B.Sc. in Computer Science and Engineering Thesis

The Study of Coverage and Connectivity in an Underwater Sensor Network

Submitted by

Major Kazi Israt Zahan
201014013

Major Md. Asheque Alahi
201014016

Priyanka Rani
201014044

Supervised by

Dr. Mahmuda Naznin
Associate Professor, BUET

Department of Computer Science and Engineering
Military Institute of Science and Technology

CERTIFICATION

This thesis paper titled **“The Study of Coverage and Connectivity in an Underwater Sensor Network ”**, submitted by the group as mentioned below has been accepted as satisfactory in partial fulfillment of the requirements for the degree B.Sc. in Computer Science and Engineering on December 2013.

Group Members:

Major Kazi Israt Zahan
Major Md. Asheque Alahi
Priyanka Rani

Supervisor:

————————————-

Dr. Mahmuda Naznin
Associate Professor
BUET

CANDIDATES' DECLARATION

This is to certify that the work presented in this thesis paper is the outcome of the investigation and research carried out by the following students under the supervision of Dr. Mahmuda Naznin, Associate Professor, BUET, Dhaka, Bangladesh.

It is also declared that neither this thesis paper nor any part thereof has been submitted anywhere else for the award of any degree, diploma or other qualifications.

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Major Kazi Israt Zahan
201014013

——————————————-

Major Md. Asheque Alahi
201014016

——————————————-

Priyanka Rani
201014044

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Major Kazi Israt Zahan
Major Md. Asheque Alahi
Priyanka Rani

ABSTRACT

Oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance are the applications of Underwater sensor nodes. Moreover, unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with sensors, will enable the exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. Underwater acoustic networking is the enabling technology for these applications. Underwater networks consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. In this thesis, we have made a detailed survey of different research work on underwater sensor network. Furthermore, we provide our research overview and comparative study in a table format.

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LIST OF ABBREVIATION

CB : Cube

HP : Hexagonal Prism

RD : Rhombic Dodecahedron

TO : Truncated Octahedron

UWSN : Under Water Sensor Network

COS : Coverage Optimization by Sampling

CHAPTER 1

INTRODUCTION

1.1 Underwater Sensor Network

Underwater sensor nodes will find applications in oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Moreover, unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with sensors, will enable the exploration of natural undersea resources and gathering of scientific data in collaborative monitoring missions. Underwater acoustic networking is the enabling technology for these applications. Two major differences between terrestrial sensor networks and underwater sensor networks are network dimensionality (i.e., 3D instead of 2D) and communication medium (i.e., acoustic instead of radio). Terrestrial wireless sensor networks, where sensors are deployed on earth surface and where the height of the network is smaller than the transmission radius of a node, can usually be modeled as two-dimensional (2D) networks. However, in many underwater sensor networks, nodes may be placed at different depths of an ocean and thus these networks must be modeled as three-dimensional (3D) networks.To make these applications viable, there is a need to enable underwater communications among underwater devices. Underwater sensor nodes and vehicles must possess self-configuration capabilities, i.e., they must be able to coordinate their operation by exchanging configuration, location and movement information, and to relay monitored data to an onshore station. Wireless underwater acoustic networking is the enabling technology for these applications. Under-Water Acoustic Sensor Networks (UW-ASNs) consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area. To achieve this objective, sensors and vehicles self-organize in an autonomous network which can adapt to the characteristics of the ocean environment [1]. A broad range of applications for underwater acoustic sensor networks are as follows :

- **Ocean sampling networks:** Networks of sensors and AUVs, such as the Odyssey-class AUVs, can perform synoptic, cooperative adaptive sampling of the 3D coastal ocean environment.
- **Undersea explorations:** Underwater sensor networks can help detecting underwater oilfields or reservoirs, determine routes for laying undersea cables, and assist in exploration for valuable minerals.
- **Environmental monitoring:** UW-ASNs can perform pollution monitoring (chemical, biological and nuclear). Example: It may be possible to detail the chemical slurry of antibiotics, estrogen-type hormones and insecticides to monitor streams, rivers, lakes and ocean bays (water quality in situ analysis)
- **Disaster prevention:** Sensor networks that measure seismic activity from remote locations can provide tsunami warnings to coastal areas or study the effects of submarine earthquakes (seaquakes).
- **Assisted navigation:** Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.
- **Mine reconnaissance.** The simultaneous operation of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.
- **Distributed tactical surveillance:** AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems. Example: a 3D underwater sensor network is designed for a tactical surveillance system that is able to detect and classify submarines, small delivery vehicles (SDVs) and divers.

Underwater networking is a rather unexplored area although underwater communications have been experimented since World War II, when, in 1945, an underwater telephone was developed in the United States to communicate with submarines [2]. Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive sea water only at extra low frequencies (30300 Hz), which require large antenna and high transmission power. For example, the Berkeley Mica 2 Motes, the most popular experimental platform in the sensor networking community, have been reported to have a transmission range of 120 cm in underwater at 433 MHz by experiments performed at the Robotic Embedded Systems Laboratory (RESL) at the University of Southern California. Optical waves do not suffer from such high attenuation but are affected by scattering. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams. Thus, links in underwater networks are based on acoustic wireless communications [3]. The traditional approach for ocean-bottom or ocean-column monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the instruments [4]. This approach has the following disadvantages:

- **No real-time monitoring:** The recorded data cannot be accessed until the instruments are recovered, which may happen several months after the beginning of the monitoring mission. This is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring.
- **No on-line system reconfiguration:** Interaction between onshore control systems and the monitoring instruments is not possible. This impedes any adaptive tuning of the instruments, nor is it possible to reconfigure the system after particular events occur.
- **No failure detection:** If failures or mis-configurations occur, it may not be possible to detect them before the instruments are recovered. This can easily lead to the complete failure of a monitoring mission.
- **Limited storage capacity:** The amount of data that can be recorded during the monitoring mission by every sensor is limited by the capacity of the onboard storage devices (memories, hard disks).

Therefore, there is a need to deploy underwater networks that will enable real-time monitoring of selected ocean areas, remote configuration and interaction with onshore human operators. This can be obtained by connecting underwater instruments by means of wireless links based on acoustic communication. Many researchers are currently engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Although there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays [5], require very efficient and reliable new data communication protocols. Major challenges in the design of underwater acoustic networks are:

1. The available bandwidth is severely limited.
2. The underwater channel is severely impaired, especially due to multi-path and fading.
3. Propagation delay in underwater is five orders of magnitude higher than in radio frequency (RF) terrestrial channels, and extremely variable.
4. High bit error rates and temporary losses of connectivity (shadow zones) can be experienced, due to the extreme characteristics of the underwater channel.
5. Battery power is limited and usually batteries cannot be recharged, also because solar energy cannot be exploited.
6. Underwater sensors are prone to failures because of fouling and corrosion.

The communication architecture of underwater acoustic sensor networks can be reference architectures for two-dimensional and three dimensional underwater networks, and several types of autonomous underwater vehicles (AUVs) which can enhance the capabilities of underwater sensor networks. The network topology is in general a crucial factor in determining the energy consumption, the capacity and the reliability of a network. Hence, the network topology should be carefully engineered and post-deployment topology optimization should be performed, when possible. Underwater monitoring missions can be extremely expensive due to the high cost of underwater devices. Hence, it is important that the deployed network be highly reliable, so as to avoid failure of monitoring missions due to failure of single or multiple devices. For example, it is crucial to avoid designing the network topology with single points of failure that could compromise the overall functioning of the network.The network capacity is also influenced by the network topology. The capacity of the underwater channel is severely limited. it is very important to organize the network topology such a way that no communication bottleneck is introduced. The communication architectures introduced as a basis for discussion of the challenges associated with underwater acoustic sensor networks. The underwater sensor network topology is an open research issue in itself that needs further analytical and simulative investigation from the research community. Static two-dimensional UW-ASNs for ocean bottom monitoring is constituted by sensor nodes that are anchored to the bottom of the ocean. Its typical applications may be environmental monitoring, or monitoring of underwater plates in tectonics [6]. Static three-dimensional UW-ASNs for ocean column monitoring includes networks of sensors whose depth can be controlled by means of different techniques and may be used for surveillance applications or monitoring of ocean phenomena (ocean biogeochemical processes, water streams, pollution).Three-dimensional networks of autonomous underwater vehicles (AUVs) include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles.

