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Survey paper

Internet of underwater things communication: Architecture, technologies, research challenges and future opportunities

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ABSTRACT

Recently, the Internet of things (IoT) paradigm has proliferated all aspect of life. The improvements IoT has made in business and industry has raised the possibility of extending its use to underwater environments, which also impacts human life. Consequently, Internet of Underwater Things (IoUT) research is intensifying. As in IoT, to deploy a successful application in IoUT, an optimal communication network is required. However, underwater environments pose unique technical challenges for setting up such networks. The aim of these networks is to achieve optimal performance required for efficient and reliable transmission within IoUT. Communication is the lifeline of a network and involves the transmission of information along a medium or path. Thus, it is critical to understand the impact of underwater environment on IoUT communication. Overall, IoUT communication utilizes underwater and terrestrial equipment. We focus on underwater communication where the medium is water and information is transmitted as acoustic/sound signals. With respect to physical, Medium Access Control (MAC) and network layers, we investigate issues associated with designing optimal IoUT networks. The underwater ecosystem varies spatially with time so, knowledge of prevailing underwater regional profiles at any time is essential. Profiles enable the construction of necessary constraints that affect optimized performance of IoUT networks. We analyze the constraints imposed by different regional profiles of underwater ecosystem and their impact on optimal IoUT communication. These constraints affect performance goals required for successful IoUT network deployment. The analysis is useful for developing state-of-the-art IoUT communication strategies based on stochastic optimization models.

1. Introduction

Today, information (data) gathering has become vital for improving the quality of human life because information can be found in almost every "thing". The Internet of Things (IoT) is an ecosystem that is interconnecting and providing communication between any "thing" and every "thing" (devices) to collect information (data), which can be used to improve the way we live. It is well-known that approximately three-quarters of the Earth's surface is covered by water in forms such as salt water (the oceans and seas) and fresh water (lakes, rivers, snow, ice) [1]. Thus, it is expected that the "things" in underwater environment will also be included in the IoT ecosystem because they also generate data that impact human lives. However, the underwater environment operates differently from the terrestrial environment. Therefore, some architectures, protocols, and standards designed for the IoT may not be directly applicable in the underwater environment. Hence, the need for an Internet of Underwater Things (IoUT) paradigm wherein tailored concepts will be developed to solve the inherent communication challenges presented by the underwater environment. In simple terms, IoUT should support a platform that allows remote monitoring and collection of data from "things" (devices) under water through the Internet [1]. The IoUT is a part of the IoT through which "things" in the earth's water bodies (oceans/sea, rivers, lakes, and streams) are digitally connected. It is an ecosystem that interconnects heterogenous underwater smart "things" (devices) using limited or no human intervention [2]. These smart devices include underwater sensors and vehicles such as Autonomous Underwater Vehicles (AUV), Remotely Operated Vehicles (ROVs), underwater trackers, submarines, sea-bots, and underwater drones. The purpose of the IoUT is to facilitate an integrated, reliable, and coordinated communication network that links devices under the water surface and on land so that high-quality underwater physical data can be collected. IoUT also provides Internet connectivity for remote

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access of data related to the underwater habitat anytime, anywhere.

1.1. Motivations for IoUT

The motivation for the IoUT cannot be overstated. Data gathered by the IoUT ecosystem can be utilized for monitoring the state of the waterbody. Such monitoring enables the detection and prediction of changes to the natural state of underwater so that the impact of the change on human and aquatic life can be measured and controlled. For example, rapid temperature and salinity changes, tremors or shifts can indicate changes in climatic conditions which will enable the prediction of potential natural disaster, pollution, or threat to aquatic life. Information from the underwater habitat can be retrieved in video format to facilitate the exploration of sea and biological resources available underwater to improve human life. Specifically, data in video form is used for scientific research (e.g., climate change/disruption), commercial, and military activities. The underwater habitat consists of massive fauna and flora that affects life on the terrestrial habitat. For example, the oceans regulate and determine terrestrial climatic conditions. Changes in the fauna and flora may indicate water pollution. Pollution level can be monitored, and further pollution can be averted by using the information provided by interconnected underwater sensors collecting and transmitting actual data about underwater fauna and flora conditions. In addition, early detection of seismic conditions through the IoUT can reduce the impact of cyclones, storms, tsunamis, and coastal flooding that can occur due to climate change. Other motivations for the IoUT includes oil pipeline repair, shipwreck surveys, fish farming activities and ecological monitoring.

To reap the full benefits of the IoUT, the IoUT needs to be well integrated with the IoT. However, due to the differences in the ecological nature of the underwater and terrestrial ecosystems, the IoT architecture and standards are not applicable for the IoUT. Thus, there is a need to design specific technologies tailored for the IoUT. The unique features of the IoUT that must be considered when developing its communication technologies include:

a) *IoUT enables communication between devices that are underwater and on terrestrial land*: IoUT will connect devices (on land and in water) operating in different ecological environments and with different technologies for collecting data [3].
b) *The main transmission media within the IoUT ecosystem is water*: the IoUT will connect oceans, seas, lakes, and rivers which cover about 72% of the earth's surface. Thus, in many cases, devices underwater are only able to transmit their data via the water medium.
c) *Data can only be efficiently propagated via acoustic signals (soundwaves)* [3]: Electromagnetic (EM) signals experience high attenuation and absorption in water and optical signals suffer high absorption and scattering in water. However, acoustic signals have lower attenuation and absorption and propagates through longer distances than EM and optical signals in water. Thus, acoustic signals are more practical for carrying information in the IoUT ecosystem [4,5].
d) *IoUT will be exposed to high signal interference:* due to the underwater noisy environment and movement activities of deep water, surface water and buoy marine life, the IoUT ecosystem inherently experiences a high level of noise interference.

1.2. Main contributions of this research

The main contributions of this research work are as follows:

- With a focus on underwater IoUT communication, we review recent research works that address communication challenges within the IoUT environment.
- We present open research issues associated with designing optimal network protocols for IoUT. Specifically, we discuss challenges/issues related to physical, Medium Access Control (MAC) and network layers.
- We analyze the constraints imposed by the underwater habitat and their impact on the achievement of an optimal communication network in the IoUT ecosystem.
- We also analyze how water properties affect optimal IoUT communication in terms of network performance parameters provided by any communication media.

The rest of the paper is organized as follows. In Section 2, we briefly discuss applications that can harness the IoUT. Section 3 describes the IoUT underwater communication architecture by focusing on the communication process, components and existing network topologies. The IoUT underwater communication occurs over acoustic channels, and therefore research works on signal processing and routing are paramount in achieving a reliable and efficient IoUT ecosystem. Thus, in Section 4, we highlight current research works related to signal processing and routing in the IoUT. The analysis of these research works is based on the strategy used, research challenges addressed, results achieved, and the benefits to IoUT applications. In addition, we also review existing IoUT research testbeds and projects. Section 5 presents future research challenges and opportunities in the IoUT area. Section 6 concludes the paper.

2. Applications in the IoUT ecosystem

Some of the goals of IoUT include monitoring, tracking, exploration and surveillance of the underwater ecosystem. In this section, we present a few applications that can be improved using an efficient communication network deployed in the IoUT. These applications may require real-time or non-real time communications among IoUT devices. Moreover, the IoUT devices may need intermittent or constant connectivity for the transmission of information. The information sent and received may be in text, sound (voice), image, video or multimedia format.

1 *Military operations*: for military marine operations, an important activity is sea surveillance through submarine communication and underwater seabed 3D imagery.
2 *Commercial operations*:

- Deep sea natural resources exploration: The IoUT enables a seamless connection between offshore and onshore oil and gas platforms for effective drilling and tapping of underwater natural resources [6]. Early detection and repair of leaking oil pipelines are also possible. In addition, oil pipeline performance, condition and diagnostic information can be transmitted via the IoUT communication network for pipeline monitoring.
- Fish-farming: this is a process of breeding and cultivating fishes in an enclosed undersea area for commercial purposes [6]. IoUT devices can be deployed to monitor and track the changes in the conditions of the enclosed environment. The data collected are important for pollution detection, feeding level, waste deposit, and water quality tracking.

1 *Water transportation*: IoUT can enable ships and boats to wirelessly communicate with devices placed under the water to obtain information on seismic conditions, temperature variations and turbulent activities in different geographical regions of the ocean or sea. This information can help prevent potential shipwrecks. In addition, the information can enhance seaport security and inspection of ships that dock at the seaports [7].
2 *Undersea mission critical operations:* Data gathered from underwater devices can facilitate better sea search and rescue missions such as locating lost shipping containers, and humans. Moreover, some underwater devices can be used to carry out specific rescue missions in

deep undersea regions, most especially in undersea regions that are perilous for human to reach [8].

3 *Scientific research activities*: IoUT will enable the tracking of the underwater ecosystem in real-time for the detection of changes [6]. The information gathered can be analyzed to provide predictions about climate change, tsunami, earthquake, storms. and warning notifications and services to areas that may be affected by the changes detected.
4 *Aquatic life exploration and monitoring*: this involves tracking of the aquatic ecosystem in real-time for the detection of changes [9].
5 *Leisure activities*: water-based sports (e.g., rowing, sailing, surfing, and skiing) and underwater recreation and tourism (e.g. scuba diving and snorkeling) can also benefit from the IoUT. Data collected from the underwater environment can be used to monitor the underwater condition that could affect these sporting activities.
6 *Oceanography and meteorological data tracking*: Oceanography involves the scientific exploration of rivers, ocean and sea activities, while meteorological activities enable weather forecast [10,11].

In relation to IoUT applications, key network requirements that improves users' quality of experience include availability, accuracy, reliability, and integrity. We discuss these requirements in section IIIB.

3. IoUT underwater communication architecture and network

As more intelligent devices are deployed in the IoUT ecosystem, the need for communication and networking among these devices will keep growing. Since the IoUT ecosystem is characterized by a sparse network density, the establishment and maintenance of communication links will be challenging. Thus, a robust communication architecture is essential for the IoUT [3]. The main component of a communication architecture is the communication path/medium/channel through which the information being communicated is transported. Due to its unstable medium, the IoUT requires a flexible communication architecture that can adapt to varying environmental scenarios and application requirements that exists in the ecosystem. Thus, at different levels of the TCP/IP protocol stack, well-defined adaptable protocols that can enable real-time reconfiguration are paramount. Real-time reconfiguration is the ability of a communication architecture to adapt its networking techniques and protocols during a communication process. Such functionality facilitates flexible architectures and pave way for the improvement of protocols and the addition of new protocols. In addition, due to the energy limitation of IoUT devices, an efficient architecture should reduce energy wastage and prolong the lifetime of networks in the ecosystem. In this section, we present the major components that enable the communication network architecture in the IoUT ecosystem. First, we describe a typical communication process within the ecosystem to identify the components that define a generic communication architecture for the IoUT. Second, we describe each of these components and then present different communication network topologies that facilitate data transmission in the IoUT.

