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A survey on deployment techniques, localization algorithms, and research challenges for underwater acoustic sensor networks

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Summary

In recent years, wireless sensor networks (WSNs) have attracted the attention of both the research community and the industry, and this has eventually lead to the widespread use of WSNs in various applications. The significant advancements in WSNs and the advantages brought by WSNs have also enabled the rapid development of underwater acoustic sensor networks (UASNs). In UASNs, in addition to deployment, determining the locations of underwater sensor nodes after they have been deployed is important since it plays a critical role in many applications. Various localization techniques have been proposed for UASNs, and each one is suitable for specific scenarios and has unique challenges. In this paper, after presenting an overview of potential UASN applications, a survey of the deployment techniques and localization algorithms for UASNs has been presented based on their major advantages and disadvantages. Finally, research challenges and open research issues of UASNs have been discussed to provide an insight into future research opportunities.

KEYWORDS

deployment techniques, localization algorithms, potential applications, research challenges, underwater acoustic sensor networks

1 | INTRODUCTION

Underwater wireless communication has become an important data transmission technology and brought many opportunities to various applications in military and commercial water environments by inspiring researchers not only in academia but also in the military and industry sectors in several unique ways. Some of the typical applications of underwater wireless communication are pollution monitoring in aquatic environments, collection of data recorded at ocean-bottom stations, remote control in the offshore oil industry, early warning and disaster detection, discovery of new natural resources, and intrusion detection and underwater surveillance.[1] As a result, recent years have witnessed the proliferation of such application scenarios.

However, underwater wireless communication channels are subject to harsh and unique environmental conditions and hence often display severe attenuation characteristics, time-varying multipath fading, frequency dispersion, limited bandwidth, and power resources of acoustic devices, etc. In addition, the variable speed of sound and the extreme signal propagation delays create a unique set of challenges. Due to these reasons, underwater communication channels are complex to model and difficult to control. On the other hand, as a result of the advancements in underwater communication technologies and progresses in the development of sophisticated coherent modulation and demodulation technologies as well as coding and decoding techniques, exploiting the advantages and overcoming the challenges have become possible. Although there are many challenges in the acoustics domain, as it is widely accepted, acoustics provide the most obvious medium to enable underwater communications compared to optical and radio frequency (RF), since acoustic signals attenuate less than the others and are able to travel further distances.[2]

As a result of the technological advancements in underwater communications, many underwater multihop ad hoc networks and underwater acoustic sensor networks (UASNs) have been deployed. Due to the significant interest in accurate and energy-efficient monitoring of aquatic environments for environmental, commercial, scientific, safety, and military reasons, UASNs are used for various applications, such as oceanographic data collection, offshore exploration, mine reconnaissance, environmental and pollution monitoring, disaster prevention, tsunami and earthquake warning, distributed tactical surveillance, and assisted navigation.[1-4] As shown in Figure 1, UASNs consist of a large number of underwater sensor nodes with acoustic onboard modems and a limited number of surface stations and autonomous underwater vehicles that collect data reported from those nodes and communicate with onshore stations through radio communication or satellite communication. However, for successful UASN applications, there are many challenges that need to be addressed. Due to their limited spectrum and slow acoustic propagation velocity, high frequency utilization and network throughput must be achieved in UASNs. To overcome the time-varying and attenuated acoustic signal channel for reliable and high-speed data transmission, various techniques, such as acoustic channel estimation, signal processing, modulation, and decoding schemes must be in place. In addition, to improve limited UASN performance resulting from the limited bandwidth, computing and power resources, optimizations for spectrum, and power efficiency are needed. Finally, some UASN applications are inherently loss and delay-sensitive, and hence their application-depended Quality of Service requirements must be addressed accordingly. Due to the abovementioned reasons and the dynamic topology changes, UASNs require novel network control protocols and algorithms.

Deployment is one of the fundamental requirements of UASNs where the deployment technique supports key network services, such as topology control, routing, and boundary detection. Because of the challenging characteristics of underwater acoustic channel and complex three-dimensional (3D) space, several factors need to be taken into consideration during the deployment of UASNs.[5]

Localization is of critical importance and one of the most important tasks in UASNs, especially in mobile UASNs. If the gathered data is not associated with location information, it cannot be spatially reconstructed onshore. Since the gathered data can only be interpreted meaningfully when it is referenced to the location of the node, localization becomes a key problem for the success of UASN applications. Localization is required for several purposes, including target detection, node tracking, routing protocols, and data tagging.[6,7] Unfortunately, underwater communication is seriously limited by the harsh conditions of the underwater channels, such as variable and long propagation delays and multipath interference, and negative effects of the underwater acoustic medium, such as Doppler distortion and very high attenuation.[8] These characteristics pose challenges towards designing efficient and reliable localization techniques that fulfil desirable properties, such as high accuracy, fast convergence, wide coverage, low communication costs, and good scalability.

Underwater acoustic sensor networks can be used for a wide range of applications and offer a promising solution to many demanding applications. However, as well as being

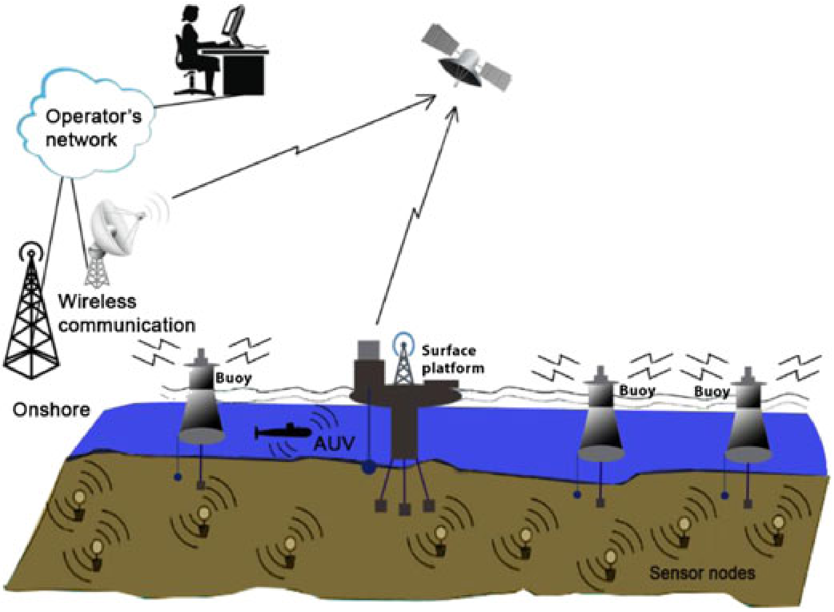

FIGURE 1 A typical underwater sensor network

exciting, they are highly challenging due to unpredictable and harsh underwater environments and unique characteristics including large propagation delay, limited communication bandwidth, high bit error rate, and node mobility. As a result of these challenges and the unique features of underwater communications, existing technologies and solutions cannot be directly applied to UASNs. Hence, to realize reliable and scalable UASNs, new solutions in deployment techniques and localization algorithms are highly demanded. Moreover, considerable amount of research activities are needed to address research challenges and handle open research issues of UASNs.