1.2 Two-dimensional Underwater Sensor Networks

A reference architecture for two-dimensional underwater networks is shown in Figure 1.1. A group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. Underwater sensor nodes are interconnected to one or more underwater sinks (uw-sinks) by means of wireless acoustic links. Uw-sinks, as shown in Figure 1.1, are network devices in charge of relaying data from the ocean bottom network to a surface station. To achieve this objective, uw-sinks are equipped with two acoustic transceivers, namely a vertical and a horizontal transceiver. The horizontal transceiver is used by the uw-sink to communicate with the sensor nodes in order to (i) send commands and configuration data to the sensors (uw-sink to sensors); (ii) collect monitored data (sensors to uw-sink). The vertical link is used by the uw-sinks to relay data to a surface station. In deep water applications, vertical transceivers must be long range transceivers as the ocean can be as deep as 10 km. The surface station is equipped with an acoustic transceiver that is able to handle multiple parallel communications with the deployed uw sinks. It is also endowed with a long range RF and/or satellite transmitter to communicate with the onshore sink (os-sink) and/or to a surface sink (s-sink). Sensors can be connected to uw-sinks via direct links or through multi-hop paths. In the former case, each sensor directly sends the gathered data to the selected uw-sink. However, in UW-ASNs, the power necessary to transmit may decay with powers greater than two of the distance [7], and the uw-sink may be far from the sensor node. Consequently, although direct link connection is the simplest way to network sensors, it may not be the most energy efficient solution. Furthermore, direct links are very likely to reduce the network throughput because of increased acoustic interference due to high transmission power. In case of multi-hop paths, as in terrestrial sensor networks [8], the data produced by a source sensor is relayed by intermediate sensors until it reaches the uw-sink. This may result in energy savings and increased network capacity, but increases the complexity of the routing functionality. In fact, every network device usually takes part in a collaborative process whose objective is to diffuse topology information such that efficient and loop free routing decisions can be made at each intermediate node. This process involves signaling and computation. Since energy and capacity are precious resources in underwater environments, as discussed above, in UW-ASNs the objective is to deliver event features by exploiting multi-hop paths and minimizing the signaling overhead necessary to construct underwater paths at the same time.

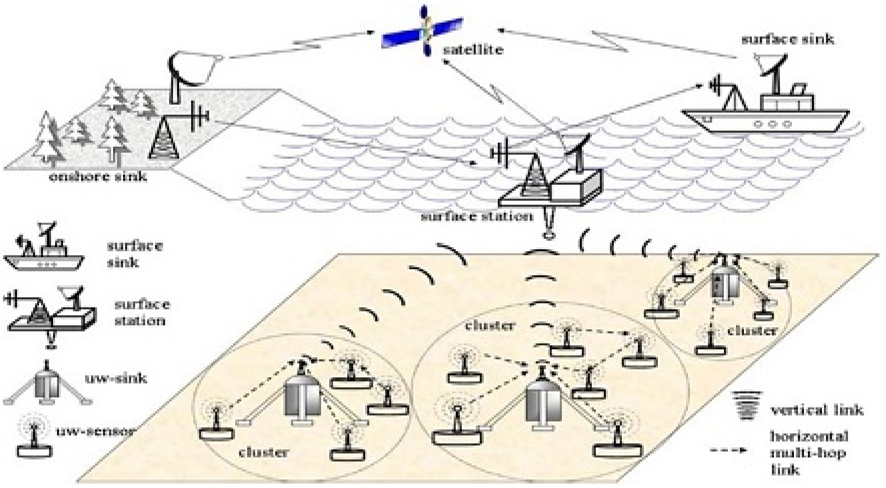


Figure 1.1: Architecture for 2D underwater sensor networks [6]

1.3 Three-dimensional Underwater Sensor Networks

Three dimensional underwater networks are used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom sensor nodes, i.e., to perform cooperative sampling of the 3D ocean environment. In three-dimensional underwater networks, sensor nodes float at different depths in order to observe a given phenomenon. One possible solution would be to attach each uw-sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node [9]. However, although this solution allows easy and quick deployment of the sensor network, multiple floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering. For these reasons, a different approach can be to anchor sensor devices to the bottom of the ocean. In this architecture, depicted in Figure 1.2, each sensor is anchored to the ocean bottom and equipped with a floating buoy that can be inflated by a pump. The buoy pushes the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire that connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor. A challenge to be addressed in such an architecture is the effect of ocean currents on the described mechanism to regulate the depth of the sensors. Many challenges arise with such an architecture, that need to be solved in order to enable 3D monitoring, including:

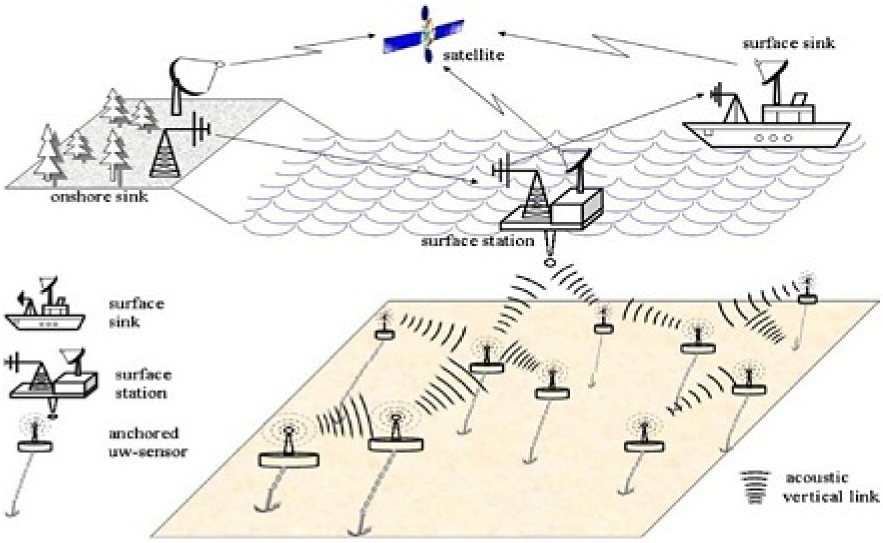


Figure 1.2: Architecture for 3D underwater sensor networks [6]

- **Sensing coverage:** Sensors should collaboratively regulate their depth in order to achieve 3D coverage of the ocean column, according to their sensing ranges. Hence, it must be possible to obtain sampling of the desired phenomenon at all depths.
- **Communication coverage:** Since in 3D underwater networks there may be no notion of uw-sink, sensors should be able to relay information to the surface station via multi-hop paths. Thus, network devices should coordinate their depths in such a way that the network topology is always connected, i.e. at least one path from every sensor to the surface station always exists.

While most terrestrial sensor networks can usually be modeled as two dimensional (2D) networks, these underwater sensor networks must be modeled as 3D networks. There are two different network architectures for 3D underwater sensor networks The first one is a hierarchical architecture that uses a relatively small number of robust backbone nodes to create the network where a large number of inexpensive sensors communicate with their nearest backbone nodes, and packets from a backbone node to the sink is routed through other backbone nodes. This hierarchical approach allows creating a network of smaller number of expensive backbone nodes while keeping the mobile sensors simple and inexpensive. Along with network topology, we also study energy efficiency and frequency reuse issues for such 3D networks. The second approach is a nonhierarchical architecture which assumes that all nodes are identical and randomly deployed. It partitions the whole 3D network space into identical cells and keeps one node active in each cell such that sensing coverage and connectivity are maintained while limiting the energy consumed. Sensing and communication coverage in a 3D environment are rigorously investigated in [10]. The diameter, minimum and maximum degree of the reachability graph that describes the network are derived as a function of the communication range, while different degrees of coverage for the 3D environment are characterized as a function of the sensing range. These techniques could be exploited to investigate the coverage issues in UW-ASNs.

