Underwater Wireless Sensor Networks: A Review

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Abstract: Several disciplines like science, engineering, and biological industry have been influenced by sensor networks which have brought sensing and computation into reality. The possibility of having these sensors physically assigned close to the target whose parameters are to be observed enables remote monitoring of various aspects of the physical world. Wireless channeling of information beneath the ocean or generally underwater has provided the best technological ways of oceanic observations. Ocean bottoms have been monitored traditionally by deploying oceanographic sensors that obtain information at distinct and fixed ocean zones. The oceanographic instruments are then recovered when the tasks are completed. This implies that data cannot be monitored remotely since there is no collaborative communication of obtained data between the collection point and the monitoring end. The data recorded can also be destroyed in case of a non-successful mission. Oceanic observations have been made primarily possible by sensor networks carefully laid out under the waters. Underwater sensor networks can also be achieved wirelessly by establishing communications between sensors and monitors without major cabling. These are known as Underwater Wireless Sensor Networks (UWSNs). The UWSNs are comprised of various gadgets like vehicles that can operate autonomously under the water and sensors. Deployment of these gadgets is done in targeted acoustic zones for the collection of data and monitoring tasks. Bilateral communication is established between stations based on the ground and different UWSNs nodes. This enables instantaneous remote monitoring and communication of information from the specified oceanic zones to engineering personnel based on the shores. This paper looks at the various aspects of Underwater Wireless Sensor Networks UWSNs including their importance, applications, network architecture, requirements, and challenges and in their deployments.

1 INTRODUCTION AND MOTIVATIONS

Emerging technologies around vehicles that are autonomous and sensor deployment capabilities have motivated the scheme of networking of sensors under the water. Although this comes with communication problems, technology on acoustics can be manipulated to turn the scheme into practicality. For short-range links, techniques of communication that are interdependent have been advanced(Amoli, 2016). These techniques include radio frequency, optical, and communications that are electrostatic. These are utilized for ranges between 1m to 10m to exploit the high bandwidths involved. Large and highly powered antennas are required for such high bandwidth signals because of their high attenuation tendencies. Longer ranges of communication are affected mainly by sounds of low speed, propagation of diverse paths that vary in time, and bandwidths that are limited and depend on distance. Propagation through diverse paths varying in time coupled with the fact that sounds have low speeds plus bandwidths that are limited and dependent on distance brings ramifications of substandard quality and high throughput(Felemban et al., 2015; Lloret, 2013).

With advances in microelectromechanical devices, sensors can be miniaturized with low power consumption, thus increasing the capabilities of processing and operation in different underwater scenarios. Integration of internet protocols with UWSNs architectures can support M2M and IoT structures for up-to-date monitoring of underwater events. The USWNs nodes have also been found to be widely compatible with a variety of sectors. However, the demands and conditions of UWSNs that include accessibility, environmental friendliness, endurance, privacy, and complexity make the acoustic networks of UWSNs distinctive and difficult to apply practically for developers. Mo-

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tivations for UWSNs include (Felemban et al., 2015; Chandrasekhar et al., 2006):

- The architecture is self-diagnosing since interactive anomalies can be sensed and corrected during the acquisition of data(Lloret, 2013).
- Allows analyzing the data during data acquisition; therefore, adjustments can be made on sensors inputs and outputs for desired observations(Felemban et al., 2015; Amoli, 2016).
- Contrary to cables deployed underwater, UWSNs offer a distributed structure that allows for application to various frameworks. This makes the UWSNs architectures appreciably flexible for the provision of support in underwater surroundings(Chandrasekhar et al., 2006).
- The cost of deployment is low compared to cabled sensor networks(Felemban et al., 2015).

UWSNs importance is widely seen in applications that are swiftly gathering favor in the enablement of progress around the disciplines of oceanic observations and monitoring systems. Further, UWSNs has gained ground in surveillance of deep seas, earthquake and tsunami monitoring and forecasting, aquatic animal's activities and plants tracking, reconnaissance and surveillance by the military, extraction of gas and oil, monitoring of leaking and spillage of oils, detection of mines and also in fisheries(Felemban et al., 2015; Amoli, 2016; Chandrasekhar et al., 2006). These applications can be classified in terms of monitoring aspects, military aspects, navigation, and forecasting of disaster occurrences and their management. These classes of application can then be classified into respective subclasses(Lloret, 2013). Monitoring underwater activities involves deploying sensors networked to track the surrounding environment related to its properties and features of interest. Here, the tangible and substantial environment is monitored. This monitoring approach of classification can also be subdivided into monitoring the quality of water, aquatic life monitoring, and sub-water exploration monitoring. The quality of water is monitored with regard to the well-being of aquatic life such as fish and other living things above the water. Monitoring of underwater environment can range from applications to large oceans to canals. The farming of fish is considered one of the best sources of economic growth(Felemban et al., 2015; Amoli, 2016; Chandrasekhar et al., 2006). Thus there is a need for uncompromising monitoring of the fish habitats for a near-perfect living condition. Deployment of sensors has been accomplished to monitor the environmental conditions of individual fish species to create a conducive environment for fish farming. In (Felemban et al., 2015; Lloret, 2013), UWSNs have been utilized to assess the quantity of food that has not been eaten and the capital waste on the farm(Felemban et al., 2015). The design has been deployed for testing in fish farming of marine flora and fauna. A group of wireless network of sensors was used for precise analytical monitoring of farm water pollution. Applications have also been developed for trout farming to keep track of water quality in the pools. The chemical composition of the water is monitored for a given period, and an algorithm is deployed to show the input-output information for a given number of pools(Felemban et al., 2015; Amoli, 2016; Chandrasekhar et al., 2006).

The algorithm is used to provide alerts in case the measured conditions surpass the set threshold. These conditions include conductivity of electricity, oxygen, and ammonium nitrogen levels. Autonomous vehicles can also be integrated with sensors to collect samples of water from reservoirs of drinking water. The processed information is then transmitted to a location remotely(Lloret, 2013; Felemban et al., 2015). UWSNs can also be applied in monitoring river pH composition by utilizing sensor nodes. These nodes are made to process the collected data. A comparison is then made between the threshold parameter values and the collected data. Wireless modules are then utilized to transmit the processed information to a remotely located station. Other parameters that can be monitored in water include temperature, oxygen dissolved, and pollution(Amoli, 2016). Temperature sensors are deployed under the water, and the values are communicated wirelessly and then displayed in tabular and graphical presentations. The visualization of the collected information from under the water can be through web applications or cellular platforms. Mostly, floating nodes with GPRS convey the underwater information to a remotely located station. Sensors can be deployed under the water to monitor pollutants such as wreckages and spillages to monitor water pollution(Chandrasekhar et al., 2006; Felemban et al., 2015). Monitoring of water habitats includes applying UWSNs to monitor the coral reefs or any other plants under the water and monitoring the activities of marine animals/organisms(Lloret, 2013; Chandrasekhar et al., 2006).

