Underwater Wireless Sensor Networks: Enabling Technologies for Node Deployment and Data Collection Challenges

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***Abstract*—The development of underwater wireless sensor networks (UWSNs) has attracted great interest from many researchers and scientists to detect and monitor unfamiliar underwater domains. To achieve this goal, collecting data with an underwater network of sensors is primordial. Moreover, real-time information transmission needs to be achieved through efficient and enabling technologies for node deployment and data collection in UWSN. The Internet of Things (IoT) helps in real-time data transmission, and it has great potential in UWSN, i.e., the Internet of Underwater Things (IoUT). The IoUT is a modern communication ecosystem for undersea things in marine and underwater environments. Intelligent boats and ships, automatic maritime transportation, location and navigation, undersea discovery, catastrophe forecasting, and avoidance, as well as intelligent monitoring and security are all intertwined with the IoUT technology. In this article, the enabling technologies of UWSN along with several fundamental key aspects are scrupulously explained. The study aims to inquire about node deployment and data collection strategies, and then encourages researchers to lay the groundwork for new node deployment and advanced data collection techniques that enable effective underwater communication techniques. Besides different types of communication media, applications of UWSNs are also part of this article. Various existing data collection protocols based on the deployment models are simulated using network simulator (NS 2.30) to analyze and compare the performance of state-of-the-art techniques.**

***Index Terms*—Data collection, data communication, node deployment, underwater wireless sensor networks (UWSNs).**

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I. Introduction

THE WIDESPREAD adoption of the wireless sensor network (WSN) in various application areas and the speedy development of the sensor technology have encouraged the development of the underwater WSN (UWSN) in the oceans. Just like underground, sensor nodes, and vehicles are deployed under the water for environmental monitoring. The ability to physically distribute devices while sensing and monitoring them opens up new opportunities to observe and act on both above and below the Earth [1]. UWSN is emerging as an enabling technology for aquatic applications and exploration. At the same time, UWSN and terrestrial WSN both share some common properties, such as wireless connectivity, whereas, at the same time, share many points of difference too, like medium, bandwidth, mobility, etc. As a result of these differences, new specialized protocols and methods for working in underwater networks are required [2]. UWSN is being deployed for a wide range of marine applications, such as natural disaster prevention, oceanographic data collection, pollution or environmental monitoring, weather recording, navigation, and enemy attack protection.

The applicability of Internet of Things (IoT) for underwater communication combined to form Internet of Underwater Things (IoUT) as shown in Fig. 1. IoUT emerged as an influential tool for real-time underwater communication. IoUT is helpful in environmental assessment, assistance in various activities, such as water exploration and accident prevention. The IoUT is defined as the network of smart interconnected underwater objects. Implementation areas of IoUT are environmental monitoring, underwater exploration, disaster prevention, and military [3]. As compare to the customary monitoring approaches, to deploy sensor nodes in the aquatic environment and also monitoring through the IoUT can effectively increase the environmental monitoring capabilities. The IoUT is a new revolution for the Blue Economy sector, offering

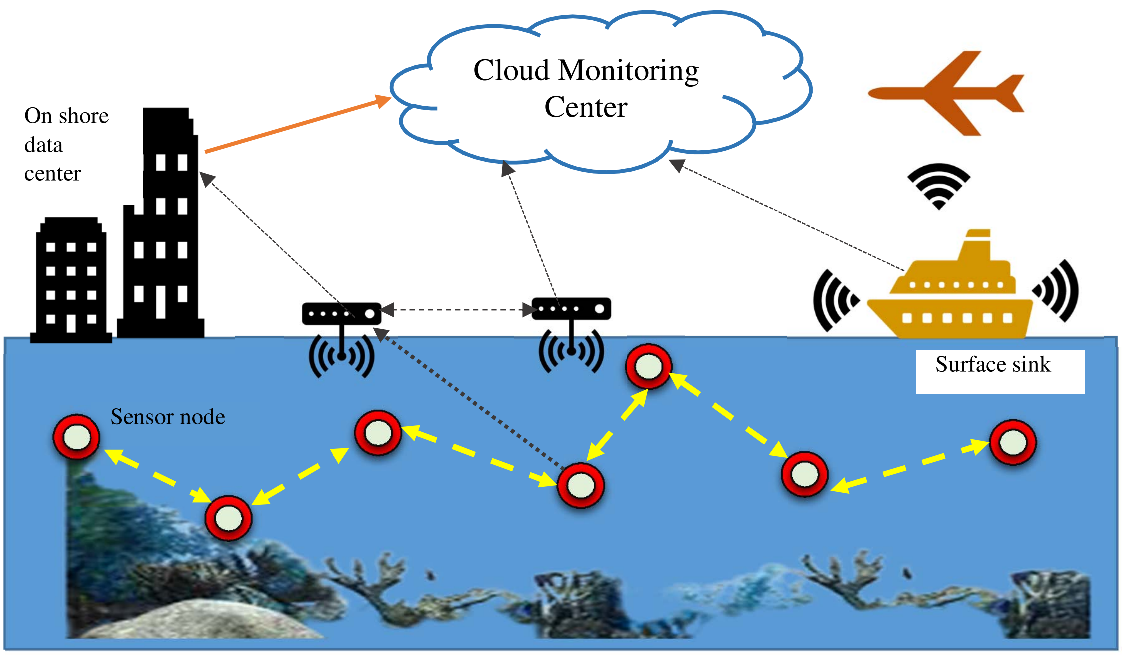

Fig. 1. IoUT.

the capacity to discern, automate, and transmit information in marine and ocean environments using minimal technologies similar to those used in conventional IoT. It necessitates unique underwater functionalities that are at the heart of the created system. An extensive research in IoUT has been conducted and tests for a variety of applications, including underwater athletics, amusement, and ecotourism. FunDive is a revolutionary wearable technology for divers developed under the EC EASME ARCHEO-SUB that allows for real-time tracking of the swimmers' positions and medical conditions. It requires only two components one is a small undersea sensor and other is an aquatic tablet. An acoustical modem, aquatic networking, and data compression circuitry, also a battery system, are all housed in the compact underwater sensor node. A specific application is installed on the table that is connected to the node. Divers can use the system to converse underwater, locate themself, and navigate to locations of interest. Sensors are deployed at sea bed, transfer the data toward sea surface nodes by horizontal or vertical links. This data in real time is transferred to on-shore station using IoUT. Moreover, IoUT evolved as a promising network system having interconnected underwater devices used to improve speed of data collection and other QoS for the system. The future directions for implementing IoUT handling big data in terms of electrical conductivity, dissolved oxygen, and temperature in an underwater environment through ROVs and portable UWSNs [4].

The UWSN architecture includes both static and mobile nodes. A static sensor unit is usually placed on the sea floor and connected to a sink unit. In mobility assisted network, sensor nodes can travel freely, that results in dynamic network topology. The mobile nodes need mainly two transceivers for increasing the data collection capacity of the network. These can be ROVs, AUVs, and sea gliders. The ROVs can be submerged robots, ships, and also submarines. Since the communication is sent directly to the ROVs, sensors with large amounts of data and close to the ROVs can use radio communication, while sensors with small data transmission or far away from the ROVs can use acoustic channels [5].

A. Motivation and Significance

Some deadly disasters, like Tsunamis are caused by the movement of tectonic plates in the oceans. Although it cannot be stopped now, prior knowledge of these disasters can save many lives. This encourages us to uncover these catastrophes so that effective and preventive measures can be taken in advance. By deploying UWSN, one can think of a future time when there will be more control over all underwater activities. Hence, this research helps in exploring numerous areas of application or possibilities under the water also. It will also help to prevent, or at least mitigate, further loss of natural habitat life. This control will be gained by deploying such sensors underwater to sense the danger and inform us in time. Here, one critical aspect is that exploration of the ocean or aqueous is not an easy task. Researchers from academia and industry are trying to make use of technological advancements in WSN to replace the traditional ocean exploration methods. Hence, a reliable and efficient communication system is the need of the hour to unravel the unknown.

The availability of modern sensor node technologies and the rapid growth of UWSNs has enforced the essential requirement to assure that attention is expanding every year because of their compatibility and extensive applications in various domains.

B. Organization

This survey aims to offer the readers comprehensive insights of UWSN and the in-depth knowledge of node deployment and

TABLE I
COMPARATIVE ANALYSIS OF THE PROPOSED STUDY WITH RECENT SURVEYS IN UWSN

Influence	Previous Study					Proposed Study
	[6]	[7]	[8]	[9]	[10]	
UWSN Architecture	✓	×	✓	✓	✓	✓
Different Research Fields in UWSN	×	×	×	×	✓	✓
Comparison with Existing Survey	✓	×	×	×	×	✓
Node Deployment	×	×	×	✓	×	✓
Data Collection	×	×	×	×	×	✓
Simulation Tools	×	×	×	×	×	✓
Existing Data Collection Technique using Simulator	×	×	×	×	×	✓
Applications	✓	×	✓	✓	×	✓
Issues and Challenges	✓	×	✓	✓	✓	✓

data collection in UWSN. To the best of our knowledge, there is no survey covering both the broad range of node deployment and data collection methods with UWSN fundamentals. This work's primary focus is to broaden the horizons of potentials related to underwater exploration and familiarize the existing node deployment technique, their advantage and disadvantages so that effective strategies providing maximum coverage with the minimum number of nodes to conceive future applications. Along with it, survey targets at examining the difficulties with the existing scheme of data collection. The problem in the current scenario of data collection can be avoided and providing real-time underwater communication. To boldly and explicitly illustrate the contributions in this article are as follows.

1) This article enable the readers with a robust and coherent understanding of UWSN terminologies. Also, motivation for researchers to work in this emerging area is depicted by stating various applications.
2) Meticulously demonstration of node deployment, with the taxonomy of existing models and the comparative analysis based on various parameters is presented. The challenges of node deployment with upcoming issues are also discussed.
3) Detailed analysis of UWSN's data collection approaches that are prerequisites for effective communication in almost all the applications with taxonomy based on intermediate or forwarding node is discussed.

Table I summarizes and compares the recent existing survey with the proposed survey. In this table, various existing study are compared on the basis of different parameters focusing on node deployment and data collection field that are important for many applications.

The remainder of this article is organized as follows. This survey consists of a total of seven sections. The communication techniques in UWSN is discussed in Section II. The node deployment techniques with their comparison are discussed in Section III. Data collection methods with literature are presented in Section IV. UWSN applications are summarized in Section V. The performance comparison of some of the existing data collection techniques is compared and analyzed in Section VI. Section VII presented the future challenges in IoUT and outcomes of the study. In the end, the conclusion is presented in Section VII.

C. Communication Techniques in UWSN

UWSN is that vast area with different fields and avenues for research, such as the design of efficient routing protocols, node localization techniques for data capturing, node deployment strategies for better coverage, communication protocols, and different communication mediums. For better sensing and surveillance schemes in UWSN, i.e., to acquire data timely, it is required to understand ocean environments' complexities.