1.3.1 Sensor Networks with Autonomous Underwater Vehicles

AUVs can function without tethers, cables, or remote control, and therefore they have a multitude of applications in oceanography, environmental monitoring, and underwater resource study. Previous experimental work has shown the feasibility of relatively inexpensive AUV submarines equipped with multiple underwater sensors that can reach any depth in the ocean [11]. Hence, they can be used to enhance the capabilities of underwater sensor networks in many ways. The integration and enhancement of fixed sensor networks with AUVs is an almost unexplored research area which requires new network coordination algorithms such as:

- **Adaptive sampling:** This includes control strategies to command the mobile vehicles to places where their data will be most useful. This approach is also known as adaptive sampling and has been proposed in pioneering monitoring missions such as [12]. For example, the density of sensor nodes can be adaptively increased in a given area when a higher sampling rate is needed for a given monitored phenomenon.
- **Self-configuration:** This includes control procedures to automatically detect connectivity holes due to node failures or channel impairment and request the intervention of an AUV.

Furthermore, AUVs can either be used for installation and maintenance of the sensor network infrastructure or to deploy new sensors. They can also be used as temporary relay nodes to restore connectivity. One of the design objectives of AUVs is to make them rely on local intelligence and less dependent on communications from online shores [13]. In general, control strategies are needed for autonomous coordination, obstacle avoidance and steering strategies. Solar energy systems allow increasing the lifetime of AUVs, i.e., it is not necessary to recover and recharge the vehicle on a daily basis. Hence, solar powered AUVs can acquire continuous information for periods of time of the order of months [14]. Several types of AUVs exist as experimental platforms for underwater experiments. Some of them resemble small-scale submarines (such as the Odyssey-class AUVs [11] developed at MIT). Others are simpler devices that do not encompass such sophisticated capabilities. For example, drifters and gliders are oceanographic instruments often used in underwater explorations. Drifter underwater vehicles drift with local current and have the ability to move vertically through the water column. They are used for taking measurements at preset depths [15]. Underwater gliders [16] are battery powered autonomous underwater vehicles that use hydraulic pumps to vary their volume by a few hundred cubic centimeters in ordernto generate the buoyancy changes that power their forward gliding. When they emerge on the surface, global positioning system (GPS) is used to locate the vehicle. This information can be relayed to the onshore station while operators can interact by sending control information to the gliders.Depth capabilities range from 200 m to 1500 m while operating lifetimes range from a few weeks to several months. These long durations are possible because gliders move very slowly, typically 25 cm/s (0.5 knots). In [17], a control strategy for groups of gliders to cooperatively move and reconfigure in response to a sensed distributed environment is presented. The proposed framework allows preserving the symmetry of the group of gliders. The group is constrained to maintain a uniform distribution as needed, but is free to spin and possibly wiggle with the current. In [18], results are reported on the application of the theory in [17] on a fleet of autonomous underwater gliders during the experiment on Monterey Bay in 2003 [12].

1.4 Commonly Used Terminology

Here, we give some commonly used terminologies.

1. **Volumetric quotient:** This is the ratio of the volume of a polyhedron to the volume of its circum-sphere. If Voronoi tessellation of a 3D space gives identical space-filling polyhedron of a fixed radius, then the higher the volumetric quotient of that polyhedron, the smaller the number of nodes required for full 3D coverage.

2. **Polyhedron:** This is a three-dimensional shape consisting of finite number of polygonal faces.

3. **Polygon:** This is a two-dimensional analog of polyhedrons. The general term for any dimension is polytope.

4. **Space-filling polyhedron:**A space-filling polyhedron is a polyhedron that can be used to fill a volume without any overlap or gap (a.k.a. tessellation or tiling).

5. **Voronoi cell:** In three-dimension, for any (topologically) discrete set S of points in Euclidean space, the set of all points closer to a point c of S than to any other point of S is the interior of a convex polyhedron called the Voronoi cell of c. The set of

such polyhedrons tessellate the whole space, and is called the Voronoi tessellation corresponding to the set S. Voronoi.

6. **Kelvins Conjecture :** “What is the optimal way to fill a three dimensional space with cells of equal volume, so that the surface area (interface area) is minimized?” Kelvin’s answer to his question was 14-sided truncated octahedron having a very slight curvature of the hexagonal faces and its isoperimetric quotient is 0.757. But Kelvin couldnt prove that the structure is optimal.

7. **Keplers Conjecture:** Another closely related problem is Keplers sphere packing problem. The problem is to find the most efficient way to pack equal-sized spheres. In 1611, Kepler made a guess that the face-centered cubic (FCC) lattice was the most efficient of all arrangements, but was unable to prove it. After four hundred years of failed efforts, Keplers conjecture was finally proved to be correct by Thomas Hales in 1998 [8].

The Voronoi tessellation of the FCC lattice is rhombic dodecahedron. Although FCC lattice is the optimal solution for sphere packing, in this paper we will show that truncated octahedron, which is the Voronoi tessellation of body-centred cubic (BCC) lattice, actually require 43.25% fewer nodes for our problem.

1.5 Thesis Organization

The objective of this thesis is to study the coverage and connectivity in an Underwater Sensor Network (UWSN). The thesis is organized as follows: in Chapter 2, we discuss about some related research work. In Chapter 3, we provide our research overview and comparative study. Finally in Chapter 4, we give a summary of our research with a future direction.

CHAPTER 2

PRELIMINARIES

2.1 Some Research Work on UWSN

In this chapter, we give an overview of some related research work on coverage and connectivity in UWSN. In Section 2.2, hierarchical and non-hierarchical architecture of 3D UWSN is discussed [19]. In Section 2.3, coverge preserving deployment in UWSN is discussed [20]. In Section 2.4, the coverage and connectivity from three dimensional perspective of UWSN is discussed [21]. In Section 2.5, coverage optimization algorithm based on sampling in a 3D UWSN is discussed [22].

2.2 Hierarchical and Nonhierarchical UWSN Architecture

Placement of nodes in terrestrial and underwater sensor network mainly differs in network dimensionality because of transmission medium that is acoustic instead of radio. Thereby, terrestrial network can be modeled as 2D whereas the nodes in UWSN can have different depths and thus these networks must be modeled as 3D networks [23].

In [19], the authors discuss two different network architectures for 3D underwater sensor networks. The first one is a hierarchical architecture that uses a relatively small number of robust backbone nodes to create the network where a large number of inexpensive sensors communicate with their nearest backbone nodes, and packets from a backbone node to the sink is routed through other backbone nodes. The second approach is a nonhierarchical architecture which assumes that all nodes are identical and randomly deployed. It partitions the whole 3D network space into identical cells and keeps one node active in each cell such that sensing coverage and connectivity are maintained while limiting the energy consumed.

In [24], the authors find the least ratio of communication and sensing range as 1.7889. Here they use these results as a basis to determine where to place backbone nodes in their hierarchical network.

2.2.1 Hierarchical 3D Network Architecture

Here, the authors try to minimize the number of backbone nodes with the condition that mobile sensors can communicate to the backbone node and backbone node can communicate to the neighboring backbone node.

To perform this task the authors assumes a spherical communication model where any two backbone nodes can communicate if,

$$d(distance) \leq r_{bs}(\text{deterministic threshold})$$

Where, r_{bs} = distance between the backbone node and sensor.
r_{bb} = distance between two backbone nodes.

Network Topology:

The authors investigate the problem and find that it can be analyzed from the point of view of the shape of virtual Voronoi cell where it has the highest volume among all placement strategies with the limitation that the radius of its circumsphere can not exceed r_{bs}.

Thereby the radius of circumsphere must always be equal to rbs and so the volumes of the circumspheres of all Voronoi cells are the same and equal to 4 $\pi r_{bs}^3/3$.

