IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 22 August 2023, accepted 30 September 2023, date of publication 12 October 2023, date of current version 18 October 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3324292

RESEARCH ARTICLE

Grid Deployment Scheme for Enhancing Network Performance in Underwater Acoustic Sensor Networks

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This work was supported by the Deputyship for Research and Innovation, Ministry of Education, Saudi Arabia, under Project INST187.

ABSTRACT Researchers have achieved significant progress on the problem of Sensor Node Deployment (SND) in Underwater Acoustic Sensor Networks (UASNs) in terms of enhancing underwater communication. However, most studies focus on enhancing coverage, connectivity, selective network performance metrics, and/or deployment expenses at the cost of other critical factors. Given the limited resources and difficulties with using renewable energy sources to recharge UASN batteries, it is necessary to minimize Energy Consumption (EC) through the node deployment mechanism to extend network lifetime. Therefore, in this paper, the author proposes the Distributed Deployment Optimization algorithm using Grid-based Depth Adjustable (DDOGDA) based on grid node deployment for 3D network architecture. With this model, this paper endeavors to monitor the underwater environment with the minimum number of underwater nodes while meeting the QoS requirements of a tsunami-monitoring application in the Solomon Islands. The proposed algorithm considers Geographic Information System (GIS) data, non-environmental factors, and the unique characteristics of underwater sensors. These factors were used to provide guidance on how to place nodes properly to achieve certain objectives. Herein, the proposed algorithm is compared to six other node deployment algorithms. Simulation results indicate that our proposed algorithm surpasses random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment in terms of End-to-End Delay (E2ED), EC, and Packet Delivery Ratio (PDR) by 266%, 183%, and 22%, respectively.

INDEX TERMS Disaster-monitoring application, end-to-end delay, energy consumption, network performance, node deployment, packet delivery ratio, time-sensitive application, underwater acoustic sensor networks.

I. INTRODUCTION

With the recent advances in UASNs, underwater nodes are a promising technology that can support several types of underwater applications, such as those for environmental monitoring, assisted navigation, disaster prevention, sports, and the military [1], [2], [3], [4], [5]. Real-time monitoring in UASNs is very important to time-sensitive monitoring applications as it is necessary to avert or warn of potential disasters (e.g., flood, volcanic eruption, tsunami, earthquake, and pipeline malfunction/break/leak) which can have severe impact on human and marine life as well as national, regional, and global economies [6]. Therefore, a new and reliable mechanism is necessary to achieve the requirements of target applications through an advanced UASN [7]. Different underwater applications have different requirements and hence different node deployments can be used to meet those requirements [8]. In comparison to Terrestrial Wireless Sensor Network (TWSN) communication, each underwater application must consider the details of the target area and the requirements of the target underwater application to properly handle high and variable propagation delay,

The associate editor coordinating the review of this manuscript and approving it for publication was Jiajia Jiang.

limited bandwidth, high transmission loss, multipath effect, and Doppler spread [9], [10], [11], [12]. In addition, non-environmental and environmental factors, such as network size, packet size, network load, current, seismic activity, and noise must be considered as these factors make designing efficient underwater communication more challenging. Network topology also has a strong impact on network performance [13]. All these factors must be taken into consideration when designing an optimal algorithm for SND in order to make the model an efficient approach for underwater applications.

In the last decade, node deployment algorithms for TWSNs have been investigated, but there are significant differences between TWSNs and UASNs, so this research is not directly applicable to UASNs [14]. For example, in TWSNs, node deployment is applied to the 2D deployment space, while applications in UASNs require deployment in the 3D deployment space [15]. While 2D is sometimes used in UASNs, it limits the functionality of the network because the 3D nature of the environment cannot be considered. This is why at least 3D is preferred for underwater applications. Node deployment in 2D for TWSNs has been studied intensively, but the solutions obtained cannot be implemented in UASNs, as most underwater applications rely on 3D [16], [17], [18]. In comparison to TWSNs, communication in UASNs is not stable, there is the need to address the unique characteristics of acoustic channel, and there is limited battery coupled with the inability to recharge using any sort of renewable energy [19]. Furthermore, the underwater environment is an extremely severe one in comparison with that of TWSNs, which correlates to variation of delay, current, depths, and the other characteristics of acoustic channel [20], [21]. These characteristics pose great challenges to the design of an effective mechanism for network deployment in UASNs. Most studies on 2D node deployment for TWSNs also do not consider the topographic information of the target application [15]. This leads to inefficient node deployment mechanisms and poor performance that may not meet the target application's QoS requirements. Therefore, existing node deployment solutions in TWSNs cannot be directly implemented in UASNs and hence a new node deployment mechanism is necessary [22], [23].

Node deployment in UASNs can be categorized into 2D, 3D, and 4D network architectures. In all network architectures, underwater nodes must collaborate to deliver packets to the sink node [24]. These network architectures share similar challenges, such as determining the minimum number of nodes to monitor an Area of Interest (AoI); determining the optimal location of sensor nodes, relay nodes (also known as gateway nodes), and sink nodes (also known as surface stations); determining the optimal depth to achieve full coverage and connectivity; enabling collaboration between nodes to transmit data through multi-hop paths; and optimizing network performance while minimizing the utilization of the low network resources [25], [26], [27], [28], [29]. To address the above challenges and meet the QoS requirements of target applications, a new algorithm is necessary for UASNs.

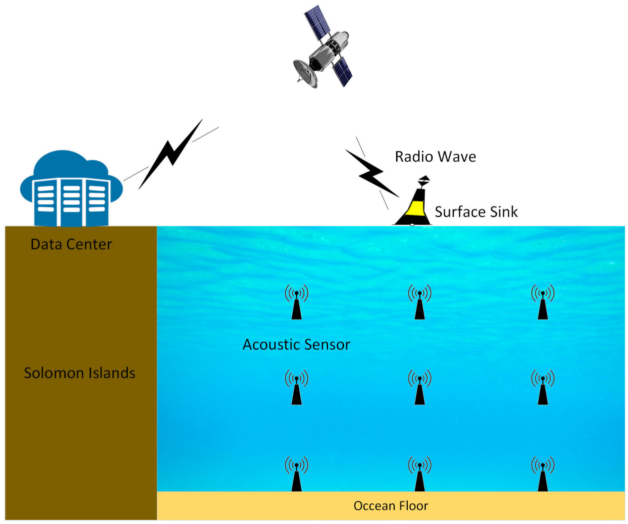

FIGURE 1. Components of 3D network architecture.

A typical underwater network consists of a set number of underwater nodes with limited resources to monitor an AoI [15], [30]. Particularly, a UASN in 3D network architecture consists of sensor nodes, relay nodes, and sink nodes as shown in Figure 1. Optimization of node deployment can be achieved through deploying sensor, relay, and sink nodes appropriately [31]. The location of each one of these nodes plays an important role in meeting the QoS requirements of the target application. When optimizing underwater communication, there are several factors to keep in mind (e.g., coverage, connectivity, sensor deployment, gateway deployment, sink deployment), which have great influence on the performance of the UASN and thus must be duly considered [15], [30]. Designing an efficient node deployment algorithm can enhance network performance. Therefore, the proposed node deployment algorithm considers the coverage area, available data rate, network size, packet size, network load, and other characteristics to achieve better network performance while meeting the QoS requirements of the target application.

The balance of this paper is organized as follows. Section II discusses the background of SND algorithms. Section III discusses related research articles and highlights the unique design characteristics examined in each. Section IV explains the proposed SND algorithm. Section V presents the details of the experimental setup and evaluation metrics utilized in this study and compares the results with those of other algorithms. Section VI concludes this paper while Section VII describes some future directions.