Underwater acoustic communication is an important part of underwater data collection. To achieve high communication speeds and high data rates, the system transmits multiple channels simultaneously and is based on a modulation system that uses cable connections called orthogonal frequencies multiplexing. This allows researchers to output hundreds of bits at a time [11].

In UWSN, we have three existing approaches and an advanced approach called magnetic induction (MI) for underwater communication [12]. These are as follows.

1) The very first technology used was electromagnetic (EM) waves, i.e., radio frequency (RF) that is popular for communication over short ranges with the high data rate.
2) The optical signal technique is used under the water to attain large bandwidth and high data rate [13].
3) Most widely used technology is acoustic communication used for the longest-range communication under the water.

Additionally, we have another approach: MI communication based on time-varying magnetic wave. Currently, research in this communication field is of great interest for many researchers [14]. It can address the issues of dynamic channel conditions and the larger antenna size due to using EM wave. MI-based underwater communications possess numerous encouraging and exclusive features, such as channel behavior, minor signal propagation delay, adequately long communication range with high bandwidth, and underwater stealth operations [15].

Opposite to terrestrial or ground-based wireless communication, RF signals behavior is different or not respondent below the water [16]. Underwater communication channels are dynamic in nature depending upon the action to varying depths inside water. At some areas, the communication medium is dense along with more salinity of water, with it, even the high-frequency RF signals face an increased attenuation [17].

EM communication with low-frequency signals needs a large sized antenna that is impractical in the underwater sensor network. Table II shows the comparison of different mediums of communication used in UWSN based on various parameters [18]. Despite many benefits of using an acoustic medium in an underwater environment for communication, the speed is slow compared to other mediums. These communication patterns are chosen based on different situations like the distance between the surface buoy and deployed nodes like for

TABLE II
COMPARISON OF DIFFERENT MEDIUMS OF COMMUNICATION USED IN UWSN

Framework	**Magnetic Induction**	**Acoustic Medium**	**EM Medium**	**Optical Medium**
Speed	3.33×10^7 m/s	1500 m/s	3.33×10^7 m/s	3.33×10^7 m/s
Effective range	10-100m	Up-to few kms	Up-to 10 m	Approx. 10-100m
Delay	Low	High	Medium	Low
Data Rates	~Mb/s	~Kb/s	~Mb/s	~b/s
Bandwidth	Less than EM	1-100KHz	~ MHz	Less than 150MHz
Antenna Size	Comparatively Small size	0.1m	0.5m	0.1m
Cost	Low	High	High	Low
Transmission Power	High	More than 10W	mW-W	mW-W
Attenuation Factor	Conductivity	Conductivity	Frequency and Conductivity	Absorption
Effect on marine life	No	Yes	Yes	Yes

small distance underwater communications, optical, and magnetic field signals are appropriate to use [19]. Long-distance underwater communication is attained using acoustic signals. Here, these communication mediums explained in detail.

Acoustic Medium: United States settled the first underwater audio communication setup using a single sideband (SSB) suppressed carrier amplitude modulation between 8 and 15 kHz carrier frequencies [20]. This is one of the most preferred signals used in numerous underwater applications, because of its absorption characteristic in an aqueous environment. However, data transmission is slow in acoustic communication as compared to other mediums. Due to the low absorption characteristic, signals travel at more extended range [21]. Despite the fact that acoustic waves are used for long-distance communication, it cannot provide high-bandwidth signals. Based on signal propagation distance, acoustic waves are categorized as very short, short, medium, long, and very long distances. The acoustic channel model described by Stojanovic [18] where the path loss characterizes acoustic signals that depends on the distance among sender and receiver. The attenuation or path loss over the distance d and frequency f is given by

$$A(d, f) = A_0 d^k a(f)^d \tag{1}$$

where A_0 is a normalizing constant, $a(f)$ is the absorption coefficient, and k is spreading factor. The acoustic path loss (in dB) is given by using the following equation:

$$10\log A(d, f)/A_o = k.10\log d + d.10\log a(f). \tag{2}$$

The first part in (3.2) denotes the spreading loss, and the second part shows the absorption loss. The factor k in the first part represents the geometry of propagation. Its commonly used values according to different shapes are $k = 2$ for spherical, and $k = 1$ for cylindrical spreading. Using Thorp's formula, the absorption coefficient can be presented by the equation

$$10\log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 \cdot 10^{-4} f^2 + 0.003. \tag{3}$$

It gives $a(f)$ in dB/km for f in kHz. This equation works for frequencies above a few hundred Hz, and if the frequencies are lower then, the equation can be

$$10\log a(f) = 0.002 \frac{f^2}{1+f^2} + 0.11 \frac{f^2}{4100+f^2} + 0.011f^2. \tag{4}$$

The sea's ambient noise is usually exhibited by four sources: 1) shipping; 2) turbulence; 3) thermal noise; and 4) waves. Ambient noise sources can be defined by Gaussian statistics and continuous power spectral density. Coates [19] gave the empirical formula to provide the four noise components' power spectral density in dB per Hz as a frequency function in kHz

$$10 \log N_t (f) = 17 - 30 \log f \tag{5}$$

$$10 \log N_{sh} (f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log (f + 0.03) \tag{6}$$

$$10 \log N_w (f) = 50 + 7.5w^{0.5} + 20 \log f - 40 \log (f + 0.4) \tag{7}$$

$$10 \log N_{th} (f) = -15 + 20 \log f \tag{8}$$

where N_t is turbulence noise, N_{sh} is shipping noise, N_w is wave noise, and N_{th} is thermal noise. Here, w is the speed of wind measured in meter per second, and s is the shipping factor having value from 0 to 1. The overall power spectral density of the ambient noise is determined by

$$N(f) = N_t(f) + N_{sh}(f) + N_w(f) + N_{th}(f). \tag{9}$$

Electro-Magnetic Medium: This communication medium is recognized at a higher bandwidth. Whereas, high attenuation causes constraint to affect the quality of the communicated signal considerably. In these big antennas of approximately 0.5 m is needed, affecting the design complexity and cost [23]. Extensive research work has been conceded regarding RF frequencies, but sea water conductivity affects it from the high losses. Also, in sea water 4 mhos/m is considered as the average conductivity, i.e., two orders higher than fresh water conductivity. Because of this, absorption loss increases at high frequencies [24]. The absorption coefficient of sea water, i.e., $\alpha\_$ *sea water* is related to conductivity as

$$a\_\text{sea water} = \sqrt{\pi f \mu \sigma} \tag{10}$$

where f is the operating frequency in kHz, σ the water conductivity, and μ the permeability. Opposite to it, the absorption

TABLE III
VALUES FOR DIFFERENT TYPES OF WATER

Types of Water	***Chlorophyll concentration*** ***C* (mg/m^3)**	***Absorption coefficient*** ***a* (λ) (m^{-1})**	***Scattering coefficient*** ***b*(λ) (m^{-1})**	***Wavelength function*** ***parameter c*(λ) (m^{-1})**
Pure sea	0.005	0.053	0.003	0.056
Clean ocean	0.31	0.069	0.08	0.151
Coastline ocean	0.83	0.088	0.216	0.305
Turbid harbor	5.9	0.295	1.875	2.170

coefficient of freshwater, i.e., α_fresh water is fundamental frequency independent and calculated by

$$\alpha\text{\_fresh water} \approx \frac{\sigma}{2}\sqrt{\frac{\pi}{\epsilon}}. \tag{11}$$

Here, ϵ is the permittivity defined. Therefore, RF communication is better in fresh water. However, it needs a huge sized antenna that is not feasible under the water.

Optical Medium: This offers a high data rate transmission, but scattering and absorption affect signal strength and accuracy [25]. The optical medium possesses many explicit characteristics during communication at different frequencies over distinct ranges with a diverse underwater medium. Schirripa et al. [26] stated that with advanced bandwidth, optical communications could provision progressive data rates with comparatively lower acoustic or RF communication latency. However, an optical medium can never totally oust the acoustic communication. Scattering and absorption are two mechanisms that damage the light propagation in water and deteriorate optical medium use in underwater communication. The propagation in water of collimated light is described by the attenuation coefficient $c(\lambda)$. Where $c(\lambda)$ is wavelength function parameter. As described by Xu [27], this is a summation of term a (λ) (absorption coefficient) and b (λ) (scattering coefficient)

$$c(\lambda) = \ a\ (\lambda) + b\ (\lambda). \tag{12}$$

The variation in the values of a (λ) and b (λ) comes due to different water types along with fluctuating wavelength as shown in Table VI. There can be different water types in underwater communications [28], such as pure sea water, clean ocean water, coastline ocean water, and turboid harbor water. Here, distinct values of chlorophyll concentration C illustrate different types of water. So, the coefficient for absorption $a(\lambda)$ and scattering $b(\lambda)$ will be

$$a(\lambda) = \left[a_w(\lambda) + 0.06a_c(\lambda)C^{0.65}\right] \times\{1 + 0.2\exp[-0.014(\lambda - 440)]\} \tag{13}$$

$$b(\lambda) = 0.30\frac{550}{\lambda}C^{0.62} \tag{14}$$

where a_w shows the pure water absorption coefficient and a_c is a nondimensional quantity. Here, chlorophyll concentration C, (in mg/m^3) is used as the open parameter. The experimental values of these coefficients are depicted in Table III.

MI: This highly efficient communication medium based on a time-varying magnetic field is newly used to transmit information between different ends. Due to this property, it exhibits exceptionally reliable and steady channel performance, with minor multipath fading, high bandwidth, high communication range, and small-size coil antennas requirement. Akylidz et al. [29] examined that the standard and most used acoustic waves while promising longer communication ranges in underwater communication exhibit long propagation delay and unpredictable and irregular channel behavior.

UWSN is a broad research area with many fields, such as node deployment, data collection, data aggregation, data fusion, underwater communication, localization of nodes, etc. As data collection is used in almost every application of UWSN, it needs significant attention. In the next section, the existing data collection techniques proposed by many researchers are discussed.

II. NODE DEPLOYMENT IN UWSN

A substantial amount of research has concentrated on node deployment algorithms as they are of utmost importance for every part of UWSN. To improve packet delivery ratio (PDR), most research aims for maximum coverage and high network connectivity with the fewest required nodes and energy consumption [30]. UWSN networks are more prone to issues, such as the mobility of deployed nodes, high latency, 3-D deployment, and communication delays related to the deployment of sensor nodes in particular monitored areas. Along with the assurance of coverage and connectivity, node deployment also aims to reduce energy consumption. The advancement in extensive deployments of UWSN is intended to monitor large zones of oceanic water.