Analysis:

Here, the authors try to determine the ratio among different models of shape.

The authors start with four different models, namely CB (Cube), HP (Hexagonal Prism), RD (Rhombic Dodecahedron) and TO (Truncated Octahedron) model. As per [24], volumetric quotients of cube as

$$2/\sqrt{3}\pi = 0.36755$$

hexagonal prism as

$$3/2\pi = 0.477$$

rhombic dodecahedron as

$$3/2\pi = 0.477$$

and truncated octahedron as

$$24/5\sqrt{5}\pi = 0.68329$$

Thereby, CB, HP and RD model respectively require 85.9%, 43.25%and 43.25% more backbone nodes than the TO model.

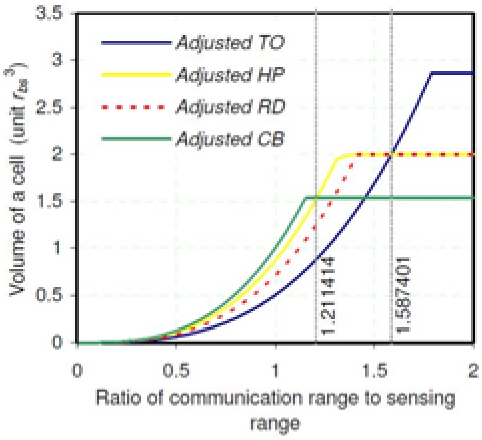


Figure 2.1: Comparison of different placement models for hierarchical network [19]

From Figure 2.1, it is found that when $r_{bb}/r_{bs} \geq 1.587401$, Adjusted TO model can be used; when $1.587401 > r_{bb}/r_{bs} \geq 1.211414$, Adjusted HP is the best option and when $r_{bb}/r_{bs} < 1.211414$, Adjusted CB has the best performance.

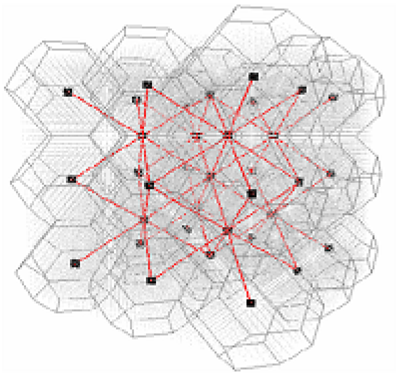


Figure 2.2: A TO based hierarchical network [19]

Communication among Nodes:

The authors try to determine the communication mode for the backbone and the mobile sensors both. The authors find that there is interference in both at backbone and mobile sensors if they share the same channel.

Thereby, it has to be made sure that backbone nodes and mobile sensors communicating over same channel are sufficiently far apart. This requires them to apply frequency reuse. [25].

Energy Consumption:

The authors compare energy efficiency for their four original models, namely CB, HP, RD, TO model. They assume that all mobile sensors are always on and they send packet to nearest backbone node with same signal strength with minimum r_{bs}.

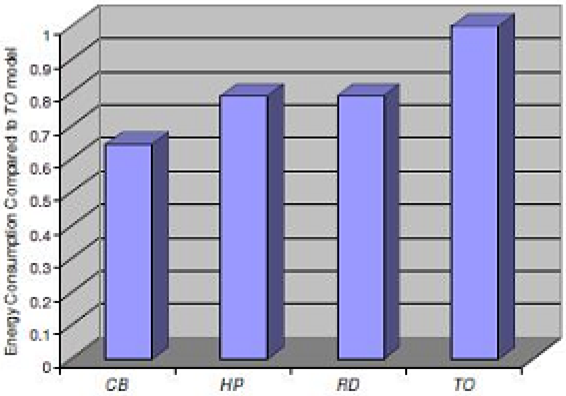


Figure 2.3: Per packet energy consumption comparison among various models [19]

Following table shows power consumption ratio of each of the four models with respect to TO model.

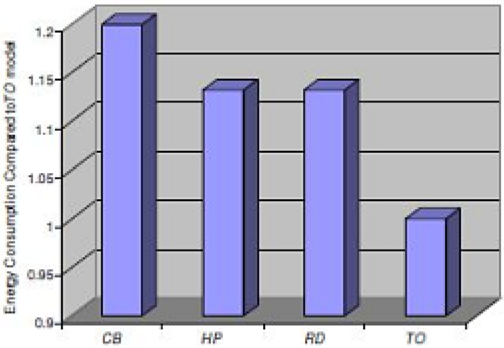


Figure 2.4: Total energy consumption comparison among various models [19]

Table 2.1: Power consumption ratio per packet for each model with respect to TO model [19]

Model	Power consumption ratio per packet
CB	0.64548
HP	0.79054
RD	0.79054
TO	1.00000

Table 2.2: Power consumption ratio of entire network in each model with respect to TO model [19]

Model	Power consumption ratio per packet
CB	0.64548 *1.859 = 1.199
HP	0.79054 * 1.4325 = 1.1325
RD	0.79054 * 1.4325 = 1.1325
TO	1.00000

Power consumption by entire network in each model with respect to TO model is shown in the Table 2.2. Power consumption per backbone node is highest in TO model because TO model deploys far fewer backbone nodes than any other model.

2.2.2 Nonhierarchical Network Architecture

The authors describe about nonhierarchical deployment where a predetermined backbone network is not feasible due to ocean current, gravity, fish and other marine animals, etc. The aim was to determine a workable combination of similar neighboring cells among different models with high energy efficiency and less power consumption. The authors experimented with six models described earlier with different combination in neighboring cells with the limitation that the maximum distance between the active nodes of any two neighboring cells cannot exceed the transmission radius. To perform this task the authors assume that the sensors are uniformly and densely distributed over a 3D space and all sensor nodes are identical. They also assume that the transmission range is much smaller than the length, width or height of the 3D space.

Analysis: Here, the authors analyze all six models with a given fixed transmission radius r_t. In CB model A cell has 26 first tier neighboring cells where,

$$r = r_1/max(2\sqrt{2}, 2\sqrt{3}, 4) = r_1/4 = 0.25r_1$$

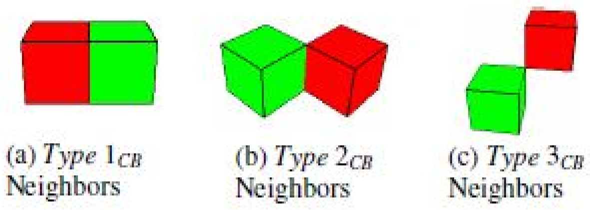

(a) *Type* 1_{CB} Neighbors (b) *Type* 2_{CB} Neighbors (c) *Type* 3_{CB} Neighbors

Figure 2.5: Different types of neighbors in CB model [19]

In Alt-CB model a cell has 16 first tier neighboring cells where,

$$r = r_1/max(2\sqrt{2}, 2\sqrt{3}, \sqrt{34}/3) = 0.288675r_1$$

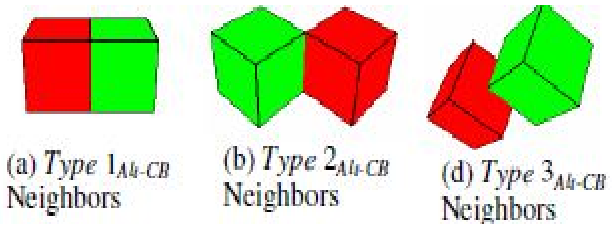

(a) *Type* $1_{Alt\text{-}CB}$ Neighbors (b) *Type* $2_{Alt\text{-}CB}$ Neighbors (d) *Type* $3_{Alt\text{-}CB}$ Neighbors

Figure 2.6: Different types of neighbors in Alt-CB model [19]