In this paper, a survey of UASNs with a special focus on potential applications as well as deployment techniques, localization algorithms, and research challenges is given. This paper mainly presents a detailed review of potential application scenarios of UASNs and different deployment techniques and localization algorithms for realizing these potential application scenarios. Moreover, the challenges in meeting the requirements posed by both emerging and existing UASN applications are also presented. The rest of the paper is organized as follows. Section 2 reviews potential UASN application scenarios. A review of existing deployment techniques proposed for UASNs is presented in Section 3. Section 4 presents existing and emerging localization algorithms proposed for UASNs. Challenges of UASNs are investigated in Section 5. Discussion on UASNs and open research issues are given in Section 6. Finally the paper is concluded in Section 7.

2 | POTENTIAL APPLICATIONS

Underwater acoustic sensor networks can monitor many physical variables such as pressure and water temperature and as well as variables such as certain pollutants, turbidity, and conductivity. Therefore, there are numerous potential application scenarios for which UASNs can be used. While scientific UASN applications observe the environment, industrial UASN applications monitor and control commercial applications.[9] On the other hand, military and security UASN applications mainly aim at securing or monitoring ships or port facilities and providing communication with submarines and divers. Table 1 presents a list of common UASN applications falling into all the 3 categories.

3 | DEPLOYMENT TECHNIQUES

Underwater acoustic sensor networks are composed of different kinds of underwater sensor nodes to collaboratively perform some tasks over a 3D space. Underwater acoustic sensor network deployment techniques are typically classified into 3 main categories based on the mobility of nodes, namely, static deployment, self-adjustment deployment, and movement-assisted deployment, respectively.[10] The deployment techniques consider deployment-related factors such as node types, deployment objectives, computation complexity, and energy consumption.

Different from most of the existing deployment techniques assuming 2D sensor network architectures, 3D networks like most UASNs require sophisticated design considerations and factors along with high computation complexity; therefore, extending 2D deployment techniques to 3D UASNs cannot address UASN deployment requirements, and it is required to design new deployment techniques that explore geometric properties of 3D UASNs.[10,11]

While deployment techniques can be evaluated based on many factors, including deployment objectives, node types, processing type, either centralized or distributed, computational complexity, and energy consumption, each technique has some advantages and disadvantages. Different from 2D UASNs for which sensor nodes are usually deployed only at the bottom of a specific region or on the water surface, for 3D UASNs, sensor nodes float at different depths to observe the entire region.[5,10,11] Based on the existing literature, UASN deployment techniques can be divided into 3 main categories, namely, static, self-adjustment, and movement-assisted, respectively.[10] Tables 2, 3, and 4 present an overview of existing deployment techniques.

- Static deployment: It assumes that UASN nodes are static and do not change their positions after their initial deployment. Although this is not a realistic approach, most UASN deployment techniques are based on this principle since it simplifies the design complexity of the deployment technique and reduces the deployment cost. After the initial deployment, bottom sensor nodes may organize in a cluster-based architecture and forward gathered data to surface stations by multihop paths.[4,10] While deploying sensor nodes randomly can be viewed as the most practical way and in some scenarios in which there exists no prior knowledge of the deployment region or deterministic deployment is impossible, it is generally not preferred due to cost-related issues.
- Self-adjustment deployment: It assumes that each sensor node has the ability of adjusting its position after initial deployment, and this way, the deployment technique can meet certain requirements such as improving network connectivity, reducing coverage overlaps, and increasing link quality.[10,14] For the goal of horizontal position adjustment, the sensor nodes are typically attached to floating buoys. On the other hand, for vertical position adjustment, the sensor nodes attached to the floating buoys with wires adjust their depths by controlling the length of the wires.

TABLE 1 A list of the common (underwater acoustic sensor network) UASN applications

Application	Category	Objectives	Node Requirements
Monitoring geological processes	Scientific	Gathering data related to monitoring of important geological processes for different purposes including disaster prevention, such as earthquake or tsunami warning	Underwater sensor nodes
Monitoring environment and pollution	Scientific	Gathering data related to various water characteristics such as temperature, oxygen level, salinity, dissolved matter, and the levels of pollutant contents	Underwater sensor nodes
Imaging or counting animal life or aquatic plants	Scientific	Imaging or counting fish, mammals, microorganisms, or aquatic plants such as coral reefs	Underwater sensor nodes
Mine reconnaissance	Industrial	Determining locations of specific mines	Autonomous underwater vehicles (AUVs) or unmanned underwater vehicles (UUVs)
Oil or mineral extraction	Industrial	Demining oil or specific minerals and installing necessary underwater equipment to extract them	AUVs or UUVs
Monitoring and controlling underwater pipelines	Industrial	Monitoring and controlling underwater pipelines to prevent damage and provide immediate repair	AUVs or UUVs
Monitoring and controlling commercial fisheries	Industrial	Providing facilities to monitor and control commercial fisheries	Underwater sensor nodes, AUVs or UUVs
Monitoring and securing port facilities	Military and security	Providing security for port facilities	Underwater sensor nodes, AUVs or UUVs
Monitoring and safeguarding ships in harbours	Military and security	Monitoring of ships in foreign harbours	AUVs or UUVs
Detecting and removing mines	Military and security	Detecting mines in sea and oceans, and removing them	AUVs or UUVs
Offshore exploration	Military and security	Exploration of unexplored regions	AUVs or UUVs
Providing communication with submarines and divers	Military and security	Using submarines and divers to communicate with	Underwater sensor nodes, AUVs or UUVs
Distributed tactical surveillance	Military and security	Collaboratively monitoring specific areas for surveillance, reconnaissance, targeting, and intrusion prevention, such as submarine detection and mine countermeasure missions	Underwater sensor nodes, AUVs or UUVs
Assisted navigation	Military and security	Assisting navigation of battle ships or improving their navigation accuracy with the aid of UASNs	Underwater sensor nodes, AUVs or UUVs

- Movement-assisted deployment: It assumes that one or more mobile sensor nodes that can assist during node deployment are available. The mobile sensor nodes such as autonomous underwater vehicles AUVs, unmanned underwater vehicles (UUVs), and gliders follow a predefined trajectory to patrol over a specific region to cooperate with other underwater sensor nodes to fulfil specific monitoring tasks.[10,31] Compared with traditional wireless sensor nodes, underwater sensor nodes are rather expensive, and the overall costs rapidly rise for deep water scenarios. In this regard, underwater mobile sensor nodes play a key role in network coverage, data collection, and data processing.[31-33]