UWSNs can be applied to monitoring marine activities by monitoring the surrounding environment of the marine organisms through acoustic device networks. To transmit the marine environmental conditions, information from one sensor to another can be accomplished by utilizing TDMA protocols. The obtained data can then be used to develop ecosystem models capable of predicting changes in the underwater environment and changes in climate conditions(Almutairi and Mahfoudh, 2017; Felemban et al., 2015). Currently, deployment of such a system has been accomplished in Queensland, Australia, with sensing capabilities, wireless conveyance of information to a ground remotely located station, visualization of measured data, and an alert system in case of anomalies have been deployed. In this scheme, a rough and ready system that uses a cluster or a topology of stars for direct transmission of information to a buoyant gateway has been used. Data is then transmitted remotely to a control station from the gateway. Seashells are also monitored as part of marine habitat in China, such as Zhejiang province(Almutairi and Mahfoudh, 2017). UWSNs have an application in monitoring seismic activities such as oil extraction from fields under the water(Aldosari et al., 2020). Fluctuation of the oil reservoir is studied over time in a 4-D model for evaluation of the performance of the oil fields and application of ad hoc interventions. Traditionally, onshore fields are continuously monitored through daily, quarterly, or annual surveillance through permanent instruments(Aldosari et al., 2020; Almutairi and Mahfoudh, 2017). Conversely, submerged oil fields are more demanding because the deployment of sensors is not presently permanent in the oil fields underwater. Therefore, monitoring of tectonic fields is accomplished using ships. The ships are fixed with an array of sonar as sensors and actuators made of air cannons(Aldosari et al., 2020; Almutairi and Mahfoudh, 2017). Evaluating such submerged oil fields is highly costly and can only be applied to submerged fields less frequently. Multiple channels of tectonic data are collected using individual sensors. A single sensor is designed to collect 24 bits per channel at a frequency of 500 Hertz. Data is captured when an event of seismic nature occurs, consequently giving 60-kilo bytes of features of data for every sensor used in a tectonic event. The data rate of 5-kilo bytes per second is involved for 120s per sensor to transmit the information for a single hop. For oil fields that cover the typical zones of 8km by 8km, sensors are deployed approximately at a 50m grid(Aldosari et al., 2020), implying that a highly larger number of sensors are utilized to provide total coverage. A layered communication channel is also implied because some nodes of sensors are connected through communication media that are non-acoustic. Buoys augmented with high-speed Radiofrequency capabilities are utilized for the wireless transmission of data. Supernodes can also be implemented for a five-by-five network segment. All sensors are in the vicinity of two jumps around a supernode, and retrieval of all information can be accomplished within an hour(Aldosari et al., 2020; Almutairi and Mahfoudh, 2017).

Application of UWSNs in exploration involves inspection and survey of a substantial amount of submerged minerals(Almutairi and Mahfoudh, 2017; Aldosari et al., 2020). The exploration under the water can further be classified into exploring innate resources and monitoring of pipelines and cables for gas and oil exploration under the water. UWSNs have been developed in (Felemban et al., 2015) for the location and investigation of cast iron crust(Almutairi and Mahfoudh, 2017). An autonomous underwater vehicle that is operated remotely has been utilized onsite to explore the crust minerals attaining a depth of 3000 meters under the ocean surface. The vehicle is augmented with a system that can do mapping of the ocean bed. Therefore, it is an emerging technology to combine an acoustic network of sensors and remotely operated underwater vehicles to excavate minerals buried deep into the ocean beds(Almutairi and Mahfoudh, 2017; Aldosari et al., 2020).

Underwater sensor systems can be utilized in the detection of various facets of applications in military aspects. Here, AUVs are equipped with sonars for imaging, detectors for metals, and cameras for missions in detecting submerged ocean mines(Almutairi and Mahfoudh, 2017; Felemban et al., 2015). This setup is also used for port securities(Aldosari et al., 2020; Lloret, 2013). Submarines are usually augmented with several underwater architectures of sensors to aid in surveillance and monitoring. Detecting submerged mines ensures that military ships execute risk-free voyages(Khan et al., 2021; Aldosari et al., 2020; Chandrasekhar et al., 2006). Since the mines are composed of unique materials that are ferrous, they can be separated from clutter under the ocean since these clutters are usually nonmetallic. The application of UWSNs in surveillance encompasses detection of foreign intrusion in demarcated international water spaces such as warships from a defined enemy. The UWSNs not only assist in detection and surveillance but can also be utilized for navigation purposes. Since the underwater topology is exceedingly uneven, arbitrary, untraversed, and exponentially increasing in depth, UWSNs come in handy in navigation. This provision of navigation capability can be extended to civilian ships, boats, and even fishing vessels. Because of the different transmission mediums involved, the navigation devices used on land cannot be used under the sea or ocean, further cementing the importance of a setup of an underwater network of sensors(Khan et al., 2021; Almutairi and Mahfoudh, 2017).

2 UNDERWATER WIRELESS SENSOR NETWORKS ARCHITECTURES

Generally, the performance of acoustic networks is dependent on the design of the topology. Effective topology increases the reliability of the network of the sensors and vice versa. Additionally, energy is conserved in an efficient topology of underwater acoustic sensors. Therefore, an optimized network model of UWSNs must be adopted depending on the area of deployment(Alharbi et al., 2015). Different methods of classifying UWSNs include classification according to the mobility of the nodes, i.e., half-static, fully static, and dynamic models, and classification according to node depth, i.e., 2D model and 3D model structures(He et al., 2018; Alsulami et al., 2020b). Since attenuation is experienced underwater during radio frequencies, communication between UWSNs must be accomplished using acoustic mode. The acoustic linking has been optimized over the years to mitigate challenges such as delays that are longer, high disparities, and sensing abilities that are unstable(Alharbi et al., 2014; Alsulami et al., 2019). Therefore, the development of efficient topology of sensor networks has been influenced by motivating factors such as difficulties presented by compounded underwater surroundings and the need for sensing in marine monitoring applications. In the process of development for the progress of the 2D model environment to 3D structures evolution, a myriad of UWSNs were designed with regard to different applications after proper optimization techniques have been utilized to improve the performance of the topology configuration. Hence, formally and generally, it is not wrong to classify the topologies into 2D, 3D, 4D, and UWSNs based on vehicles operating autonomously underwater(He et al., 2018).