II. BACKGROUND

SND has a strong impact not only on coverage and connectivity, but also on the QoS of UASNs [27], [32], [33], [34], [35]. Utilizing a large number of sensors to monitor

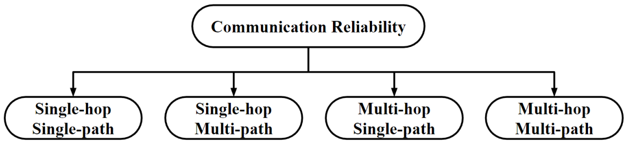

FIGURE 2. Communication reliability.

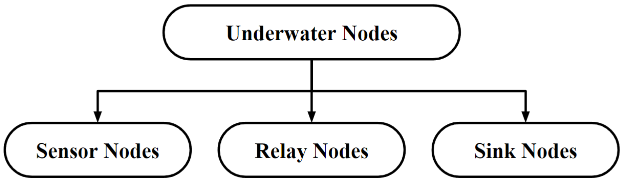

FIGURE 3. Underwater nodes.

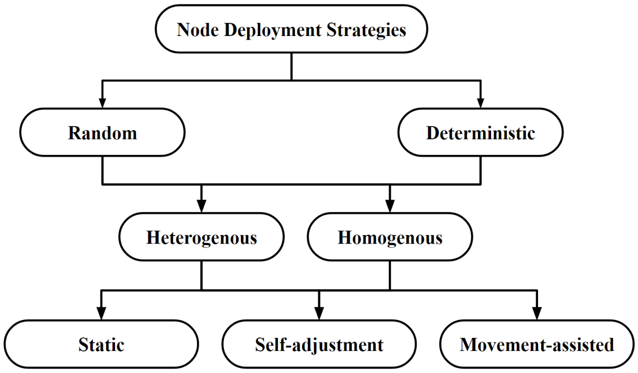

FIGURE 4. Node deployment strategies.

an AoI can address scalability and reliability concerns but comes at an increased total cost [36]. Underwater nodes can reach one another through single-hop single-path, single-hop multi-path, multi-hop single-path, or multi-hop multi-path as shown in Figure 2. Therefore, node deployment planning is crucial to fully meeting the requirements of underwater applications [37].

SND algorithms can be classified into optimal location of the sensor nodes, relay nodes, and sink nodes, as shown in Figure 3. Each one of these nodes can act as a sensor node by collecting data within its sensing range and reporting it to the sink node. The location of each of these nodes plays a crucial role in achieving full coverage and connectivity as well as achieving high performance in underwater communication [6], [38], [39]. Therefore, it is necessary to consider the locations of all these nodes when developing an optimal SND algorithm. The location of all these nodes also depends on the size of the simulation area. Different applications are required to monitor different sizes of AoIs. In a large-size simulation area, a single sink node may not be enough to achieve high network performance, indicating it is necessary to utilize multiple sinks for such applications. In contrast, a small AoI can be monitored properly with a single sink node.

The deployment of underwater nodes in UASNs can be classified into different deployment strategies [24], [28], [36], [37], [40] that can be either random or deterministic, as shown in Figure 4 [41]. Addressing SND issues can be achieved via heterogeneous sensor network or homogeneous sensor network [22], [42], [43]. Moreover, resolving coverage and connectivity issues can be achieved more efficiently through deterministic node deployment as the method can minimize the number of underwater nodes needed [36], [44]. In both random and deterministic node deployments, underwater nodes can be organized in a triangular, grid, or hexagonal pattern. Moreover, underwater nodes can cover an AoI sparsely or densely. When the distance between the underwater nodes is large, resolving some issues–such as full connectivity and detecting node failure–becomes more challenging. For example, full connectivity can be achieved through long transmission range and node failure can be detected when no packets are received at the sink node at regular intervals. To avoid false node failure detection, failure is only determined when the sink nodes do not receive any packets from a particular sensor node after an established threshold value is reached. Only after this set time period has passed is the sensor identified as failing. In contrast, network performance may also be affected when the distance between underwater nodes is short, due to the increased chance of interference between neighboring nodes, which consumes higher energy and shortens network lifetime [23]. Thus, it is wise to use lower numbers of sensors to meet the QoS requirements of target applications and hence lower the total cost [45]. Additionally, deployment strategy relies on two different data reporting systems, event-driven and on-demand, depending on the type of application. Some underwater applications require underwater nodes to monitor an AoI on an event-driven basis while others require on-demand monitoring. The network lifetime in event-driven and on-demand reporting systems is dependent on the conditions of the severe environment and the requirements of the underwater application. For example, Deep-ocean Assessment and Reporting of Tsunami (DART) requires underwater nodes to report the potential of tsunami regularly, which consumes higher energy and hence shortens network lifetime. In contrast, applications that monitor oil/gas pipelines require event-driven reporting, which means fewer packets need to be transmitted to the sink node, which thereby extends network lifetime.

The main objective of optimal node deployment is to monitor an AoI with the minimum number of sensor nodes to achieve maximum coverage and connectivity while meeting the QoS requirements of an underwater application. Node deployment algorithms can be classified as single-objective or multi-objective [43], as shown in Figure 5. In the former, the algorithms proposed in previous studies have focused on only a single issue, such as coverage or connectivity, or only a single performance metric. In the latter, the algorithms proposed in previous studies have focused on multiple issues. Clearly, addressing node deployment problems with multi-objective approach is more appropriate to achieve optimal solutions for target monitoring applications.

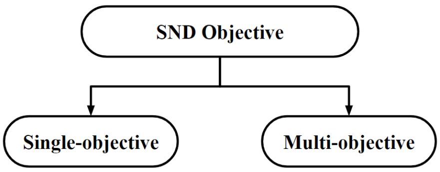

FIGURE 5. SND objective.

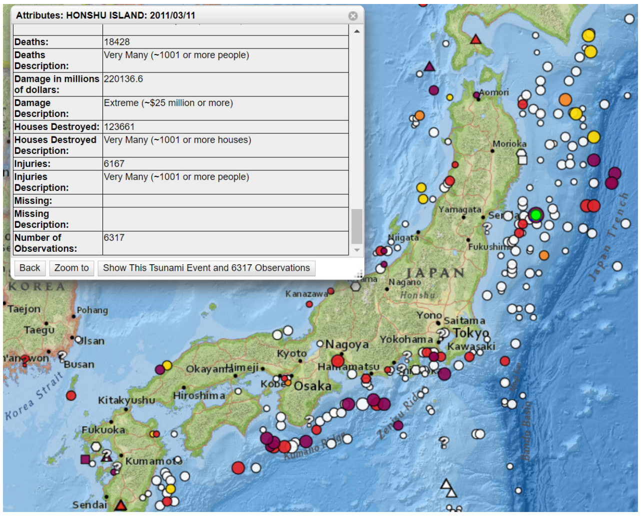

FIGURE 6. Impact of tsunami events [46].

As observed from the literature review, most research papers have focused on coverage, connectivity, and/or selected performance metrics while some papers ignored some of these issues. Therefore, in this study, the author aims to resolve SND issues by designing an optimal location method for underwater nodes for a tsunami monitoring application. As can be observed from this section, designing an optimal SND algorithm is a very challenging problem as many factors must be considered in order to achieve the QoS requirements of the target application.