3.1 | Performance metrics

Design of UASNs presents several challenges while dealing with various application requirements and diverse constraints. In this regard, deployment techniques and their performance analysis are required to provide insight on design parameters and system behaviours. To satisfy a certain level

TABLE 2 A comparison of the existing static underwater acoustic sensor network (UASN) deployment techniques

Technique	Sensor Types	Deployment Objectives	Centralized/ Distributed	Advantages	Disadvantages
3D-random, bottom-random, and bottom-grid[5]	Underwater sensor node and underwater gateway	Minimizing overlapping coverage	Centralized	Low computational complexity and low energy consumption	Complexity depends on targeted coverage ratio
Efficient surface gateway deployment scheme[12]	Underwater sensor node and underwater gateway	Optimizing gateway deployment	Distributed	Low energy consumption, enabling to investigate the dynamic redeployment of gateway nodes, and offline solving large-scale UASN deployment problems.	High computational complexity
Truncated octahedral tessellation of 3D space[13]	Underwater sensor node	Guaranteeing full coverage	Distributed	Low energy consumption and determination of the minimum transmission radius needed to maintain connectivity among neighbouring nodes in various placement strategies.	High computational complexity
Multipath virtual sink architecture[14]	Underwater sensor node and cluster head	Maximizing network lifetime	Centralized	Low energy consumption, reliability achieved from redundancy provided by multipath data delivery, and mitigating the contention between underwater sensor nodes	High computational complexity
Deployment algorithm (UDA) for underwater sensor networks[15]	Underwater sensor node, surface gateway, and relay node	Minimizing transmission loss	Centralized	Clustering, duty-cycled network operation, and low energy consumption	High computational complexity
Locating sensor nodes represented via a truncated octahedron to fill out 3D space[16]	Underwater sensor node and virtual sink	Ensuring successful data delivery	Distributed	Robustness, low computational complexity, and low energy consumption	As operating frequency increases, more nodes are required with short internode distance to maintain a transmission loss threshold.
Tetrahedron deployment scheme for 3D UASNs[17]	Underwater sensor node and anchor node	Maintaining of good network connectivity	Centralized	Outperforming random deployment schemes and cube-based deployment schemes in terms of localization error and localization ratio	Trade-off between the number of anchor nodes and localization error

of detection quality in aquatic monitoring applications, it is desirable that events in the deployment region can be detected by a required number of underwater sensor nodes. Hence, one of the most important problems in UASNs is how to perform node deployment for achieving desired coverage requirements. The following is a list of common performance metrics used to evaluate the efficiency and performance of the deployment techniques.

- Coverage: It indicates the ratio of covered area of active sensing to the whole area of interest.
- Connectivity: It indicates whether all the sensor nodes in the UASN have a path to the surface station or not.[23]
- Lifetime: It is defined as the time after which a certain fraction of sensor nodes run out of their energies or a cluster head runs out of its energy.
- Expected path length: It indicates the expected path length of a sensor node to the surface station in terms of number of hops.[23]
- Average node degree: It shows average number of neighbours of a sensor node in the resulting UASN topology.

TABLE 3 A comparison of the existing self-adjusting underwater acoustic sensor network deployment techniques

Technique	Sensor types	Deployment Objectives	Centralized/ Distributed	Advantages	Disadvantages
Distributed node deployment scheme[11]	Underwater sensor node and cluster head	Minimizing overlapping coverage	Distributed	Low computational complexity	High energy consumption and the effect of water current
Adaptive topology reorganization scheme[18]	Underwater sensor node	Maintaining network connectivity	Distributed	Energy-efficiency and low computational complexity	Based on building a tree-like multihop hierarchical routing topology
Diving cube method[19]	Underwater sensor node	Minimizing uncovered areas	Centralized	Maintenance of coverage and low computational complexity	High energy consumption
The game theory field design[20]	Underwater sensor node	Enabling sensor nodes to follow event distribution	Centralized	Low energy consumption and event-driven coverage control	High computational complexity
Fish swarm–inspired underwater sensor deployment[21]	Underwater sensor node	Automatic coverage of event areas	Distributed	Intelligent algorithm and low computational complexity	High energy consumption
Differentiated deployment algorithm[22]	Underwater sensor node	Achieving differentiated deployment	Centralized	Differentiated coverage and low energy consumption	High computational complexity
Fully distributed node deployment scheme[23]	Underwater sensor node and dominator node	Maximizing coverage and guaranteeing connectivity	Distributed	Low computational complexity, guaranteeing node connectivity regardless of the sensing and transmission range and achieving coverage performance very close to coverage-aware node deployment schemes	Requirement of ultrasonic sensors

4 | LOCALIZATION ALGORITHMS

In UASNs, localization plays a key role in many application scenarios. Being characterized by large propagation delays, the variable speed of sound and stringent bandwidth limitations, underwater acoustic channels pose a set of unique challenges for localization in UASNs. The main challenges of the localization problem in UASNs are

- Anchor node deployment: Underwater acoustic sensor network localization algorithms require reference nodes called as anchor nodes or beacons. This issue is challenging. Because in deep sea 3D UASN applications, in addition to surface buoys, it may be needed to deploy anchor nodes on the sea floor at a few kilometres depth.[2,6]
- Node mobility: Underwater sensor nodes inevitably drift due to uncontrollable reasons such as underwater currents, winds, and shipping activities. While the locations of surface buoys acting as reference nodes can be precisely located through Global Positioning System (GPS) updates, the locations of submerged underwater nodes cannot be precisely determined,[3,6] and this affects localization accuracy.
- Signal reflection: There may be some reflecting obstacles especially in harbour or near-sea underwater environments. They may affect the accuracy of range measurements since non-line-of-sight (NLOS) signals reflected from these can be mistaken for line-of-sight (LOS) signals.
- Internode time synchronization: Except for the case when appropriately deployed acoustic beacons are available, GPS signals cannot be used to synchronize the times of underwater sensor nodes to compensate for clock drifts since they are severely attenuated under water.

