions were used to build the literature review design. It has been noticed that designing the underwater networked sensor as a transceiver, namely a "modem", has gained the interest of researchers who focus on the physical layer. Meanwhile, the networking aspect, which includes communication network algorithms designed for static and dynamic networked modems, has gained interest in multiple applications. These components form the underwater networks as an IoUT system, including data collection and processing. Thus, researchers propose various IoUT system architectures that suit the requirements for underwater networks and data processing techniques that improve the overall system performance. These three research directions have been defined to guide the work in this literature review as depicted in the triangle on the left side of Figure 2.

Detailed examination of the papers showed that only 6.1% of the research focused on evaluating previous work, as shown in Figure 13 (right-top pie chart). Out of the articles that were collected in the last 30 years, only six review articles were published that included the literature of over 163 sources during the last three decades. The scarcity of systematic literature evaluations has inspired us to conduct this review.

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