2.1 2D Network Models

In an ordinary 2D topology, the nodes of the sensors, which have a smaller size due to unique underwater surroundings, are set upon the ocean bed. The 2D structure models can be classified into isomorphic and heterogeneous topologies. Initially, marine investigations are directed towards the coastal areas. For these observations of marine interests, sensors of similar functionalities are placed on the ocean bed or seabed to extract data and detection functionalities. Sinks on the surface can be utilized for the acquisition of information from nodes under the water. This is made possible by an acoustic channel link. Sinks under the water acquire information from deep-sea sensors and relay it to ground-based control stations. Therefore, it is necessary to provide sinks under the water and transceivers that are acoustic. These transceivers should be vertical and horizontal. The horizontal transceivers have the purpose of communicating with nodes regarding data collection or command provision as they are being received from the control station offshore. The data is sent to the control station on land using the transceivers that are vertical. The vertical transmitter receivers must be of sufficient range since the ocean depths are large. The sinks placed on the surface are supplied with RF transmitters of a wide range and also acoustic transmitter-receivers for the management of communications that are parallel by design. Models that allow for the application of two-dimensional detection at ocean beds with similar detection capabilities in every sensor placed for detection are known as isomorphic models, as shown in figure 1 (He et al., 2018). In the isomorphic model, data is sent to the

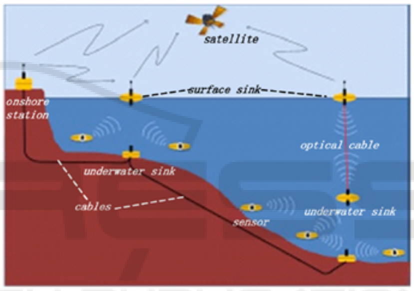

Figure 1: A 2D architecture of isomorphic model.

sinks from the sensors. From the sinks, the information is then relayed to the control station located on land. The isomorphic structure is best applied for detection in shallow areas because of communication limitations in sensor distances(Alhumyani et al., 2015; He et al., 2018). To improve model performance for marine areas far from the coastal lines, cable tethering is utilized to connect sinks placed at the surface and sinks placed under the water. This setup brings about convenience and improves communication reliability under the water. Tethering also guarantees the exchange of information in a reliable fashion between sensors with a simple, convenient deployment(He et al., 2018). However, the model is suitable only for comparatively stable networks. This is only possible using routing structures that do not demand time to time rationalization for Shallow Ocean water surrounding.

Additionally, the model is optimized for localized monitoring of the environment and cannot perform well for spaces of large expanse. It is therefore ineffective in areas deemed as deep regions of ocean or sea. For the sinks under the water, the collected information by the sensors is often relayed by utilizing multi-jump routing. In this model, there are sensors close to the sinks that are submerged under the water(Khan et al., 2021). These sensors are designed to transmit the collected information and also function as communication nodes during heavy loads. Due to the homogeneous capacity of isomorphic model sensors, there is a high-energy consumption by the nodes and thus a high failure rate. The intersymbol interference phenomenon is also likely to occur due to several sensors sending data at similar times(Felemban et al., 2015; He et al., 2018). It is inconvenient to deploy sinks in some regions. Therefore sensors located at the bottom of the sea are constrained to relay information to the sinks at the surface by utilizing audial communications. This results in high energy demand by the nodes(He et al., 2018). To solve the above problems and challenges, a heterogeneous model can be utilized for such regions. The heterogonous model incorporates aquatic sensing and a gateway configuration of center nodes known as hub sensor nodes. In addition to monitoring the ocean bed, the gateway is also utilized to transmit the collected information to the sinks at the surface. The gateway has acoustic transmitter-receiver modules, namely, horizontal and vertical structures. The horizontal configuration enables interaction among the nodes in a cluster. It releases directive information on configuration, and at the same time, it collects the data sensed(Khan et al., 2021; Aldosari et al., 2020). The data is sent to the control station on land using the transceivers that are vertical. Therefore, this model solves the issue of rapid consumption of energy in the sensor nodes for such a configuration. The configuration also relieves the cost of deploying wired cables and therefore utilizes the flexible wireless transmission of data. It is essential to consider the gateway number and the position of the aquatic clusters when constructing this model. Additionally, there is a resultant interference and decrease in transmission of standard packets due to the execution of a horizontal collection of information and vertical forwarding of data at similar times(He et al., 2018).

2.1.1 Mechanisms of Configuration in 2D Models

The network configuration is perceived here as the placement of sensors under the sea or ocean waters to construct a reliable and stable topology. The deployment processes in the 2D model configuration are the deterministic and random approaches(Alsulami et al., 2020b).

- **Deterministic Approach**

In the deterministic deployment approach, the state of the environment being monitored is considered, and the positions of sensors are organized reasonably. Arranging the sensors well involves consistently deploying these sensors for complete coverages and deploying non consistently for occasion-oriented coverages(Alsulami et al., 2019). For complete coverage of the area being monitored using a minimum number of sensors, they should be deployed uniformly to minimize superimposed areas between the sensors. Triangular configuration deployment techniques have been proposed in literature where the two-dimensional monitored regions are split into various equal-sided triangles(Alhumyani et al., 2015). Deployment of sensors is then performed at triangle vertices to realize enormous coverage under minimum sensors. The sides of the equal-sided triangles can be adjusted to achieve maximum coverage with the assurance that minimal overlapping regions between sensors will occur(Alsulami et al., 2020a). Grids of hexagonal or square shapes have also been proposed as construction structures for two-dimensional networks. These can be applied to spatially and open deterministic planes of 2Ds. Sensors can be deployed non-uniformly to tackle the problem of amorphous areas with several obstacles(He et al., 2018).

- **Random Approach**

Random approach deployment is utilized when the marine surrounding being monitored has a wide variation of conditions that are not easy to explore completely. This type of deployment involves sparsely deploying nodes at distinct locations and intensively deploying at a large scale(He et al., 2018; Alsulami et al., 2020a). Sensors are typically deployed randomly in harsh underwater environments by throwing them out of a ship or plane. Algorithms utilized in deploying randomly consider coverage of network and connectivity for the realization of complete sensor coverage. However, more sensors are required for complete coverage with a resultant increase in the cost of deployment and maintenance(Alsulami et al., 2020b). Only key regions must be considered for efficient coverage that guarantees less number of utilized sensors(Alsulami et al., 2020a).

- **Clustered Approach Deployment**

Here, clustering of sensors is done based on a single-hop from a gateway made of cluster nodes to a sink on the ocean surface. Sensors can also be clustered in a multi-jump communication method. In clustered approach, algorithms are utilized for the placement of sensors according to regular grids. This technique of deployment cannot, therefore, be applied to complex environments(He et al., 2018; Alsulami et al., 2021). In this approach, the selection of position is taken into consideration when clustering unrelated sensor nodes. Optimization of the position and quantity of nodes is easy since there is no distinct definition of topology(Alsulami et al., 2020a).

2.1.2 Strategies of Optimization in 2D Models

Mostly, the methods applied for optimization to improve execution in 2D models consider the adjustment of power, modeling of the graphics, and numerous coverages(He et al., 2018). This enhances the network's performance by improving connectivity, coverage and minimizing the required quantity of nodes. The energy or power consumption pertaining to the network can also be reduced by optimization techniques that consider the following: control of frequency, optimization through interpolation, and classification of clusters(Alharbi et al., 2015). Delay of transmission is also reduced, and data quality is improved when execution optimization techniques are utilized. The aim of optimizing the topology is to stabilize the network and enhance its performance. These optimization techniques seek to improve the network parameters like the interval from one node to the next, the number of nodes, and how the nodes are linked(Alsulami et al., 2019).