Underwater acoustic sensor network architectures are typically grouped based on the spatial coverage and motion ability of nodes, such as 2D/3D UASNs or stationary/mobile/hybrid, respectively.[2,5] Basically, the underwater localization problem aims at determining the position for each underwater sensor node in a network when the positions of anchor nodes, sometimes referred to as reference nodes, are given, and the knowledge of some internode distances,

TABLE 4 A comparison of the existing movement-assisted underwater acoustic sensor network deployment techniques

Technique	Sensor Types	Deployment Objectives	Centralized/ Distributed	Advantages	Disadvantages
Prediction assisted dynamic surface gateway placement algorithm[24]	Underwater sensor node and surface gateway	Maximizing coverage	Distributed	Prediction of future node positions and low computational complexity	High energy consumption
Event-based motion coordination[25]	Underwater sensor node and AUV	Driving AUVs to targets	Distributed	Event-based operation and low computational complexity	High energy consumption
Near-optimal routing and placement of mobile data collectors[26]	Underwater sensor node and data collector	Maximizing network lifetime	Distributed	Prediction of energy expenditure	High computational complexity and high energy consumption
Delay constrained placement scheme[27]	Underwater sensor node and data collector	Maximizing network lifetime	Distributed	Taking delay constraints into consideration	High computational complexity and high energy consumption
Gateway deployment optimization framework[28]	Underwater sensor node and surface gateway	Minimizing average end-to-end delay	Distributed	Finding a near-optimal solution	High computational complexity and high energy consumption
Synchronization-based survey[26]	Underwater sensor node and AUV	Minimizing distance and travel time	Distributed	Low computational complexity and detection of failure and recovery	High energy consumption
Adaptive strategy for performing data collection[29]	Underwater sensor node and AUV	Minimizing travel time	Centralized	Low computational complexity and ensuring the collection of data and	High energy consumption
Communication-constrained data collection[30]	Underwater sensor node and AUV	Minimizing travel time	Centralized	Taking link quality into consideration	High computational complexity and high energy consumption

Abbreviation: AUV; autonomous underwater vehicle.

either the real physical distances or virtual distances such as the number of hops, exists. In this section, the localization algorithms in the literature are presented and compared in detail. Furthermore, future research directions of localization algorithms in UASNs are analysed.

In the literature, many underwater localization algorithms exist. They take into account a number of factors, including the network topology, signal propagation models, device capabilities, and energy requirements, as localization accuracy depends on many factors including noise, propagation losses, fading, the number of anchor nodes, the constellation of the anchor nodes, and relative position of the node to be localized. In addition, scheduling mechanism and period affects the localization accuracy and, different from the others, is an adjustable parameter.[34]

The localization algorithms using anchor nodes can be broadly classified into 2 main categories: range-free algorithms or range-based algorithms. On the other hand, based on the processing type, the localization algorithms can be grouped under 2 categories, distributed and centralized localization algorithms, respectively. Distributed localization algorithms are preferred by most of the UASN applications, as they are suitable for online underwater monitoring systems. Nevertheless, they require processing on the underwater sensor nodes.[2] Distributed and centralized localization algorithms can be further divided into 2 categories as prediction-based or estimation-based algorithms. Prediction-based localization algorithms are generally used in mobile UASNs, and their accuracy depends on the underlying node mobility model. Usually, the performance of all localization algorithms depends on 4 main factors, namely, communication range, initial reference, the position of initial reference node, and the number of nodes. In this section, all the underwater localization algorithms in the previously mentioned classes are analysed, summarized, and finally compared from anchor type, ranging method, accuracy, localization coverage, localization time, message communication, time synchronization, computational complexity, and energy consumption aspects.

Based on node mobility as preferred in the literature,[2,3,6,7] underwater localization algorithms can be classified into 3 main categories, namely, stationary localization algorithms, mobile localization algorithms, and hybrid localization algorithms.[7] Tables 5, 6, and 7 present a comparison of the existing localization algorithms.

- Stationary localization algorithms: They assume that all underwater sensor nodes are static. The nodes are attached to either ocean floor units or surface buoys at fixed locations.
- Mobile localization algorithms: They assume that all underwater sensor nodes are mobile. The nodes move

TABLE 5 A comparison of the existing stationary localization algorithms

Algorithm	Ranging Method	Anchor Type	Message Type	Advantages	Disadvantages
Area localization scheme[35]	Range-free	Fixed anchors	Active	Low computational complexity and average localization time	Limited localization coverage, low localization accuracy, and high energy consumption
Hyperbola-based approach[36]	TDoA	Fixed anchors	Active	High localization accuracy, medium localization coverage, and low computational complexity	Unsuitable for large-scale UASNs and high energy consumption
Probabilistic localization approach[37]	Not specified	Fixed anchors	Active	High localization accuracy, medium localization coverage, low computational complexity, and low energy consumption	Unsuitable for large-scale UASNs
Asymmetrical round trip-based localization approach[38]	Round trip time	Fixed anchors	Active	Large localization coverage, high localization accuracy, and low computational complexity	Long localization time and high energy consumption
Underwater silent positioning scheme[39,40]	TDoA	Fixed anchors	Silent	High localization accuracy, low computational complexity, low energy consumption, and short localization time	Unsuitable for large-scale UASNs due to its limited localization coverage
Underwater sensor positioning scheme[41,42]	Not specified	Fixed anchors	Silent	Low computational complexity and short localization time	High energy consumption, low localization accuracy, and unsuitable for large-scale UASNs due to its limited localization coverage
Ray bending-based localization algorithm[43]	ToA	Fixed anchors	Active	Average localization time, high localization accuracy, low computational complexity, and low energy consumption	Unsuitable for large-scale UASNs due to its limited localization coverage
Localization scheme for large scale underwater networks[44]	TDoA	Fixed anchors	Active	Large localization coverage and low computational complexity	Long localization time, low localization accuracy, and high energy consumption
	Range-free	Sensor array	Active	Large localization coverage, average	High energy consumption

(*Continues*)

TABLE 5 (Continued)

Algorithm	Ranging Method	Anchor Type	Message Type	Advantages	Disadvantages
Maximum likelihood source localization[45]				localization time, high localization accuracy, and low computational complexity	
Reactive localization technique[46]	Not specified	Surface buoys	Active	Low energy consumption and providing good accuracy in densely deployed networks	Limited localization coverage, long localization time, and high computational complexity
Hierarchical localization approach[47,48]	ToA	Surface buoys and underwater anchor nodes	Active	Large localization coverage	Long localization time, low localization accuracy, high computational complexity, and high energy consumption
Node discovery protocol and localization[49,50]	Not specified	Anchor-free	Active	Large localization coverage	Long localization time, low localization accuracy, high computational complexity, and high energy consumption
Anchor-free localization algorithm[51]	Signal arrival time	Anchor-free	Active	Large localization coverage, energy efficiency, and suitability for both static and dynamic networks	Localization accuracy depends on node speed if node mobility is involved.
Principal components analyses–based probabilistic localization approach[52]	Signal measurement	Anchor-free	Active/Silent	Improved localization accuracy due to principal components analyses projection, not being affected by reflected signals, and tolerating to multipath signals	High computational complexity
On-demand asynchronous localization scheme[53]	Round trip time	Anchor nodes, AUVs	Active/Silent	Two modes of localization exist. A high-accuracy, on-demand mode and a passive, lower-accuracy listening mode	Lack of a specific method of collision handling
Surface based anchor-free localization algorithm (SBR-AL)[54]	ToA	Anchor-free	Active	Good localization accuracy	Frequency of the water surface has a strong effect on the localization error
	AoA		Active		