3.1. IoUT communication process

The communication architecture of the IoUT consists of devices that are equipped with acoustic or Radio Frequency (RF) transmitters and receivers or both. These devices include sensing devices, gateway devices, sink stations, and remote stations. The underwater sensing devices, which have mainly acoustic communication capability sense and gather the required information from the underwater environment. The information is then forwarded to sink stations (i.e., buoys, autonomous surface vehicles (ASVs), or ships) on the water surface.

The relaying of information to the sink station can be through single hop or multi-hop communication. In single hop communications, sensing devices transmit the information directly to the sink station. In multi-hop communications, the transmission of information to the sink station is either through a gateway device (cluster head) or via other sensing devices. The information received by the sink station is transmitted to the monitoring center on terrestrial land via RF channels. This information is then analyzed and processed at the monitoring center and utilized for various IoUT applications [12]. The communication process in the IoUT uses several components.

In the next subsections, we outline and discuss these components, which are the types of data that can be generated, the devices that generate the data to be transmitted (source), the signal and transmission medium that convey the signal from the source to the destination.

3.2. Components of the IoUT communication architecture

3.2.1. Data

Most of the data collected in IoUT is about the physical conditions and events happening in the underwater environment. Data type can be text, image, video or multimedia. This data is used for monitoring, tracking, exploration, and surveillance. For example, data gathered may be analyzed to detect when certain water physical parameters of interest such as temperature exceeds a pre-determined threshold value. Recorded events are used to study and explore the underwater environment.

3.2.2. Devices

IoUT devices can be classified as underwater devices and buoy (surface) devices and they can be stationary or mobile. Such devices are submarines, ROVs, AUVs, underwater sensors. Stationary devices are mostly deployed at specific target areas and mobile devices are required to roam within the water precinct. Other devices are located at remote stations on terrestrial land. Devices on terrestrial land can be linked to the Internet or other remote locations to provide access to underwater data collected. The IoUT primary devices are underwater sensors. These are small (micro or nano sensors), intelligent, and battery-powered devices and modems with acoustic communication capability [13,14]. These devices collect underwater parameters of interest and relay it to the gateway node or sink station via the underwater acoustic medium. The type of IoUT sensor device deployed depends on the application scenario and the type of data to be collected. For example, devices used to collect video or image data are used by underwater observatory systems for short term underwater monitoring, tracking, survey or exploration applications. Buoy devices are sink stations with acoustic and RF communication capability. These stations receive information from the gateway devices over the underwater acoustic medium and transmit the information to remote terrestrial stations over the RF communication medium. Gateway devices are underwater devices with acoustic communication capability, large memory size, and high processing capability. These devices collect information from the underwater sensing devices and relay it to the sink station on the water surface [15]. AUVs and ROVs are remotely operated to monitor underwater events over large areas.

3.2.3. IoUT Under water acoustic communication medium and signal

Sound waves travel farther in water than Electromagnetic (EM) wave and optical waves because the absorption of sound is relatively low in water. However, sound waves have a low propagation speed (~1500 m/s), with a delay over tens or even hundreds of milliseconds. Although EM waves can travel over long distances in air, they fade exponentially in water [15]. Therefore, acoustic (sound) signals are most effective for underwater communications. In this subsection, we analyze the acoustic transmission medium (water) and acoustic signal (sound) properties which affect performance measures necessary to ensure high quality communications between devices in the IoUT.

a) **Underwater transmission medium**

A transmission medium is the physical communication path between signal transmitters and receivers. Such a medium can be guided (cables or optical fiber) or unguided (air, space, water). The quality of a transmission is determined by the characteristics of the medium and the characteristics of the signal [16]. Since water is the primary medium for signal transmission between IoUT underwater devices, in this sub-section, we analyze the properties of water in the context of performance measures used to rate communication media. For any medium, the performance level is determined by its transmission characteristics. The measures are used to set goals when designing communication systems that will use such media. These measures, which determine the quality of transmission over a media include:

- **Level of availability**: this refers to the extent (partial (limited but irregular), temporal (limited but time-based) or continuous (unlimited)) to which a medium readily provides a connection link for the propagation of signal between devices. It takes the strength (connectivity level) of such a link into account and is determined by (1) the possible transmission frequency and range that can be achieved in the medium, (2) effect of variations in the medium's physical properties due to change in atmospheric condition (e.g., temperature or pressure), (3) level of predisposition of devices to interference from the surrounding. The level of availability affects the data transfer rate which is determined by the transmission capacity (amount of signal/data that can be transported in a period) and achievable transmission speed.
- **Level of accuracy**: it is the minimum achievable degradation or impairment that a signal is prone to while traversing a medium. This is determined by the amount of attenuation and interference/noise, which distorts the signal as the transmission distance increases. The level of accuracy affects the amount of signal loss and error experienced in a medium.
- **Level of reliability**: this refers to the minimum delay that can be achieved within a medium (on time implies no delay) [17]. It is determined by the maximum frequency and range of transmission that is permitted by the medium such that minimal or no repeaters are required between two devices to achieve an end-to-end communication. Each signal repeater tends to limit the transmission speed; thus, the level of reliability impacts signal transmission delay experienced in a medium.
- **Level of integrity:** refers to error level that can be imposed on a signal due to changing conditions within the medium. A high level of integrity implies a low chance of error (change) or no error (no change) in the transmitted signal.

The properties of water that affects the measures presented above include:

i. **Motion/vibration**: The form of water is liquid and thus it is highly prone to intermittent flows and continuous movements. The effect of water motion (e.g. water waves and drifts) caused by turbulence, tides or current is intermittent transmission connectivity and noise. Intermittent connectivity arises from the displacement of reflection point, thus resulting in scattering and Doppler spreading due to the changing transmission path length. Consequently, the communication path can be temporarily lost [18,19], thereby affecting the level of availability of the medium. Noise may be classified as ambient noise and site-specific noise [20]. Ambient noise includes sea turbulence, breaking waves, rain, and they occur in the quiet sea water background. Site-specific noise occurs in certain places only. Such noise includes ice cracking in polar regions [20]. These noise sources cause interference and affects communication accuracy. Water waves may also cause the drifting of devices, thus affecting communication response and consequently delay and loss of communication signal may occur. These affect the level of accuracy and reliability of water as a transmission media.

ii. **Optical properties**: Reflection and refraction in water are two properties that lead to multipath formation [21]. Reflection can happen at the surface, bottom, and by any objects, and refraction occurs within the water. The effect of multipath culminates in the fact that a ray of signal transmitted by a source follows different paths and gets to the receiver as multiple signals. If a ray of signal is reflected, the receiver receives the originally transmitted signal and the reflected signal. This property affects the level of accuracy and integrity of signal transmission in water. The ultimate effect of these properties includes the loss of communication signal due to signal being deflected in different directions.

iii. **Physical properties**: These include temperature, salinity, and pressure. They affect the propagation of signal in water and vary with the depth and location of the water body [21]. At the surface of the water body, temperature and pressure are usually constant. However, in colder climatic regions, temperature decreases with increase in depth. These variations in temperature, pressure, or salinity in different regions causes density gradients which affect the optical properties of water. For example, high to low temperature gradients cause refraction in water. These fluctuations in physical properties affect the level of availability, reliability, and accuracy of the waterbody as a transmission medium. Section V presents an analysis of the effect of the fluctuations on sound propagation speed in water.

b) **Acoustic (sound) signals.**

Acoustic transmission involves the propagation of information through sound (acoustic) signals. These signals are pressure waves generated by a disturbance that propagates through a medium [22,23]. Generally, the performance of a signal through a medium is measured by propagation speed, resilience to the medium's atmospheric conditions which are determined by the extent of attenuation, path loss, and fading. In this sub-section, we present some of the limitations and benefits of acoustic transmission that exist because of the attributes of sound waves (acoustic signals). The limitations and benefits are presented along with the sound signal attributes, which include:

- **Signal frequency:** acoustic signals are low frequency waves which offer low data rate, limited bandwidth and incur high delay. However, such signals have long wavelengths. Thus, acoustic waves can travel long distances and are used for relaying information over several kilometers [23,24].
- **Dependency of speed on temperature:** the propagation speed of sound through a media depends on the temperature of the media. The average speed of sound increases as the temperature of the media increases [23]. However, depending on the density of the medium, the sound transmission speed can be low and inconsistent with temperature, thus resulting in high and variable propagation delays [25,26].
- **Dependency of intensity on frequency:** intensity is the energy of sound waves. A high intensity sound wave has high frequency. The available bandwidth of a sound signal is about 1 kHz at 100 km, which is extremely low. However, at shorter distances, the bandwidth increases, thus making short range transmissions of sound signals faster and more reliable than long range transmissions.
- **Absorption:** sound wave can be absorbed by other materials. An inherent property of sound waves transmission is that path loss depends on the signal frequency [6]. This dependence is due to absorption loss.
- **Spreading:** sound waves can be reflected and thus spread easily causing spreading loss, which increases with distance [6]. This property causes the attenuation of sound waves, which makes long range transmission a challenge.

- **Transmission distortion:** varying temperature gradients in the transmission medium causes the refraction of sound signals [21], thus causing intermittent, unreliable, and delay-prone connectivity.
- **Reverberation:** is a re-occurrence of sound after it is generated. It is created when sound signal is reflected followed by further reflections and then decaying as the sound is absorbed by surfaces of objects in the space. This property causes the loss of sound waves pattern and leads to signal distortion in time domain. This affects quality of transmission in terms bit error rate and data loss [27].
- **Masking by noise:** sound waves can be easily masked when combined with an interfering sound wave during its transmission, leading to loss and error in transmissions [28]. These forms of noise lead to highly dynamic changes in the transmission link error rates and link outages [6].

Due to the characteristics of the IoUT, acoustic communication may not be suitable for all applications. We discuss a few of these applications briefly in Section 2. For example, the limitations of the acoustic medium (as Table 1 shows) make it unsuitable for military applications, where high speed and reliable communication is required. Therefore, with a focus on their limitations and best applications, Table 1 presents a performance comparison of three commonly used transmission media suitable for the underwater environment [25].

3.3. IoUT communication network

Underwater Sensor Network (USN) connects spatially distributed autonomous smart underwater sensing devices with communication and computing capabilities and limited or no storage capacity. The seamless connection between these sensors can be acoustic, RF or optical communication links. However, USNs based on acoustic communication are the most practical option for IoUT underwater devices because EM and optical signals do not propagate well underwater.

The deployment of USNs depend on the purpose and requirements of the IoUT application for which a network is to be set up. USNs can be classified based on deployment location, topology, and device agility. Deployment location is concerned with the placement of IoUT devices. Devices can be deployed on the surface, in shallow or in deep water regions of the waterbody depending on the target area of the IoUT application. Topology of a network determines how the underwater device is arranged within a network. Deployment of USNs can also be according to the agility of the devices within the network. Such deployments can be stationary, mobile or a hybrid (combination of stationary and mobile). The deployment of hybrid devices is frequently determined by the state of the water tides, purpose of the network, and the type and amount of data to be collected. Stationary deployments are used when the IoUT application is for a target area, such as surface, shallow or deep-water regions where there are minimal or no water currents and tides in the water environment. Mobile deployments are mostly used in areas where water currents are high and can also be for surface, shallow or deep-water regions. Hybrid deployment is a combination of stationary and mobile deployment, which can be utilized in any water area depending on the IoUT application.