In HP model a cell has 20 first tier neighboring cells where,

$$r = r_1/max(\sqrt{10}, \sqrt{8}, \sqrt{14}) = r_1/\sqrt{14} = 0.26726r_1$$

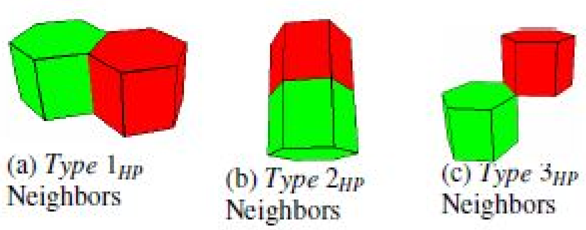

(a) *Type* 1_{HP} Neighbors (b) *Type* 2_{HP} Neighbors (c) *Type* 3_{HP} Neighbors

Figure 2.7: Different types of neighbors in HP model [19]

The Alt-HP model has 12 first-tier neighboring cells for each cell where,

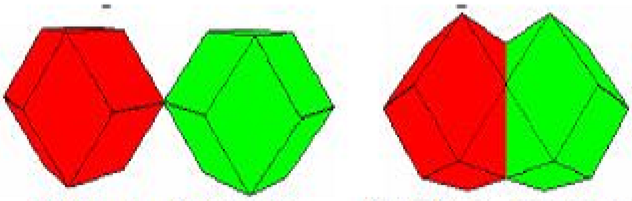
$$r = r_1/max(\sqrt{10}, \sqrt{34}/3) = r_1/\sqrt{34}/3 = 0.297r_1$$

(a) *Type* $1_{Alt\text{-}HP}$ Neighbors (d) *Type* $2_{Alt\text{-}HP}$ Neighbors

Figure 2.8: Different types of neighbors in Alt-HP model [19]

In RD model a cell has 18 first tier neighboring cells where,

$$r = r_1/max(4, \sqrt{10}) = r_1/4 = 0.25r_1$$



(a) *Type* 1_{RD} Neighbors (b) *Type* 2_{RD} Neighbors

Figure 2.9: Different types of neighbors in RD model [19]

In TO model a cell has 14 first tier neighboring cells where,

$$r = r_1/max(2\sqrt{17}/\sqrt{5}, 2\sqrt{14}/\sqrt{5}) = r_1\sqrt{5}/2\sqrt{17} = 0.271163r_1$$

The Minimum Sensing Range:

Here, the authors estimate that the sensing range must be at least equal to the maximum distance between any two points of a cell. This maximum distance is essentially the diameter of a cell and equal to twice of the corresponding radius.

Distributed Partitioning Scheme:

Here, the authors determines the distributed partitioning scheme for all models with the limitation that the individual cell id is. As the technique is similar for all models, the authors only provide calculation only for the TO model. For TO model the center of a virtual cell can be expressed by the general equation,

$$f(u,v,w) = \left(x + (2u+w)r_1/\sqrt{17}, y + (2v+w)r_1/\sqrt{17}, z + wr_1/\sqrt{17}\right)$$

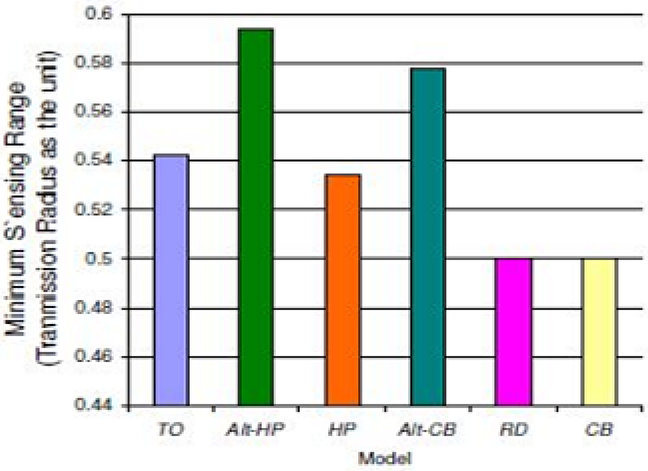


Figure 2.10: Minimum sensing range in various models [19]

Three integers (u,v,w) can be used as unique cell id with the cell containing IS has the cell id (0,0,0). As an example, cell id (-1, -1, 2) has its center in,

$$x, y, z + 2r_1/\sqrt{17}$$

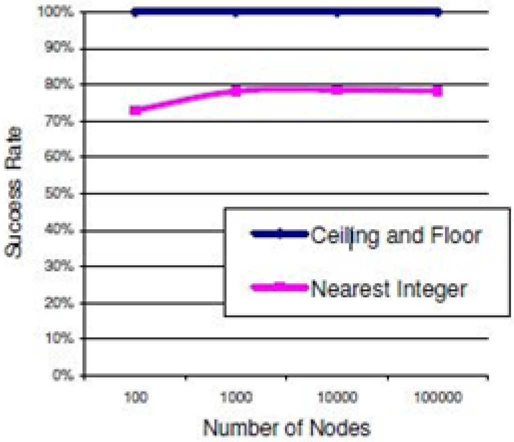


Figure 2.11: Cell ID prediction accuracy [19]

2.3 Coverage Preserving Deployment in UWSN

In [20], deployment strategies for two-dimensional and three dimensional architectures for underwater sensor networks are proposed, and deployment analysis is provided.

2.3.1 The Minimum Number of Sensors for Coverage

For 2D network, the authors determine the minimum number of sensors and uw-gateways to achieve communication and sensing coverage and provide guidelines on how to choose the optimal deployment surface area, given a target region. For 3D network the authors evaluate different deployment strategies and determine the minimum number of sensors needed to achieve the target sensing coverage. The authors analyze the graph properties of devices (sensors and uw-gateways) when they are deployed on the ocean surface, sink, and reach the bottom.

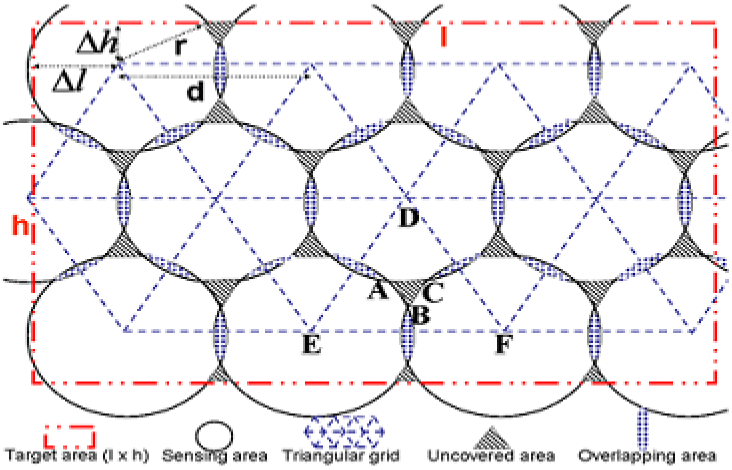


Figure 2.12: Triangular-grid Surface Deployment [20]

The authors use sensors with same sensing range r. According to them optimal deployment to cover a 2D area with minimum number of sensors is to center sensors at the vertex of a grid of equilateral triangles. With this configuration by adjusting the distance d among the sensors (i.e. the side of the equilateral triangles), it is possible to achieve full coverage and this is $d = \sqrt{3}r$.

In order to compute the minimum number of sensors to cover a target area with sides l and h they first comput the optimal margin Δl and Δh from the upper-left sensing circle. They denote the minimum number of sensors as N^*.

$$N^*(l,h,d^*,r) = [(1-d^*)/d*+1]*[(2-\sqrt{3}h-6d^*+4\sqrt{3}r)/3d^*+1]$$

Here, l and h are the length and height of the target area respectively.