A. Node Deployment Introduction

The deployment of nodes is one of the fundamental concerns in UWSN [31]. The node deployment problem can be indicated as having a designated area D_a to be covered and N number of sensors. The main concern is determining how to locate these N sensor nodes to set up a UWSN that meets the system requirements and its capability to discover relevant events happening in designated area D_a. Here, node deployment may directly affect node (sensor/sink) locations their connections and availability. UWSN in some conditions provides a 3-D domain, where all the objects are in constant motion. As a result, node deployment, which is a costly task in these harsh aquatic environments becomes challenging [32]. There are substantial topological changes as deployed nodes are free to float in water. It is assumed that numerous homogeneous underwater sensor nodes having limited capabilities are submerged into the sea area to monitor environmental changes

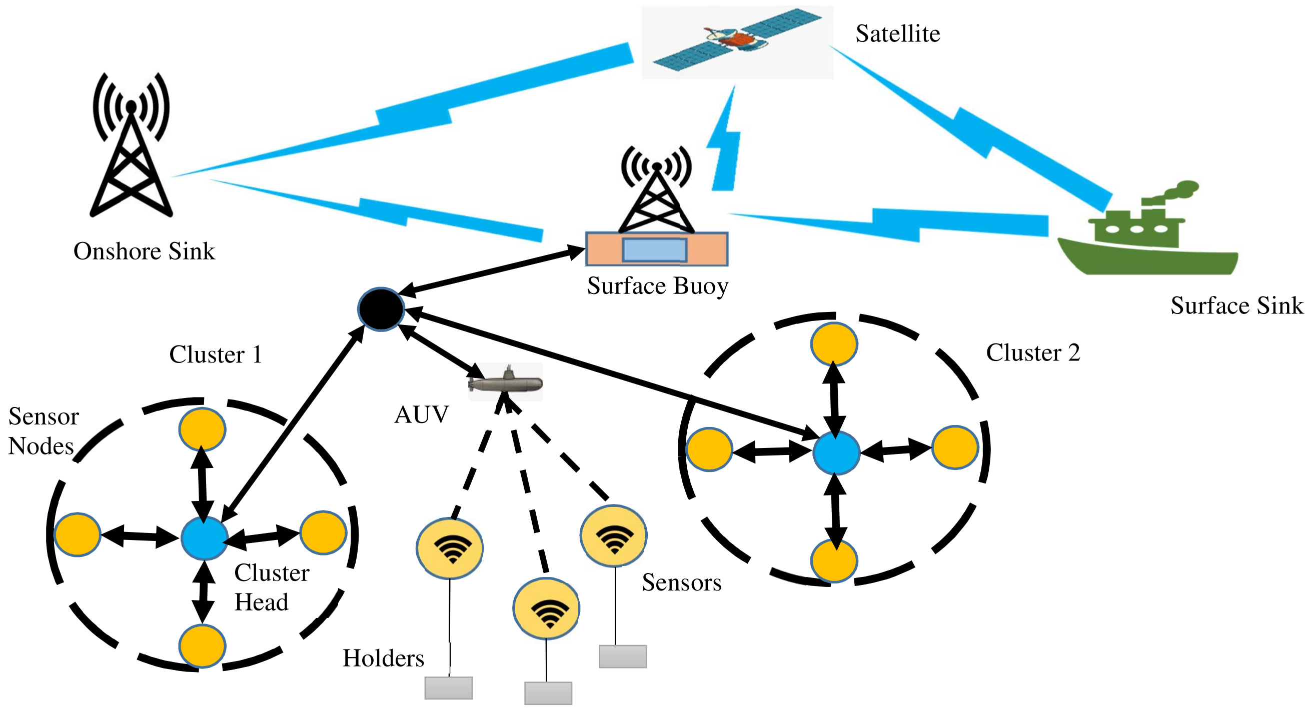

Fig. 2. Typical node deployment scenario.

and record useful ecological changes in the form of data, as shown in Fig. 2.

Several researchers are focusing on node deployment issues in UWSN over the past few years [33]. In AUV-aided data collection, the sensor nodes' deployment information plays a critical role as nodes have to communicate with AUVs. The AUVs can navigate using the node location information (in some cases already known), to stop near a sensor to gather data. The deployed sensor nodes are examined as static or fixed nodes because nodes are anchored to the ocean floor or sea bed [35]. For sensor node deployment, network topology also plays an essential role in almost all issues, such as communication performance of a network, power consumption, and reliability with fault tolerance proficiencies.

B. Node Deployment Related Work

Sensor network deployment techniques are essential for any network, as stated by Deif and Gadallah [36]. The placement of nodes may directly affect their locations, connection, and availability of the network.

The node deployment algorithms for UWSN are divided into three main categories: 1) self-adjustment; 2) static; and 3) movement assisted [37], as shown in Fig. 3. Further, these algorithms have different schemes or techniques.

In static or fixed node deployment arrangement, all the nodes are static even next to the initial deployment under the water. The deployed sensor nodes are either linked with surface buoys through the fins or anchored at the ocean bottom surface but must be considered to have fixed places. This type of deployment can also be categorized further into regular and random deployment.

In self-adjustment deployment, as clear from the name, nodes are autonomous and can adjust according to the depths by automatically using floating buoys or determining some desired positions by using mobile sensors. These algorithms can also be further classified based on coverage, i.e., uniform and nonuniform coverage deployment algorithms. Some mobile sensor nodes under the water that monitor the designated region come under the category of movement-assisted deployment to cooperate with other sensors to accomplish various patrolling, controlling, and monitoring activities.

In movement-assisted deployment, sensor nodes mobility is considered, it is initiated mainly by water current or water drift with other marine animal movements. The two main varying parameters over different deployments types are mobility and density in underwater sensor networks [38]. It can be static, semi-mobile, and mobile. Every individual node is attached to the docks or anchored buoys or placed at the seafloor in static. In the semi-mobile network, nodes are suspended from the buoys positioned by any ship and are temporary but then left on that place from hours to any long-time durations. To obtain a satisfactory network performance, a flexible deployment technique is required. The node deployment scheme considers factors such as type of nodes, i.e., homogeneous or heterogeneous, deployment objectives regarding area coverage, computation complexity at the node or at the surface buoy, energy consumption, etc.

Many researchers have proposed different node deployment techniques to achieve the objectives of maximum coverage and connectivity. Liu et al. [39] devised a distributed, virtual forces-based node deployment algorithm (DABVF), to enhance network coverage. A mobility model that contemplates node density, node mobility, and node residual energy with efficiency

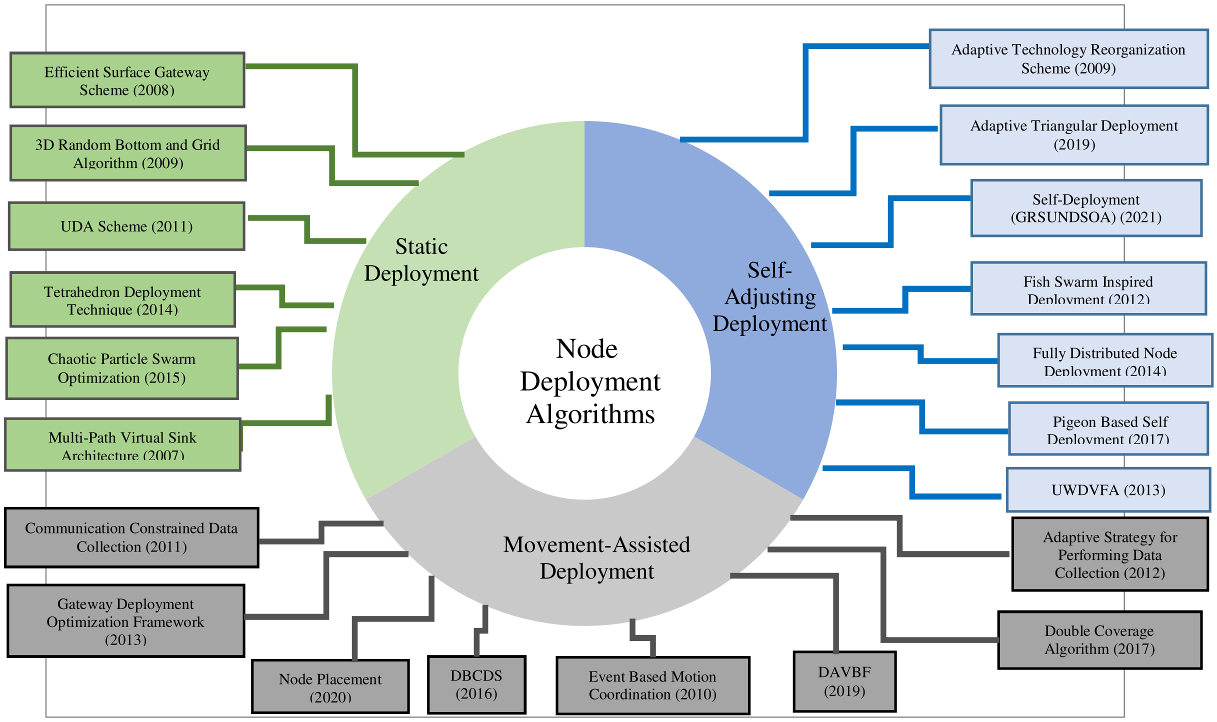

Fig. 3. Taxonomy of node deployment algorithms in UWSN.

is recognized to ameliorate the node mobility process during the node deployment procedure. Ding et al. [40] anticipated with double coverage scheme to solve the premature sensor failure caused by extreme energy consumption. It is based on mobile node deployment in UWSN.

Jiang et al. [41] propounded a node deployment algorithm having connected dominating set (DBCDS). This algorithm consists of freely mobile nodes to solve the deployment problem. A comparison with existing procedures is made for UWSNs that cannot recover the system coverage, high network connectivity, and underwater communication optimization with the movement energy consumption during deployment. The drawback in this methodology is that sometimes it does not effectively address node mobility, that is a key issue in UWSN.

Su and Wang [42] presented the chaotic particle swarm optimization algorithm. With the experimental outcomes, the authors contributed that this technique could effectively increase the convergence speed and network coverage. Kim et al. [43] devised an adaptive triangular system regulating sensor distribution depending upon the communication performance variation below the water. For predicting the distance among sensors, a performance surface model is employed by approximating the communication efficiency founded of spatio-temporal environment issues. Therefore, UWSNs used with adaptive triangular implementation algorithms can reach the maximum communication speed at the optimal number of nodes. The mechanism for coping with delays in real-time communication has to be improved in this technique.

Li et al. [44] considered the mobile sensor nodes deployment problem in a self-adaptation arrangement if all nodes are permitted to traverse spontaneously in the space. Traditional virtual force algorithm (VFA) is nominated as a reference for its ease and distributed implementation for 3-D area. Authors introduced the concept of additional equilibrium force and central gravitation to make the deployment more obtainable and reasonable. Various test cases and algorithms are applied to evaluate the performance of the proposed improvement, namely, coverage ratio and homogeneous degree.

The main drawback in this approach is that it is ineffective for fast data gathering applications, since communication delays are not factored into the equation while transmitting data.

Yu et al. [45] presented a Pigeon-based scheme (PSA) for UWSN to reduce the limitations of coverage, connectivity, network deployment, network reliability, and energy consumption. The sink node first finds out its single hop nodes and maximizes network coverage in its region in this algorithm. Other single hop nodes split the network into various layers and also form a cluster for every layer. There can be improvement in this technique is that cluster head (CH) can use sleep wake-up scheduling to manage the energy problem.