Table 1
Performance of transmission media for the underwater environment.

Media Criteria	Acoustic	RF	Optical
Loss	0.1-4dB/km	3.5-5dB/m	0.39-11dB/m
Data rate	10-100kbp	1-10Mbps	10—100Gbps
Delay	~667ms/km	0.03ms/Km	0.03ms/Km
Range	~1-10km	~10m	~100m
Velocity in water	1500m/s	2.26 × 10^8 m/s	2.25 × 10^8 m/s
Data rate limiting factors	Temperature, salinity, pressure	Conductivity, permittivity	Absorption and scattering
Benefit	Transmits over longer range	Immune to noise	High speed
Limitation/s	High delay, low bandwidth	EM interference, low frequency propagation	Affected by scattering and line of sight
Best application	Deep sea transmission	Water-terrestrial transmission	Short range, high data rate transmission

The type of topology implemented for a network can affect the network Quality of Service (QoS) parameters such as throughput, delay, delay variation, and data loss. Thus, an optimal topology needs to be determined for any network that must be set up for an IoUT application scenario [3]. The choice of an optimal topology is subject to certain constraints dictated by the underwater environment and the requirements of the IoUT application. Environmental constraints include water velocity, temperature, pressure, and salinity within the location of interest and network coverage area. Application requirement constraints include distance between sensor devices and sink stations, which is determined by the required depth of deployment. The depth of deployment can be surface-water (open-water), shallow-water or deep-water. Other application requirement constraints are projected transmission throughput, amount of data to be collected, deployment period (short term or long term), cruciality and urgency of the application. Moreover, the type of topology deployed for a network in the IoUT determines the signal processing scheme that is utilized within such networks. The common topologies of any USN are:

3.3.1. One-dimensional (1-D) topology

Fig. 1 depicts the 1-D topology. In a 1-D USN topology, sensing underwater devices are deployed autonomously using a star topology where the transmission of information from the sensor devices to the sink station is via a single-hop horizontal communication link. Each sensor collects and transmits the underwater information it senses to the sink station [29]. All sensing devices communicate with the sink station but not with each other. This topology is mostly applicable for shallow water application scenarios where the distance between the sensing devices and the sink station is quite short (e.g., coastal monitoring).

3.3.2. Two-dimensional (2-D) topology

Fig. 2 depicts a 2-D USN topology. Sensing devices are deployed in clusters in a 2-D USN topology. Each cluster has a cluster head that relays the information from each cluster member to the sink station. Only cluster heads have communication links to the sink station. In this topology, the transmission of information is via a two-hop communication: (i) members of the cluster communicate with cluster head using a horizontal acoustic communication link and (ii) cluster head communicates with sink station using vertical acoustic communication. 2-D USN can be used in fish farming, where the sensing IoUT devices gather data used for monitoring the water conditions around the fish cultivation environment [30]. 2-D-USN can also be deployed to monitor underwater plates in tectonic regions.

3.3.3. Multi-dimensional (M-D) topology

Fig. 3 depicts a multi-dimensional topology for USNs. In a M-D USN topology, the deployment of sensing devices is in clusters but with no cluster head and these devices operate in a co-operative manner. Co-operative operation between devices means that sensing devices within a cluster collaboratively relay sensed and gathered data for each other. The transmission of information to the sink station is via collaborative multi-hop communication, where information is relayed to the sink station over two or more hops.

Each sensing device in the cluster has a communication link to every sensing device within its cluster and at least one sensing device in the cluster has a vertical communication link to the sink station. This topology is applicable for deep underwater deployment where the sensing devices generate and transmit a lot of data and the distance between the sensing devices and the sink station is very far. Such application includes

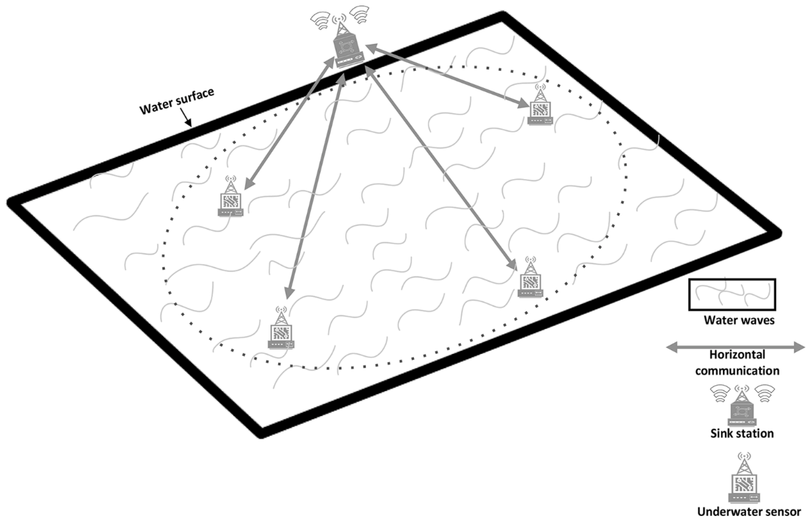


Fig. 1. One-dimensional USN topology.

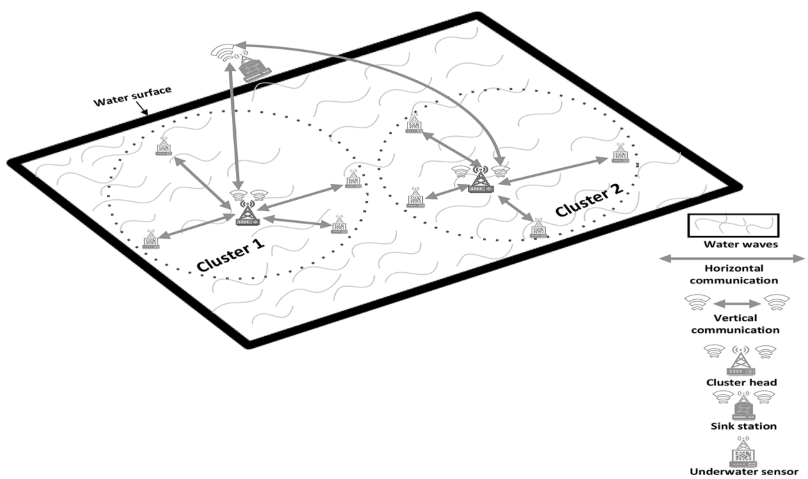


Fig. 2. Two-dimensional USN topology.

ad-hoc underwater networks that are used for time-critical, delay-intolerant deep undersea rescue and search missions or deep-water explorations or surveillance. In addition, applications that require devices in shallow water or water surface to communicate with devices in deep water can be deployed using multi-dimensional topology.

4. IoUT communication: research challenges, proposed solutions, projects, and testbeds

4.1. Research challenges

Most IoUT research challenges are about QoS guarantee. In this section, we analyze QoS requirements that define constraints for physical, Medium Access Control (MAC) and network layer protocols used in IoUT. Successful propagation of a signal through a media is measured with QoS metrics. Some challenges in IoUT can be attributed to QoS performance issues of acoustic transmission in water, which are:

4.1.1. Delay variation

acoustic transmission exhibits random signal variation due to water surface motion and fluctuations in sound speed. IoUT devices displaced due to water movements contribute to variations and changes in channel response. This occurs due to Doppler effect, which causes frequency shifting and spreading [20], thus creating non-uniform distortion across the signal bandwidth. In addition, sound propagation speed through water is extremely slow and varies due to variation in the physical properties of water (e.g., temperature, salinity, pressure) at different times and water regions.

4.1.2. Data-rate

the fact that acoustic communication data rate depends on distance, affects the design of IoUT networks. The effect is prominent when communication is between devices within a long range of each other. However, this motivates for a multi-hopping network topology within the IoUT [20]. In addition to improving data rate within the network, multi-hopping achieves energy efficiency for IoUT devices. Since the speed of sound varies with temperature and pressure, data rate may become unstable in certain water regions.

4.1.3. Delay

Large delay variations are also caused by severe multipath propagation. The slow speed of sound waves and significant multipath phenomena cause very large channel delay spread. In shallow water, the delay spread is in the tens of milliseconds whereas in deep water, it can be in the order of seconds [6,20]. Such large delay variations cause severe Inter-Symbol Interference (ISI) due to time-spreading.

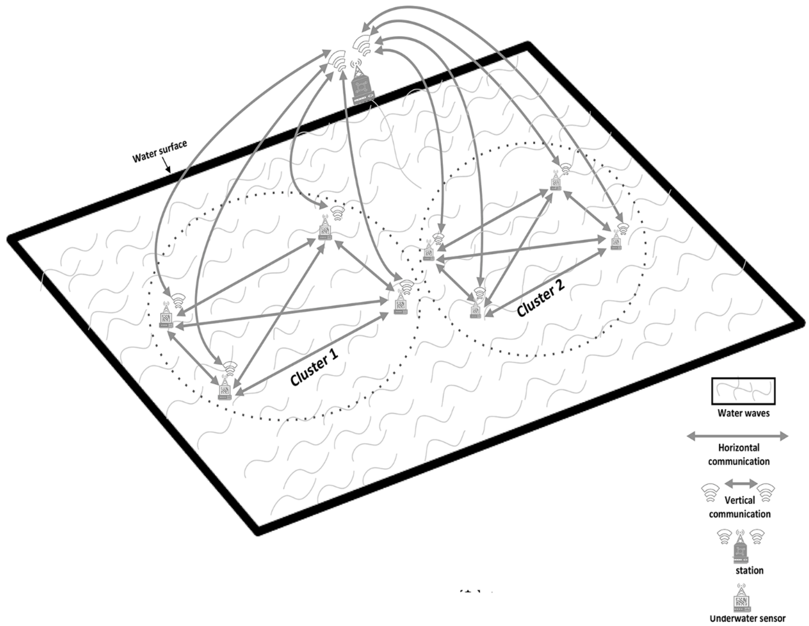


Fig. 3. Multi-dimensional USN topology.

4.1.4. *Loss and bit error*

The three sources of energy loss for sound waves in water include [6]: (i) absorptive loss: this occurs due to the conversion of the sound wave's energy into another form, which is then absorbed by the water medium; (ii) geometric spreading loss: the sound wave's energy decreases with longer distances as it propagates away from its source of transmission; (iii) scattering loss: this occurs due to the reflection of incident waves by irregular surfaces, such as the non-uniformities in the water column and interactions of sound waves with non-ideal sea surfaces and obstacles in the waterbody [6,27]. Each of these sources contribute independently and cumulatively to the overall loss experienced during communication between IoUT devices. In addition, the inherent background noise in waterbodies can mask sound signals and change its spectral pattern, thus causing transmission errors.