(*Continues*)

TABLE 5 (Continued)

Algorithm	Ranging Method	Anchor Type	Message Type	Advantages	Disadvantages
Underwater reflection-enabled acoustic-based localization[55]		Geographically positioned nodes localized by an anchor-free localization algorithm such as surface-based anchor-free localization algorithm		Good localization accuracy	Requirement of using multimodal directional piezoelectric underwater transducers
Multianchor nodes collaborative localization[56]	Not specified	Surface buoys, anchor nodes, and ordinary nodes	Active	High localization ratio, small localization error, and low energy consumption	High computational complexity
Fine-grained localization algorithm[57]	ToA	Fixed anchors	Active	High localization accuracy, large localization coverage, low communication cost, and low energy consumption	Multipath issue can have a strong impact on localization accuracy.
Multiobjectivization-based localization[58]	N/A	Magnetic sensor array	Silent	High localization accuracy and robustness	Requirement of using triaxial magnetometers

Abbreviations: AoA, angle of arrival; TDoA, time difference of arrival; ToA, time of arrival; UASNs, underwater acoustic sensor networks.

using propelled equipment or freely drift with water currents.

- Hybrid localization algorithms: In these algorithms, both stationary and mobile underwater sensor nodes exist.

Regardless of the classification of underwater localization algorithms, desirable properties of all the localization algorithms are high accuracy, fast processing, low communication overhead 100% coverage or near full coverage, and easy implementation.

4.1 | Ranging methods

Underwater acoustic sensor network localization algorithms generally require several anchor nodes, underwater sensor nodes with known locations, and distance/angle measurements between these anchor nodes and the node to be localized.[3] During deployment, anchor nodes may be placed at fixed known locations or may be equipped with special hardware that allows them to learn their locations from a positioning server, such as the GPS and Global Navigation Satellite System. To estimate the location of an unknown underwater sensor node, most UASN localization algorithms use distance/angle measurements between the underwater sensor node to be localized and the anchor nodes or a combination of distance and angle measurements. Almost all localization algorithms are based on lateration and angulation. While angulation-based UASN localization algorithms use the geometric principles of triangles and the bearing information, lateration-based UASN localization algorithms use the distance between 2 underwater sensor nodes and intersecting circles.[3] In 3D UASNs, underwater sensor nodes generally use their pressure sensors to obtain their depth. Therefore, the localization problem can be simplified to estimate the 2D coordinates of the nodes.

In UASNs, to take advantage of the slow propagation speed of sound under water, time of arrival and time difference of arrival are used to obtain distance and angle measurements. Received signal strength indicator is not a convenient way of calculating range because of the time-varying properties of the underwater environment and due to the fact that the signal strength does not vary monotonically with range. Also, Angle of arrival is not widely used in UASNs since it requires the use of expensive and large directional antennas. In measuring distances, the accuracy of propagation models plays a key role.[80] However, modelling underwater acoustic propagation is a rather complicated task. While, in shallow water, there are important effects from the seabed, in deep water, variations of the sound speed in the water dominate.

TABLE 6 A comparison of the existing mobile localization algorithms

Algorithm	Ranging Method	Anchor Type	Message Type	Advantages	Disadvantages
Energy-efficient ranging for post-facto self-localization[59]	ToA	Anchor-free	Active	Large localization coverage and low computational complexity	Long localization time and high energy consumption
Motion-aware self localization[60]	ToA	Anchor-free	Active	Large localization coverage and low computational complexity	Long localization time, average localization accuracy, and high energy consumption
Collaborative localization[61]	ToA	Anchor-free	Active	Short localization time, low computational complexity, and low energy consumption	Limited localization coverage and average localization accuracy
Absolute positioning[62]	TDoA	GPS-positioned hydrophone	Active	Short localization time and low computational complexity	Limited localization coverage, low localization accuracy, and high energy consumption
3D underwater target tracking[63]	TDoA	Floating anchor nodes	Active	Large localization coverage, short localization time, low computational complexity, and low energy consumption	Localization accuracy highly depends on the application scenario
AUV-aided localization[64]	ToA	AUVs	Silent	Low computational complexity	High localization time
Dive'N'Rise positioning[65]	ToA	Dive'N'Rise beacons	Silent	Low computational complexity	Long localization time
Scalable localization scheme with mobility prediction[66]	ToA	Surface buoys and underwater anchor nodes	Active	Large localization coverage	Long localization time, low localization accuracy, and high computational complexity
Multistage AUV-aided localization[67]	ToA	AUVs	Silent	Large localization coverage, short localization time, high localization accuracy, and low computational complexity	High energy consumption
Multistage localization protocol using mobile beacons[68]	ToA	Mobile nodes	Silent	Large localization coverage, short localization time, and low computational complexity	Average localization accuracy and high energy consumption
Time of arrival–based tracked synchronization[69]	ToA	Anchor nodes and mobile nodes	Active	Good localization accuracy and suitability for nodes not capable of 2-way communication such as submersibles due to 1-way anchor transmissions for localization	Requiring the use of accurate clock-crystal and an inertial measurement unit
Real-time collaborative tracking[70]	Time of flight	Anchor nodes and mobile nodes	Active	Low energy consumption, low communication overhead, and effective fusing of position information by using a factor-graph–based method	Localization accuracy mainly depends on the extent of time the node to be localized is in direct communication with anchor nodes
Distributed localization scheme based on mobility prediction[71]	Not specified	Surface buoys and anchor nodes	Active	Low communication cost and good accuracy	Localization coverage depends on node density and some ideal assumptions are used.

Abbreviations: AUVs, autonomous underwater vehicles; GPS, Global Positioning System; TDoA, time difference of arrival; ToA; time of arrival.