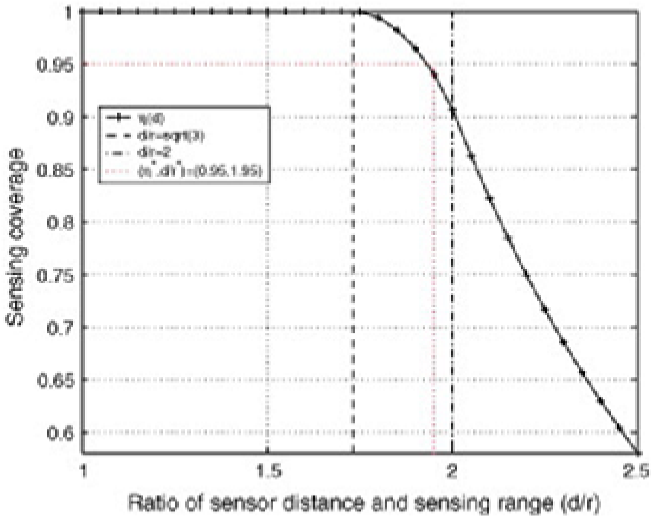


Figure 2.13: Sensing coverage [20]

2.3.2 3D Deployment Strategies

Author proposes three deployment strategies for three-dimensional UW-ASNs in order to obtain a target coverage of the 3D region.

- 3D-random strategy
- Bottom-random strategy
- Bottom-grid strategy

Winch-based sensor devices are anchored to the bottom of the ocean in such a way that they cannot drift with currents.Sensors are assumed to know their final positions by exploiting localization techniques.

3D-random:

This method does not require any form of coordination from the surface station. Sensors are randomly deployed on the bottom, where they are anchored. Sensors randomly choose a depth and float to the selected depth.

Bottom-random:

In this method sensors are randomly deployed on the bottom, where they are anchored. Surface station is informed about their position on the bottom. Surface station calculates the depth for each sensor to achieve the target coverage ratio. Sensors are assigned a target depth and float to the desired position.

Bottom-grid:

It needs to be assisted by one or multiple AUVs, which deploy the sensors.Grid deployment on the bottom of the ocean. Each sensor is also assigned a desired depth by the AUV and accordingly floats to achieve the target coverage ratio.

The authors didn't develop a mathematical framework to study the 3D sensing coverage. Also they didnt devise an algorithm to set and adjust the depth of sensors.

2.4 Coverage and Connectivity in 3D UWSN

In [21] , the authors work on the coverage and connectivity issues of 3D networks, where the goal is to find a node placement strategy with 100% sensing coverage of a 3D space, while minimizing the number of nodes require for surveillance and also to find out the minimum ratio of the transmission range and the sensing range in such a placement strategy. The design of 3D networks is surprisingly more difficult than the design of 2D networks. To show the best way of placing nodes in three-dimension they consider geometrical properties of some space filling polyhedron [26][27] such as cube, dodecahedron, icosahedrons, octahedron, and tetrahedron.In this case Kelvins conjecture [28] is used to justify that the placement of nodes in the middle of truncated octahedrons cells, which are, created by Voronoi tessellation of a 3D space. Proving optimality in many 3D problems is surprisingly difficult, They define a metric called volumetric quotient, which is the ratio of the volume of a polyhedron to the volume of its circumsphere. If Voronoi tessellation of a 3D space gives identical space-filling polyhedron of a fixed radius, then the higher the volumetric quotient of that polyhedron, the smaller the number of nodes required for full 3D coverage. Since the sensing region of a node is spherical and spheres do not tessellate in 3D, they find a space-filling polyhedron that best approximates the sphere. In other word, they find a space-filling polyhedron such that if each cell is modeled by that polyhedron, then the number of cells required to cover a volume is minimized, where the distance from the center of a cell to its farthest corner (i.e. radius of a cell) is not greater than the sensing range R. For the work, the assumption they follow as follows :

- All nodes have identical sensing range R. Sensing is omni-directional and the sensing region of each node can be represented by a sphere of radius R, having the sensor node at its center.

- The sensing range R is much smaller than the length, the width, or the height of the 3D space to be covered, so that the boundary effect is negligible and hence can be ignored.
- Any point in the 3D space to be covered must be within the sensing range R from at least one node.
- If the locations of the nodes are fixed, their location is arbitraty. If the nodes are mobile, the nodes are initially randomly deployed, and their movement is unrestricted. Thus, we ignore the physical constraints of placing the nodes, and we assume that the placement strategy is free to place a node at any location in the network.

For the research, at first they find out the volumetric quotient of Cube, Hexagonal Prism, Rhombic Dodecahedron and Truncated Octahedron using formula volumetric quotient $= V/(4/3\pi R^3)$ where R is the maximum distance from its center to any vertex and V is the the volume of that Polyhedron.

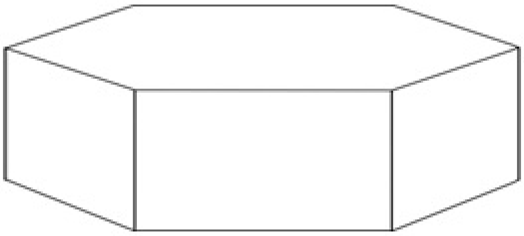


Figure 2.14: Hexagonal Prism [29]

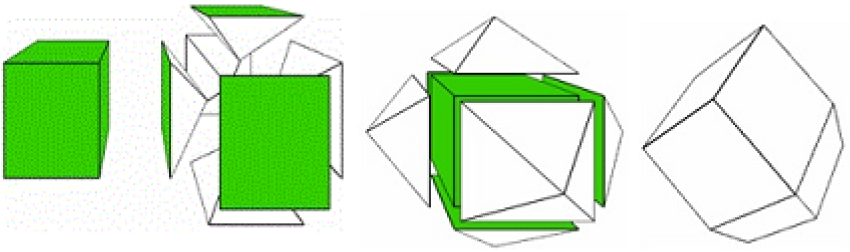


Figure 2.15: Construction of Rhombic Dodecahedron from two identical cube [21]

Among all the polyhedrons considered, the truncated octahedron gives the best volumetric quotient. They also compare the number of nodes required by each type of polyhedron. The number of nodes required by the cube is 0.68329/0.36755=1.859 times that of the truncated octahedron. For the hexagonal prism this value is 0.68329/0.477=1.4325 and for the rhombic dodecahedron it is 0.68329/0.477=1.4325. Table 2.3 summarizes the results.

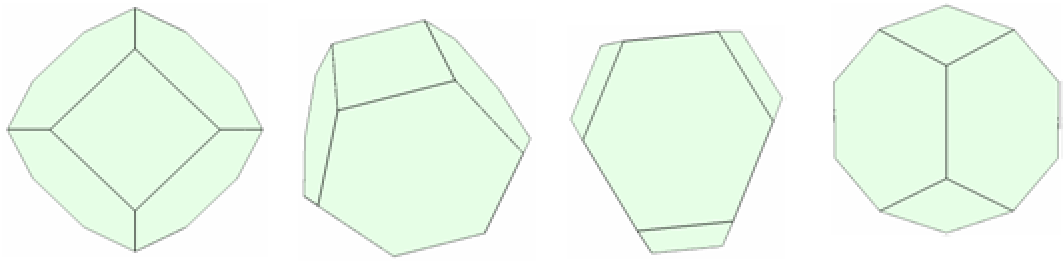


Figure 2.16: Truncated Octahedron [21]

Table 2.3: Volumetric Quotient of Different Types of Spacefilling Polyhedrons [21]

Polyhedron	Volumetric quotient	Number of nodes needed Compared to truncated octahedron
Cube	0.36755	85.9% more
Hexagonal Prism	0.477	43.25% more
Rhombic Dodecahedron	0.477	43.25% more
Truncated Octahedron	0.68329	same

They provide strategies (algorithms) to pinpoint the location where the nodes should be placed such that the Voronoi cells are their chosen space-filling polyhedrons. They take an arbitrary point (preferably the center of the space to be covered) as an input and place a node there. Then they find the locations of other nodes relative to this center node. So the input to their algorithm is sensing range R and the co-ordinates of the point, say (c_x, c_y, c_z), which act as a seed for the growing lattice. Distributed versions of the algorithms can use the location of the leader node as the seed. For placement strategy they consider that the coordinate system is defined by three axes: u, v, and w, which are parallel to the x, y, and z axes, respectively and the center of the coordinate system is (c_x, c_y, c_z). If a node is placed at every integer coordinate of the following u, v, and w-coordinate system then they get the respective polyhedron tessellation. They gave the equation for finding out the location of each node in Cube, Hexagonal Prism, Rhombic Dodecahedron and Truncated Octahedron tessellation. The required minimum transmission range to maintain connectivity among neighboring nodes depends on the choice of the polyhedron. When the cube is chosen, the distance between two neighboring node is $2R$ / 3.Thus the transmission radius must be at least $1.1547R$. If the hexagonal prism is used, then the transmission range must be at least $2R = 1.4142R$ to maintain connectivity with the neighbors along the axes u and v, and the transmission range must be at least $2R/\ 3 = 1.1547R$ for communication along the w-axis.