4.2. *Research solutions*

Next, we analyze several works that have been proposed to solve the QoS research challenges discussed in the previous subsection. Such research works enable successful deployment of IoUT networks. These solutions involve mechanisms, protocols, and algorithms that can improve sound signal processing and transmission in water. We focus on transmission processes at the physical, MAC, and network layer.

4.2.1. *Physical layer issues and protocols*

The IoUT ecosystem is characterized by different applications. Thus, there is no one-size-fits-all protocol. Each protocol addresses specific challenges based on the deployment scenario. This sub-section presents the techniques proposed for addressing some physical layer signal processing challenges in the IoUT. The signal processing mechanism presented includes time synchronization and modulation schemes.

4.2.2. *Time synchronization*

Time synchronization is the simultaneous ordering of the clock between any two entities or devices in a network. IoUT devices are prone to drifting due to tidal waves and currents that occur at varying velocities. Since there is always a form of motion in the ecosystem, these facts need to be considered when designing IoUT networks. An implication of motion-induced environmental variation for IoUT is the incoherence of timing between devices during pre-communication processes [27]. Thus, it is necessary to have efficient synchronization and channel estimation protocols in place. IoUT applications that require time synchronization are those (e.g., tracking or monitoring) deployed for use over a long period of time [27]. In addition, time critical applications require synchronization between devices and throughout network's lifetime [31]. Table 2 presents some IoUT time synchronization schemes.

4.2.3. *Modulation*

Modulation schemes for IoUT networks should be based on realistic assumptions about underwater scenarios. For example, one such assumption could be to consider the fact that noise in the underwater

Table 2
IoUT Time Synchronization schemes.

Refs.	Challenges addressed	Research solution	Benefit for IoUT
[32]	Device-to-device synchronization to reduce delay between stationary nodes	Time Synchronization for High Latency (TSHL) performs energy efficient estimation and compensation for clock skew and offset with linear regression	Reduction in the large and variable propagation delay between two stationary devices
[33]		MU-Sync, uses the same process as TSHL but the cluster heads perform calculations for other devices within its cluster	Synchronization between moving devices in the IoUT ecosystem
[34]		D-Sync performs a similar calculation as in MU-Sync but integrates the Doppler estimate of the physical layer	Synchronization between devices that are designed to be mobile within the ecosystem
[35]	Re-synchronization due to movement of devices	Cross layer design with time stamping at the MAC layer	Synchronization between highly mobile devices
[35]	Network-wide synchronization as devices move	Mobi-Sync allows mobile synchronization	Synchronization between devices in areas where mobility is required or with high tidal currents

environment is not uniformly distributed. Moreover, simulation platforms and testbeds should consider actual values of parameters related to underwater communications. If the actual bandwidth for sound in water is used, then practical bandwidth-efficient modulation methods can be designed. Although some legacy modulation schemes can be tuned for underwater communication applications, they may not beenergy-efficient. In addition, such schemes are complex to implement in constrained devices because they cause network performance degradation thus, making them unsuitable for IoUT communications. One research solution for modulation in IoUT communication is to select the most eligible modulation technique that can save energy and prolong the network lifetime prior to signal transmission [17]. Matching the acoustic channel variations with signal transmission parameters can help with the selection of a suitable modulation scheme. Currently, this approach is a rapidly evolving research area given its potential in improving signal modulation and bandwidth optimization in IoUT.

Table 3 presents some state-of-the-art modulation schemes that have been proposed or deployed in underwater applications. The main schemes include Orthogonal Frequency Division Multiplexing (OFDM) and Direct Sequence (DS) Spread Spectrum (DSSS). OFDM and DS based schemes have proven most efficient and delivered better results in underwater communication network deployments [6]. It is worth noting that different modulation techniques have their benefits and limitations in different IoUT application scenarios because they have been designed to solve specific challenges.

4.2.4. MAC layer process, protocols, issues and schemes

Channel allocation is performed by MAC protocols. MAC schemes, in

Table 3
IoUT State-of-the-art Modulation Schemes.

Modulation Scheme	Refs.	Challenges addressed	Research solution	Benefit for IoUT
DSSS variants	[36]	Signal to Noise Ratio (SNR) fluctuations	DSSS schemes provide spreading gain and thus minimize errors. Due to coarse time synchronization, receivers can achieve good performance. The scheme proved suitable for acoustic communication applications	Provides robust communication over noisy channels and efficient multiple access for different signals
	[37]	Inter Symbol Interference (ISI) caused by multipath propagation	Quadrature Phase Shift Keying (QPSK)-DSSS can overcome the effect of multipath in under water channels. Under simulation and experimental conditions, the BER of QPSK and QPSK-DSSS were compared in an underwater channel model. QPSK-DSSS showed better performance	Reduction of multipath effect
Multicarrier schemes	[38]	Impact of multipath effect	MultiCarrier-Multiple Chirp-rate Shift Keying (MC-MCrSK) can achieve a higher data rate with reduced multipath	Improved multi-user access and channel data rate for IoUT networks
	[39–41]	High data rate, spectral efficiency, reduction of impulse and high frequency noise	OFDM, Filtered Multitone (FMT) and Staggered Multitone (SMT) are applicable in different application scenarios and achieve good results based on the requirements of the application scenario. OFDM mitigates noise	
Adaptive techniques	[42]	Randomness of channel conditions	Scheme utilizes a decision tree, which is used to select the modulation scheme to be implemented for specific channel scenario under a target BER	Design of IoUT Software-Defined Modems that can adapt modulation schemes with channel conditions to maximize channel capacity, reliability, efficiency, and end-to-end throughput
	[43]	Long propagation delay that affects the transmission of Channel State Information (CSI)	Reinforcement learning is applied with the Dyna-Q algorithm to predict channel state and calculate throughputs for each modulation order at different channel states. Dyna-Q chooses the modulation order based on the returned CSI from the receiver	Maximize communication throughput within an IoUT network
	[44]	Achieving optimal throughput under a target average BER	Implementation of two-level adaptive modulation using OFDM. First, only modulation levels are adjusted while power is allocated uniformly across subcarriers. Second, modulation and power levels are adjusted adaptively	
Automatic Modulation Recognition	[45]	Reduces and suppresses the influence of environmental noise	Combining Principal Component Analysis (PCA) with Artificial Neural Network (ANN) classifier. While PCA extracts the principal components of different modulation modes, ANN classifier performs modulation recognition for a signal	Enables the implementation of Software-Defined Networks for IoUT
	[46]	Modulation classification for modulation recognition schemes	From the experimental results, the proposed scheme recognized the M-ary Phase Shift Keying (MPSK) modulation signals from Underwater Acoustic Communication (UAC) signals with an excellent recognition rate	Reduces effect of varying channel conditions due to changing atmospheric conditions within the IoUT ecosystem
	[47]	Optimization of choice of modulation scheme	Combination of Convolutional Neural Network (CNN) and Long Short-Term Memory network (LSTM) can facilitate a deep neural network model for modulation recognition	Can use relevant modulation scheme within any IoUT network
Chirp Multiplexing	[48]	Achieving high data rate with low error rate in the presence of the Doppler effect	Quasi-Orthogonal Chirp Multiplexing (QOCM) provides resilience against Doppler effect by leveraging the advantages of chirp signaling and orthogonal multiplexing	For reliable long-range underwater communications at moderately high data rates
	[49]		The Orthogonal Chirp Division Multiplexing (OCDM) which originates from the Fresnel transform exploits the multipath diversity of the channel, to achieve good spreading and diversity gains, leading to quasi-error-free transmission at low SNR	

Table 4
IoUT Medium Access Control schemes.

Techniques	Refs.	Challenges addressed	Research solution	Benefit for IoUT
CDMA-based	[51–53]	Optimization of channel access by multiple devices	Combines CDMA and Interleave Division Multiple Access (IDMA), a variant of CDMA to improve channel access. CDMA uses user-specific spreading codes, while IDMA uses chip-level interleaving to distinguish different devices.	Implementation in IoUT shallow water networks
	[54]		Uses a handshake process prior to implementing CDMA, which is also an option for multiple access optimization. An initial operation involving a three-way handshake Request To Send (RTS), Clear To Send (CTS) and Data (RTS-CTS-DATA) is executed. RTSs are obtained from devices before a CTS that is addressed to these devices is sent. Then, devices respond, and their signals are received simultaneously using the CDMA operation	
	[55]	Achieves high throughput, low channel access delay and low energy consumption in deep water	UnderWater-MAC (UW-MAC combines CDMA with ALOHA and incorporates an algorithm to jointly set the optimal transmit power and code length. It implements an adaptive way to dynamically find an optimal trade-off between throughput, delay, and energy consumption according to an IoUT application's requirements	Allows the creation of an adaptive system, which enable protocols to meet the requirements of IoUT applications
	[56]	Minimizes Multiple Access Interference (MAI)	Hyperbolic Frequency-Modulated (HFM) signals which assign unique HFM signal to each user at the transmission side can reduce MAI	
Hybrid MAC schemes	[57]	Achieves Peak to Average Power Ratio (PAPR) and Multi-User Detection (MUD)	Single Carrier Frequency Division Multiple Access-Interleave Division Multiple Access (SC-FDMA-IDMA) can resolve the issue of PAPR and MUD independent of the channel length and the number of users	Increases power efficiency of devices in IoUT networks
	[27]	Efficient allocation of bandwidth between multiple devices	Demand Assigned Multiple Access (DAMA) allocates channels to devices only when they request an allocation	Efficient on-demand channel access for multiple devices in the IoUT
	[27]		Bandwidth-on-Demand (BoD) allocates variable sized bandwidth as requested by the device	Avoids wastage of bandwidth

combination with modulation techniques, enhance signal processing [50]. However, a major challenge for the deployment of underwater acoustic networks is the development of a multiple access technique tailored for the underwater environment. Such MAC protocols should orchestrate access to the network in a order to achieve high network throughput, latency, energy efficiency, scalability, and adaptability. In addition, they should avoid collision and network degradation. Table 4 summarizes some proposed research works on MAC schemes for IoUT.

4.2.5. Network layer issues, strategies and protocols

In any communication network, typical network layer protocol functions include ensuring end-to-end delivery of data packets by using addressing, route discovery, and traffic routing techniques. In the IoUT environment, underwater communication is characterized by high latency, low transmission rate and the use of constrained devices with limited computation capability and lifetime [1]. Thus, these issues need to be taken into consideration in the design of network layer protocols and algorithms.

Due to the unusual characteristic of the acoustic channel, the network layer of IoUT underwater networks needs to also address challenges related to energy efficiency, real-time route discovery and data transmission, end-to-end delay tolerant connectivity, video streaming application, multi-hop routing in a continuously changing environment, interoperability of heterogeneous IP and non-IP devices, localization and resource allocation and optimization. Lastly, additional constraints need to be considered when designing the IoUT's next generation network layer protocols. These constraints include network resource constraints, device constraints, and environmental constraints which result from the inherent properties of water [31].