Almutairi and Mahfoudh [46] designed an underwater 3-D self-distributed deployment algorithm based on virtual forces (UW-DVFA). This work's main goal is to expanse the random network deployment in the 3-D region to guarantee full coverage area and high connectivity of the network. This process guarantees the maximum coverage area and connectivity in the network. The drawback in this technique is that the authors mainly targeted to expand the randomly deployed network in 3-D area.

Pompili et al. [23] considered triangular grid positioning of sensors for underwater communication as the pioneering effort and originated important geometric properties. For example,

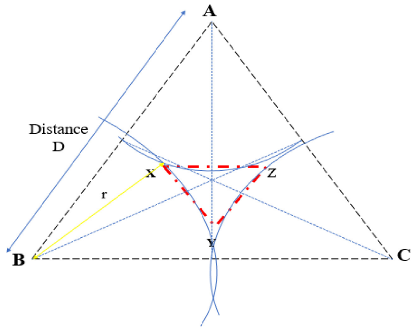

Fig. 4. Triangular-grid node deployment.

take the general scenario of sensor nodes with identical sensing range r. This technique is for a 2-D rectangular area with the least number of sensor nodes and deploying every node at the grid's vertices, as shown in Fig. 4. By adjusting distance D within nodes (side of the equilateral triangles), the coverage rate can increase and can achieve full coverage. It is also mathematically proved, when $D = \sqrt{3}r$, the overlapping areas can be minimized and the maximum coverage can be attained.

However, it requires a comparatively large number of sensor nodes. To overcome this problem, authors framed a function to find the required least number of sensors required to be deployed to maximize the coverage area for sensing. Yan et al. [25] for improving the coverage area and to handle energy-related problem proposed a growth ring style uneven node depth-adjustment self-deployment optimization algorithm (GRSUNDSOA). The improvement scope in this technique is that authors should also considered the mobility of nodes in mobile-assisted UWSN.

Jiang et al. [114] proposed guaranteed full connectivity node deployment (GFCND) method along with the location dispatch based on command nodes (LDBCNs) algorithm. This algorithm considers that deployment strategies for UWSN should provide full connecting systems and also achieves the location correction of commonly sensor nodes, including sink and command nodes. The main advantage of these algorithms is that it provides a comparatively large coverage percentage and a fully connected network. The drawback in this technique is that it does not work much on collision avoidance of deployed sensor nodes.

Gola and Gupta [115] designed an efficient node deployment technique for enhancing coverage and connectivity (END-ECC) that works for the main objective of node deployment that is for better coverage and connectivity. In this technique, the entire network is mainly separated into three layers that is top layer, middle layer, and last is bottom layer. The proposed END-ECC algorithm comprises of three phase, namely, root selection, formation of tree structure, and in the end calculation of the depth of different deployed nodes. This technique provides improved coverage and connectivity. The main concern in this technique is that it does not solves the problem of coverage overlapping.

C. Node Deployment Challenges

Due to the peculiar underwater communication characteristics, there are many deployment issues for UWSN, i.e., significantly different from WSN. Hence, for scalable and better node deployment in UWSN, the challenges are listed as follows.

Deployment: The deployment of wireless sensor nodes is the base for all kinds of communication in the network, in such a way that it could cover maximum region. It should be performed with lots of care and attention as it is considered sparser in the networks under the water and environment is completely different.

Communication Stability: It is totally dependent on the communication mediums, such as acoustic, optical, and EM, that are used for all types of operation and communication and their characteristics.

Robustness: Nodes in the network are not stable as the water current keeps on shifting and sensor nodes used for many specific applications keep on moving from their locations.

Spatial Correlation: UWSNs are sparser in deployment so spatial correlation in aqueous networks is less likely to happen due to the highly distant sensor nodes of the network.

Expenditure: The sensor node that are used under the water are bit expensive comparatively due to extra requirements to work under critical aqueous environment.

Power Requirements: UWSN imposes high power consumption due to complex processing signals and underwater parameters imposed by ocean or sea.

For a better understanding of node deployment protocol properties, an overview is presented in Table IV.

III. Data Collection Approaches/Techniques

When we talk about optimizing any wireless network, attention should focus on efficient ways of accomplishing data on the application layer. For achieving this, techniques need to be found, which reduces the amount of communication data to reduce power consumption. Some useful methods are required to manage collected data from different sensor nodes [56].

These approaches include data collection, data compression, data fusion, data forwarding, data dissemination, and data aggregation, as shown in Fig. 5.

Data collection from UWSNs is vital for many applications, including collecting sensing data from different deployed sensor nodes [57]. Data compression is a technique of packing data, eliminating redundant information, data fusion that combines heterogeneous data to more abstract information or events, and data aggregation as a particular class of data fusion covering the local preprocessing of homogeneous data to usable information sets [58].

UWSN consists of numerous autonomous sensor nodes to employ aggregation and forwarding of data so that aggregated data could reach the node designated as the sink node. After establishing such networks, the main challenges are high cost, operational energy, and memory, limited lifetime of a sensor and communication range. When this aggregator node gathers the recognized information from neighboring nodes, it will process and ultimately transmit it to the sink [59].

Data aggregation protocols within the application layer offer promising capabilities for reducing the amount of data payload [60]. In UWSNs, the sensed data from a particular

TABLE IV
UWSN NODE DEPLOYMENT PROTOCOLS PROPERTIES COMPARISON

Parameter/ Reference	Maximum Coverage	High Network Lifetime	Minimum number of nodes	High Connectivity	Low Energy Consumption	Longer Delay	Good Topology Control	Centralized Coverage	Distributed Coverage	Scalability	Mobility
Liu et al. [39]	✓	✓	✓	-	✓	-	-	-	✓	-	✓
Kim et al. [43]	-	-	✓	✓	-	✓	✓	-	✓	-	✓
Wang et al. [47]	✓	-	✓	-	✓	-	✓	✓	-	-	-
Wang et al. [48]	✓	-	-	✓	✓	-	-	-	✓	✓	✓
Ding et al. [40]	-	✓	✓	-	✓	-	✓	-	✓	-	✓
Yu et al. [45]	✓	✓	-	✓	✓	-	✓	-	✓	-	-
Wei et al. [30]	-	✓	✓	-	✓	-	✓	✓	-	-	-
Jiang et al. [41]	✓	✓	-	✓	✓	-	-	-	✓	-	-
Su & Wang [42]	✓	-	-	-	✓	-	-	-	✓	-	✓
Senel et al. [51]	✓	-	-	✓	-	-	-	-	✓	-	✓
Ibrahim et al. [50]	✓	-	-	✓	✓	-	✓	-	✓	✓	✓
Li et al. [44]	-	-	-	-	-	-	-	✓	-	-	✓
Hollinger et al. [52]	-	-	-	✓	-	-	-	✓	-	-	✓
Yingying et al. [33]	✓	✓	-	✓	✓	-	-	-	✓	✓	✓
Yoon and Qiao, [53]	-	✓	-	-	✓	-	-	-	✓	-	✓
Golen et al. [54]	✓	-	✓	-	✓	-	-	✓	-	-	✓
Teixeira et al. [37]	-	-	-	-	-	-	-	-	✓	-	✓
Pompili et al. [23]	✓	✓	-	✓	✓	-	✓	✓	-	✓	-
Akkaya and Newell, [38]	-	-	-	✓	-	✓	-	-	✓	-	-
Domingo, [49]	-	-	-	✓	✓	-	✓	-	✓	-	✓
Ibrahim et al. [50]	-	-	✓	-	-	✓	-	-	✓	-	-
Seah and Tan [55]	✓	✓	-	✓	✓	-	✓	✓	-	-	-

area can be directed toward the sink node either directly, i.e., in hop-by-hop or transported via multiple hops. But all the sensed data does not always make sense, which means that it is unnecessary and redundant.

Hence, sensed data must be aggregated or concise at intermediate sensor nodes by adopting suitable data fusion techniques. Data fusion provides many facilities like it reduces many collisions that can occur because of the large amount of data that can come and create colossal traffic, which helps stop getting data from malicious nodes as data is first aggregated. It also helps in making many other data related decision [61].

A. Data Collection

Data collection is a significantly hot research area compared to data forwarding, data fusion, and aggregation in UWSNs. It is because if accurate data (nonmalicious data) is collected from a reliable node (nonmalicious node), only it can process and utilized efficiently. In UWSN, numerous nodes are connected and arrayed with other surrounding nodes to collect the sensing data and forward it to the surface node. The surface/sink nodes act as the processing system of UWSN [62]. The nodes communicate using a high-speed optical communication or acoustic communication system under the water also IoUT is also used when data needs to be send to onshore stations. The IoUT is an evolving communication environment dedicated to communication aquatic objects in the marine and aquatic environment. The IoUT technology is closely linked to smart ships and shipping, coastal and ocean intelligence, automatic transportation, location and navigation, underwater mining, disaster prediction, and prevention, as well as research monitoring and security. IoUT affects many types of people ranging from a small Scientific Observatory to a medium-sized port for international trade at sea.

In UWSN, some efficient algorithms have been proposed not only for adequate data collection properties, such as seawater salinity, temperature, and pressure but also for marine environmental monitoring. Recently, underwater pollution monitoring is successfully done in many projects by deploying UWSN.

In the future, it can also be utilized to real-time monitor the projects for seismic, military, and volcanic activities which is a challenging task till now due to nonavailability of efficient

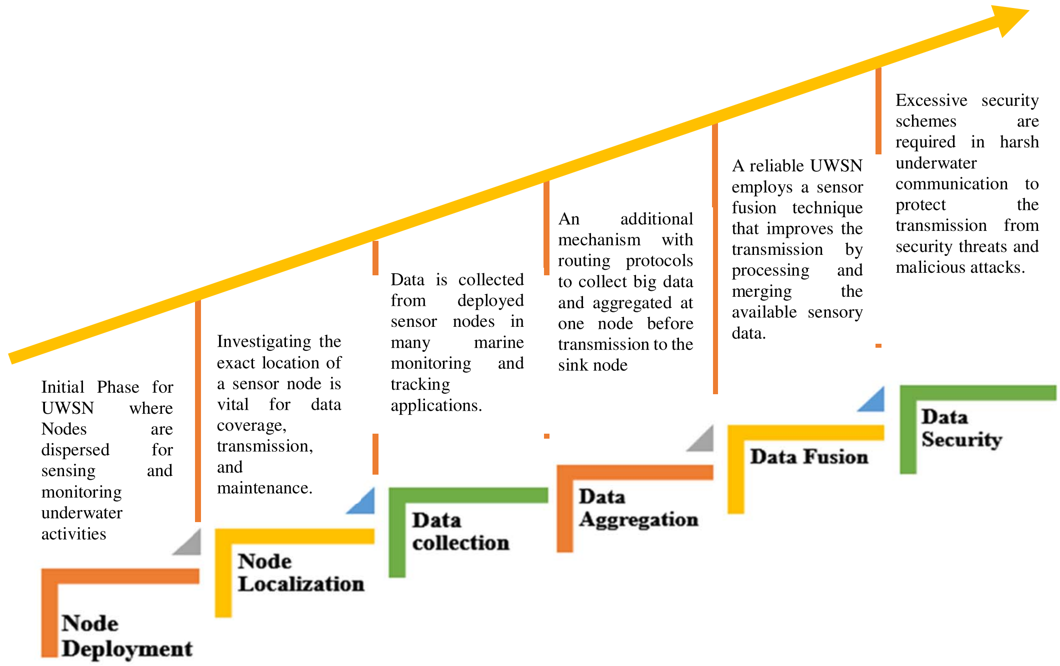

Fig. 5. Phases in data collection.

data collection strategies [63]. Many researchers have explored the data collection methods and techniques, and they have explained some challenges faced during data collection phase. There are many challenges for collecting data under the water, out of which some of the main challenges in UWSNs are as follows.