Several destructive tsunami events have occurred over the last decade, each of which resulted in the loss of many human lives. Figure 6 shows the tsunami events that occurred during this time period and notes the impact of each of these events in terms of the number of deaths. In addition, this figure classifies the tsunami events using color coding (i.e., white, yellow, orange, red, and purple), where: (i) white represents a tsunami event where the number of deaths was zero or unknown; (ii) yellow represents an event where the number of deaths was between 1 and 50; (iii) orange indicates the number of deaths was between 51 and 100; (iv) red denotes that the number of deaths was between 101 and 1,000; and (v) purple is used to indicate that the number of deaths was 1,001 or more [46]. The total loss of life during these incidents could have been reduced by the deployment of sensor nodes underwater that would have generated an early warning for evacuation [47], [48]. Tsunamis are caused by underwater earthquakes that result in huge waves of water being generated that can drown an entire island [49]. The speed of a tsunami depends on the water depth. The greater the depth of the water, the faster the tsunami. In ultra-deep-water, a tsunami's speed can reach up to 500 mph, but it slows down as it approaches coastal areas [49]. Therefore, it is necessary to deploy underwater sensors to monitor underwater pressure to evaluate the potential of tsunami incidents [50], [51]. More particularly, a tsunami can be detected by analyzing the pressure fluctuations to differentiate between normal waves and tsunami waves [19], [52]. To have an effective tsunami warning system, packets must be transmitted to the sink node successfully with minimal delay as the speed and timeliness of the warning will save human lives [19], [53]. To achieve this type of effective system, it is vital to deploy sensor nodes properly to achieve maximum coverage and connectivity, minimum E2ED and EC, while also maximizing PDR.

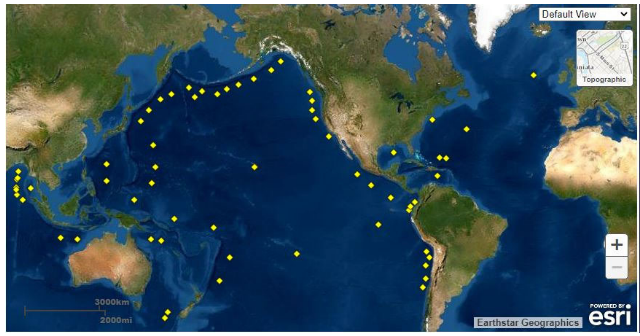

FIGURE 7. DART stations [56].

Over the years, many devastating tsunamis have occurred across the globe resulting in the deaths of many people [54]. There is clearly a critical need for reliable warning systems to save human lives. In the last decade, UASNs have received a great deal of attention in the area of oceanic research, due to the wide range of underwater applications. However, some ocean research still relies on 1D network architecture where it deploys underwater sensors in the ocean and then retrieves them to analyze the collected data [55]. Clearly, this is not an efficient approach to monitor underwater environments. It is also not a method that can support time-sensitive applications designed to predict natural hazards. Therefore, it is necessary to monitor underwater applications with an automated sensor network that can meet the QoS requirements of the target applications [51]. The underwater disaster application is considered an event-driven reporting system, which must be monitored at all times to save human lives. Currently, there are 39 stations around the planet, as shown in Figure 7, implemented in regions where a destructive tsunami has occurred in the past [46], [55]. The deployment of these stations is part of the DART project that is maintained by the National Oceanic and Atmospheric Administration (NOAA). Each one of these stations is composed of underwater sensors on the ocean floor and a sink node at the surface level, meaning these stations monitoring for the potential of a tsunami incident employ 2D network architecture. The main objective of the DART system is to provide accurate readings of the underwater pressure with minimal delay to generate early warning for tsunami and avoid issuing false alarms for evacuation [45]. In such a critical application, efficient communication between nodes is very important to transmit the pressure status underwater with minimal delay [52].

III. RELATED WORK

The SND problem is critical for underwater applications as it has a great influence on network performance. SND can be organized in 2D, 3D, or 4D network architecture. The type of network architecture depends on the type of applications that must be monitored. Each application has different requirements and may require different network architectures. Thus, some underwater applications require 2D network architecture, the majority require 3D network architecture, and a very few applications require 4D network architecture in UASNs. The capabilities of sensor nodes in underwater Wireless Sensor Networks (WSNs) have limited resources compared to those of other electronic devices. This means that, due to their limited resources, deploying sensor nodes in a severe environment makes it more challenging to meet the QoS requirements of an application.

To develop a suitable SND algorithm for a target application that also enhances network performance, many issues must be addressed, including coverage holes and connectivity issues. Currently, most studies do not address all these issues when developing an SND algorithm, resulting in degradation of network performance in multiple metrics. Therefore, it is very important to establish the optimal location of sensor nodes, relay nodes, and sink nodes to achieve high performance and meet the QoS requirements of an application.

Jiang et al. [57] proposed a Redeployment based on Virtual Forces (RBVF) algorithm where a node adjusts its depth based on virtual forces algorithm. RBVF focuses on maximal coverage area when redeployment is needed. In [57], the authors also considered water flow force and proposed a Virtual Forces Redeployment based on Energy Consuming (VFRBEC) model to minimize EC. Simulation results show that RBVF can achieve higher coverage and requires less moving distance compared to other algorithms. Moreover, simulation results also indicate that VFRBEC can achieve the same coverage compared to RBVF with lower EC. However, despite these benefits, both RBVF and VFRBEC focus on the coverage problem and ignore connectivity, cost, and other performance metrics. In addition, while both RBVF and VFRBEC enhance the coverage area, some areas remained uncovered.

Similar to RBVF [57], Liu et al. [20] proposed a distributed node Deployment Algorithm Based on Virtual Forces (DABVF) to achieve excellent coverage while reducing EC. DABVF algorithm takes into consideration node density, node residual energy, and node mobility to optimize the location of underwater nodes. Simulation results reveal that DAVBF achieves higher network coverage, reduces EC, balances node residual energy, and enhances the location of node distribution compared to other node deployment algorithms. DABVF focuses on resolving coverage holes by achieving k-coverage, which involves having several underwater nodes monitor an identical area. This indicates that in this scenario numbers of underwater nodes overlap one another, which may cause an increase in collisions between nodes [58]. In addition, another problem of k-coverage is the high cost of underwater nodes, which is ignored in this study.

Almutairi and Mahfoudh [59] proposed UnderWater Distributed Virtual Force Algorithm (UW-DVFA) to address coverage holes and connectivity issues in 3D network architecture. The main objective of this study was to achieve full coverage and connectivity through random node deployment. To accomplish this, the proposed algorithm requires sensor nodes to redeploy their positions to more sparsely populated or unpopulated areas. Simulation results reveal that the proposed algorithm achieves full coverage when sensor nodes number from 400-500. The results of this study also show that delay decreases as the number of sensor nodes increases. One of the major issues of this study, however, is that the total number of sensor nodes is extremely high relative to the simulation area. Since underwater sensor nodes are extremely expensive, this makes the proposed algorithm inefficient for monitoring real-world underwater applications. Moreover, the authors assumed that by achieving full coverage, connectivity issues would be resolved. This is a false assumption as having sensor nodes cover the whole simulation area does not mean all nodes can communicate with each other. This means there is still the possibility of isolated nodes that cannot communicate with other sensor nodes, which hence degrade the network performance. Shadow zones negatively affect network connectivity and underwater communication as they create signals [60]. Therefore, it is necessary to deploy underwater nodes in such a way that ensures connectivity and minimizes signal transmission loss.

Li et al. [61] first analyzed an AoI for 3D network architecture that involved deploying a sink node to a predetermined location so that it can reach underwater sensors with minimal delay. Underwater sensors are deployed randomly after which each sensor adjusts its depth by adjusting its anchor wire connected to the sensor. The depth adjustment is based on AoI. The authors propose a node deployment algorithm for the sink node where it changes its position according to the column of the underwater sensors. The surface area is broken down into multiple columns. Each column has an underwater sensor that monitors an AoI. To minimize delay, the minimum distance between two nodes is when both are in a straight line. Thus, the proposed node deployment algorithm requires the sink node to change its position to achieve minimum distance and line up with a given underwater sensor. Although the proposed algorithm can minimize delay between a single underwater sensor and the sink node, its requirements increase the delay for other underwater sensors to the sink, due to the sink relocating. To avoid increasing delay in this way, the underwater sink should be deployed in the middle of an AoI. Or, this model can be utilized but with the use of multiple underwater sink nodes; however, this will increase costs. Another limitation of this study is that it did not address coverage holes, connectivity issues, and other performance metrics.