Generally, there are 5 methods of modelling underwater acoustic propagation, and the choice of propagation model depends on the application scenario.[81,82] While ray theory is often the most efficient one for high frequency, modal theory usually describes lower frequency propagation, especially in shallow water environments.[81-84] On the

TABLE 7 A comparison of the existing hybrid localization algorithms

Algorithm	Ranging Method	Anchor Type	Message Type	Advantages	Disadvantages
Silent localization of underwater sensors using magnetometers[72]	Range-free	Anchor-free	Silent	Large localization coverage, short localization time, low energy consumption, and low computational complexity	Low localization accuracy
Localization scheme with a mobile beacon and a pressure sensor[73]	Range-free	One mobile anchor node	Silent	Large localization coverage and low computational complexity	High energy consumption
3D multipower area localization scheme[74,75]	Range-free	Surface buoys and mobile detachable elevator transceivers	Silent	Large localization coverage and low computational complexity	Low localization accuracy and high energy consumption
Time-synchronization free localization[76]	ToA	Surface buoys	Active	Large localization coverage and low computational complexity	Long localization time, low localization accuracy, and high energy consumption
Localization with directional beacons[77]	Range-free	AUVs	Silent	Low computational complexity and low energy consumption	Limited localization coverage, long localization time, and low localization accuracy
Using directional beacons for localization[78]	Range-free	AUVs	Silent	Low computational complexity and low energy consumption	Limited localization coverage, long localization time, and low localization accuracy
Cooperative underwater localization[79]	Round-trip time and ultra short base line measurements	AUVs	Silent	Based on the extended Kalman filter, using range data to limit error rate increase and reducing localization error after obtaining more accurate data	Limited localization coverage, high computational complexity, and the requirement of using inertial measurement unit and guidance and navigation system

Abbreviations: AUVs, autonomous underwater vehicles; ToA, time of arrival.

other hand, the easiest and quickest propagation model is energy flux theory. Parabolic equations and finite elements are the most computationally intensive and highest fidelity models, and they can represent all aspects of acoustic propagation such as interface scattering, range dependence, and 3D effects.[81-84] Specifically, parabolic equations are more suitable for highly 3D situations and finite element models are more suitable for highly range dependent waveguides.[85]

Underwater localization algorithms typically use acoustics-based approaches; two of the most common approaches are short baseline (SBL) and long baseline (LBL). In the SBL approach, a ship follows the underwater sensor nodes and uses a short-range acoustic emitter to perform underwater localization.[3] On the other hand, in the LBL approach, acoustic transponders are deployed either on moorings around the area of operation or on the seafloor. By using triangulation, underwater sensor nodes in the transmission ranges of a set of sound sources estimate their locations. However, both of these approaches cannot be used by underwater localization algorithms since the LBL approach uses long range signals. Although it is theoretically possible to choose nonoverlapping frequency bands for the operation of the LBL approach and UASN communications, in typical operations, long range signals create interference and hence disable the communication among the underwater sensor nodes. The SBL approach involves a ship in the operation area and hence is not feasible for mobile and large-scale UASNs.[3]

4.2 | Performance metrics

Evaluating the relative performance localization algorithms is very important for both researchers and practitioners, either when choosing of existing and emerging algorithms which best fit the requirements of a given UASN application or when validating a new algorithm against the previous state of the art. The following is a list of common performance metrics used to evaluate the efficiency and performance of the localization algorithms.

- Communication cost: It is used to quantify the energy efficiency of localization algorithms. It is defined in terms of the average number of messages transmitted per node to realize localization estimation.[86]

- Coverage: It is a measure of the proportion of ordinary sensor nodes that are successfully localized.
- Time: It quantifies the time taken (either in seconds or iterations) to achieve the desired coverage.
- Accuracy: It quantifies the localization error, which is typically Euclidean distance between estimated and actual locations of an ordinary node.

5 | RESEARCH CHALLENGES

Underwater acoustic sensor networks enable the realization of many military and nonmilitary applications including monitoring of the climate change, examining the population of coral reefs and the life of animals, and earthquake and tsunami warning systems. Underwater acoustic sensor networks consist of small and inexpensive sensor nodes housing various sensors onboard and communicating underwater via acoustics. While UASNs are very promising with the unique features they offer, unpredictable underwater conditions such as high water pressure, uneven depths of underwater surface, and unpredictable activities make it difficult to design and deploy underwater networks.[87] In addition, sensors used in UASN nodes are susceptible to underwater challenges, and their effectiveness may decrease severely. However, defected/dead UASN nodes can be replaced by AUVs or nonautonomous remotely operated underwater vehicles. Autonomous underwater vehicles or remotely operated underwater vehicles can also be used to provide scalability to existing UASNs by adding new nodes. However, since UASN nodes are in continuous motion because of the currents, locating them is rather difficult. Moreover, traditional positioning and localization systems do not work underwater.[87] As it is very difficult to deploy the networks, which can work reliably and efficiently, although they are associated with high initial and maintenance costs, in some specific, highly critical applications, tethered connections may be preferred.

Although in the past network designers addressed the challenges raised by the deployment of underwater networks through low-power acoustic communication and protocols for high-latency time synchronization and multiple and/or scheduled data access,[32,88] many challenges in terms of reliable extraction of data, localization, distributed clock synchronization, and energy management still exist or have not been fully addressed.

The bandwidth of the underwater acoustic channel is very low compared to the competitive technologies, and underwater communication has low data rates; for most acoustic modems, it is up to 20 Kbps.[32,89-91] Although there are commercial acoustic systems operating at higher frequencies, for instance, a commercial acoustic system called HERMES can provide data rates up to 87 768 Kbps at the maximum range of 180 m,[92,93] most acoustic systems operate below 30 kHz, and the acoustic signal propagation speed in an underwater acoustic channel is around 1500 m/s, very low compared to the speed of RF.[91,94] This high propagation delay causes multipath propagation to stretch over time delay and affects the performance of real-time UASN applications. On the other hand, in terms of range, compared to ones based on the competitive technologies, systems based on acoustic waves can reach great distances, over 20 km.[95]

In UASNs, in addition to the node-related challenges such as limited energy and stringent computation and memory resources, communication related challenges such as the low link quality mostly due to the multipath propagation and time-variable nature of the communication medium and the large propagation delay resulting from the slow speed of sound[96] need to be taken into consideration by UASN designers to ensure a good level of connectivity and coverage.[32]

Due to both node and network-level factors, UASNs have distinct characteristics. Nodes in UASNs are expensive since they have more complex transceivers and are integrated with the hardware protection systems. They need more power due to the complex signal processing at their receivers to compensate for the channel impairments and to higher distances.[1] To be able to do data caching because of the intermittent underwater channel, they have enough storage capacity. Underwater acoustic sensor networks are generally sparsely deployed networks due to the involved costs and deployment-related challenges.[97] Table 8 presents a summary of the research challenges.

6 | DISCUSSION AND OPEN RESEARCH ISSUES

While considerable research efforts have been directed to UASNs, there are many open issues that need to be addressed. In this section, we focus on the open issues on underwater localization as well as common application scenarios and associated challenges in UASNs. Table 9 presents a summary of the research issues that need to be addressed.