1) The underwater acoustic channel quality varies with time. It will depend on many underwater circumstances such as temperature, weather condition, pressure, and salinity of the water [64].
2) Communication synchronization among AUVs and different dispersed underwater sensor nodes with efficient route planning.
3) The AUV movement speed is affected by many issues, such as water flow, pressure, hurdles, etc.
4) Storage can also be a matter of concern, as most data gathering method run on a cloud. Because of the distant cloud position from the data source nodes, communicating it would result in high energy consumption.
5) Localization accuracy affects data collection in UWSNs.
6) UWSNs have highly dynamic topologies. In UWSNs, frequent changes in the network topology occur that strongly affect the marine communication.

There are mainly three methods to collect sensed data from deployed sensor nodes multihop, AUV aided, and hybrid [65]. Previously, most data collection schemes were based on the multihop data collection method. But after technology enhancement over time, many researchers perform AUV-aided data collection and got improved results. Many researchers recently adopt an improved scheme that associates multihop mechanisms with AUV-aided data collection, known as the hybrid data collection scheme. This scheme shows the enhancements as it combines the features of multihop and AUV-aided data gathering method. The advantage of multihop methods is that the total communication delays are shorter than those by AUV-aided data collection. This is due to the fact that the speed of sound is faster than AUV speed [66]. However, the problem of unbalanced energy consumption is countered by the multihop method. This problem occurs because sensors in the neighborhood of the sink node deplete the energy faster, and consequently, drain the energy rapidly compared to other nodes. Hence, relay nodes serving as the intermediate nodes become inefficient over time because of rapid energy utilization by neighbor nodes [67]. After that, this energy depletion problem causes frequent disconnections in an extensive network. It is commonly termed as energy hole problem around the sink node.

In AUV data collection, the sensor nodes are generally armed with the acoustic communication modules under the water. The AUV needs to navigate the sensor nodes' proximity to achieve the data due its limited communication range [68]. This approach's benefit comes from the fact that the AUV need not visit all the nodes or monitoring areas every time. Here, it is considered to divide the network into clusters having CHs and gateway nodes to transfer data between clusters. The other nodes will forward the sensed data to the CH directly or through multiple hops. Hence, AUVs have to visit only the CH for data collection, and this approach would shorten the traveling distance and time [69]. The nodes communicate point-to-point using a high-speed optical communication or acoustic communication system. All the sensors have a diversity of sensing capabilities, including size, cameras, pressure, and water temperature.

B. Data Collection Related Work

In the recent past, some excellent schemes for data collection have been developed for UWSNs by researchers. The

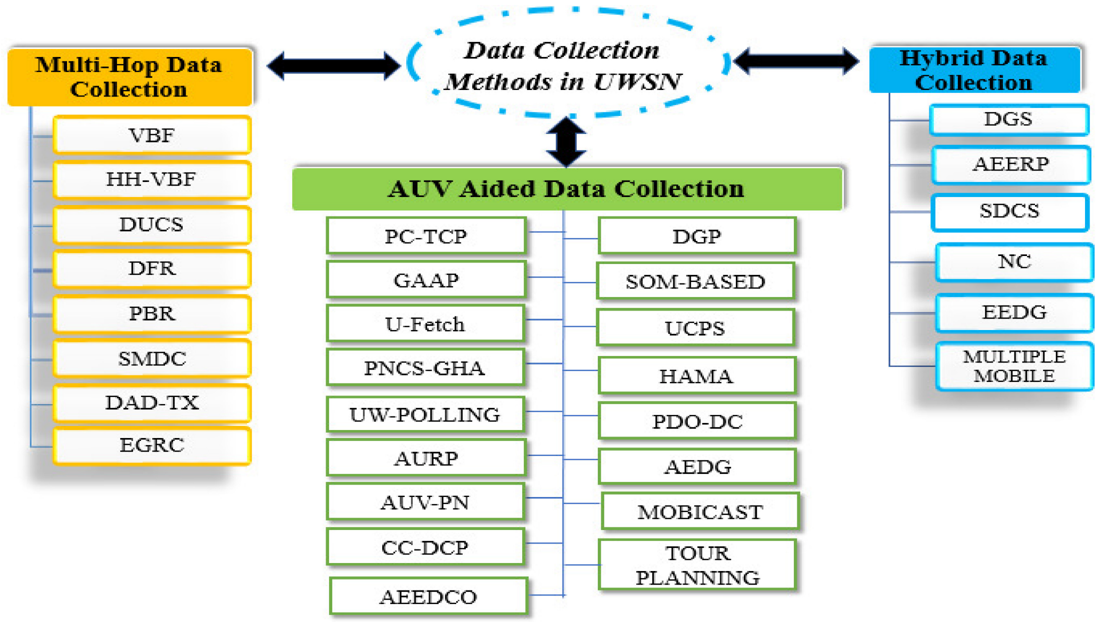

Fig. 6. Taxonomy of UWSN data collection methods.

main problem to be solved is identifying a path with minimal data collection cost within an appropriate range [70]. The data collection methods are classified into three categories of multihop, AUV aided, and hybrid methods, as shown in Fig. 6.

Multihop Data Collection: Xie et al. [71] designed a vector-based forwarding (VBF) protocol, which is one of the fundamental protocols where packets are forwarded between the sources and target through a fixed virtual pipeline. But it is not suitable for the sparse network. The protocol does not work well when mobility is high. Nicolaou et al. [72] presented the forwarding protocol based on hop-by-hop vector (HH-VBF) to overcome this problem. It increases the possibility of finding a node in the pipeline. This protocol works does not well when the network has void regions. The multihop data transmission can be hierarchical, grid-based, and grouped or clustered network structure that works well in the deep sea, but not in the shallow sea. Hwang and Kim [73] devised a directional flooding protocol (DFR) to route the packets for the increase in reliability. It is used when communication links are more prone to packet loss. But the protocol faces a problem when there is no node near to the sink means in the void regions.

AUV-Aided Data Collection: AUV-assisted data collection is more convenient according to some recent developments because AUVs balance the sensor's power consumption and simplify the network's design. Chen and Lin [74] devised a mobicast protocol that avoids the low efficiency of the network. In this, sensors form a 3-D geographic region near all AUV under the water called 3-D ZOR. This is a very effective technique but sometime the delay get increased as the network get denser with a high number of nodes. Han et al. [75] depicted the PNCS-GHA method, where AUV collects data based on probabilistic neighborhoods. In AUV-assisted underwater protocol (AURP), multiple AUVs are utilized as the relay nodes for collecting data packets from gateway nodes to get data reached sink node. Here, each gateway node is liable for collecting data from underwater deployed sensor nodes. Thus, sink nodes and gateways should repeatedly broadcast their interest in gathering data. Further, this data is utilized by other sensor nodes to choose the next hop to visit by minimizing the path length. In AUV-PN, AUV is used to visit the identified areas for collecting the aggregated data in cluster-based networks. AUV partitions the deployed network using Voronoi criteria and further moves into the network with already decided lawn-mower pattern to disseminate the collected data. The problem of void region is not effectively handeled by this AUV-based technique. Li et al. [76] devised a cognitive technique for acoustic transmission, known as dolphin-aware data transmission (DAD-Tx) using multiple hops in UWSN. Noncollaborative sensing and simplified modeling of dolphins' activities motivated authors to propose a probabilistic method for capturing the stochastic characteristics similar to communications among dolphins'. Authors have formulated the DAD-Tx optimization problem for maximizing the throughput.

According to Hollinger et al. [77] during data collection by AUVs, it needs to sail into the sensor's vicinity (equipped with the acoustic communication modules) to acquire the data correctly with limited communication range. Therefore, to gather the data from UWSN with AUV-assistance is referred to as a communication-constrained data collection (CC-DCP). This method does not work well in an area where sensor communication excellence contrasts amid sensor nodes that results in probabilistic neighborhoods of dissimilar dimensions. Lasheng et al. [78] proposed a subtree merging-based data collection algorithm (SMDC) that utilizes more sensor nodes to continuously sense and collect data, especially in a given area.

Chang and Shih [79] proposed data collection using a docking station to deal with the limited power of the AUV and minimizes the length of routes and the overall time of the

AUVs. However, acoustic transmission leads to a considerable propagation delay such that it is quite challenging to plan the tour path of AUVs. Faigl and Hollinger [80] devised an efficient approach to collect data from sensor nodes deployed in oceans autonomously. In this, each sensor node is equipped with modules for wireless communication ability and recover data remotely. This is the most convenient method but, due to the lack of the communication technology available in UWSN like optical or wireless acoustic modems, its tough to collect data without a mobile underwater vehicle. Another optimization technique is to use a self-organizing map (SOM) to deal with the TSP problem. SOM can be helpful to solve those problems where target locations are not explicitly prescribed. Jea et al. [81] proposed in earliest times, the algorithm for load balancing that balances the services by the number of sensor nodes.

Authors had considered multiple mobile elements for purposes of data collection. Yan et al. [82] developed a solution for energy-efficient AUV-assisted UWSN data collection strategy. A novel two-stage solution is suggested by the authors. In the first stage, sensors relay physical data at a short range data collector with multihop acoustic communication. The designated AUV regularly visit to recover data through high-speed visible light communication in the second stage. Su et al. [83] proposed a new coordination method for data gathering using AUV in sparsely distributed UWSN. Bölöni et al. [84] depicted the explanation and exploration of algorithms for scheduling data communication with an application-dependent value in UWSN. Authors have described that it is quite possible to explore more efficient scheduling strategies. These types of strategies allow the sensors to acoustically transfer the digests of sensed information so that the Value of Information (VoI) conveyed is maximized.

MacMohan and Plaku [85] considered the limited energy resources of an AUV in underwater communications. To manage this issue, they effectively plan a collision-free and dynamically attainable trajectory that empowers the AUV to achieve many targets while reducing the distance traveled and accrued penalty. The success of this technique is derived from combining sampling-based motion planning with PC-TSP solvers. Vasilescu et al. [86] presented a novel platform for UWSN to monitor long-term environment monitoring. Nodes' point-to-point communication using a high-speed optical system integrated with the TinyOS for broadcasting using an acoustic protocol. Favaro et al. [87] devised U-Fetch, having two levels coordinated access where head nodes retrieve data from neighbors nodes to send whole data toward mobile sink in bunches through a contention-free link.