Zhang et al. [62] proposed a multiple sink node deployment algorithm for 2D network architecture to minimize E2ED and EC. This algorithm relies on Cuckoo optimization algorithm to optimize the location of sink nodes. In addition, this study evaluated the impact of multiple sink nodes in terms of E2ED and EC. The location of the sink nodes plays a crucial role in enhancing underwater communication. However, due to the high cost of sink nodes, it is necessary to require only the minimal number necessary to achieve reduced delay and EC. The results of this study reveal that the proposed algorithm achieves lower E2ED and EC. The simulation results also show that as the number of surface sinks increases, E2ED and EC decrease. However, this study relies on a large number of sensor nodes and sink nodes, which increases the cost. Another problem is that the authors assumed that sensor nodes are directly connected to the nearest sink node through single-hop fashion, which is not the case in most underwater applications. Commonly, underwater sensors transmit collected data to relay nodes to reach the sink node. This means that the proposed algorithm will not be an efficient approach to monitor most underwater applications. Moreover, this study ignores other sensor node deployment algorithms, such as the impact of deploying sensor nodes randomly, coverage holes, connectivity issues, cost, and other metrics of network performance. This study also relies on TDMA MAC protocol, which commonly results in high delay compared to other MAC protocols and hence is not an efficient approach for monitoring time-sensitive applications.

Liu et al. [63] proposed an optimal sensor node deployment for relay nodes and flow allocation called Alternative Flow and Relay-node Adjustment (AFRA) in 3D network architecture for UASNs. UASNs consist of sensor nodes, relay nodes, and sink nodes. Commonly, in 3D and 4D network architectures, data packets get transmitted through relay nodes to reach the sink node. Since underwater nodes are equipped with a very limited battery that is difficult to recharge or replace, this study aims to minimize EC through relocating relay nodes. This means that to extend the network lifetime, relay nodes are utilized. To achieve this, the distance between the sensor nodes, relay nodes, and sink nodes should be reduced. As the distance between nodes decreases, there is lower EC required to transmit packets between intended parties. Therefore, it is critical to find the optimal location of the relay nodes from the sensor nodes, other relay nodes, and the sink nodes, to minimize EC and hence extend the network lifetime. Particularly, this study proposes Relay-node Adjustment algorithm to readjust relay nodes to an optimal location to achieve the above goals. Simulation results reveal that the proposed algorithm can result in higher network lifetime compared to other algorithms. However, since sensor nodes are randomly deployed, coverage holes and connectivity issues may exist and hence this may not be an efficient solution for time-sensitive applications. Furthermore, this study relies on a large amount of sensors in a small target area, which increases the cost and the potential of collision.

Kahriman et al. [64] proposed sink node deployment algorithm to maximize coverage for 2D network architecture that only requires a low number of sensors. The placement of sink nodes plays a critical role not only in enhancing coverage, but also network performance. Therefore, it is very critical to deploy sink nodes appropriately to assist in meeting the QoS requirements [65]. The optimal location of the sink node is chosen when a sink node can connect with the highest number of underwater sensors. For example, if the sink node can communicate with 8 sensor nodes in location x and can communicate with 10 sensor nodes in location y, location y is considered the optimal location. The optimal location of the sink nodes is then compared to the positioning of the correlated number of underwater sensors to determine the total number of sensors required to maximize coverage. The study also analyzes the amount of power needed to transmit packets between intended parties. Analyzing the power level involves determining the amount of energy a sensor node must consume to transmit packets to the sink node. This means that the power level can tell us which algorithm can best minimize EC and optimally extend network lifetime. The simulation results reveal that the proposed algorithm achieves higher coverage rate and lower EC compared to a similar algorithm. However, coverage holes and connectivity issues still exist due to the method for locating the sensor nodes. In addition, EC could be further reduced if the authors consider the chance of collisions between sensor nodes.

Nazrul Alam and Haas [18] proposed an SND algorithm to address coverage and connectivity issues in 3D network architecture. This study focused on enhancing coverage and connectivity in a network where sensor nodes are deployed randomly. To achieve full coverage in such a random node deployment, many sensors must be deployed, but only a select number of the nodes need to be active to achieve full coverage. This study aims to choose the appropriate nodes to maintain as active to ensure full coverage while others are put in sleep mode to extend the network lifetime. The main objective of this paper was to analyze the relationship between maximum coverage and maximum connectivity in 3D network architecture. To accomplish this, the proposed algorithm divides the network into virtual cells using truncated octahedron tessellation technique, where only a single sensor node is active in each cell. Specifically, the proposed algorithm requires changing the radius of each cell in order to achieve k-coverage. Simulation results reveal that 2D network architecture outperforms 3D network architecture

TABLE 1. Summary of the design characteristics and common performance metrics of SND algorithms in UASNs.

Proposal	Year	SND Target	SND Strategy	Network Architecture	Mobility	Coverage	Connectivity	E2ED	EC
[67]	2014	Sen	Random	3D	No	✓			✓
RBVF, VFRBEC [57]	2018	Sen	Random	3D	No	✓			✓
DABVF [20]	2019	Sen	Random	3D	Yes	✓			✓
[59]	2017	Sen	Random	3D	Yes	✓	✓	✓	
[61]	2012	Sin	Random	3D	No			✓	
[62]	2016	Sin	Deterministic	2D	No			✓	✓
AFRA [63]	2017	Rel	Deterministic	3D	No			✓	✓
UW-DFA [18]	2015	Sen	Random	3D	Yes	✓	✓		✓
[66]	2019	Sin	Deterministic	2D, 3D	No			✓	✓
[68]	2009	Sen	Deterministic	3D	No		✓		✓

Sen: Sensor nodes, Rel: Relay nodes, Sin: Sink nodes

in 1-coverage, whereas 3D network architecture results in better coverage than 2D network architecture in k-coverage. In addition, the proposed algorithm uses selected nodes and hence consumes less energy. The main issue with this study is that it requires many sensors in each cell, hence this is not a cost-efficient approach due to the high cost of underwater nodes. One of the fundamental requirements to developing an optimal sensor location algorithm while achieving full coverage and connectivity is that the AoI is monitored with the minimum number of sensors. Since nodes are randomly deployed, another false assumption is that of full connectivity, which may not be achieved. Some nodes may be isolated from others and hence unable to connect to the other sensor nodes in the network. This also indicates that there is a possibility of coverage holes with this proposal. All of the aforementioned issues can impact network performance metrics, such as E2ED, EC, and PDR.

UASNs have been used to monitor different sizes of AoI. Sending a large amount of data from underwater sensors to a single sink may result in high delay. Therefore, Albarakati et al. [66] focused on the optimization of the multiple sink deployment for time-sensitive applications to monitor a large area. Particularly, the optimal location of the sink and relay nodes depends on the type of network architecture to achieve minimum E2ED and EC. The relay node is responsible for forwarding data from sensor nodes to the sink node. In addition, the proposed algorithm utilizes the characteristics of geometric distribution of AoI, which helps to achieve more accurate results for a real-world underwater environment. Simulation results reveal this proposed method can minimize E2ED and EC. However, the proposed method was not compared with other node deployment schemes. Instead, the authors compared their method to different network architectures. In addition, this study deployed underwater nodes randomly, which may result in high delay, coverage holes, and low connectivity. All these issues were ignored in this study. Deploying multiple sink nodes is suitable for a very large area to enhance network performance. However, the simulation area in this study is considered a small area and a single sink node should be sufficient if sensor nodes and relay nodes are deployed at appropriate locations.