Although various underwater vehicles, observatories, and sensors require a communication link with data rates ranging from few to tens of Mbps and in case of stationary devices, these can be achieved using fibre optic or copper cables at the expense of significant maintenance issues, the current available underwater acoustic communication devices can support data rate up to tens of kbps for long distances,

TABLE 8 A summary of the research challenges

Challenge	Category	Effects	Proposed Solution
Unpredictable underwater conditions	Node-level/ network-level	Difficulty in design and deployment steps	Before deployment, a predeployment site survey may be greatly helpful to analyse underwater conditions, and this way increases the reliability and success of the underwater network.
Unscalability	Network-level	Existing UASN technology is not fully suitable for large-scale underwater applications covering a large area.	Since it is essential to design a UASN for exploring underwater environment, strategies to expand to more nodes should be designed. While budget constraints restrict this severely, AUVs or ROVs can be used to add more nodes or replace defected nodes.
Large propagation delay, multipath propagation, and time-variable nature	Network-level	Loss of network connectivity and network topology changes	Network designers must take intermittent underwater channel into consideration to ensure a good level of connectivity and coverage
Limited data rate and low link quality	Network-level	Unsatisfactory application performance	Performing caching at underwater nodes and doing complex signal processing to compensate for underwater channel impairments
Limited energy and stringent resources	Node-level	Limited overall network performance and lifetime	Realizing deployment by taking into the limited lifetime of underwater sensor nodes into consideration and deploy redundant nodes at some locations to ensure connectivity
High equipment cost and difficulty involved in deployment	Node-level/ network-level	Sparse and random deployment	Sparsely deploying underwater sensor nodes while providing good level of coverage and connectivity

Abbreviations: AUVs, autonomous underwater vehicles; ROVs, remotely operated underwater; UASNs, underwater acoustic sensor networks.

ranging in kms, and up to hundreds of kbps for short distances.[98] On the other hand, underwater optical wireless communication provides up to a few Gbps depending on the transmission distance, transmission power and source, typically either laser or LED.[99-101] Similarly, in Burrowes and Khan,[102] it was shown that RF conduction method can deliver up to 1 Mbps based on sea water frequency response obtained by transmitting a 1-μs pulse. Che et al[103] show that using the same technology, data rates up to 1 Mbps at ranges 0.5, 0.8, and 1 m and up to 12.5 Mbps in a wideband solution with 6.25 MHz bandwidth and with quadrature phase-shift keying modulation can be delivered.[103] It was shown that even higher data rates can be achieved using higher order modulation than quadrature phase-shift keying.[104] Hence, there is an urgent need that researchers in ocean propagation should consider how to increase throughput for underwater acoustic communications.

While there have been significant advances at higher communication stack layers of UASNs to establish reliable and efficient communications, it is now clear that since underwater communication bandwidth is very limited, there will never be a single solution to address all the requirements.[3] Hence, underwater communication systems must be designed in such a way that they will adaptively reconfigure themselves to the changing topology and environmental conditions. In addition, cross-layer approaches that consider the energy indicators of the underwater sensor nodes and the link quality in the underwater communication medium are the 2 other open issues. In this respect, another important research issue is to establish common benchmarks for comparison of performance of underwater communication schemes and network protocols.

Although most acoustic systems may operate in a frequency range between 10 and 15 kHz and the total communication bandwidth is typically very low, 5 kHz, these systems are in fact wideband since they use a bandwidth that is not small compared with the centre frequency of the signal. Due to frequency-dependent fluctuation rates and frequency-dependent attenuation, traditional narrowband channel models are not suitable for underwater acoustic communication systems.[81,83,84] Because the frequency selectivity of the medium violates the assumption of uncorrelated taps and requires a ultra wide band channel model. Correlative channel sounders preserve wideband properties, too.

Different from WiFi and cellular networks, in UASNs, standards that specify modulation, coding parameters, or medium access and routing protocols have not been developed yet. Each manufacturer has developed proprietary schemes for their modems, and hence, modems developed by a manufacturer are not able to communicate with modems developed by other manufacturers. In addition, current modems include sophisticated Media Access Control (MAC) and routing protocols, and this exacerbates the problem existing in the physical layer.[105,106] Therefore, de facto standards for modulation, coding, and other protocols must be developed to achieve interoperability. Otherwise, designers

TABLE 9 A summary of the research issues that need to be addressed

Research Issue	Category	Underlying Reason	Effects	Proposed Solution
Adaptive reconfiguration	Network-level	Limited underwater communication bandwidth	Limited application performance, changing network topology	Underwater communication systems must be designed in such a way that they will be able to reconfigure themselves adaptively to the changing topology and environmental conditions.
Cross-layer approaches at communication stack layers	Node-level and network-level	Restricted node lifetime and low link quality	Limited application performance, changing network topology	Cross-layer approaches that consider the energy indicators of the underwater sensor nodes and the link quality in the underwater communication medium are needed.
Lack of standardization	Node-level	Each manufacturer has developed proprietary schemes for their modems.	Modems developed by a manufacturer are not able to communicate with modems developed by other manufacturers.	Standards that specify modulation, coding parameters or medium access, and routing protocols must be developed.
Lack of interoperability	Node-level and network-level	Current modems include sophisticated MAC and routing protocols and this exacerbates the problem existing in the physical layer.	Underwater communication equipment developed by different manufacturers cannot communicate with each other.	De facto standards for modulation, coding and other protocols must be developed to achieve interoperability.
The need for ranking the relative performance of candidate technologies and selecting appropriate standards	Node-level / network-level	High cost and complexity of trials and experiments at sea	Some UASN deployments exhibit limited performance.	Physics-based simulation, emulation, and hardware-in-the-loop technologies should be used to estimate performance.
The need for deployment techniques and localization algorithms for large-scale UASNs	Network-level	Most of the existing deployment techniques and localization algorithms are only suitable for small scale UASNs.	Since most UASN applications are based on large scale UASNs, current deployment techniques and localization algorithms are not appropriate.	It is necessary to develop deployment techniques and localization algorithms suitable for large scale UASNs. In addition, an analysis of the localization error and the distribution model must be performed to reduce localization errors.
Verification of localization and position	Network-level	Most UASNs are deployed in rather complex and unsafe environments.	Limited localization performance	Realistic algorithms for localization and position verification should be designed.
Dynamic collaboration of multiple anchor nodes	Network-level	In large scale UASNs, when the number of anchor nodes is limited, dynamic collaboration of multiple anchor nodes enables to localize unknown nodes.	Limited localization performance in large-scale UASNs	Hybrid and mobile UASN localization algorithms must be developed.
The need for developing a realistic node mobility model	Node-level and network-level	Existing node mobility models are not suitable for realistically modelling the movement of underwater sensor nodes.	Slow localization and inability of taking the advantage of mobile nodes	The development of a realistic node mobility model is needed. Also, anchor nodes' movement paths must be

(*Continues*)

TABLE 9 (Continued)

Research Issue	Category	Underlying Reason	Effects	Proposed Solution
				adjusted according to the parameters related to underwater information.
The need for anchor node-assisted localization algorithms	Network-level	High cost of underwater sensor nodes, especially for deep water applications	Since underwater sensor nodes are expensive and their costs rise highly for deep water applications, mobile-node assisted localization algorithms can play a key role in improving localization performance.	Mobile anchor node-assisted localization algorithms must be specifically designed.
The problem of sensing and communication coverage for UASNs	Network-level	Sensing and communication coverage issues have not been investigated enough.	Limited application performance in large-scale deployments.	It is necessary to study UASN deployment issues, deployment solutions, and their theoretical bounds.
Adaptive sleep-scheduling mechanisms	Node-level	Limited node lifetime	Limited node lifetime can affect overall network lifetime.	Sleep scheduling mechanisms can effectively increase the network lifetime. Hence, duty cycles must be taken into consideration.