This sub-section discusses routing and addressing functions of the network layer in IoUT.

4.2.6. Routing strategies

As for routing strategies, we present the benefits but not the limitations of routing protocols in Table 5 because there is no one-size-fits-all solution. Moreover, each protocol is often best suited for a specific application scenario within the IoUT.

4.2.6.1. Addressing techniques. Most devices in the IoUT may use a combination of addressing schemes such as Internet Protocol (IP) addressing schemes, non-IP schemes, or MAC address. There are several options for addressing devices. Devices may use dynamic addressing that do not require pre-configuration and can be included in an existing network automatically [69]. Another option is for devices to have fixed addresses. The challenges associated with addressing of devices in the IoUT includes:

- Possibility of overlapping addresses or address collision.
- Ensuring minimal duration for address configuration and assignment especially for new devices joining the network.
- Eliminating the need for time synchronization of network components.
- Minimizing energy consumption.

4.2.6.2. Resource allocation optimization. Once an IoUT application requirement has been identified, to deploy a successful IoUT network that will implement support the application, efficient network resource allocation, and resource optimization is paramount. Thus, constraints that could affect an optimal network performance must be understood [70]. Subsequently, constraints-aware protocols can be designed to provide robust solutions [31]. For example, if an IoUT application require devices to be stationary, an effective protocol for this scenario may consider the effect of mobility due to water velocity changes and the constraints that affects the sound signal, to provide network connectivity needed by the application. The constraints present in the IoUT ecosystem can be classified as device constraints (are determined by the type of device) and environmental constraints (these are determined by the region of deployment of the application). Region can be surface water, shallow water, mid-latitude or deep-water with varying velocity (tide or current), temperature, salinity, and pressure. These factors affect the sound speed and thus network data rate offered by networks in the IoUT. Resources to be allocated includes channel link, (frequency of

Table 5
IoUT Routing Strategies.

Strategy	Refs.	Challenges addressed	Research solution	Benefit for IoUT
Cross-layer	[58]	The fact that metrics for successful data transmissions are on different layers of the network protocol stack and they interact and are dependent on each other	The authors considered cross-layer interactions between routing metrics and the deployed application physical layer requirement. Each node selects its next hop, by minimizing energy consumption subject to the varying conditions of the underwater channel and the deployment application requirements such as delay and bit error rate	Application deployments (such as undersea disaster and rescue missions) that require tailored and different end-to-end delays and error requirement
		Meeting the different QoS requirements of co-existing data traffic	The authors of [58] also utilized the interaction between modulation, Forward Error Correction (FEC), MAC and routing functions to enable multiple heterogeneous devices to efficiently and fairly share the underwater acoustic medium	Applications that require the co-existence of data traffic with different QoS requirements (such as delay-sensitive and delay-tolerant data traffic as well as loss-sensitive and loss-tolerant traffic) generated by heterogeneous devices. For example, multimedia applications such as undersea state information acquisition for surveillance or exploration
Multipath aware	[59]	Existence of asymmetric links due to propagation delays	Directional Flooding-Based Routing (DFR) uses link quality, source's location, location of 1-hop neighbors and final destination. Forwarding devices are decided based on link quality	Prolonged network lifetime and reduced energy consumption
Multi-hop	[60]	Maintaining connectivity during end-to-end long-distance data transmissions	Channel Aware Routing Protocols use link quality information for multi-hop routing. Devices that have recently and successfully transmitted data to neighbors are selected as relays	
Adaptive	[61]	Heterogeneous devices and dynamic environmental conditions	Focused Beam Routing establishes dynamic route by determining the next-hop at every device on the path to destination after appropriate devices have proposed themselves as possible next-hop	Suitable for IoUT networks deploying stationary and mobile devices, which are not synchronized Enables optimized minimum energy per bit consumption
Resource aware, adaptive and self-organizing	[62]	Maximizing network output subject to device and environment resource constraints	Distributed Underwater Clustering Scheme (DUCS) sets up intra-cluster and inter-cluster communication by using a distributed algorithm to partition network into clusters. Cluster heads are selected randomly, and cluster heads communicate to forward packets to final destination. It avoids information flooding and saves energy.	For long-term non-time-critical applications prone to random node mobility and without GPS support
Delay minimization	[63]	Network delay optimization	The authors used Opportunistic-based Routing (OR) and introduced a metric which is the computed expected end-to-end latency from a device to the destination when at least one forwarder of the packet successfully receives it. The OR routing problem was formulated as a nonlinear optimization model, which was solved using a two-step heuristic algorithm	Suitable for time-critical applications
Topology aware	[64]	Re-discovery and recovery of routes due to changing network topology which results from continuous node movements	Vector Based Forwarding (VBF) allows data to be forwarded via a virtual routing pipe (vector) from source to destination. Only devices closer to the pipe or vector participate in data forwarding. Forwarding is by broadcasting to devices located in the vector in the direction of the destination. Variants of VBF have been proposed	Application scenario that requires continuous mobility of devices and high-water velocity region that is vulnerable to random node mobility
Localization	[65]	Unpredictable device mobility by nodes in a deep underwater network deployed	Depth Based Routing uses the depth information (distance from water surface) of devices to forward packets from the source to the destination. Devices have depth sensors. Data is forwarded by a device if its depth is less than the sender's depth	Useful for deep water application. Protocols based on localization can avoid potential communication link failures in cases where devices are prone to move anytime
	[66]		Hop-by-Hop Dynamic Address Based (H2-DAB) technique uses dynamic addressing and water depth level to provide robust routing. Packet forwarding is based on the greedy method algorithm	Solves the issue of device mobility in water body regions, vulnerable to high tidal waves and water currents
Energy efficient	[67]	High energy consumption due to high computation and overhead	Information-Carrying Based Routing Protocol (ICRP) allows data packets to carry the control packets used for information sharing	Application scenarios where devices and the network have short lifetimes
Reliability aware	[68]	Unreliable data delivery due to erroneous data and data loss that result from the underwater propagation environment	Source Routing for Underwater Networks (SUN) uses link's SNR en-route to sink device and hop distance from sink device to choose the next hop	Applications scenarios that require reliable data delivery

Table 6
Recent IoUT projects.

Focus	IoUT Project	Networking Operation	Operating frequency	Data Rate	Coverage Range	Capability(ies)
Networking Technologies	**Seatooth** [71]	Two-way short distance transmission between underwater devices. It uses a hybrid of acoustic and RF communication capabilities	low frequency radio waves from 1 Hz to 2.485 GHz	2.4 Kbps	1.5m-5m	Reliable communication in challenging sub-sea environments such as in shallow or turbid water, in the presence of bubbles or contaminants, near to large sub-sea structures or through the seabed, concrete, and metal structures
	JANUS [72]	Handshake, synchronization and initial device discovery on 11.5 KHz band. Once devices are synchronized, they switch to a frequency band shared by both devices. The systems can then switch to a different frequency or protocol shared by both parties, depending on bandwidth, distance, or security requirements	900 Hz to 60 KHz	80 bps	Up to 28 km, but can achieve ~10 km for underwater transmission	(1) Allows a packet size of 56-bits and employs Frequency-Hopped Binary Frequency Shift Keying (FH-BFSK)(2) Provides redundancy checking for reducing errors(3) Can communicate with wireless-enabled buoys to facilitate network coverage extension
Test Bed	**SEANet** [73]	A software-defined underwater acoustic modem and network testbed that provides the research community with an open architecture and programmable platform for IoUT networking research	Not applicable	Not applicable	Not applicable	(1) Cross-layer and protocol-independent (2) Used for protocol development and as an abstraction for researchers to develop prototypes, new protocols and transmission schemes. (3) Allows design of software-defined network protocols and transmission schemes (4) Enables flexibility in defining, adding, updating and swapping components (hardware, software).
Simulator	**SUNRISE** [74]	An open software-defined architecture modem and protocol stack that facilitates open collaborative research developments	Not applicable	Not applicable	Not applicable	Simulation, emulation and replay testing to evaluate underwater communication networks, perform at-sea experiments, validate test conducted on the SUNRISE networks over a variety of applications and environments

transmission), bandwidth, and transmission time.

4.3. IoUT communication projects and testbeds

To reap the full potential of the IoUT, it is important to select an appropriate technology that meets the requirements of an application to be deployed. In Table 6, we summarize four recent projects (network technologies, testbed, and simulator) that have been developed for the IoUT.

5. Future opportunities

In this section we present future opportunities for research works in the IoUT area. These research opportunities involve identifying the challenges that may inhibit the realization of the IoUT. The challenges are due to the following:

5.1. Communication protocol/algorithm

The protocols used in the IoT cannot be directly applied to IoUT. The properties of the transmission medium and characteristics of sound signals presented in Section 3 affects the design of communication protocols. There are several challenging requirements that cannot be met by IoT communication protocols. These need to be considered in the design of IoUT communication protocols. Moreover, to achieve optimized end-to-end communication in a constrained environment such as the IoUT, we need specific protocols for different categories of application scenarios for the IoUT environment. For example, communication protocols for a fish farming network set up will be different from protocols for undersea search rescue mission. Thus, the IoUT presents the opportunity to develop suites of communication protocols, from which choices can be made as applicable. The choice of communication protocol depends on the application scenario where the network will be deployed.

5.2. Multi-hop routing

Multi-hop routing faces several challenges in underwater IoUT networks. For example, in certain portions of the water environment, there may be links with fast changing data rates, delay, or error rate due to rapid changes in the environment. As such, it would be difficult to make decisions on which node should be a relay and which node should not. In addition, some links may exist only in one direction. This is because a node close to the shore may be able to communicate with a node offshore, but the channel may be too harsh or experience a very high bit error rate in the opposite direction due to the upslope bathymetric profile. A bathymetric profile causes a high number of reflections of equivalent power to the reflected signal. These issues create substantial imbalance in routing paths which has severe effects on multi-hop routing in the IoUT environment. Evolutionary mathematical algorithms may be implemented to address this challenge.

5.3. Resource allocation and optimization protocols

Another challenge in the IoUT ecosystem is how to allocate resources fairly and how to fully utilize network capability to achieve optimize end-to-end transmissions. The goal of any network is to enable successful end-to-end transmission. In the IoUT, successful end-to-end transmission is defined as the achievement of the goals of an application for which a network is set up. It varies for each network, and it involves the optimization of network resources subject to relevant constraints. Such goals are the IoUT application's expected network performance measures such as the level of reliability, availability, accuracy or integrity presented in Section 3. Thus, successful transmission occurs when optimized reliability, availability, integrity or accuracy are achieved, subject to the network resource constraints, environmental constraints, device constraints, and application constraints.

Successful transmission is determined by first setting the application's end-to-end transmission goals and thresholds. For example, low delay, high throughput, low loss or low error or no loss or no error. The goal may be to achieve a reliable end-to-end transmission, which means setting a threshold for delay and loss, because reliability is determined by a combination of error and loss. Second, these goals and thresholds are simultaneously optimized (minimized) subject to relevant constraints such as achievable data rate of the network setup, delay constraints, number of devices in the network and network deployment range. In addition, the optimization process is also subject to environmental constraints, device constraints, and network resource constraints. Resources to be allocated includes channel link, frequency of transmission, data rate and transmission time.