There are many factors that play a critical role in resolving SND issues, such as SND target, SND strategy, network architecture, and mobility. In all underwater applications, the main goal is to enhance network performance metrics while maximizing coverage and connectivity and utilizing a low number of sensor nodes. To evaluate SND algorithms properly, it is necessary to first identify which factors and metrics have been considered in the development of an optimal SND algorithm that can meet the QoS requirements of a target application. In Table 1 the design factors and performance metrics that have been used in recent research papers are summarized. A check mark in the table means that the study focused on the given SND issue (e.g., coverage, connectivity, E2ED, EC) or compared the proposed algorithm with other SND algorithms based on specific network performance metrics. As is shown by the table, two network performance metrics are used in the evaluation: E2ED and EC.

As observed from the literature review, most research studies have focused on SND to resolve coverage holes, connectivity issues, and/or enhance selective performance metrics through random node deployment algorithms. Although related research papers enhance these factors, further enhancement can be achieved by considering the location of all types of underwater nodes (e.g., sensor, relay, and sink) through a deterministic distributed node deployment algorithm.

IV. METHODOLOGY

To develop an optimal SND algorithm for a real scenario of a particular underwater application, certain information is collected about the target application [69]. In addition, the researcher focused on ultra-deep-water (depth greater than 1,500 m) where more than one tsunami event has previously occurred [70], [71]. Therefore, in this study, the focus was on an application that monitors for the potential of tsunami in the Solomon Islands. Since 1926, this area has experienced several devastating tsunami events [72].

To start, GIS data, such as depth and simulation area, must be collected through NOAA, GeoMapApp, or Esri [46], [56], [73], as shown in Figure 8. Second, the requirements of the NOAA standard must be met, which require sensor nodes transmit collected data to the sink node every 15 min to assess the potential for a tsunami. In order to meet the requirements of the target application, this study focused on 3D network architecture where multiple nodes are placed at multiple depths. Next, this case study is evaluated based on a real underwater modem. For this, it is necessary to

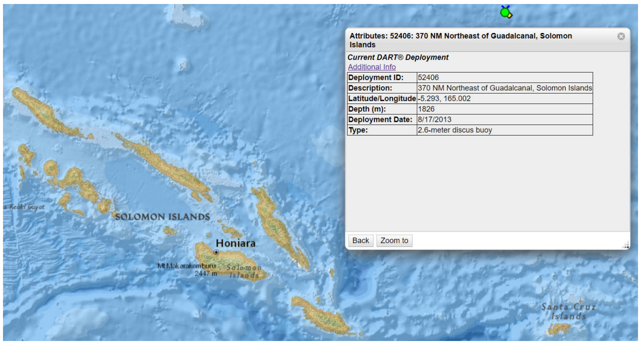

FIGURE 8. GIS solomon islands [46].

choose an appropriate underwater modem that can offer high data rate while consuming lower energy to extend network lifetime [74]. Using the above information allows for the development of an optimal SND algorithm that can meet the QoS requirements of the target application.

By considering the delay between nodes, packet size, available data rate, network size, network load, transmission range of underwater modem, and coverage of an AoI, the optimal distance between the underwater nodes is chosen to meet the QoS requirements of the tsunami application. The proposed SND scheme aims to minimize E2ED and EC while maximizing coverage and connectivity and minimizing cost using the characteristics of a real underwater modem. Our proposed node deployment algorithm relies on the GIS of the target area. Since this study is focused on detection of a tsunami event, the chosen setting for monitoring for tsunami was the Solomon Islands in the South Pacific Ocean. The delay between nodes depends on the available data rate, where the available data rate depends on the distance between nodes. Long distances between nodes result in lower available bandwidth, whereas short distances between nodes can offer higher data rates. Higher data rate results in lower delay and vice versa. To minimize delay and EC, the results suggested utilizing a higher data rate, small network size, small packet size, and low network load. In addition, since the cost of underwater nodes is extremely expensive compared to the cost of nodes in TWSNs [10], [29], it was necessary in this study to minimize the total number of underwater nodes utilized. The required number of sensor nodes increases as the AoI increases. In addition, the minimum number of nodes required to fully monitor the AoI relies on the sensing range.

Although higher overlapping areas can cause interference, these can also increase network reliability when a sensor node fails. High network reliability and low interference can be achieved by scheduling data transmissions properly. In such cases, overlapping will not be an issue. Most studies view overlap as always having a negative impact on network performance, but this is actually dependent on the amount of overlap between neighboring nodes and the technique of data transmission employed. Overlap between neighboring nodes can be handy to ensure reliability in case of sensor node failure. In other words, overlap between neighboring nodes

TABLE 2. Required information for designing suitable SND of target application.

Type of Information	Description
Target Application	Determine the target underwater application is considered as a real-time or non-real-time application.
Network Architecture	Select the appropriate network architecture (1D, 2D, 3D, or 4D) that is suitable to address the targeted issues.
Target Area	Collect GIS information about the AoI, such as depth level (shallow-water, deep-water, ultra-deep-water), topographic information, and size.
Characteristics of Underwater Nodes	Determine the available data rate, sensing range, and communication range of underwater nodes.
Communication Reliability	Determine how the flow of data from underwater nodes can reach the sink node (single-hop single path, single-hop multi-path, multi-hop single-path, or multi-hop multi-path).
Data Reporting System	Determine how data must be reported (event-driven or on-demand).
Mobility	Determine whether underwater nodes must be static or mobile to meet QoS requirements.
Coverage and Connectivity Techniques	Determine how underwater nodes are interconnected (1-coverage, k-coverage, 1-connectivity, k-connectivity).
Network setup	Determine the network size, packet size, and network load that is suitable to meet the requirements of the target application.

can be useful to broadcast packets through multi-hop multi-path networks. Therefore, it is necessary to have overlap between nodes to ensure reliability and maximize network performance in case of node failure. Table 2 lists the required information to propose a suitable SND algorithm that meets the QoS requirements of the target application.

In this work, underwater nodes are deployed with the focus being to meet the QoS requirements of the time-sensitive application while resolving coverage and connectivity issues. Particularly, underwater nodes are deployed in such a way so as to reduce the interference level and hence enhance network performance. In this work, a DDOGDA for 3D network architecture is developed in such a way so as to meet the QoS requirements of the target application. The main aim of this algorithm is to deploy underwater nodes in locations where the interference level is minimized. Minimizing the interference level can minimize delay and EC, which are critical metrics to meet the QoS requirements of such time-sensitive applications.

To deploy underwater nodes properly, the proposed algorithm divides the AoI into grids. First, an underwater sink is deployed in the middle of the AoI so that E2ED can be minimized. Next, each underwater modem is deployed one by one to ensure full coverage and connectivity. Each node must be deployed within the target AoI to ensure that deployed underwater nodes can monitor the whole AoI. If any node has been deployed outside the target AoI, it must relocate itself. Once a node has been deployed within the target AoI, the number of neighbors within the Sensing Range (SR) of each node must be discovered. Each node must have a neighbor to avoid node isolation. Next, each node must cover a unique area within the grid target area to avoid two nodes covering the same area and wasting network resources. Once the nodes meet the above criteria, this ensures the position of nodes with k-connectivity, avoids node isolation, and confirms 1-coverage. To double check that the chosen position of a node is appropriate, each node must transmit data packets and the sink node must receive these transmitted packets with no loss. If a node within the SR can reach only one node among a number of nodes, it must relocate itself to avoid node isolation. Similarly, if a node fails to cover a unique area within the target area, it must relocate itself to ensure k-connectivity and 1-coverage. When a node transmits data packets toward the sink node that cannot be received by the sink node, this indicates that the position of the node is not reachable and hence it must relocate itself. This process repeats until all underwater nodes have been deployed in an appropriate location within the AoI. The DDOGDA algorithm process is shown in Algorithm 1. Table 3 defines the meaning of each symbol in Algorithm 1.