In the case of the rhombic dodecahedron, the minimum transmission range required is $2R$ $=1.4142R$ for communication with any neighbor. Finally, if the truncated octahedron is used, then the transmission range must be at least $4R/\ 5 = 1.7889R$ along the axes u and v, and the minimum transmission range is $R2\ 3\ /\ 5 = 1.5492R$ along the axis w. The results are summarized in Table 2.4.

Table 2.4: Minimum Transmission Range for Different Polyhedrons [21]

Polyhedron	u-axis	v-axis	w-axis	Max of Min Transmission Range
Cube	1.1547R	1.1547R	1.1547R	1.1547R
Hexagonal Prism	1.4142R	1.4142R	1.1547R	1.4142R
Rhombic Dodecahedron	1.4142R	1.4142R	1.4142R	1.4142R
Truncated Octahedron	1.7889R	1.7889R	1.5492R	1.7889R

Their research results indicate that the use of the Voronoi tessellation of 3D space to create truncated octahedral cells results in the best strategy. In this truncated octahedron placement strategy, the transmission range must be at least 1.7889 times the sensing range in order to maintain connectivity among nodes. If the transmission range is between 1.4142 and 1.7889 times the sensing range, then a hexagonal prism placement strategy or a rhombic dodecahedron placement strategy should be used. Although the required number of nodes in the hexagonal prism and the rhombic dodecahedron placement strategies is the same, this number is 43.25% higher than the number of nodes required by the truncated octahedron placement strategy. They verify by simulation that their placement strategies indeed guarantee ubiquitous coverage. Their results presented in this paper could be used for extending the processes of 2D network design to3D networks. This paper does not include the energy efficient scheme in the 3D Network.

2.5 3D Coverage Optimization

In [22], the authors propose an optimization algorithm for 3D coverage. According to them almost all of the coverage strategies are based on a premise that sensors are deployed in a specific location and stay there so that the maximum coverage of 3D space is achieved.

However, sensor nodes are usually deployed at random and are impossible suspended at specified location without any connection in water. Therefore, they propose a 3D coverage optimization algorithm for underwater 3D sensor networks (UWSNs) in which sensor nodes are randomly deployed and are fixed by cables, in which quadratic programming is applied to coverage optimization problem in 2D plane and 3D space. For this purpose they assume that a large number of underwater sensors are distributed in an area of interest. They assume that a 3D UWSN contains two types of sensor nodes: one is used for communications and is deployed on the water surface. the other is used for sensing and is deployed underwater. Coverage optimization algorithm is performed by sink nodes and there position are fixed on the water surface. All sensor nodes that are deployed underwater have homogeneous models; that is, all sensors have binary sensing coverage models [22] and there depth are dynamic. Thus, the sensing model is a sphere, and all sensors adopt the radius of the sensing sphere model.

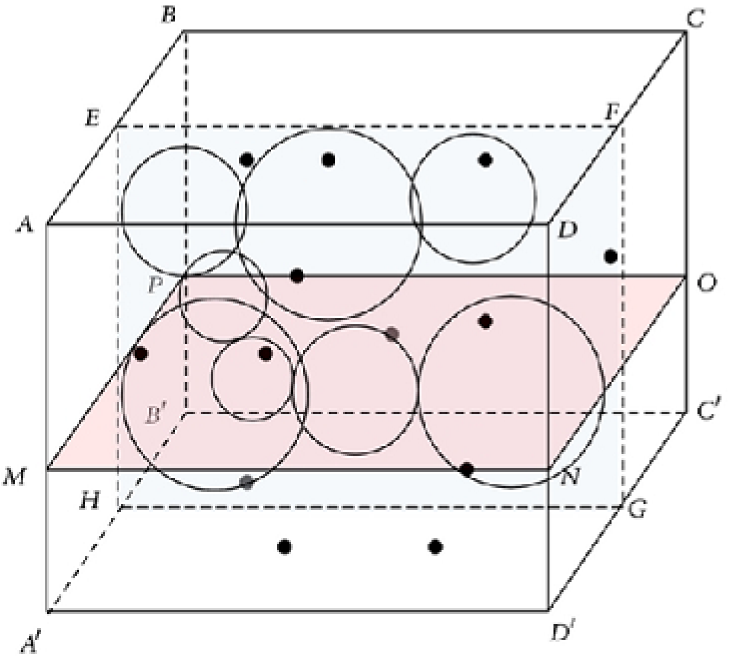


Figure 2.17: Coverage model in underwater 3D space [22]

In this algorithm at first the coverage problem in 3D space is converted into a 2D plane for heterogeneous networks via sampling plane in the target 3D space. Second, the optimization in the 2D plane is converted into an optimization in a line segment by using the line sampling method in the sample plane.

Here, the sample planes intersect with the sensing spheres. The samle plane is an arbritary plane in 3D space intersect the boundary of 3D monitoring space to form polygon MNOP, as shown in Figure 2.17. The plane area which is contained by polygon MNOP is defined as sample plane. A coverage optimization algorithm is executed to change the radious and locations of the sensing circles in the sample planes. Sensing circle is formed when the sensing sphere and sample plane intersect, a circle in the plane will be formed. The circle center is the projection of sensing sphere to sample plane, and the radius of the circle is $\sqrt{R^2 - d^2}$.

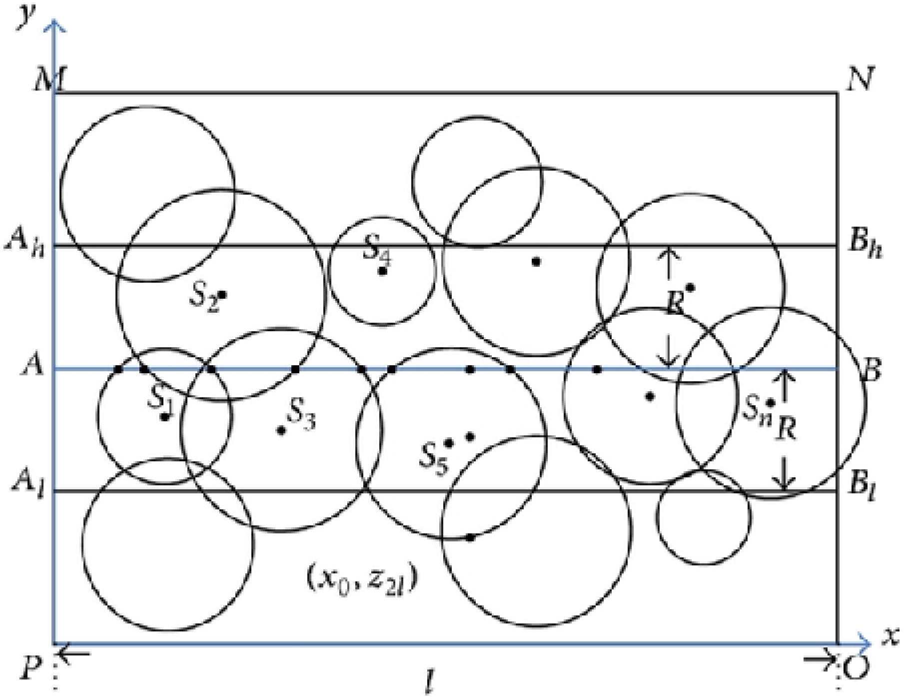


Figure 2.18: Sensing circles in a horizontal sample plane [22]

Thereafter, the sensor nodes corresponding to the sensing circles is redeployed according to the new radious and locations of the sensing circles.