5.4. IoUT constraints and implications

In addition to the fundamental limitations imposed by sound propagation, there are system constraints that affect the operation of an IoUT network. These constraints are imposed by the underwater environment and affect the design of IoUT networks [75]. To achieve optimal IoUT performance, it is desirable to consider these constraints when designing physical and network layer scheme/algorithms/ protocols for routing and signal processing. The network layout/architecture for the deployment of applications are also affected by these constraints because the latter limits network performance.

5.4.1. Device constraints

a *Transmission speed*: Devices can only transmit at data rates less than or equal to their available and configured data rate. This limits the available data transmission rate if the channel can offer more than the device data rate. In addition, the low transmission speed of sound in water constrains the throughput efficiency of the network.

b *Transmission power*: Transmission power is affected by propagation distance and usually, it is greater than the receiving power. Typical values are about 10-20 Watts [76]. The received power ranges from 100 mW for activities such as listening and link detection to no more than a few Watts required for high-rate signal detection. In idle mode, typical values are not higher than 1 mW [76]. Moreover, there is a trade-off between transmission power and device battery life.

c *Battery life*: The overall network lifetime depends on the lifetime of all devices within the network. Energy is consumed when transmitting, thus energy consumption during a communication process is proportional to the transmission power. Energy can be saved by transmitting at a higher bit rate to minimize the number of retransmissions. However, typical IoUT devices are constrained due to limited battery life, and they are difficult to re-charge [3,4].

5.4.2. Environmental constraints

Environmental constraints are imposed by the state of the underwater area where an IoUT application is deployed. Such constraints limit the performance of IoUT networks. The physical properties of water which affect these constraints include temperature, velocity, pressure, depth, and salinity [77]. Moreover, the performance of a communication network is dictated by the transmission speed offered by the network. In the underwater environment, the transmission speed depends on the propagation velocity/speed of sound waves. However, sound waves propagation in an underwater environment is governed by the spatial structure of the speed of sound, which is a function of the physical properties of water (temperature, pressure, salinity and depth) [78]. Therefore, these physical properties of water have significant effect on the achievable sound speed during transmission in underwater environments. It is worth noting that ambient pressure is directly proportional to depth.

The basic representation of the speed of sound in water is given by Eq. (1) [78,79] below:

$$c\,(D,S,\ \mathrm{T}) = 1446.96 + 4.591\mathrm{T} - 5.305\ \times 10^{-2}\mathrm{T}^2 + 2.374\ \times 10^{-2}\mathrm{T}^3 + 1.340(S-35) + 1.63\ \times 10^{-1}D + 1.675\ \times 10^{-7}D^2 - 1.025\ \times 10^{-2}\mathrm{T}(\mathrm{S}-35) - 7.139\ \times 10^{-13}\mathrm{T}\mathrm{D}^3 \quad (1)$$

where, **c** is the velocity (speed) of sound waves in meters per second (m/s), **D** is the water depth in meters (m), **S** is the salinity of water in parts per thousands (PPT) and **T** is water temperature in degrees Celsius (^0C). Note that Eq. (1) is valid for the bounds: $\mathbf{T} = 0^0C \le \mathbf{T} \le 30^0C,\quad 30 \le S \le 40\quad \mathrm{PPT},\ 0 \le D \le 8000\quad m.$

Using Eq. (1), we observed the variation of the speed of sound in water **(c)** as Figs. 4, 5 and 6 shows. Firstly, we considered a scenario where the water temperature increases, for different water depth regions with the same saline conditions. Fig. 4 (a) shows that for increasing values of **T** from 0^0C to 30^0C, with **S**= 40PPT, c increases in all the different water regions from 1000m to 8000m. Thus, **c** increases as **T** increases and c also increases as the water depth, **D** increases. Next, we consider a water region with D=5000m. If **S** and **T** are the varying properties, c increases with **T** as Fig. 4 (b) depicts but coincides (remains equal) for different saline conditions in the same water region. Overall, Fig. 4(a) and (b) shows that the speed of sound increases as the water temperature increases, and it also increases in deeper water regions. However, in a water region experiencing different saline conditions, **c** does not change, except **T** changes. In conclusion, sound moves faster in deeper water regions and at higher temperatures.

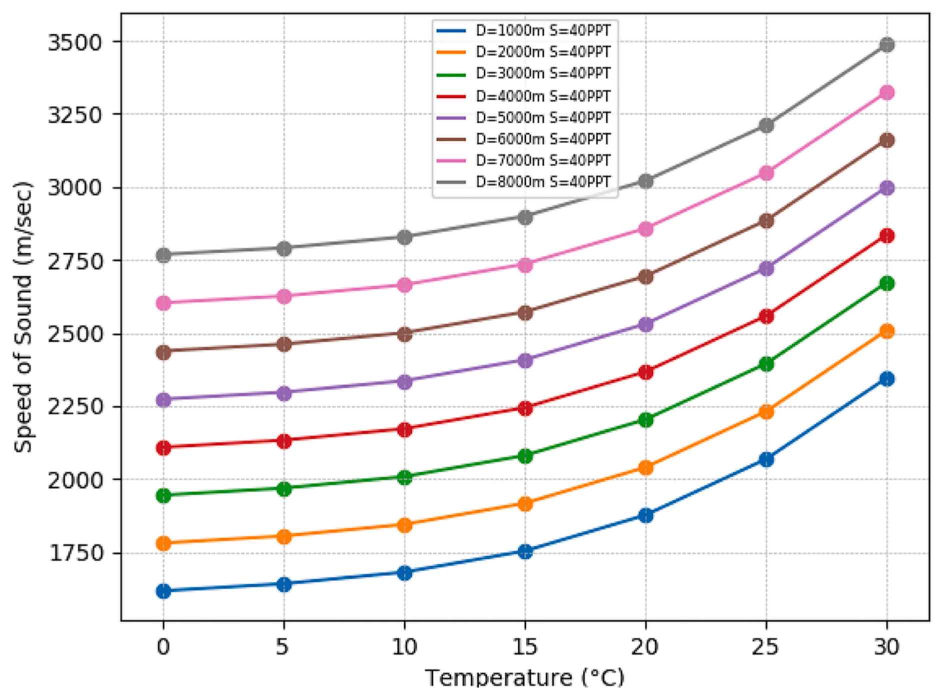
Fig. 5 shows the variation of c as the water salinity changes from 33PPT-40PPT. For all water depth (1000m -8000m deep) with the same temperature (20^0C), **c** remains the same as **S** increases while if the water depth increases, c increases as we move into deeper water regions of the same salinity as Fig. 5(a) shows. Varying the saline conditions do not affect **c. H**owever, if **S** and **T** are constant e.g., S=33PPT and T=20^0C, **c** increases when the water depth increases. Thus, sound moves faster when the water depth increases. Even, when temperature **(T)** conditions vary for a particular water depth (5000m) as Fig. 5(b) shows, **c** remains constant as salinity increases. However, **c** increases as temperature increases when salinity is the same in a certain water depth. For example, when for **D**=5000m, when **S**=33PPT, **c** increases as **T** takes on values from 0^0C to 30^0C, Therefore, sound travels faster with higher water temperature conditions. In conclusion, Fig. 5 depicts that changing saline conditions have negligible to no impact on the speed of sound in water unless the temperature and depth changes.

Fig. 6 (a) shows the behavior of **c** in different water depth regions when the water temperature is the same and salinity changes**.** As salinity changes from 33PPT to 40PPT, and T remains at 20^0C, **c** coincides with equal values for all the different saline conditions and increases as water depth increases. At water depth of 1000m, whether salinity is 33PPT or 40PPT, **c** is the same (~1850m/s). **c** changes when the water depth changes i.e., at 2000m, **c**=~2015m/s, thus confirming that in the same water depth region, varying saline conditions has no impact on sound speed in water. However, as the depth increases**, c** increases irrespective of the saline condition. When water salinity changes but **T** and **D** does not**, c** is the same for all the different saline conditions. Fig. 6 (b) shows that when T is varied and **S** is constant**, c** increases as **T** increases in the same water depth region. In water depth of 1000m, **c** increased from about 1500m/s to 2400m/s as **T** increases from 0^0C to 30^0C. This confirms the speed of sound increase with increase in temperature and water depth.

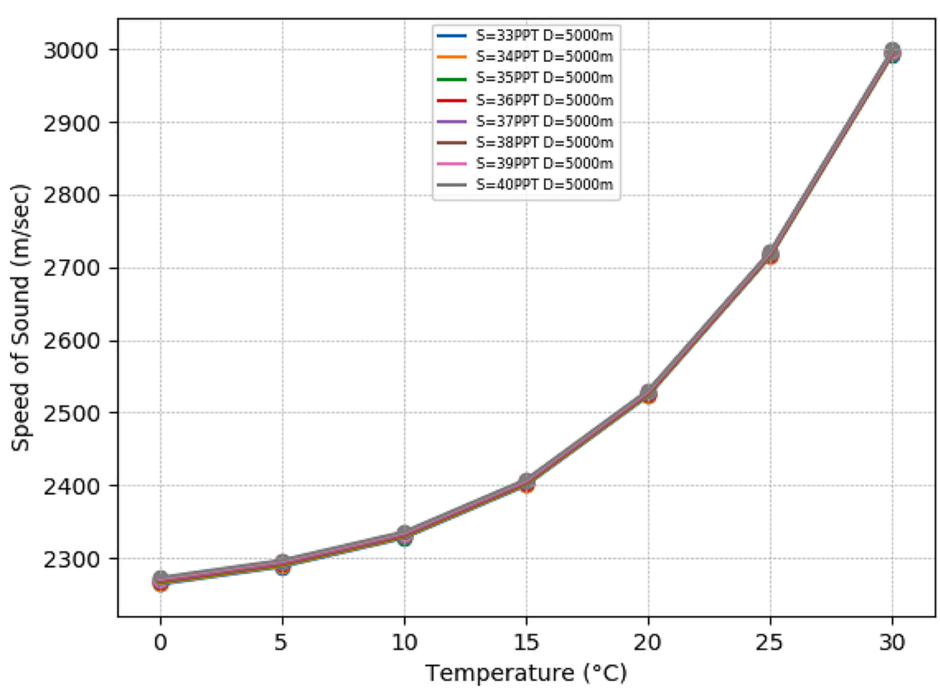
Using the observations from Eq. (1) as explained in the previous section, we now discuss how affects the performance of communication networks deployed in the IoUT environment.

a *Water Velocity:* this is the speed at which water moves. It is measured in m/s. Generally, sound waves travel faster (~1500 m/s) in water and through longer distances than in air (∼342 m/s). However, the sporadic water velocity changes due to water tide/drift can cause sound waves to bend easily, so distortion of sound waves is more likely to occur in water than in air. The impact of the variation in water velocity is that it changes the water structure and consequently affects the sound waveform construction and propagation amplitude [80]. The effect of this variation on network performance is that it leads to amplitude errors which cause signal errors and losses at any receiver in the network. As water velocity changes, the initial ray angle becomes distorted thereby causing a gradual increase in signal errors as the sound wave signal propagation distance increases. In addition, the signal error and loss increase gradually with propagation distance [80]. Variations in the water velocity also have a significant impact on the ray path or direction of the sound waves leading to multi-path effects and path losses. Lastly, variations in water velocity also affects the travel time of sound waves water environment and ultimately the communication delay.

b *Water temperature:* this is the amount of thermal energy of water molecules measured in ^{0}C. From Eq. (1), the sound propagation speed depends on temperature. Similar to how the speed of gas



(a)



(b)

Fig. 4. Speed of sound vs temperature.