Abbreviation: UASNs, underwater acoustic sensor networks.

must be able to rank the relative performance of candidate technologies and select standards for realistic topologies, application scenarios, and underwater environments.

Usually, by performing a set of simulation studies, existing localization algorithms are evaluated based on performance metrics. On the other hand, simulation studies alone are not enough for the realization of UASN applications successfully. Therefore, due to the high cost and complexity of trials and field experiments at sea, emulation and hardware-in-the-loop technologies and physics-based simulation should be used to estimate performance[107] and must be designed to involve the presence of shadow zones, jamming, and natural interference. The use of field experiments and test beds is essential and supports more accurate performance analysis and system characterization.[32] Moreover, such work can increase overall robustness in different conditions and enable the analysis of total system cost and energy requirements.[32]

Although in recent years, localization in UASNs has greatly attracted the attention of the research community, and this has resulted in various innovative ideas and solutions, it still needs a considerable research effort. It must be taken into consideration that UASN applications can be roughly divided into 2 main categories as long-term nontime-critical aquatic monitoring and short-term time-critical aquatic exploration.[108] While the former is supposed to work for a long time, and the data collected by the underwater sensor nodes are not real-time data. Therefore, for the applications in this category, energy saving is a critical issue. On the other hand, the latter focus on real-time data. Therefore, the applications in this category deal with making efficient data transfer and do not focus on energy saving.

At present, the existing deployment techniques and localization algorithms are only suitable for small scale UASNs. However, most UASN applications are based on large scale UASNs. Therefore, it is necessary to develop deployment techniques and localization algorithms suitable for large scale UASNs. Especially, in 3D large scale UASNs, another fundamental issue is to address the problem of supporting full coverage, while ensuring full network connectivity.[10,109] Hence, efficient and distributed schemes to provide the maintenance of full sensing coverage and connectivity are essential. In addition, in large scale UASNs, when the number of anchor nodes is limited, dynamic collaboration of multiple anchor nodes[110] enables to localize unknown nodes.[33] Since stationary UASNs are only used for specific applications, probably, the future research direction efforts are to be directed to the localization algorithms of hybrid and mobile UASN localization algorithms. Based on this direction, one of the important issues is the development of a realistic node mobility model.[111,112] Although, in the literature, there are many node mobility models, these models are not suitable for realistically modelling the movement of underwater sensor nodes.[113] In addition, due to their importance in improving underwater localization accuracy, the node mobility models developed for adjusting anchor nodes' movement paths according to the parameters related to underwater information are needed.[114] Moreover, the impact of the localization algorithms on clustering protocols and location-based routing still needs to be addressed.[2]

As underwater sensor nodes are expensive and their costs rise highly for deep water applications, mobile anchor node-assisted localization algorithms must be specifically designed.[33] Also, based on a set of simulation studies, an analysis of the localization error and the distribution model must be performed to reduce localization errors in real UASN applications. Moreover, the problem of sensing and communication coverage for UASNs has not been investigated enough.[4] Therefore, it is necessary to study UASN deployment issues, deployment solutions, and their theoretical bounds for UASNs.

For long-term UASN applications, sleep scheduling mechanisms can effectively increase the network lifetime.[115,116] Therefore, the existing localization algorithms must be adopted to consider node duty cycles or redesigned. Nevertheless, to ensure continuous aquatic monitoring from all sensor node locations, replacing energy-depleted nodes is inevitable. But this replacement is very expensive, especially in large-scale UASNs. Therefore, effective joint policies which both involve routing and node replacement decisions to minimize the overall replacement cost are needed.[117,118] Last but not the least, as well as systematic performance evaluation models, realistic algorithms for localization and position verification should be designed as most UASNs are deployed in rather complex and unsafe environments.

7 | CONCLUSION

There is an increasing demand for the underwater monitoring and exploring systems. However, due to the constraints and challenges produced by the harsh underwater environment, none of the realized UASN applications is perfect. There are still many problems for the implementation of the underwater sensor network systems. Although considerable research efforts have been directed to UASNs in recent years, successful implementation of potential application scenarios and their benefits depend on understanding and exploring the recent progress in underwater acoustic communication and UASNs. Therefore, UASNs require strong cooperation between the implementers and the research community.

In UASNs, deployment and localization are 2 of the most fundamental and important tasks. They pose a set of challenges in UASNs due to the acoustic transmission medium. In this paper, a detailed review of potential UASN applications and research challenges has been given. In addition, a survey of the existing deployment techniques and different localization algorithms, which can be applied to the domain of UASNs, has been presented. They have been compared, and their advantages and disadvantages have been discussed.

To advance the design and development of UASNs, seamless interaction between the physical, MAC, and routing layers is needed. In addition to improving the interaction of the layers, the capabilities of the layers should be enhanced. On the physical layer, sophisticated algorithms and modulations should be implemented in microcontrollers used in UASN nodes to achieve higher bandwidth utilization, longer transmission distances, and reduced bit error rates in an energy-efficient manner. On the MAC layer, new mechanisms and approaches are needed to take full advantage of hardware advances. In the routing layer, to address frequent topology changes and guarantee reliable delivery, state-of-the art self-configuring techniques should be implemented in existing and proposed routing protocols.

Although, in recent years, research on UASNs has significantly advanced, a number of major challenges have not been solved yet. In essence, the development of new analytical and computational models and novel test beds plays a key role in the efforts for the large-scale underwater communications and sensing since it supports accurate system characterization and performance analysis efforts. Moreover, since each UASN is designed and deployed with different goals in mind, UASN designers should consider different options from low-cost, low-performance components to high-cost, high-performance components, and include both stationary and mobile node configurations. Although, in this paper, we have discussed characteristics of the underwater channel and UASN applications and outlined future research directions, there are still many challenging problems need to be addressed, especially for the localization of mobile UASN nodes. For future work, we plan to extend our work to investigate the effects of integrating different underwater communication characteristics into the existing underwater localization algorithms in different underwater scenarios and study the relative performances of the existing underwater localization algorithms. We also plan to analyse the impact of the coexistence of localization and routing algorithms under different accuracy requirements, coverage restrictions, and overhead limitations as well as integrating the mobility pattern of underwater nodes with node mobility prediction algorithms and mobility-based topology control.

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