2.2 3D Network Models

In this model, nodes are deployed in a floating manner at varying ocean depths(Alhumyani et al., 2015). The nodes are anchored at the bottom of the ocean with wires attached to the anchors to control node depths. Buoys that are placed horizontally on a plane can also be utilized in controlling the node depths. The 3D network structure can be classified into isomorphic and heterogeneous. The isomorphic can further be sub-classified into dynamic and static design models(Alhumyani et al., 2015). The static structure designs are placed at various depths to cover large areas of the region being monitored. Connecting pressure-sensitive nodes accomplish the varying depth to an anchor chain or a buoy through a cable whose length can be adjusted. Anchoring the buoys to the ocean bottoms mitigates the challenges of exposure to enemy targets and navigation problems. Deployment in the 3D structure of the isomorphic model is as shown in figure 2 (He et al., 2018; Ibrahim et al., 2009; Alhumyani et al., 2015).

The challenges experienced by the 2D models are avoided in 3D structures, enabling deployment in complex harsh, and extremely deep regions of the sea

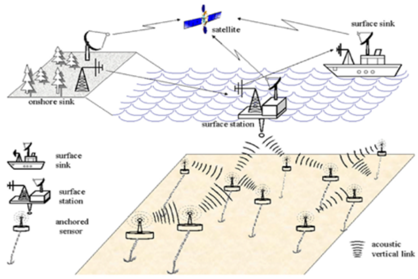

Figure 2: A 3D architecture of UWSNs (Bhaskarwar and Pete, 2021; He et al., 2018).

or ocean(He et al., 2018; Alsulami et al., 2019). Some of the drawbacks of 3D environments include: the positions to anchor the sensors must be initially determined in the early stages of deployment, the length of the cable limits the distance of adjustment in the vertical orientation, the energy demand by the sensors determines how frequently the adjustments of the depths should be done. The anchors that have been used to hoist the sensors have also been found to be sensitive to currents from the ocean, basin-scale vortex, plus various factors of the environment. Quick energy consumption is also experienced when sending data from sensors at the bottom of the ocean to sinks at the surface because multi-jump routing and nodes of isomorphic structures are utilized as relays(Bhaskarwar and Pete, 2021; He et al., 2018).

3D UWSN model outputs are improved by augmenting their performance with vehicles operating autonomously underwater known as AUVs(Bhaskarwar and Pete, 2021). Dynamic 3D structure model based on AUVs is as shown in figure 3 (He et al., 2018).

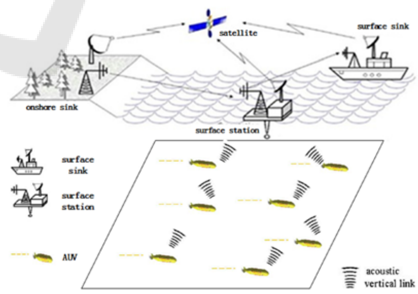

Figure 3: Dynamic 3D Model based on AUVs (Bhaskarwar and Pete, 2021).

The AUVs are used for supporting the GPS modules for tracking of position. AUVs perform analysis of the flow rate with an allowance of controllable operations since they have a high computation capacity. The AUVs have an adjustable speed of movement and position. This model is challenging to apply in large-scale proportions because of the high cost involved. Consequently, 3D models that are dynamic and heterogeneous have been proposed and designed to lower the costs of constructing UWSNs.

2.2.1 Mechanisms of Configuration in 3D Models

There are different strategies of configuration for various types of 3D models. The techniques of deployment can be classified based on node characteristics. For three-dimensional models that are considered static, anchoring of every sensor is done on the ocean bead, and there is a restriction of independent movement(Alsulami et al., 2019). The deployment methods can be classified as deterministic, self-adaptive, and force-based virtual deployment (Zhang et al., 2019).

- **Deterministic Approach**

This deployment can be classified as uniform and non-consistent. It is necessary that UWSNs give a 3D monitoring of the underwater surrounding, but there are autonomous movement limitations because of energy requirements. A minimum number of sensors should also be utilized to realize maximum placement in a large area(Zhang et al., 2019; Alhumyani et al., 2015). Therefore, it has been proposed that a sequence of polyhedral top-up designs with regards to conjecture by Kelvin be utilized(Alhumyani et al., 2015).

- **Self-adaptive Approach**

This deployment technique involves random anchoring of sensors on the bottom of the sea. The depth of the sensors is also determined randomly(Alsulami et al., 2020a). The adjustment made on the anchor length selects the desired depths of the sensors. Every individual sensor then relays its ultimate location to a station onshore. Algorithms have been proposed under this approach, where the clustering of sensors is done by controlling the depth of sinking of individual sensors(Alsulami et al., 2019). The algorithm works along with the idea that coverage under 3D structure ensures continuous interconnection between the sensors. For the avoidance of superimposition in horizontal regions, preliminary planning of the position of sensors is needed. Since this deployment is random-based, numerous replicated sensors should be distributed so that the region being monitored can be covered completely(Zhang et al., 2019; Alhumyani et al., 2015).

3 APPLICATIONS OF UWSNs TECHNOLOGY

UWSN technology finds its applications in many areas grouped into three categories: Scientific, Industrial, and Security applications. The underwater sensor design ranges from simple to complex, while the prices range from few dollars to thousands of dollars depending on the monitored parameter. Sensors used to measure pressure, light penetration, and temperature are relatively low-priced. On the other hand, sensors used in applications such as estimating the concentration of chlorophyll, CO_2 monitoring, and detecting underwater objects use more complex sensor technology and hence are more expensive(Heidemann et al., 2012; Lloret, 2013). Figure 4 gives a summary of the applications of UWSN under each of the three categories stated above:

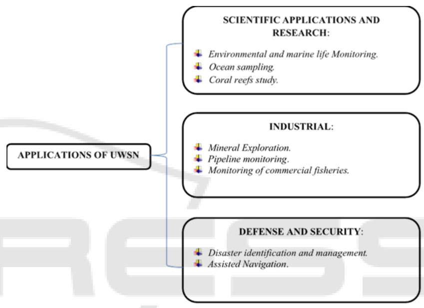

Figure 4: Applications of UWSN Technology (Heidemann et al., 2012).

Depending on the target data to be collected, deployment of underwater sensor networks is categorized as discussed below:

- **Static or Mobile Mode**

Static nodes are attached to anchored buoys or attached to the seafloor and remain there collecting and transmitting information back to the monitoring stations(Ibrahim et al., 2009; Alhumyani et al., 2015). On the other hand, mobile nodes are mounted on autonomous underwater vehicles (AUVs)5, gliders, or drifters(Heidemann et al., 2012). In doing this, one can monitor data over a large area using the same hardware. Since the mobile nodes are needed to cover a more extensive topology, they consume more energy during the data collection and relay process.