Hybrid Data Collection: Chen et al. [88] presented node cooperation (NC) scheme for the surface node data collection efficiency increase, by using the fact that UW nodes can overhear the transmission by neighbors as compared to traditional automatic-repeat-request (ARQ) protocol. Ahmad et al. [89] proposed AUV-aided energy-efficient routing method (AEERP), where AUV follows the preidentified elliptical trajectory in every cycle. These sensors can be categorized into two types as gateway nodes and other member nodes. Gateways are only meant to communicate with AUV and are also selected based on nearness to AUV trajectory and residual energy levels. Han et al. [90] devised stratification-based data gathering (SDCS) for 3-D UWSNs where the network is divided into two layers based on the Ekman Drift Model to reduce consumption of energy. The Ekman layer (upper layer), faces great water speed and thereby follows the water flow. Whereas, at a lower layer, the speed of water current is less so nodes at this layer are assumed as relatively static. A neighbor density clustering-based AUV data collection technique is used at this layer for data gathering. By engaging various data gathering schemes at different layers, the benefits of AUV-aided data gathering and multihop transmission method get combined to reduce energy consumption and improve the network lifetime. Cheng and Li [91] presented the algorithm for data gathering through sensors (DGS) in which authors have depicted the way to identify the data importance level without domain knowledge so that only necessary data is forwarded. It reduces the latency of essential data. All the existing techniques for different data collection methods are discussed in Table V.

IV. Applications

UWSN comprises several modules, such as sensors and vehicles positioned in a precise aquatic region to accomplish collaborative tracking and data gathering applications [104]. Some of the applications areas of UWSN is broadly classified into three categories, such as monitoring, tracking, and actuating applications [105]. Here, the applications of IoUT are broadly categorized according to the application areas, as shown in Fig. 7.

1) *Water Quality Monitoring:* The existing habitats living below the water are highly conscious of water quality because it is the most significant factor affecting their life.
2) *Ocean Health Monitoring:* IoUT can be used for monitoring of natural habitat living under the water like fishes, etc. This particularly mentions the underwater network established for monitoring the marine lives and the attributes and properties to have a healthy life.
3) *Sports:* With the development of IoUT, the number of UWSN applications has increased such as sports. Much of the work focuses on the biomechanical investigation of swimming with the help of inertial sensors deployed under the water. Many modern uses of bearing inertial sensors (accelerometers, gyroscopes, and magnetometers) to evaluate swimming biomechanics [116].
4) *Oil Leakage Monitoring:* The spillage of oil origins harmful effects on marine life. UWSN can help to monitor the oil spill thickness in water, helpful in the cleaning process.
5) *Underwater Resources Exploration:* The concept of IoUT can be used to locate lost resources in water with the help of UWSN architecture. In addition, the exploration of natural resources, such as metals, minerals, and corals can be benefitted with help of IoUT. This application area includes various natural resources exploration so that the crust available below the water surface or some other existing resources can be explored [106].

TABLE V
SUMMARY OF DATA COLLECTION APPROACHES BASED ON EXISTING METHODS

Sr. No.	Reference	Method Used	Year	Proposed Scheme	Implemented Techniques	Advantages	Disadvantages
1	Nicolaou et al.	Multi-hop data collection scheme	2007	Hop-by-Hop Vector Based Forwarding (HH-VBF)	Forwarding path is guided by a vector from source to destination	Improvement over VBF.	Not easy to handle unevenly distributed networks.
2	Domingo and Prior	Multi-hop data collection scheme	2007	Clustering Approach	Sensor nodes forward data CH in a single hop manner. Then, CH employ multi-hop transmission technique.	Reduce the energy consumption for cluster members.	Uniform energy consumption at CH.
3	Hwang & Kim	Multi-hop data collection scheme	2008	Directional Flooding-based Routing protocol (DFR)	Packet flooding technique to increase the reliability.	More suitable when links are prone to packet loss.	Control and packet overhead increase.
4	Wang et al.	Multi-hop data collection scheme	2015	Energy-efficiency Grid Routing based on 3D Cubes (EGRC)	It shapes an energy consumption model taking residual energy and location of SN into account to select the optimal CH	Energy Efficient	Increases computational overhead.
5	Li et al.	Multi-hop data collection scheme	2016	DAD-Tx Dolphin-Aware Data Transmission in cognitive acoustic network	Probabilistic method captures the stochastic characteristics of dolphins' communications in communications.	Maximize the end-to-end throughput.	Limited performance in a dynamic scenario
6	Dhurandher et al.	Multi-hop data collection scheme	2011	Parabola-based Routing (PBR) algorithm.	The algorithm is adaptive, and transmits packets in hop-by-hop fashion	Energy optimization and efficient data delivery.	Time constraints neglected.
7	Xie et al.	Multi-hop data collection scheme	2006	Vector Based Forwarding (VBF) protocol	The forwarding path is guided by a vector from source to target, and very limited nodes are involved in routing.	Easily find path between source and target through virtual pipeline.	Energy unbalance problem. Not suitable for sparse network.

(Continued.)

TABLE V
(*Continued*.) SUMMARY OF DATA COLLECTION APPROACHES BASED ON EXISTING METHODS

Sr. No	Reference	Method Used		Proposed Scheme	Implemented Techniques	Advantages	Disadvantages
8	Lasheng et al.	Multi-hop data collection scheme	2013	Sub-tree Merging based Data Collection algorithm (SMDC)	Employs large number of sensor nodes for continuous sensing and data collection, on a target query area especially	Prevent unnecessary energy consumption. Worked well in dense network.	Not suitable for small networks.
9	Han et al.	AUV aided data collection scheme	2017	Probabilistic Neighborhood set-based Greedy Heuristic Algorithms (PNCS-GHA)	Design of Probabilistic Neighborhood set-based Greedy Heuristic Algorithms (PNCS-GHA) for 3D UWSNs is implemented	Reduce data latency	Highly dependent on network trajectory.
10	Bölöni, et al.	AUV aided data collection scheme	2013	Algorithm for scheduling the transmissions of data with a given, application-dependent value	Design scheduling strategies for the nodes to decide when and how much information to transmit to maximize it.	Locally estimated value of data digest provides data delivery with significantly higher value.	Works well for network following only predetermined path.
11	MacMohan and Plaku	AUV aided data collection scheme	2016	Combination of sampling-based motion planning and PC-TSP solvers.	Autonomous data collection where an underwater vehicle reaches at several target regions within a specified time limit.	Collision-free and dynamically feasible trajectories.	No support for multiple AUVs.
12	Basagni et al.	AUV aided data collection scheme	2014	Greedy and Adaptive AUV Path-finding heuristic for AUV to collect packets for maximizing VoI	Determine a collection path for the AUV so that the Value of Information (VoI) of the data delivered to the sink is maximized	Maximizes the value of data delivered to the sink.	Performance degrades in random topology.
13	Vasilescu, et al.	AUV aided data collection scheme	2005	Platform for underwater sensor networks to be used for long-term monitoring.	Nodes communicate point-to-point with TinyOS stack with the help of acoustic and optical communication.	Enable systematic recording of data.	Controlling the nodes mobility in the presence of water currents.
14	Chen & Lin	AUV aided data collection scheme	2012	Mobicast Protocol	3D geographic region 3-D ZOR near all AUV under the water is formed.	Avoid the low efficiency Reduce energy consumption.	Works well only in 3D UWSNs.

(Continued.)

TABLE V
(*Continued*.) SUMMARY OF DATA COLLECTION APPROACHES BASED ON EXISTING METHODS

Sr. No.	Reference	Method Used	Year	Proposed Scheme	Implemented Techniques	Advantages	Disadvantages
15	Favaro et al	AUV aided data collection scheme	2013	U-Fetch named scheme based on two levels of coordinated access	Some cluster head nodes retrieve data locally, and send this data to the mobile sink in sets via contention-free link.	Delay is less.	Coverage is limited
16	Han et al.	AUV aided data collection scheme	2019	Prediction-based Delay Optimization Data Collection algorithm (PDO-DC)	The AUV can obtain all cluster data by traversing less cluster head nodes	Efficiently reduces energy consumption.	Fits well in large networks.
17	Signori et al.	AUV aided data collection scheme	2019	UW-POLLING	Robotic Vessels as-a-Service (RoboVaaS) project to provide innovative services for shipping activities.	Improved Network Throughput	Costly due to additional hardware
18	Yoon et al.	AUV aided data collection scheme	2012	AUV-aided Underwater Routing Protocol (AURP)	Uses AUV as a relay to collect data packets from gateway to sink	Balances energy consumption of the network	Because of long delays, not suitable in real time environment
19	Khan & Cho	AUV aided data collection scheme	2014	AUV- Path Node (AUVPN)	AUV is used to visit some identified locations for aggregating data in cluster-based network	Reduces overall transmission power of sensors. Improves lifetime of network.	Protocol overhead is more than conventional AUV-based scheme
20	Hollinger et al.	AUV aided data collection scheme	2012	Communication Constrained Data Collection Problem (CC-DCP)	AUV path planning methods that extend algorithms for variants of the Traveling Salesperson Problem (TSP).	Minimizing travel time and maximize information gathered.	Limitations on cooperation between the sensor nodes.
21	Bhadauria et al.	AUV aided data collection scheme	2011	Data Gathering Problem (DGP)	Path planning problem that arises in scenarios in which robots act as data mules to download data from stationary wireless devices	Optimal and improvement for sparse networks	Works well for predetermined path and routes

(Continued.)

TABLE V
(*Continued.*) SUMMARY OF DATA COLLECTION APPROACHES BASED ON EXISTING METHODS

Sr. No.	Reference	Method Used	Year	Proposed Scheme	Implemented Techniques	Advantages	Disadvantages
22	Su et al.	AUV aided data collection scheme	2013	Coordination scheme for data collection by using AUV in sparsely distributed UWSN.	AUV and sensor nodes adopt different cycle periods without time synchronization.	Low energy consumption during communication under the harsh underwater environment.	Performance degrades at higher levels.
23	Chang and Shih	AUV aided data collection scheme	2015	Tour-planning algorithm is proposed for data gathering in Underwater Acoustic Sensor Networks	Proposed data collection using a docking station to deal with the limited power of the AUV.	Minimize the length of routes and the overall time of the AUVs	Faces the limitations imposed by acoustic communications.
24	Faigl and Hollinger	AUV aided data collection scheme	2017	SOM-based algorithm for data collection	Variant of the TSP with Self-Organizing Map(SOM) using a multi-goal path planning framework	Optimal results comparative to other existing approaches and lower computational requirements	Does not fit well for single goal location.
25	Yan et al.	AUV aided data collection scheme	2018	Energy-efficient data collection Problem for UCPS.	Rigid graph-based topology optimization scheme is projected to reduce the sum of all weights	Topology optimization scheme can enhance the lifetime of network.	No cooperation control of multiple AUVs.
26	Han et al.	AUV aided data collection scheme	2019	High-availability data gathering method based on multiple AUV (HAMA)	Multi-AUVs move in the network and collects data from nearby trajectory nodes.	Guarantee the high availability of the data collection service.	Computational overhead.
27	Zhuo et al.	AUV aided data collection scheme	2020	AUV-aided Energy-Efficient Data Collection (AEEDCO)	cluster-based network is constructed, and selection of cluster heads is made based on maximal clique problem (MCP)	Perform well for large scale networks and longtime monitoring	Consider fixed AUV speed throughout the network
28	Han et al.	Hybrid data collection scheme	2018	Stratification-based data collection scheme (SDCS) for 3D UASNs	The network is divided into two layers based on the Ekman Drift Current Model.	Reduce energy consumption of nodes and improve network lifetime.	Comparatively high data gathering delay.