The AoI of interest is divided into nine cells. In each cell, one only sensor must exist to achieve 1-coverage and hence minimize collisions, which helps to extend network lifetime by minimizing the EC. In our proposed algorithm, the sensing range is assumed to be half of the communication range to ensure full connectivity. This way, each sensor can connect with the next hop node on the same depth level and the node on the lower depth level as they are both within its SR. To further increase communication reliability, each sensor can reach other nodes using its Communication Range (CR). Figure 9 shows how underwater nodes are deployed and communicate with each other using the proposed node deployment algorithm.

The location of sensor nodes and relay nodes is determined according to the simulation area from NOAA to monitor for a potential tsunami for the Solomon Islands. Both sensor nodes and relay nodes can reach the sink node through single-hop or multi-hop, depending on the location of the underwater nodes. In addition, sensor nodes and relay nodes can transmit packets to the sink node via single-path or multi-path. Underwater nodes are deployed at different depths to monitor the entire target area. Since the location of the underwater nodes is predetermined, this study assumes that underwater nodes do not move. This can be achieved by anchoring the nodes to ensure the underwater network is a static network. This study assumed that the sink node is not energy constrained due to its ability to use renewable energy sources (e.g., solar energy), while the sensor and relay nodes have limited energy and cannot be recharged. Since our proposed system depends on 3D network architecture, a lower power level is needed and hence this helps to extend the network lifetime and minimize E2ED.

Algorithm 1 DDOGDA Algorithm Process

```
Objective: To deploy underwater nodes properly, in a
manner that improves key factors of performance
metrics to meet the QoS requirements of the target
application.
Input: Node_i, D_p
Output: R_p, Pos_i
Initialize: Pos_i = 0, T_sn = 9, R_p = 0
while Node_i ∈ T_sn do
    Set the initial position of Node_i
    if Pos_i ∈ G_ta then
        Count N_n
        if N_n within S_r > 1 & Pos_i cover a unique area
          within G_ta then
            Connectivity = k-connectivity
            Avoid node isolation
            Coverage = 1-coverage
            Node_i transmits D_p to S_n
            if D_p of Node_i can reach S_n then
                Set Node_i = Pos_i
            else
                Change the initial position of Node_i
                if Ack_p is received then
                    R_p++
                else
                    Retransmit L_p
                end
            end
        else
            Change the initial position of Node_i
        end
    else
        Change the initial position of Node_i
    end
end
Report Pos_i
Report R_p
```

TABLE 3. DDOGDA reference table.

Symbol	Description
$Node_i$	represents the source node i where i refers to $\{1, 2, \ldots n\}$.
D_p	represents the data packets.
R_p	represents that the sink node has received the transmitted data packets.
Pos_i	represents the position of node i.
T_{sn}	represents the total number of source nodes.
G_{ta}	represents the grid target area.
N_n	represents the number of neighbor nodes.
S_r	represents sensing range.
S_n	represents the sink node.
Ack_p	represents the acknowledgment packet.
L_p	represents lost packets.

V. EVALUATION AND RESULTS

This study analyzes the performance of underwater communication based on the transmitted data from source nodes toward the sink node. To save lives, the tsunami monitoring application requires minimum delay and maximized PDR. To achieve the QoS requirements of this type of application, different node deployment algorithms must

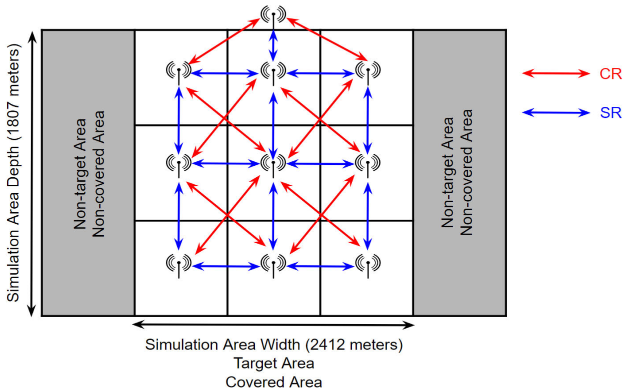

FIGURE 9. Proposed node deployment algorithm.

be investigated. To optimize the underwater communication in the tsunami application, the impact of different node deployment algorithms must be analyzed through common network performance metrics. Based on the analysis of the literature review, many recent papers have addressed the performance of underwater communication issues through random [6], [22], [23], [36], [44], [58], [63], [66], tetrahedron [11], [18], [44], cuboid [11], [18], [29], [32], [44], triangular [18], [35], [36], pipeline [6], and grid node deployment algorithms. Therefore, this research evaluates the proposed algorithm compared to other node deployment algorithms in terms of E2ED, EC, and PDR to prove how the proposed algorithm can further enhance the performance of underwater communication.

A. SIMULATION SETUP

This study utilized the Aqua-Sim tool, which is an NS-2 simulator for evaluating different node deployment algorithms [75], [76]. To assess the network performance of the proposed, random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms in terms of E2ED, EC, and PDR, the network is set up as an ad-hoc network topology so that meeting the QoS requirements of the target application is possible. In this network topology, some underwater nodes must rely on the multi-hop fashion to transmit data packets to the sink node due to the large distance between sensor nodes and the sink node. This study relies on homogeneous nodes where all nodes have the same characteristics in terms of data rate, energy consumption, operating frequency, communication range, SR, etc. In this study, all underwater nodes are stationary and deployed in a specific location according to the proposed algorithm. In the random node deployment algorithm, underwater nodes are deployed randomly. This study relies on a random function to choose random locations within the AoI for the random node deployment algorithm. In the tetrahedron, cuboid, triangular, and pipeline node deployment algorithms, underwater nodes are deployed deterministically in the AoI to shape tetrahedron, cuboid, triangular, and pipeline. In the grid node deployment algorithm, underwater nodes are deployed in random locations on each grid. Table 4 illustrates all simulation parameters utilized in this study [74], [77].

TABLE 4. Simulation parameters.

Parameters	Value
Radio propagation model	Underwater Propagation
Channel	Underwater Channel
Routing protocol	Vector-based Forward (VBF)
Number of sensor nodes	9
Number of sink nodes	1
Simulation area	2412 m × 1807 m
Simulation time	3600 s
Initial energy	10,000 J
Transmission power	2.0 W
Receiving power	0.8 W
Idle power	0.008 W
Operating frequency	26.77 kHz - 44.62 kHz
Data rate	17.8 Kbps
Network load	0.05 packets/sec
Packet size	60 Bytes
Control packet size	20 Bytes
Type of traffic	Constant Bit Rate (CBR)
Communication range	1200 m
Sensing range	600 m

B. PERFORMANCE METRICS

This study evaluated the proposed algorithm compared to the random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms in terms of E2ED, EC, and PDR. The details of these network performance metrics are described in the following:

1) End-to-End Delay (E2ED): is the total time each packet takes from source nodes to destination node divided by total number of received data packets. This is measured in seconds (s). E2ED can be calculated using:

$$E2ED\ [s] = \frac{TD}{TR} \tag{1}$$

where, TD = total delay of all packets sent from source nodes to sink node; TR = total number of received packets from source nodes to sink node.

2) Energy Consumption (EC) is the sum of the energy consumed by all nodes, including transmitted power (E_{tx}), receiving power (E_{rx}), and idle power (E_{idl}), to transmit packets between parties. This is measured in joules (J). EC can be calculated using:

$$EC\ [J] = \sum_{i=1}^{n} (E_{tx} + E_{rx} + E_{idl}) \tag{2}$$

where, n = total number of nodes in the network.