- **Short-term and Long-term Monitoring**

Deployment of underwater sensors can be for short periods ranging from a few hours to a day or for more extended periods ranging from a few months to several years. Most underwater deployments happen on a short-term basis due to the harsh aquatic environment(Heidemann et al., 2012). After a certain

Figure 5: Autonomous Underwater Vehicle – AUV (Blidberg, 2001).

period of operation, there arises the need to service the equipment and allow for recharging, especially for mobile nodes that run on battery power(Alsulami et al., 2020a).

The above factors affect the design and operation of the various equipment deployed for underwater sensing applications. The choice between static or mobile deployments and the length of the sensors' operation period before any service is required varies depending on the specific application the UWSN is applied. This next section discusses the various applications of UWSNs across multiple sectors.

3.1 Scientific Applications and Research

Water covers over 70% of the earth's surface(Felemban et al., 2015). These parts of the earth underwater remain hugely unexplored and contain vast resources and data awaiting discovery. Applications of UWSNs in scientific research revolve around environmental monitoring, ocean sampling, and monitoring of biological activities on the ocean floor(Lloret, 2013; Heidemann et al., 2012).

3.1.1 Environmental and Marine Life Monitoring

Environmental and marine life monitoring involves monitoring the underwater environment, various objects of interest, and marine life. Ecological monitoring is split into the tracking of the physical parameters of the water to determine its quality, monitoring of marine life and their habitats, and performance of underwater exploration activities for discovery or research. Tracking the ocean water quality is mainly geared towards assessing the chemical and biological waste deposited on the ocean floor(Collins, 2013). The water's oxygen levels, temperature, and pressure are also measured, and the data is sent to onshore monitoring stations for further analysis. Monitoring the quality of water ensures that aquatic life is not affected by any human activities(Kiranmayi and Kathirvel, 2015).

Some of the most common pollution instances include oil spillages, chemical and nuclear pollution from facilities close to water bodies that use the water in their operations. UWSNs make identifying any pollution cases easier than manual methods by enabling the monitoring stations to get real-time information(Kiranmayi and Kathirvel, 2015). The amount of aquatic life that has been affected can be accurately determined hence enabling timely planning of countermeasures to salvage the situation. Noticing a change in some of the nominal operating conditions of the ocean happens fast, and the possible cause is identified before any harm to human or aquatic life happens(Kiranmayi and Kathirvel, 2015). The underwater sensors deployed for such applications are primarily static(Bradbeer et al., 2007).

The aim of monitoring aquatic life such as fish, mammals, and microorganisms is to observe, study, and understand their behavior hence further expand the current scientific knowledge base(Kiranmayi and Kathirvel, 2015). The living environment of these underwater creatures is monitored and analyzed. Any human activities in the vicinity of the study area are also monitored to determine whether they impact aquatic life in any way(Felemban et al., 2015; Kiranmayi and Kathirvel, 2015). Such systems capture visual and technical data of the marine organisms and transmit it wirelessly to a control and monitoring center where the data is analyzed and triggers an alert should an unusual occurrence be detected(Collins, 2013).

3.1.2 Ocean Sampling

Ocean sampling involves the monitoring of underwater phenomena with the aim of scientific study. In this case, the underwater sensors are mounted on AUVs that move around unexplored regions of the ocean surface. The area covered by each vehicle is approximately 500 square meters for every deployment(Fattah et al., 2020a).

3.1.3 Coral Reefs Study

Coral reefs are underwater ecosystems that are built by microorganisms that live in the water. They are studied to check how human activity impacts them. A lot of data is collected and incorporated into simulations tools. One can project the impact of any change in the ocean conditions on the thriving of these underwater ecosystems(Kiranmayi and Kathirvel, 2015). Both static, as well as mobile nodes are deployed for such applications. The static nodes are used to collect data such as temperature and images of the coral reefs at certain strategic positions of the reef(Fattah et al., 2020a; Lloret, 2013). AUVs, which are the mobile nodes, are used to collect information from the stationary nodes and relay it to surface buoy nodes for transmission to the monitoring and control centers at the shore. The static nodes are built to withstand the harsh underwater environment, while the mobile nodes are limited by powering issues (batteries) and shorter lifetimes(Kiranmayi and Kathirvel, 2015). Mobile nodes are hence not used for long excursion periods due to these limitations.

3.2 Industrial

3.2.1 Mineral Exploration

Underwater sensors are used during the exploration of oil and gas deposits on the floor of the ocean. Doing this enables faster and more accurate exploration to establish the presence and viability of such resources(Maeda et al., 2011). UWSN technology is also used to monitor and control underwater rigs to ensure effective operation with minimum pollution to the surrounding environment. The other mineral that has attracted the interest of researchers in recent times is manganese crust(Lloret, 2013; Felemban et al., 2015; Kiranmayi and Kathirvel, 2015). Underwater sensor technology has been deployed to identify, locate and map these underwater deposits. AUVs mounted with optical and acoustic modules are used for such applications, facilitating significant area coverage during exploration(Maeda et al., 2011). These AUVs identify, map and monitor these manganese deposits to depths of 3000m below the water surface (Felemban et al., 2015).

3.2.2 Pipeline Monitoring

UWSNs have, in recent times, been incorporated in the monitoring of underwater oil and gas pipelines(Jacobi and Karimanzira, 2013). This is done when oil and gas are extracted from the ocean floor and transferred to the shore using pipelines. Pipelines are also used to interconnect different continents, making them a critical infrastructure that needs continuous monitoring(Jassim and Abdelkareem, 2020). The health of a vast pipeline can be determined in a short period of time compared to when manual methods are used. In doing this, somebody can take quick remedial actions if a fault is noticed(Jassim and Abdelkareem, 2020; Fattah et al., 2020a).

3.2.3 Monitoring of Commercial Fisheries

UWSNs are used in monitoring commercial fishing activities in fish farms. Fish farming is a most demanding activity that calls for continuous monitoring of the fishes' habitat to guarantee maximum production. In most cases, the fish live in a closed environment hence calling for close monitoring of their habitat to ensure that all the living conditions for the fish are optimally maintained(Chang et al., 2016; Fattah et al., 2020a). The parameters monitored are temperature, water pH, NH4 content, amount of uneaten feed, and fecal waste from the fish. This is done to determine the quality of the water and determine when a change is needed(Felemban et al., 2015). UWSN technology allows for easy management of huge fish farms when compared to traditional methods. Large amounts of data are collected and stored to help make better decisions in the future to ensure the productivity of these farms. With the continued flow of real-time data from UWSNs at their disposal, one is guaranteed to make the best decisions to ensure the commercial viability of a fish farm(Felemban et al., 2015; Lloret, 2013).