(Continued.)

TABLE V
(*Continued.*) SUMMARY OF DATA COLLECTION APPROACHES BASED ON EXISTING METHODS

Sr. No.	Reference	Method Used	Year	Proposed Scheme	Implemented Techniques	Advantages	Disadvantages
29	Ahmad et al.	Hybrid data collection scheme	2013	AUV aided Energy Efficient Routing (AEERP)	It traverses a predetermined elliptical trajectory.	Balances energy consumption increasing network lifetime	Not efficient for a dense network
30	Cheng and Li	Hybrid data collection scheme	2017	Data Gathering algorithm for Sensors (DGS)	How to identify the importance level of data without domain knowledge	Reduce the latency of important data	High energy consumption
31	Jea et al.	Hybrid data collection scheme	2005	Multiple mobile elements for purposes of data collection	Presented load balancing algorithm which balance the number of sensor nodes services	Improved Scalability	Increased latency
32	Chen, et al.	Hybrid data collection scheme	2016	Proposed Node Cperation (NC) to increase the data collection efficiency for the surface node	Several different data collection path to show data collection efficiency for a specific node cooperative underwater acoustic network	Optimal path are find out	Faces the limitations and constraints of UWSN.
33	Banaeizadeh, & Haghighat	Hybrid data collection scheme	2020	Energy Efficient Data Gathering Scheme (EEDG)	Three step solution by dividing nodes into small groups, then data is send to forwarder nodes and after that graph structure is used	Energy consumption and delays are less	Selection of forwarder node is critical.
34	Júnior et al.	Hybrid data collection scheme	2020	Data Collection Algorithm for underwater oPTical-AcoustIc sensor Networks (CAPTAIN)	It uses the concept of clustering and constructs a routing tree from the sink node along with data aggregation techniques	Energy consumption is low.	Average latency is little high

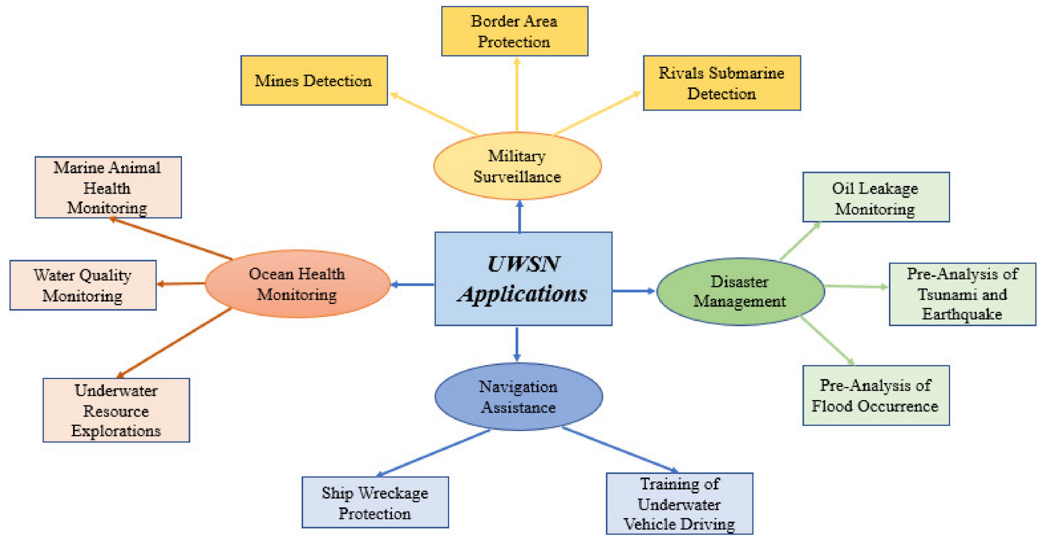

Fig. 7. Classification of UWSN application areas.

6) *Preanalysis of Earthquake or Tsunami:* Natural disaster can come at any time and place, so same is the case with the aqua environment. These disaster recovery or prevention is one of the crucial applications of IoUT. UWSN can be deployed to generate early warnings for these natural emergencies of earthquake and tsunami.
7) *Preanalysis of Flood Occurrence:* It may happen instantly and frequently also. As there is no particular method from which it can be reduced hence only the early detection or alerts for the floods is the ultimate solution to safeguard many lives, including marine life [98].
8) *Mines Detection:* There is a requirement to localize or find out the hidden mines under the water to utilize the natural resources like oil mines, which are precious natural resources that can be found deep under the water [107].
9) *Rivals Submarine Detection:* IoUT with the help of UWSN can be used to position or localization and further target submarines by using acoustic signals for communication. This leads to protection from attacks that can occur on the submarine in the water [4].
10) *Border Area Protection:* In naval force surveillance, there exist large applications of UWSN where human deployment reduction will be the benefit during detection and avoidance of enemy attack for the protection of border areas [108].
11) *Ship Wreckage Protection*: Due to underwater conditions like erosion or rust, metal fustigation limits ships' lifetime nearly up to 30 years [109]. Hence, the parts of the body of ships can be reiterated or used as raw material called ship wrecking or ship recycling. Navigation from such an area can be identified by using UWSN [110].

V. Performance Evaluation

Specific data collection algorithms are compared based on their performance, which comes under the three classifications as multihop, AUV assisted, and hybrid data collection. Although there exist numerous qualities of service parameters to analyze the protocol but related to the data collection algorithm comparison, authors have taken three main parameters, such as energy consumption, PDR, and network lifetime.

Average Energy Consumption (AEC): AEC is calculated as the total energy consumed (E_{total}) for a node while forwarding data packets (P_{sent}) once in each round

$$\text{AEC} = \frac{E_{\text{total}}}{P_{\text{sent}}}. \tag{15}$$

PDR: PDR is denoted as the ratio of data packets effectively received (P_{rec}) by the sink/receiver node to the packets actually sent (P_{sent}) by all nodes deployed in the designated region

$$\text{PDR} = \frac{P_{\text{rec}}}{P_{\text{sent}}}. \tag{16}$$

Network Lifetime: Network lifetime is the elapsed time till the first node dies in the deployed network. Also, lesser the energy consumption per transmission implies more of the network lifetime

$$\text{NL} = \frac{1}{\text{AEC}}. \tag{17}$$

The different existing data collection protocols are executed on the network simulator NS-2.30 all-in-one due to its real-time results, freeware, and open-source properties. Simulation is conducted for every protocol in multiple runs, and the average is taken for comparison. The simulation parameters considered are according to 3-D architectural environment of UWSN, and some of the other simulation parameters considered are also concise in Table VI.

A. Case I

In a multihop scenario, data collection techniques are compared w.r.t. QoS parameters as energy consumption and packet delivery ratio.

The energy consumption is compared in multihop data collection techniques, such as VBF [71], HH-VBF [72], and PBR [94]. The total energy consumed in

TABLE VI
SIMULATION PARAMETERS

Parameters	Value
Number of Nodes	100-500
Area Size	1500 m × 1500 m × 1500 m
Node Initial Energy	1000 J
Packet Size	1024 bits
Speed of AUV	3 m/s
Antenna	Omni Antenna
Simulation Time	500 sec
Traffic Source	Constant Bit Rate
Traffic Rate	50kbps
Propagation	Two Ray Ground
Transmission Power	2.0 Watts
Receiving Power	0.75 Watts

the network was significantly less than 36% in the case of HH-VBF than VBF and PBR, as in HH-VBF more suitable paths can be found as the number of nodes increased from 100 to 500, hence less energy is consumed for communication between nodes as shown in Fig. 8.

The PDR ratio is compared in different multihop data collection techniques, such as VBF, HH-VBF, and DUCS [92]. When the number of nodes is 100, packet can be lost due to distant positioning of the number of node so PDR is less but when the number of nodes increased to 400 or 500, the PDR is also enhanced in HH-VBF as with the improving node density, nodes falling in its routing pipe also increases with a fixed transmission range radius. Ultimately, more nodes got qualified for packet forwarding leads to a rise in PDR as shown in Fig. 9. In a network, when the density of nodes increases. It is good to note that the PDR increases continuously with increased nodes because more the intermediate nodes, less the packet drop, and more the delivery ratio. The PDR is 35% higher in HH-VBF compared to VBF and 30 % higher in DUCS. HH-VBF also considers traffic density factor, so its performance is far better. It will expressively enhance the robustness for packet delivery in sparse networks by improving the data delivery ratio.

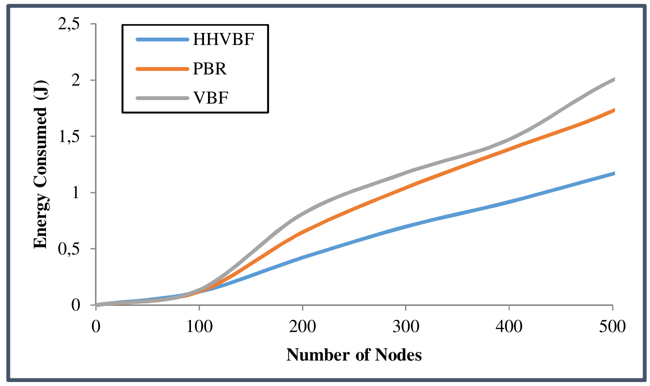

Fig. 8. Energy consumption versus number of nodes.

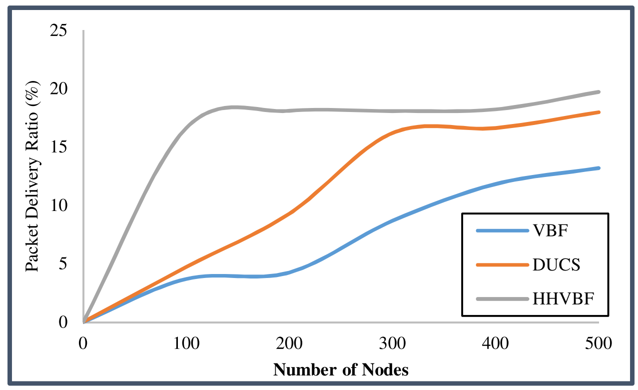

Fig. 9. PDR versus number of nodes.

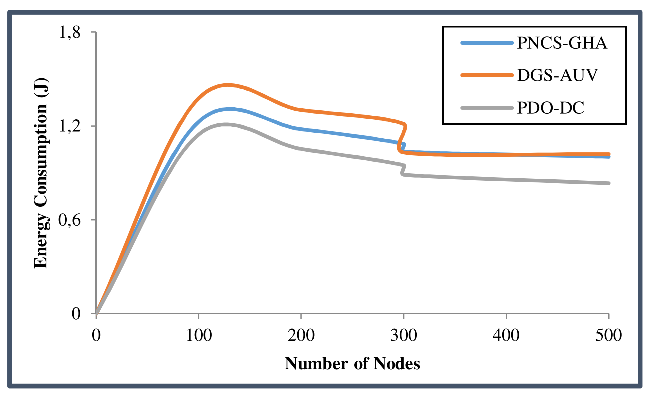

Fig. 10. Energy consumption versus number of nodes.