3) Packet Delivery Ratio (PDR) can be defined as the ratio of the total number of received packets at the sink node (TR_{sn}) to the total number of sent packets (TS). PDR can be calculated using:

$$PDR = (\frac{TR_{sn}}{TS}) \times 100 \tag{3}$$

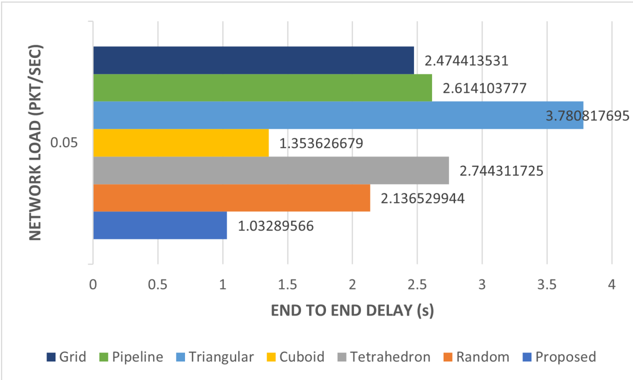

FIGURE 10. End-to-end delay.

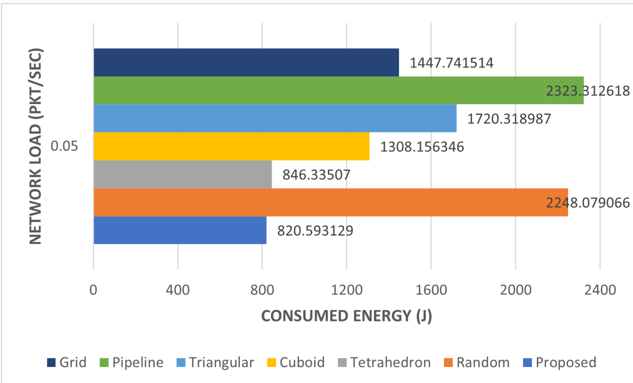

FIGURE 11. Energy consumption.

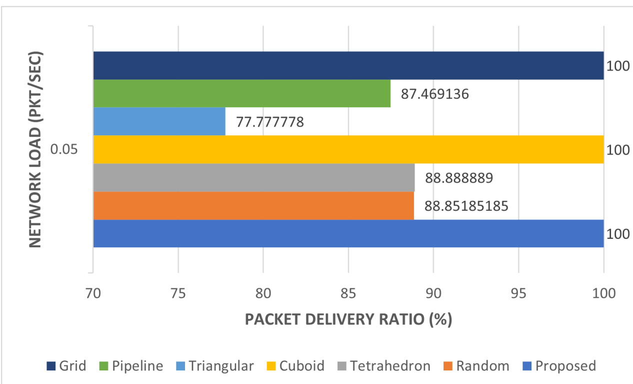

FIGURE 12. Packet delivery ratio.

C. RESULTS AND ANALYSIS

In this section, first the network performance of the DDOGDA algorithm is evaluated and then it is compared to six other different node deployment algorithms: random, tetrahedron, cuboid, triangular, pipeline, and grid. In particular, this study compares these algorithms in terms of E2ED (see Figure 10), EC (see Figure 11), and PDR (see Figure 12). Since this study relies on 3D network architecture, it utilizes a multi-hop network with nine sensor and relay nodes laid underwater and a single sink node at the surface level. The underwater nodes rely on a multi-hop network so packets from sensor nodes can reach the sink node through relay nodes. To ensure a fair comparison, it is critical to consider the coverage and connectivity ratio of the DDOGDA and other SND algorithms. Simulation results show that the DDOGDA algorithm results in maximum coverage, while other algorithms could not resolve the coverage holes. Similarly, the connectivity ratio of the DDOGDA, cuboid, and grid algorithms offer the maximum connectivity ratio while the connectivity issues remain a major problem in the random, tetrahedron, triangular, and pipeline algorithms. In terms of both coverage and connectivity, the DDOGDA offers the highest results in comparison to other algorithms. This helps to ensure that the DDOGDA can monitor the entire AoI and hence can generate an early warning for evacuation in the event of a tsunami more effectively.

Figure 10 shows the E2ED of different SND algorithms using the DDOGDA and compares the results to those of the random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms. The position of underwater nodes in any SND algorithm has a great impact on E2ED. The larger the distance between underwater nodes, the higher the E2ED, which as a result may endanger human lives. In addition, to place underwater nodes properly, the location of the sensor, relay, and sink nodes must be all taken into account. Deploying only sensor nodes properly and ignoring relay and sink nodes does not guarantee better network performance due to potential communication issues, such as coverage holes and connectivity issues. Therefore, the lower the E2ED, the higher the chance to save lives by generating an early warning for evacuation. This means that in order to minimize E2ED, it is recommended that researchers deploy underwater nodes close to one another while addressing other SND issues, such as coverage holes and connectivity issues. The E2ED varies depending on the location of the underwater nodes, where the DDOGDA algorithm offers the lowest delay compared to other node deployment algorithms. The E2ED delay in DDOGDA, random, tetrahedron, cuboid, triangular, pipeline, and grid is as follows: 1.03289566 s, 2.136529944 s, 2.744311725 s, 1.353626679 s, 3.780817695s, 2.614103777s, 2.474413531s, respectively. This shows that the DDOGDA can transfer packets to the sink node with the minimum delay in comparison to other algorithms and therefore can save human lives by generating an early warning for evacuation. In particular, DDOGDA reduces the E2ED as compared to random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms by about 106.85%, 165.69%, 31.05%, 266.04%, 153.05%, and 139.56%, respectively. This shows that the proposed algorithm can deliver packets much faster than other SND algorithms, which again correlates with greater effectiveness in generating an early warning for evacuation and saving lives. This means that delivering the packets with minimum delay can assist in avoiding the potential of catastrophic events resulting in fatalities.

Since the underwater nodes can be deployed either randomly or deterministically, neither can guarantee lower E2ED in any target application. This means that choosing the appropriate node deployment algorithm is necessary to meet the requirements of the target application. The DDOGDA, cuboid, tetrahedron, triangular, and pipeline node deployment algorithms rely on deterministic node deployment and their results vary. For example, the results of DDOGDA and cuboid node deployment algorithms provide the lowest E2ED while pipeline, tetrahedron, and random and grid deploy underwater nodes randomly. Based on the results of E2ED, the following node deployment algorithms are ranked from lowest to highest E2ED: DDOGDA, cuboid, random, grid, pipeline, tetrahedron, and triangular, respectively. This indicates that the DDOGDA outperforms the other node deployment algorithms in terms of E2ED and hence is more suitable for time-sensitive applications, such as flood, volcanic eruption, tsunami, earthquake, pipeline malfunction/break/leak, and military. The results above also show that random and grid node deployment algorithms outperform other deterministic node deployment algorithms, such as the pipeline, tetrahedron, and triangular. Moreover, the findings of this research can assist future researchers in selecting the appropriate node deployment algorithms for meeting the requirements of their target applications.