3.3 Security Applications

Applications of UWSNs involve the use of these sensors for monitoring the coastline activities and identifying any unwanted or unpermitted battleships or submarines in the vicinity(Jacobi and Karimanzira, 2013; Felemban et al., 2015; Zwanzig, 2018). Any potential enemies are determined in advance and neutralized before launching an attack, and the security teams can plan for offenses to neutralize the enemy before they strike. SeaWeb was one of the earliest underwater communication technology deployed by the military for detecting and communicating with submarines(Heidemann et al., 2012). The mode of communication underwater is usually limited to short distances compared to terrestrial communication. Current technological advances are looking into how this communication can be expanded since most parts of the underwater world remain unexplored and unexploited(Felemban et al., 2015). Optical and acoustic sensors are used in mine detection under the water. Similar to terrestrial mines, underwater mines pose a threat to aquatic activities carried out by security agencies(Dong et al., 2015). Hence, underwater sensor technologies help avert loss of life when used for reconnaissance activities to identify and neutralize any hidden threats positioned on the seafloor(Zwanzig, 2018).

3.3.1 Disaster Identification and Management

Tsunamis have been a natural disaster that has posed considerable harm to human life and activities carried out close to seas and oceans. UWSNs are deployed to monitor the conditions of the ocean floor, and if some seismic activities are noted, the sensors send a warning to the shore stations. This information can then be relayed to those near the seas, advising them to move to higher grounds(Alsulami et al., 2019; Zwanzig, 2018). In doing this, damage to property and loss of life is averted. Underwater volcanos and earthquakes are also monitored to gather information on any upcoming or expected seismic activities. At times, the ruthless behavior of oceans limits the traditional methods of gathering information and renders some areas of the sea inaccessible. This is where the underwater sensor technology comes in handy to guarantee continued monitoring of the oceanic conditions despite the rough nature of the ocean waters(Dong et al., 2015). In doing this, disasters are averted through early detection and relaying of information(Lloret, 2013).

One of the adverse effects of global warming has been increased flooding around the world. This has led to the loss of life and destruction of property when the floods strike unexpectedly. UWSN technology has found an application in monitoring such events to ensure that timely alerts are sent out, saving lives and reducing the destruction of property(Jassim and Abdelkareem, 2020; Amoli, 2016). Aquatic vitals are monitored by some stationary nodes then transmitted to a remote shore station for analysis of any impending floods. Some of the parameters monitored include water levels, thrust, and intensity of flow. Other information that is monitored includes temperature, humidity, and amount of precipitation(Arima et al., 2014). After gathering this information, prediction tools are used to determine whether a flood is imminent and when one might occur. This information guides emergency services on any evacuation that needs to be done and when it should be done. Other forms of disasters that may occur can be artificial, such as oil spillages(Arima et al., 2014; Felemban et al., 2015). These are bound to cause ecological instabilities in life on and under the water if not adequately mitigated(Amoli, 2016; Alsulami et al., 2020a; Dong et al., 2015).

3.3.2 Assisted Navigation

In assisted navigation, modern-day ships can get information about impending threats such as rocks, shoals, and submerged vehicles(Gallagher et al., 2016). This helps the crew plan for their voyages and avoid accidents such as what begot the titanic from happening. Traditional systems would depend on the manual observation of threats then communicating them to the ship's navigation team for action. Any miscalculation of danger would tend to be fatal, as was the case with the titanic(Gallagher et al., 2016; Lee et al., 2004; Felemban et al., 2015).

4 CHALLENGES AND LIMITATIONS OF UWSNs

Although UWSNs have grown in the application, they present several limitations in their deployment. These challenges require to be addressed by research to continuously improve the reliability, efficiency, and applicability of these UWSNs(Akyildiz et al., 2005). The challenges and limitations of UWSNs include Limited Bandwidth, Propagation delay, Delay Variance, Link reliability, complex acoustic environment, common standard and interface, sensor heterogeneity, hardware-related limitations, communication, and visualization challenges(Fattah et al., 2020b). To clearly understand the challenges of UWSNs, it is important to study the differences that these networks have when compared to terrestrial systems(Ryecroft et al., 2018). Firstly, underwater sensor networks are expensive when compared to terrestrial networks. The high cost is due to the complex design of underwater transceivers and the protection hardware required for protection against the harsh environmental conditions that underwater systems are exposed to(Akyildiz et al., 2005). Secondly, underwater wireless sensor nodes are sparsely deployed when compared to terrestrial nodes (Akyildiz et al., 2005). This sparse deployment is occasioned by the high cost of the underwater sensor nodes and the harsh deployment environment(Ryecroft et al., 2018). In terms of power requirements, UWSNs require more power than their terrestrial counterparts. USWNs require complex signal processing at the transceivers to compensate for noise and signal loss along the underwater transmission channel(Alsulami et al., 2019; Bhanumathi et al., 2019).

Due to intermittency of data transition in underwater systems, USWNs require additional memory for caching to mitigate the intermittency(Iqbal and Lee, 2015; Fattah et al., 2020b). On the other hand, terrestrial systems do not require huge memory for caching because data transmission is stable. Additionally, data from underwater sensor networks are more spatially correlated than that of terrestrial sensor networks(Lloret, 2013; Akyildiz et al., 2005). The reason for this is the large distances between sensor nodes in underwater sensor networks (Akyildiz et al., 2005). These differences between underwater sensor networks and terrestrial systems make the deployment of underwater sensor networks and research in these networks challenging(Akyildiz et al., 2005). The following sections look at the challenges of underwater sensor networks in more detail and how researchers are addressing these challenges(Akyildiz et al., 2005).

4.1 Limited Bandwidth

Underwater wireless sensor networks require acoustic channels to communicate. Acoustic channels have a limited bandwidth of below 30kHz due to absorption(Kilfoyle and Baggeroer, 2000). The underwater environmental factors make underwater communication channels highly variable(Awan et al., 2019). These factors make the bandwidth dependent on the frequency of transmission and the distance between two communication nodes. The acoustic channel deployed in shallow waters will be affected by a high-temperature gradient, surface noise, and multipath effect compared to a channel deployed in deep waters (Awan et al., 2019). For acoustic channels, the bandwidth increases with an increase in depth and temperature. The bandwidth also decreases with an increase in distance(Bhanumathi et al., 2019; Kilfoyle and Baggeroer, 2000). Due to bandwidth dependence with distance, it requires that the Underwater sensor network nodes be deployed as close to each other as possible. This would mean that the cost of deploying these nodes would be high, and also, the network power requirements would be high. To address the challenge of limited bandwidth, researchers have looked at the possibility of UWSNs accessing shared channels(Akyildiz et al., 2005; Ryecroft et al., 2018). To access shared channels, the media access control protocol (MAC) is used to coordinate the UWSN nodes and ensure the validity of data sent through the channel (Akyildiz et al., 2005).