B. Case II

In an AUV-assisted scenario, data collection techniques are compared w.r.t. QoS parameters as energy consumption and packet delivery ratio.

Now, the energy consumption is compared between PNCS-GHA [75], DGS-AUV [111], and PDO-DC [96] in AUV-aided data collection algorithms as plotted in Fig. 10. The unit energy consumption falls with the growing number of sensor nodes from 100 to 500.

In the PDO-DC algorithm, the sleep scheduling algorithm is introduced; hence nodes need not to continuously sense for data forwarding. Nodes only consumes energy while getting into awake condition and need to transfer the data to nearby node or AUVs. Hence less energy is consumed, i.e., 18% less from DGS-AUV and 12% less from PNCS-GHA.

The PDR is compared between DGS-AUV, PNCS-GHA, and SEDG [112]. Here, the PDR ratio in PNCS-GHA is comparatively 6% higher than the DGS-AUV and 31% SEDG as analyzed from Fig. 11.

As in PNCS-GHA, when the number of nodes increased, such as 400 or 500, the AUV is engaged to move according to the defined path for data collection from probabilistic neighborhoods as a large number of nodes are present in the path with increased number of nodes. The collected data is forwarded to the target.

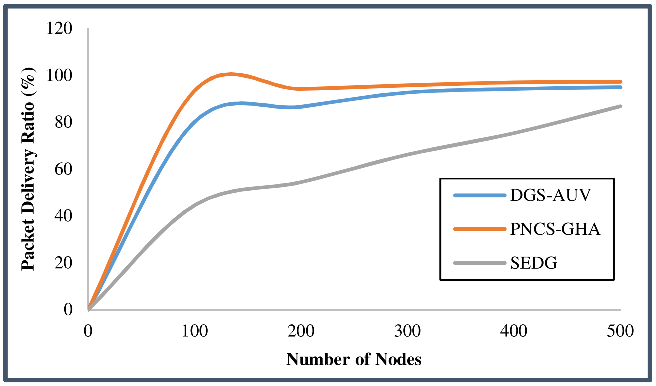

Fig. 11. PDR versus number of nodes.

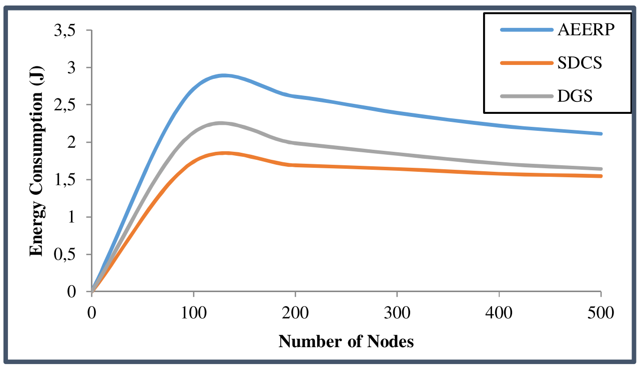

Fig. 12. Energy consumption versus number of nodes.

C. Case III

In a hybrid scenario, data collection techniques are compared w.r.t. QoS parameters.

The energy consumption, PDR, and network lifetime are compared between AEERP [89], SDCS [90], and DGS [91], the hybrid approaches as depicted in Fig. 12.

Here, it is visible from the graph that the unit energy consumption varies rapidly with an increasing number of nodes. Graph results also verify that the energy consumed in the SDCS algorithm is 13% less than DGS, whereas it is 31% lesser than the AEERP scheme. When the number of nodes increased from 100 to 500, node density increase which in turn decreases the average communication distance between the nodes. When we have the number of nodes to 500 then node density is maximum and the parallel nodes provide data to the nearby sink nodes only, and maximum nodes can remain in the sleep stage for a long duration.

The PDR ratio is also compared between AEERP, DGS, and SDCS. As clear from Fig. 13 that PDR is increasing with the increase in the number of nodes. Typically, when the number of nodes is 500, i.e., dense network, the higher the packet forwarding rate will be. The performance comparison shown in graph depicts that SDCS performs 22% better than AEERP and 9% better than DGS. It is due to the fact that in SDCS, weight judgment practice is performed at every hop for analyzing forwarding probability of data packets. Also, it is noticeable that the PDR increases continuously with the rise in the number of nodes because more the intermediate sensor nodes, less the packet drop, and more the delivery ratio.

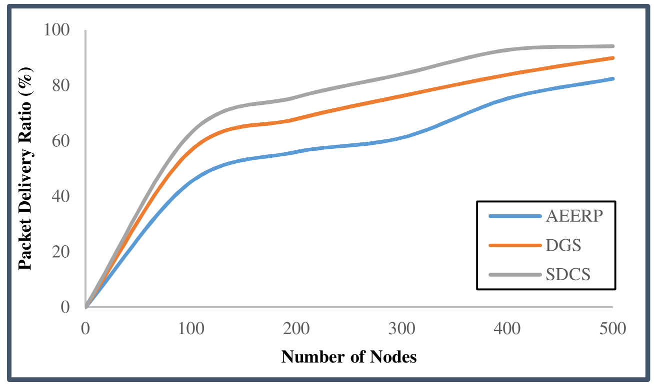

Fig. 13. PDR versus number of nodes.

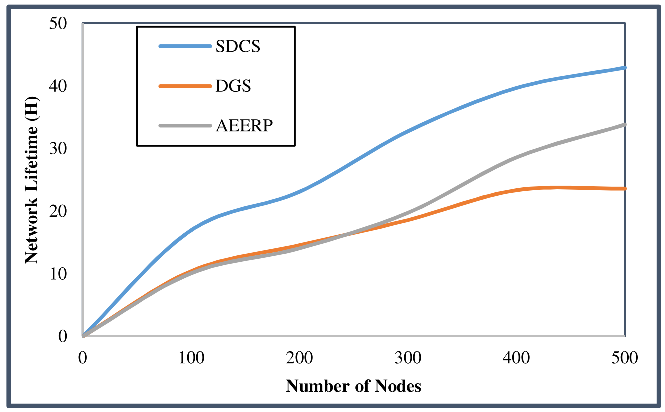

Fig. 14. Network lifetime versus number of nodes.

The network lifetime is compared between SDCS, DGS, and AEERP as depicted in Fig. 14. The lifetime period of SDCS is 40% higher than the DGS algorithm and 34% higher than the AEERP method, and it is increasing as the number of nodes is increasing. This is because, in the SDCS algorithm, the sleep wake-up system is used to reduce the load on nodes, hence when the number of nodes are 500, i.e., maximum, only nodes which are part of communication are awake which reduces the energy consumption and improves the network lifetime. Every node may enter into the sleep mode and get activated again in the next round when it has data packages to forward. So it enhances the overall lifetime period of the network.

VI. Future Challenges and Learning Outcomes

The IoUT has an impact on a wide range of sizes, from a tiny scientific instrument to a medium-sized seaport to worldwide oceanic traffic. IoUT's network architecture is inherently heterogeneous, and it must be durable enough to operate in severe settings. Some possible future directions are listed as follows.

1) *Competing Communication:* There is need for exploration of more adequate communication channel in harsh aquatic conditions. Along with this combined networking scenarios, i.e., optical and MI together as the acoustic channel, can achieve higher flexibility in bandwidth with higher data rates and reduced power.
2) *Handling of Voluminous and Real-Time Data:* There are some critical applications such as natural, oil spills,

and territory surveillance from enemy that requires real-time support via an early warning. Also there are many oceanic applications that produces or consumes large amount of data, for that integration of UWSNs and big data is one of the recent trends. But in UWSNs, big data processing faces many challenges like real-time analytics, hardware limitations, and visualization that are major research issues.

3) *Coherent Node Arrangements:* Deployments of large underwater networks helps fast and unfailing delivery of data. So, networking solutions needs to be find out that work for efficient and reliable underwater data collection.
4) *AUV Focused Path Planning:* Dynamic path planning for AUV-assisted localization techniques is still required so that, AUV can dynamically adjust its path for providing enough information to unvisited nodes so that node deployment and data collection can be done easily from those nodes.
5) *Pragmatic Architecture:* A more realistic model having insights regarding the design of 3-D UWSN should take into account the mobility of sensor nodes under harsh and critical underwater conditions.
6) *Scrimping Deployments:* Ever since underwater sensors are expensive in terms of cost, so the deployment algorithms for mobile anchor nodes should be proposed and investigated for reducing costs in deep water scenarios as well.
7) *Explicit Localization of Nodes:* For efficient and accurate localization, location information of sensors is required in many processes, such as routing, data collection, fault tolerance, etc. This field requires more productive and effective research.

The learning outcome through this study is that this manuscript offers insights into and depths of UWSN, which is a vast field in and of itself. This study offers a solid foundation for UWSN node deployment and node deployment field. There are well-known terrestrial technologies, which function well in the IoT, typically are inadequate for underwater applications, has been one of the critical problems preventing further developments in the IoUT domain. A lot of research has been done in UWSN and more is to be done in the upcoming years, driven by a wealth of theoretical and practical challenges. The continuously developing the underwater communication technology will have a great impact on the fish industry, oil industry and other transportation system as well as provide impact in the environment.

VII. Conclusion

The sagacity of underwater data collection could not be possible before the emergence of WSN and accomplished through expensive as well as tough wired networks deployment. UWSN provided those enabling technologies for radical change in various real-time underwater monitoring and surveillance applications. UWSN is that a small or large network that consist of a number of sensor nodes to perform various activities of sensing or controlling underwater activities. IoUT is a new class of IoT and is defined as a network of interconnected intelligent underwater objects. IoUT expected enables various practical applications, such as environmental monitoring, underwater research, and disaster prevention. Among these applications, IoUT is recognized as a technical capability. Underwater wireless sensor to support IoUT concept for smart city development networks became an efficient communications network. Underwater sensors can also be installed in AUVs installed underwater to monitor and research underwater minerals.

The ultimate goal of this article is to encourage research fellowship to lay the foundations for the development of advanced node distribution schemes and data collection techniques with efficient underwater communication. It will ultimately help for effective networking for enhanced monitoring and ocean exploration applications. In this survey article, authors have summarized several fundamental and critical aspects of UWSN. As data collection is used in almost every practical application of UWSN, it needs significant attention. Hence, the focus of research is data collection in UWSN that starts with node deployment, which is of three different types, i.e., self-adjusting, static, and movement assisted. For collecting reliable and purposeful data, sensor nodes need to be deployed effectively and then collect data efficiently and promptly. In this, data collection methods are divided and represented into mainly three type's multihop, AUV aided, and hybrid methods. State-of-the-art about data collection in UWSN along with node deployment techniques and algorithms is also analyzed. This manuscript might serve as a resource for future work on UWSN node deployment, data collection and for the IoUT.

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