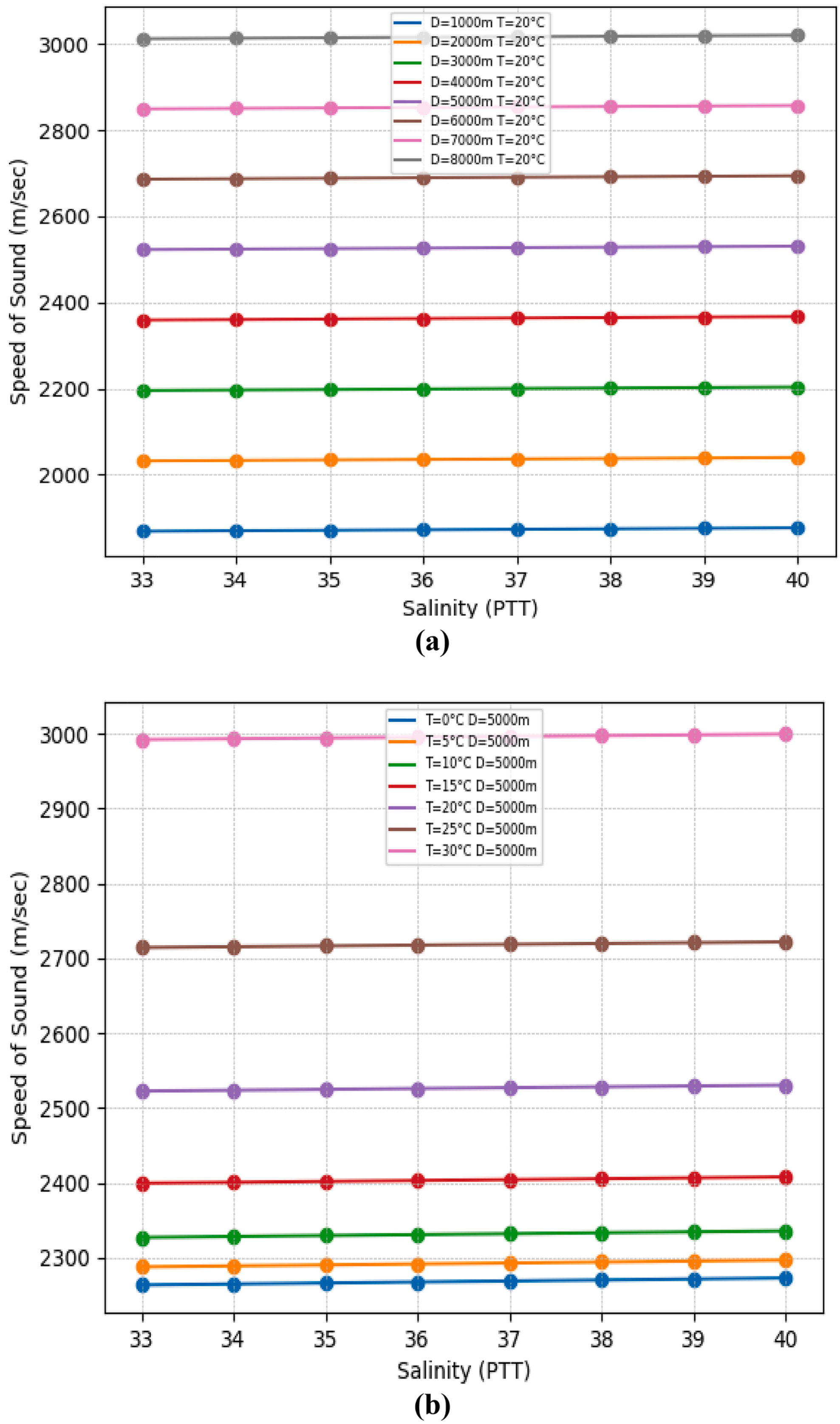


Fig. 5. Speed of sound vs salinity.

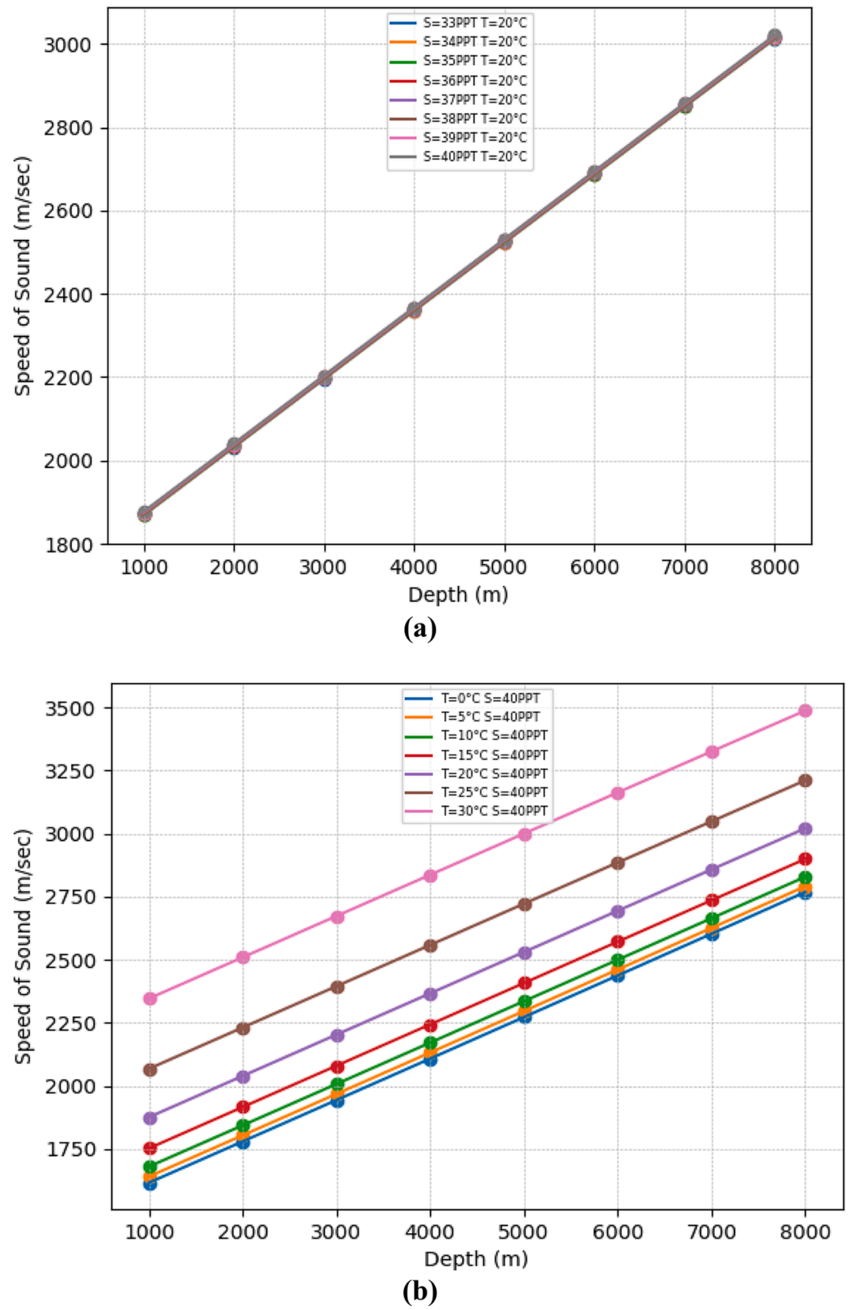


Fig. 6. Speed of sound vs depth.

molecules increases with temperature, sound waves also travel faster as water temperature increases. Thus, the temperature of underwater has a significant effect on the performance of a deployed network within IoUT. Based on the region of deployment of a network, the temperature level may vary and constrain the data rate and delay provided by the network. This is because varying temperatures alter sound speed, and thus the data rate.

c *Water pressure and depth:* pressure is the force per unit area exerted by water in underwater environment. It is measured in Newton per meter-squared (N/m2) or in decibars (dbar). Pressure in decibars is approximately equal to the depth in meters, thus pressure increases with depth [21]. If the temperature is nearly constant, the water pressure has a greater effect on the sound propagation speed in deeper regions of the underwater environment. In such a scenario, high network data rate performance can be guaranteed for any deployed IoUT application.

d *Water salinity:* this is the salt content of the underwater environment measured in parts per thousands (PPT). Salinity increases with depth of the underwater environment and becomes almost uniform at greater depths of the underwater environment. The effect of salinity is that, due to the increase in salinity with depth, the sound propagation speed also increases with depth [21].

Fig. 7 shows the generic relationship between the underwater physical properties. At a lower depth region, when the depth of the underwater environment increases, initially, the water temperature is nearly constant and then begins to decrease rapidly while the pressure and salinity increase. Typically, at higher underwater depth regions, changes in temperature and salinity tend to be negligible and the pressure continues to increase [21,81]. Variations in the physical properties of the water and the relationship between them in turn have a significant effect on the transmission speed of sound in the underwater

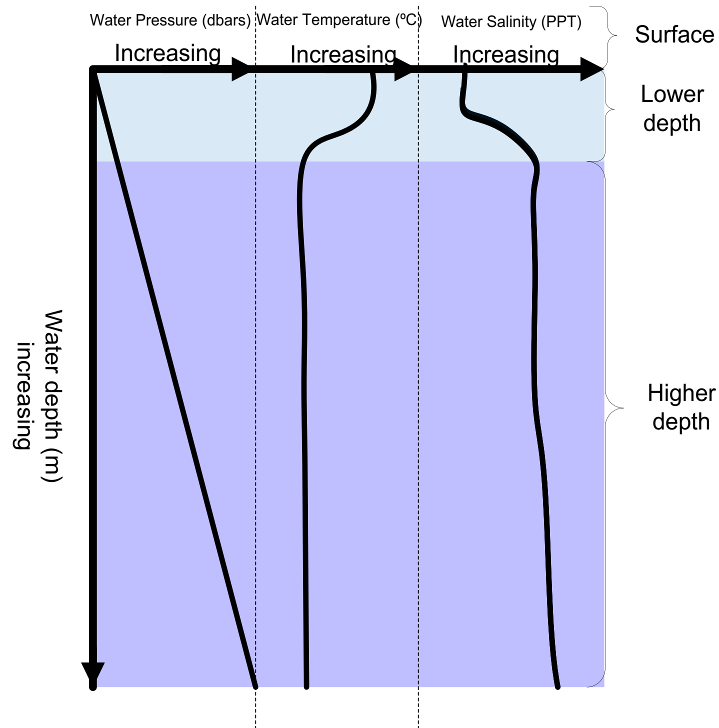


Fig. 7. Generic depiction of the relationship between the physical properties of the underwater environment [6].