4.2 Propagation Delay

High propagation delays are inherent in Underwater Sensor Networks. The protocols designed for terrestrial radio networks usually ignore propagation delays because they are small. These protocols cannot work well in underwater systems because of the high delay experienced in acoustic networks (Chen et al., 2010). Propagation delays in UWSNs are five times higher for radio networks when compared to terrestrial networks (Pompili et al., 2006). When the UWSNs are used for real-time monitoring, for example, in surveillance applications, this delay is undesirable(Ryecroft et al., 2018; Kilfoyle and Baggeroer, 2000). Protocols that take into consideration this delay need to be developed specifically for real-time monitoring in underwater applications. These protocols should restore connectivity quickly when lost and decongest congested links by dynamic rerouting to minimize propagation delay. An example of such protocol is the store and forward mechanism developed by the Delay-Tolerant Networking Research Group. This protocol uses middleware between the application and lower layers to resolve intermittent connectivity and long delays (Akyildiz et al., 2005; Kilfoyle and Baggeroer, 2000). Delays in UWSNs for some applications, such as those used for seismic monitoring, are occasioned by producing a huge amount of data when these sensors are suddenly activated. Such sensor networks require careful design to minimize the propagation delay by tuning existing networks to the characteristics of the underwater environment(Akyildiz et al., 2005; Awan et al., 2019).

4.3 Path Loss

Path loss is the decline in the power density of an electromagnetic signal as it propagates through a medium(Alhumyani et al., 2015; Ibrahim et al., 2009). In UWSNs, path loss leads to attenuation of the signal. Attenuation in UWSNs occurs when acoustic energy is converted to heat(Kilfoyle and Baggeroer, 2000; Awan et al., 2019). Signal attenuation in underwater application increases with distance and frequency, as shown in figure 6 (Akyildiz et al., 2005; Fattah et al., 2020b).

Attenuation is also caused by reverberation and scattering, and dispersion. Another critical source of path loss is geometric spreading(Kilfoyle and Baggeroer, 2000). UWSNs rely on acoustic waves for signal transmission. Acoustic waves are highly susceptible to geometric spreading. Geometric spreading refers to the propagation of sound energy due to the expansion of the wavefront (Min et al., 2012). Geometric spreading increases with distance but is independent of frequency(Min et al., 2012).

4.4 Unpredictable and Unreliable Underwater Environment

The unpredictability of the underwater environment makes it very hard to design and deploy UWSNs. Water activities are unpredictable, the water pressure is high, and the uneven seawater depth is unpredictable(Felemban et al., 2015; Amoli, 2016).

And also, nodes in underwater sensor networks are continuously moving due to water currents. Lo-

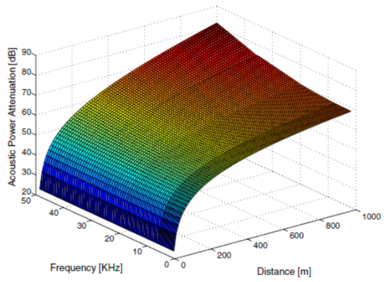

Figure 6: Attenuation vs. frequency and distance (Akyildiz et al., 2005).

calization of these nodes is therefore crucial for reliable transmission of information(Almutairi and Mahfoudh, 2017; Kilfoyle and Baggeroer, 2000; Min et al., 2012). Terrestrial localization of nodes cannot be applied to underwater networks because the underwater conditions will disorganize the nodes and network topology, making the nodes unreliable(Akyildiz et al., 2005; Chandrasekhar et al., 2006).

5 CONCLUSION

In conclusion, we wanted, in this paper, to provide researchers and readers who are interested in UWSNs valuable overview about this promising technology. We started our paper by showing the importance of this technology nowadays and presenting main motivations to have such technology. Then, We described the different architectures that have been developed by researchers so far. After that, we summarized some of the deployment approaches that are used to deploy nodes in the UWSNs. Moreover, we surveyed some of the applications of UWSNs. We also discussed core requirements of UWSNs. We discussed in this paper some of the significant challenges and limitation of UWSNs. We concluded this paper by presenting and comparing three different meduims that are used in UWSNs.

REFERENCES

Akyildiz, I. F., Pompili, D., and Melodia, T. (2005). Underwater acoustic sensor networks: research challenges. *Ad hoc networks*, 3(3):257–279.

Aldosari, H., Elfouly, R., Ammar, R., and Alsulami, M. (2020). Performance of new monitoring architectures for underwater oil/gas pipeline using hyper-sensors. In *2020 IEEE Symposium on Computers and Communications (ISCC)*, pages 1–6.

Alharbi, A., Alhumyani, H., Tolba, S., and and, R. A. (2014). Underwater sensing and processing networks (uspn). In *2014 IEEE Symposium on Computers and Communications (ISCC)*, pages 1–7.

Alharbi, A., Ibrahim, S., Ammar, R., and Alhumyani, H. (2015). Performance analysis of efficient pipeline architectures for underwater big data analytics. In *2015 IEEE Symposium on Computers and Communication (ISCC)*, pages 1014–1019.

Alhumyani, H., Ammar, R., Alharbi, A., and Tolba, S. (2015). Efficient surface-level gateway deployment using underwater sensing and processing networks. In *OCEANS 2015 - MTS/IEEE Washington*, pages 1–6.

Almutairi, A. and Mahfoudh, S. (2017). Deployment protocol for underwater wireless sensors network based on virtual force. *International Journal of Advanced Computer Science & Applications*, 8(11):241–249.

Alsulami, M., Elfouly, R., and Ammar, R. (2021). A reliable underwater computing system. In *2021 4th IEEE International Conference on Industrial Cyber-Physical Systems (ICPS)*, pages 467–472.

Alsulami, M., Elfouly, R., Ammar, R., and Aldosari, H. (2020a). Deployment of multiple computing systems in underwater wireless sensor networks. In *2020 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, pages 1–6.

Alsulami, M., Elfouly, R., Ammar, R., Aldosari, H., and Alenizi, A. (2019). Ideal number of computers for real-time underwater computing systems. In *2019 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, pages 1–5.

Alsulami, M., Elfouly, R., Ammar, R., and Alenizi, A. (2020b). A modified k-medoids algorithm for deploying a required number of computing systems in a three dimensional space in underwater wireless sensor networks. In *2020 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, pages 1–5.

Amoli, P. V. (2016). An overview on current researches on underwater sensor networks: Applications, challenges and future trends. *International Journal of Electrical and Computer Engineering*, 6(3):955.

Arima, M., Yoshida, K., and Tonai, H. (2014). Development of a four-channel underwater passive acoustic monitoring system for the use of underwater vehicles. In *2014 Oceans - St. John's*, pages 1–6.