Figure 11 shows the total EC of DDOGDA and compares the results to those of the random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms. The EC differs from one SND algorithm to the next as each one has its unique way of transmitting packets to intended parties. A higher number of packets received results in higher EC and vice versa. Similarly, higher collision rate results in higher EC and vice versa. As can be observed in Figure 11, the DDOGDA consumes the smallest amount of energy followed by the tetrahedron, cuboid, grid, triangular, random, and pipeline node deployment algorithms. In particular, the DDOGDA consumes 820.593129 joules while the tetrahedron, cuboid, grid, triangular, random, and pipeline consume 846.33507 J, 1308.156346 J, 1447.741514 J, 1720.318987 J, 2248.079066 J, 2323.312618 J, respectively. This shows that the DDOGDA consumes the least energy among the examined SND algorithms and hence can extend network lifetime in comparison to the tetrahedron, cuboid, grid, triangular, random, and pipeline node deployment algorithms by about 3.14%, 59.42%, 76.43%, 109.64%, 173.96%, and 183.13%, respectively. This shows that the DDOGDA algorithm achieves the lowest EC in comparison to the other SND algorithms and hence can maximize network lifetime, which makes it more appropriate to monitor time-sensitive applications. Moreover, extending the network lifetime of the UASN makes it more reliable and efficient by reducing its total cost. Based on the above results, it is clear that when underwater nodes are deployed deterministically, such as with DDOGDA, tetrahedron, and cuboid node deployment algorithms, less energy is consumed than when the nodes are deployed randomly, such as with grid and random node deployment algorithms. Similarly to the E2ED, not all node deployment algorithms that utilize deterministic techniques for underwater nodes can guarantee lower EC than those that use random techniques. The above results show that the grid node deployment algorithm consumes less energy than the triangular node deployment algorithm. Similarly, the random node deployment algorithm consumes lower EC than the pipeline node deployment algorithm. Therefore, it is necessary to collect information about the target application, including the GIS data of its target area and other information, to determine the most appropriate SND algorithm.

To decide the best SND algorithm in this study, it is critical to determine the type of target application (i.e., time-sensitive or non-time-sensitive). Since this research focuses on an application used for monitoring tsunamis, which is clearly a time-sensitive application, minimizing EC is not a high priority in comparison to optimizing E2ED and PDR. In the case of a disaster-monitoring application, the SND algorithm is less valuable if reported data from underwater nodes takes a very long time to reach the sink node or if some of the reported data does not reach the sink node. This endangers humans' lives and hence does not meet the requirements of the target application. Therefore, for time-sensitive applications, E2ED and PDR are given higher priority over EC. However, enhancing E2ED and PDR while also consuming lower EC is indispensable, as underwater nodes are costly and have a limited battery. Once the battery of an underwater node is drained, it must be replaced as it cannot be recharged. In this study, the DDOGDA consumes the lowest E2ED and EC in comparison to cuboid and grid node deployment algorithms, which all offer maximum PDR. Since the proposed algorithm can outperform other SND algorithms on multiple factors, this study concludes that the proposed algorithm is the most suitable for time-sensitive monitoring applications.

In Figure 12, the PDR of the DDOGDA algorithm is presented and compared to the results of the random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms. The PDR result varies depending on the node deployment strategy utilized. A higher PDR is one of the fundamental requirements to ensure that all generated packets are successfully delivered to the sink node. It can be observed from Figure 12 that the DDOGDA, cuboid, and grid node deployment algorithms achieve higher PDR compared to the random, tetrahedron, triangular, and pipeline node deployment algorithms. Due to their sparse node deployment, random, tetrahedron, triangular, and pipeline algorithms are not able to deliver large numbers of packets to the sink node. This indicates that these other SND algorithms experience coverage holes, connectivity issues, and/or a large number of Total Collisions (TC), which indicates they are not suitable for time-sensitive monitoring applications. To maximize the PDR in the random, tetrahedron, triangular, and pipeline algorithms requires additional nodes, which increases the total cost of the system. Although the DDOGDA, cuboid, and grid algorithms result in higher PDR compared to the other SND algorithms, the DDOGDA protocol achieves the maximum PDR while minimizing E2ED and EC, in comparison to the cuboid and grid algorithms. This means that the DDOGDA algorithm again outperforms the other SND algorithms.

In particular, the DDOGDA, cuboid, and grid algorithms achieve 100% while the random, tetrahedron, triangular, and pipeline achieve 88.85%, 88.89%, 77.78%, 87.47%, respectively. One of the main reasons that these node deployment algorithms did not offer maximum PDR is that in their scenarios some packets from underwater nodes cannot reach the sink node due to node isolation and/or packet collisions.

Moreover, the DDOGDA offers maximal PDR in comparison to that of the random, tetrahedron, triangular, and pipeline algorithms due to their coverage issues, by about 11.15%, 11.11%, 22.22%, and 12.53%, respectively. This indicates that the DDOGDA is considerably more suitable for tsunami monitoring underwater applications. The proposed algorithm can deliver all packets transmitted from underwater nodes while other SND algorithms miss some packets. In the context of disaster warning, missing some packets might send authorities incorrect data on what appropriate actions must be taken in a given situation, which could endanger citizens and delay alerts regarding catastrophic hazards. Therefore, it is a priority that all packets from underwater nodes to the sink node are delivered so that appropriate action can be taken. The above results show that the highest PDR is offered by two algorithms, the proposed and the cuboid, which rely on deploying underwater nodes deterministically. However, deploying underwater nodes using deterministic technique does not guarantee better PDR than those of the one relying on the random technique to meet the requirements of any target applications. The above result shows that some random algorithms outperform deterministic ones. In particular, the grid algorithm achieves higher PDR than tetrahedron by about 11.11%. Similarly, the random algorithm offers higher PDR than the pipeline and triangular algorithms by about 1.56% and 12.46%, respectively. Nevertheless, the deterministic approach has a higher chance of meeting the requirements of the target applications by requiring a lower number of underwater nodes and hence costing less.

VI. CONCLUSION

In this paper, the author develops a DDOGDA algorithm for a time-sensitive application in UASNs. The proposed DDOGDA relies on a deterministic node deployment mechanism to address coverage holes and connectivity issues while meeting the QoS requirements. This study confirms that the DDOGDA should be considered the most appropriate algorithm for use with a time-sensitive monitoring application designed to save human lives by generating an early warning for evacuation, due to its E2ED, EC, and PDR. The DDOGDA addresses the coverage holes, connectivity issues, and low network performance by utilizing an efficient node deployment scheme that improves underwater communication. Moreover, this study compared the results of the DDOGDA algorithm to those of the random, tetrahedron, cuboid, triangular, pipeline, and grid node deployment algorithms to highlight the differences between them. In particular, the DDOGDA is the most appropriate for a tsunami-monitoring underwater applications, followed by the cuboid, random, grid, pipeline, tetrahedron, and triangular algorithms, respectively. Although the cuboid and grid algorithms achieve maximum PDR, they require higher E2ED than DDOGDA, do not cover the entire AoI, and consume much higher EC due to a high number of collisions. In short, the proposed DDOGDA algorithm presents significant enhancements in comparison to other SND algorithms in terms of E2ED, EC, and PDR, which makes it the most suitable for tsunami-monitoring underwater applications. This study can serve as a guide for other researchers on how to meet the QoS requirements of target applications.

VII. FUTURE WORK

Since this study focused on stationary nodes, further investigation is needed to evaluate the following scenarios: mobile network, non-delay sensitive applications, 1D network architecture, 2D network architecture, 4D network architecture, single-hop single path, single-hop multi-path, multi-hop single-path, k-coverage, 1-connectivity, and large-scale network. Further investigation is also needed to evaluate different characteristics of underwater modems. In particular, further improvement of this research can be achieved by investigating higher data rates, communication range, and sensing range to deliver packets further with a lower number of collisions and hence minimize delay and energy consumption. Moreover, the DDOGDA algorithm needs to be evaluated in different underwater application domains and other network performance metrics. This research can also be extended to other underwater applications, such as military surveillance, environmental monitoring, pollution monitoring, oceanographic data compilation, assisted navigation, mine detection, and oil/gas spill detection. This study can also assist in other domains, such as the Internet of Things (IoT), WSN, and underground communication in monitoring environmental conditions and reporting potential disaster more reliably and efficiently. In particular, this research can assist authorities and industries in appropriate decision-making based on the current status of weather conditions, air quality, climate monitoring, and natural hazards. This functionality can also be extended to collect data from swarm drones that monitor critical areas to the ground station.

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