Table 7
Deviations in the speed of sound when the physical property of water changes [82].

Physical property	Deviations in sound speed
Temperature	3-5m/s per ^{0}C
Salinity	1.3m/s per PPT
Depth	1.7m/s per 100m

environment [81] and thus present constraints that affect the performance of IoUT communications. When there is an increase in temperature, pressure, salinity, and depth, the speed of sound changes.

Table 7 presents the deviations in the speed of sound when the various physical properties change. Depending on the season and time of day, these properties vary in different underwater regions (surface, lower depth (shallow, mid latitude) or higher depth (deep-water)).

Thus, we can determine the property constraint profiles which result in different sound propagation speeds trends in different underwater regions (as Fig. 8 shows). A profile is a combination of different physical property trends. Using Eq. (1) and Figs. 4, 5, 6, we present an analysis of possible profiles for regions of the IoUT underwater environment in Table 8.

It is worth noting that when considering the decreasing trends of a property, the sound speed trend is the opposite of increasing trends. The underwater environment profiles show some possible property combinations along with the variability in the trend of each property. From Table 8, we note that the effect of salinity on the speed of sound is minimal while the effect of either temperature or pressure dominates depending on the water depth. As such, a realistic approach to modelling the underwater environment is to consider it as a layered structure where sound propagation speed changes with location [80].

The profiles of the four layers that Fig. 8 depicts can be extracted from the analysis in Table 8 and we present these profiles in the following discussion.

- *Surface region* (open surface layer): in this region, the underwater temperature is at its highest (as Fig. 7 shows). Thus, the sound propagation speed is high. The profile of this layer is constant (fixed) depth when the temperature increases, so the dominate physical property is temperature.
- *Shallow region* (isothermal layer): here, an almost constant temperature is often experienced and sound propagation speed increases with depth due to increasing pressure (because of the last term in Eq. (1)). This layer's profile is constant temperature with increasing or decreasing depth. In this case, pressure dominates.
- *Mid-latitude region* (thermocline layer): below the isothermal layer, the temperature decreases with depth, and the sound propagation speed decreases when the depth increases. The profile of this layer is that with increasing depth, temperature decreases, and temperature dominates.
- *Deep water region* (deep isothermal layer): after the thermocline layer is the region where temperature is constant. Thus the sound propagation speed increases with depth because of an increase in the ambient pressure.

An observation from the four-layer approach is that the sound propagation speed is at its minimum in the thermocline layer. Generally, at the upper water layers, changes in salinity and temperature affect the sound speed to a greater extent than changes in pressure (depth) [21]. However, when the depth increases, changes in salinity and temperature becomes negligible and pressure has a greater effect on the sound speed [21]. Consequently, these variations cause a layered sound propagation velocity distribution in the underwater environment [80] as Fig. 8 shows. This variation in the layer distribution leads to the refraction of sound waves because each layer has different profile. Sound waves bend upwards when the speed of sound increases with depth and downward when the speed decreases with depth. Since the constraint profile for each layer varies with time, season and location, it is desirable to consider stochastic optimization models in the design of optimal IoUT network layout/ architecture and protocols/algorithms for IoUT communication schemes (signaling and routing).

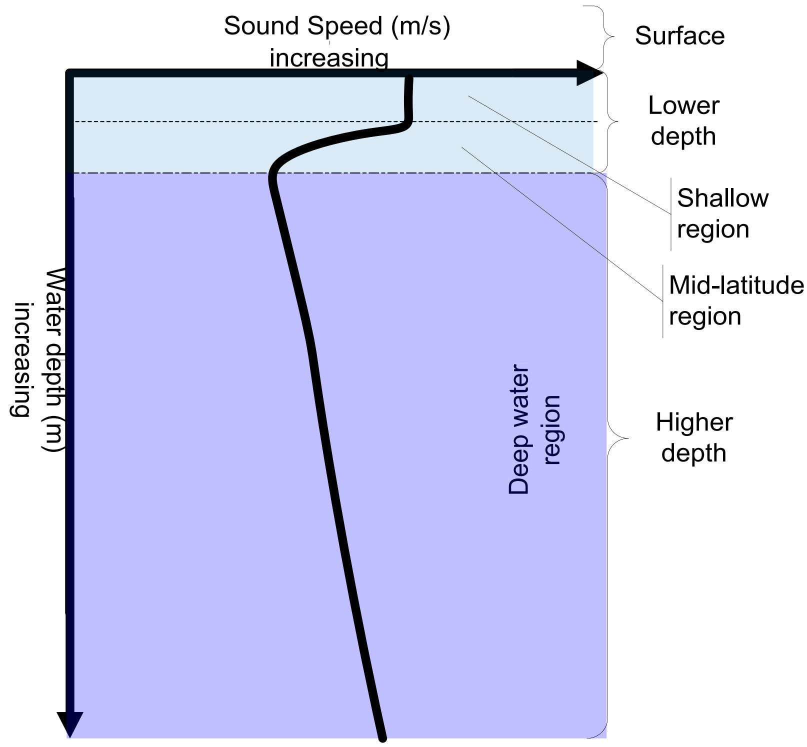


Fig. 8. Generic depiction of the speed of sound in underwater regions [6].

Table 8
Possible profiles for the IoUT underwater environment.

Profile	Combination Depth	Temperature	Salinity	Dominating property	Speed of sound Trend	Depicting figure Number
1	Constant	Increasing	Constant	Temperature	Increases	4 (a)
2	Increasing	Constant	Constant	Pressure	Increases	4 (a)
3	Constant	Increasing	Constant	Temperature	Increases	4 (b)
4	Constant	Constant	Increasing	Salinity	Slight increase	4 (b)
5	Constant	Increasing	Constant	Temperature	Increases	5 (a)
6	Constant	Constant	Increasing	Salinity	Slight increase	5 (a)
7	Constant	Constant	Increase	Salinity	Constant	5 (b)
8	Increasing	Constant	Constant	Pressure	Increases	5 (b)
9	Constant	Constant	Increasing	Salinity	Constant	6 (a)
10	Increasing	Constant	Constant	Pressure	Increases	6 (a)
11	Constant	Increasing	Constant	Temperature	Increases	6 (b)
12	Increasing	Constant	Constant	Pressure	Increases	6 (b)
13	Increasing	Decreasing	Increasing	Temperature	Decreases	8
14	Decreasing	Increasing	Decreases	Temperature	Increases	8
15	Increasing	Constant	Increasing	Pressure	Increases	8
16	Decreasing	Constant	Decreases	Pressure	Decreases	8

5.4.3. Network resource constraints and application requirement constraints

Network resource and application requirement constraints include:

Table 9
Network resource constraints with respect to underwater transmission distance [84,85].

Transmission range [km]	Frequency [kHz]	Bandwidth [kHz]	Data rate [kbps]
<0.1 (very short)	~200-300	>100	500
0.1 -1 (short)	~20	20 -50	30
1 -10 (medium)	<=10	<=10	10
10 -100 (long)	<=6	2 -5	5
>100 (very long)	~1	<1	.6

1) *propagation speed*: which is limited to approximately 1,500 m/s in the underwater environment.
2) *transmission frequency*: it is the data carrying capacity of the underwater medium. Sound wave propagation in water occurs at low frequency with the frequency range within 10Hz and 1MHz, 3) *transmission bandwidth*: is the width of the operating frequency band within the network. It is the difference between the minimum and maximum frequency that the underwater medium can offer and determines the obtainable data rate. It decreases when the transmission range increases and consequently, depends on the transmission range. This behavior distinguishes underwater communication from terrestrial communication [83], 4) *transmission rate*: is the allowable data rate in bps, determined by the bandwidth of the medium. Table 9 presents the typical approximated constraints values on frequency, bandwidth, and data rate in relation to the propagation distance. We note that when the distance increases,

frequency, bandwidth, and data rates decrease [84]. As we have explained in Section 4, this demonstrates the effectiveness of short-range transmissions in achieving optimal network performance and thus motivates for short-range, multi-hop transmissions in IoUT underwater communication networks. Short-range transmissions also lead to low attenuation of sound signals [85]. Application requirement constraints include setup distance between sensor devices and sink stations, projected transmission throughput, amount of data to be collected, and deployment period.

6. Conclusion

IoUT underwater communication involves the propagation of sound signals through the water. To achieve efficient and reliable data collection in the IoUT, optimal communication network performance is essential. However, the requirements for optimal performance are often at odds with each other because of the fluctuations in signal transmissions as a result of the spatially varying environmental conditions of the waterbody [86]. Consequently, these varying conditions impose constraints that may lead to tradeoff on some network performance measures [71]. For example, to achieve a high level of accuracy, the tradeoff may be the level of reliability, which affects the signal transmission delay. Moreover, the QoS provided by any deployed network in the IoUT depends on the constraints posed by the properties of the water medium and sound waves [87]. The lack of knowledge of these environmental variations and constraints is often a limiting factor in achieving an optimal IoUT underwater communication network [88]. Thus, it is desirable to understand all the related constraints that affect the various layers of the communication protocol stack. These constraints include device, application, network resource, and environmental constraints. Once a strong insight into these constraints has been grasped, optimized communication protocols and strategies can be designed for the IoUT environment.

In this work, we have presented an analysis of the properties of water and sound and their impact on the performance measures necessary to guarantee optimal and high-quality communication between devices in the IoUT. Since achievable performance measures are determined by communication protocols, their design must be based on the constraints imposed by the properties of water and sound. In addition, we highlighted some IoUT physical and network layer protocol research works and their results. Then, we analyzed the relevant constraints imposed by the properties of the underwater ecosystem and how they affect sound propagation speed, which directly affects optimal communication performance in the IoUT. From the analysis, we computed some possible underwater regional profiles (combination of different trends of underwater's physical property) and we found that since the underwater profiles present varying spatial and temporal constraints, it is desirable to employ stochastic optimization models in the design of communication strategies/schemes for IoUT underwater communication networks. Temporal and spatial variations in the physical properties of the water implies that the underwater environment exhibit fluctuations in different regions over time. Moreover, the IoUT ecosystem is characterized by different applications, networks, and property profiles, so there is no alone-size-fits-all protocol because a protocol that can provide an optimal performance in one water region (e.g. shallow) may perform poorly in another region (e.g. deep water).

Declaration of Competing Interest

None.

Data availability

No data was used for the research described in the article.

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