Awan, K. M., Shah, P. A., Iqbal, K., Gillani, S., Ahmad, W., and Nam, Y. (2019). Underwater wireless sensor networks: A review of recent issues and challenges. *Wireless Communications and Mobile Computing*, 2019.

Bhanumathi, S., Rajkishore, S., and Kowshik, S. (2019). Localized aided energy efficient optimal relay selection protocol for underwater wireless sensor networks. In *2019 3rd International Conference on Trends in Electronics and Informatics (ICOEI)*, pages 880–885.

Bhaskarwar, R. V. and Pete, D. J. (2021). Cross-layer design approaches in underwater wireless sensor networks: A survey. *SN Computer Science*, 2(5):1–26.

Blidberg, D. R. (2001). The development of autonomous underwater vehicles (auv); a brief summary. In *Ieee Icra*, volume 4, page 1. Citeseer.

Bradbeer, R. S., Hodgson, P., Lam, K., and Ku, K. K. K. (2007). Establishment of a three dimensional, real-time marine environment monitoring system, databuoy™ i, in the hoi ha wan marine park, hong kong, with connection to the internet. In *2007 14th International Conference on Mechatronics and Machine Vision in Practice*, pages 174–178.

Chandrasekhar, V., Seah, W. K., Choo, Y. S., and Ee, H. V. (2006). Localization in underwater sensor networks: survey and challenges. In *Proceedings of the 1st ACM international workshop on Underwater networks*, pages 33–40.

Chang, J.-E., Huang, S.-W., and Guo, J.-H. (2016). Hunting ghost fishing gear for fishery sustainability using autonomous underwater vehicles. In *2016 IEEE/OES Autonomous Underwater Vehicles (AUV)*, pages 49–53.

Chen, Y.-S., Juang, T.-Y., Lin, Y.-W., and Tsai, I.-C. (2010). A low propagation delay multi-path routing protocol for underwater sensor networks. *Internet Technology Journal*, 11(2):153–165.

Collins, A. (2013). Application of subsea wireless technology to environmental monitoring. In *2013 OCEANS - San Diego*, pages 1–5.

Dong, Y., Zhang, G., He, X., and Tang, J. (2015). Information fusion in networked underwater target detection. In *OCEANS 2015 - Genova*, pages 1–4.

Fattah, S., Gani, A., Ahmedy, I., Idris, M. Y. I., and Targio Hashem, I. A. (2020a). A survey on underwater wireless sensor networks: Requirements, taxonomy, recent advances, and open research challenges. *Sensors*, 20(18):5393.

Fattah, S., Gani, A., Ahmedy, I., Idris, M. Y. I., and Targio Hashem, I. A. (2020b). A survey on underwater wireless sensor networks: Requirements, taxonomy, recent advances, and open research challenges. *Sensors*, 20(18):5393.

Felemban, E., Shaikh, F. K., Qureshi, U. M., Sheikh, A. A., and Qaisar, S. B. (2015). Underwater sensor network applications: A comprehensive survey. *International Journal of Distributed Sensor Networks*, 11(11):896832.

Gallagher, D. G., Manley, R. J., Hughes, W. W., and Pilcher, A. M. (2016). Development of an enhanced underwater navigation capability for military combat divers. In *OCEANS 2016 MTS/IEEE Monterey*, pages 1–4.

He, M., Chen, Q., Dai, F., and Zheng, X. (2018). Topological configuration and optimization in underwater acoustic sensor networks: A survey. *International Journal of Distributed Sensor Networks*, 14(8):1550147718795359.

Heidemann, J., Stojanovic, M., and Zorzi, M. (2012). Underwater sensor networks: applications, advances and challenges. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1958):158–175.

Ibrahim, S., Ammar, R., and Cui, J. (2009). Geometry-assisted gateway deployment for underwater sensor networks. In *2009 IEEE Symposium on Computers and Communications*, pages 932–937.

Iqbal, Z. and Lee, H.-N. (2015). Deployment strategy analysis for underwater cooperative wireless sensor networks. In *2015 International Conference on Information and Communication Technology Convergence (ICTC)*, pages 699–703.

Jacobi, M. and Karimanzira, D. (2013). Underwater pipeline and cable inspection using autonomous underwater vehicles. In *2013 MTS/IEEE OCEANS - Bergen*, pages 1–6.

Jassim, W. M. and Abdelkareem, A. E. (2020). Performance enhancement of oil pipeline monitoring for underwater wireless sensor network. In *2020 International Conference on Computer Science and Software Engineering (CSASE)*, pages 38–43.

Khan, M. F., Bibi, M., Aadil, F., and Lee, J.-W. (2021). Adaptive node clustering for underwater sensor networks. *Sensors*, 21(13):4514.

Kilfoyle, D. B. and Baggeroer, A. B. (2000). The state of the art in underwater acoustic telemetry. *IEEE Journal of oceanic engineering*, 25(1):4–27.

Kiranmayi, M. and Kathirvel, A. (2015). Underwater wireless sensor networks: applications, challenges and design issues of the network layer-a review". *International Journal of Emerging Trends in Engineering Research*, 3(1):05–11.

Lee, P., Jeon, B., Kim, S., Choi, H., Lee, C., Aoki, T., and Hyakudome, T. (2004). An integrated navigation system for autonomous underwater vehicles with two range sonars, inertial sensors and doppler velocity log. In *Oceans '04 MTS/IEEE Techno-Ocean '04 (IEEE Cat. No.04CH37600)*, volume 3, pages 1586–1593 Vol.3.

Lloret, J. (2013). Underwater sensor nodes and networks.

Maeda, F., Takagawa, S., Asada, A., Maki, T., Sasaki, Y., and Yamamoto, F. (2011). Next r amp;d of measurement method of offshore minerals using the low-frequency acoustic mills-cross transmission and receiving system multibeam sub-bottom profiling method and "natsushima" cruise experiment. In *2011 IEEE Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, pages 1–5.

Min, H., Cho, Y., and Heo, J. (2012). Enhancing the reliability of head nodes in underwater sensor networks. *Sensors*, 12(2):1194–1210.

Pompili, D., Melodia, T., and Akyildiz, I. F. (2006). Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks. In *Proceedings of the 12th annual international conference on Mobile computing and networking*, pages 298–309.

Ryecroft, S. P., Shaw, A., Fergus, P., Kot, P., Muradov, M., Moody, A., and Conroy, L. (2018). Requirements of an underwater sensor-networking platform for environmental monitoring. In *2018 11th International Conference on Developments in ESystems Engineering (DeSE)*, pages 95–99. IEEE.

Zhang, W., Wang, J., Han, G., Zhang, X., and Feng, Y. (2019). A cluster sleep-wake scheduling algorithm based on 3d topology control in underwater sensor networks. *Sensors*, 19(1):156.

Zwanzig, C. (2018). Ship-based exploration of submarine gas hydrates and environmental monitoring with multibeam echo sounders. In *2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO)*, pages 1–8.