The authors analyze the algorithm based on horizontal sample plane and vertical sample plane both way. But they find it hard to resolve the problem by sampling horizontal plane because in horizontal sampling, confirming relationship among the circle sets become difficult and also this problem is a nonlinear programming problem because the upper and lower bounds of the sets and variables are nonlinear, so the problem is hard to be resolved [30]. However, they find a feasible solution after limiting the constraints of the optimization algorithm in vertical planes. Moreover, they think that the 2D plane coverage optimization in the x-z direction is similar to the y-z direction. Thus, they only sample the vertical plane in underwater 3D space (Figure 2.19).

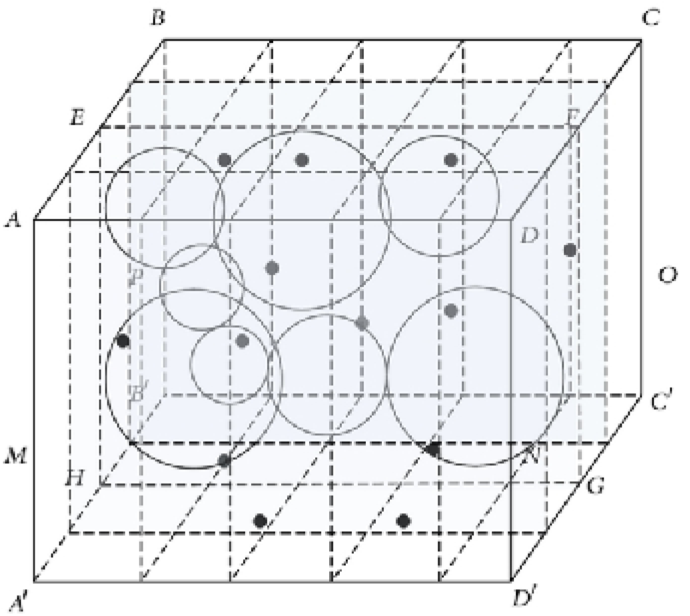


Figure 2.19: Vertical sample plane in underwater 3D space [22]

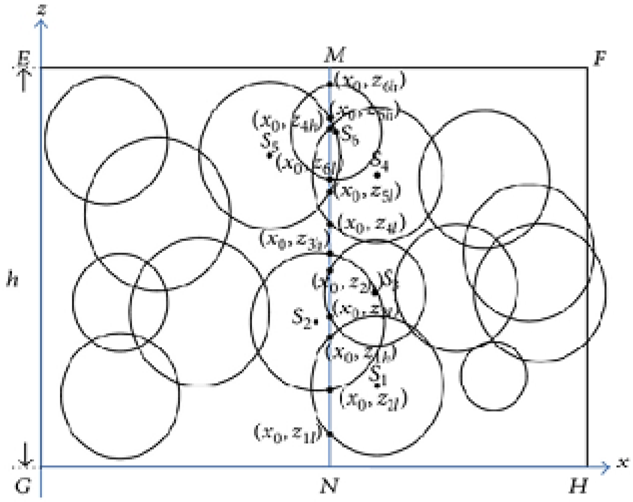


Figure 2.20: Vertical sample plane [22]

In the COS (Coverage Optimization by sampling) algorithm [22] there are two subroutine in addition to main program. The subroutines are plane coverage and line coverage. The authors presented pseudo codes for both COS algorithm and plane coverage and flowchart for line coverage [22]. The COS algorithm is performed by the sink node on land. First, a plane that is parallel to the - plane is sampled in interval (0, *R*/2) Then the positions and radii of the sensing circles in the sampling plane are calculated if the sensing spheres intersect at the sampling plane. The plane coverage subroutine is invoked then to optimize the sampling plane coverage. Thereafter, the sink node sends DEPTH messages to the underwater sensor nodes.Any node receiving a DEPTH message performs its specified movement [22] .

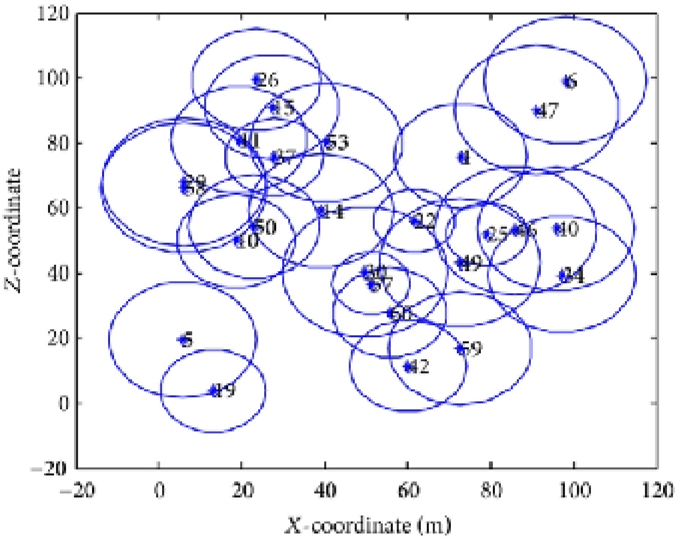


Figure 2.21: Initial position of the sensing circles after random distribution [22]

After the first optimization, additional planes are sampled according to the step length until the sampling plane is beyond the boundary of 3D space, and the optimization algorithm is conducted numerously to optimize all sampling planes coverage [22].

The authors simulate the algorithm in an environment where they assume that all messages can be transmitted/received without any errors and that the sensor nodes are uniformly distributed in a 100m x 100m x 100m 3D space. The sensing radius of the underwater sensor node is 20m, and the communication nodes that are deployed on the water surface can communicate with each other. A coordinator node is attached to the server and acts as a gateway to the UWSNs. The server implements the COS algorithm [22] and conveys the new position of the underwater sensor nodes to the coordinator. The location of an underwater sensor node is adjusted by its corresponding buoy via the cable after receiving the information. Fig-

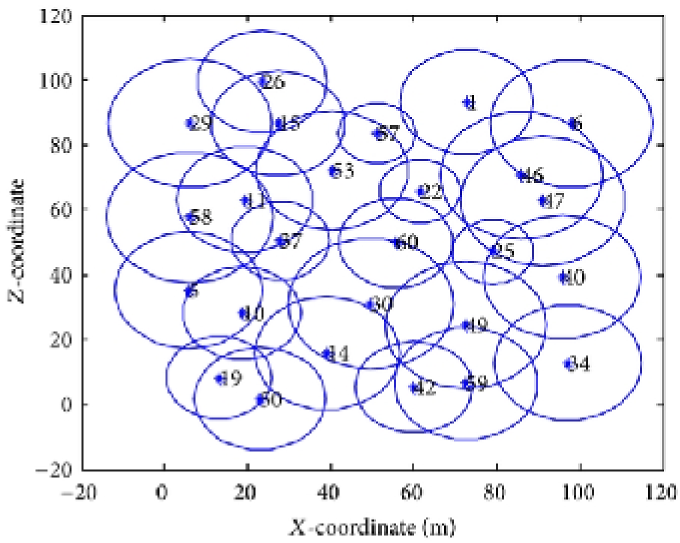


Figure 2.22: Position of the sensing circles after execution of the COS algorithm [22]

ure 2.21 shows the initial position of the sensing circles in one of the vertical sample planes after random distribution. Figure 2.22 shows the final position of the sensing circles of the COS algorithm in the same vertical sample planes.

They observe that the overlap area in Figure 2.22 is less than the overlap area in Figure 2.21. Figure 2.23 and 2.24, the patterns show that the coverage can be effectively enhanced by the COS algorithm. They consider the influence of node quantity, iteration, and sensing range in the experiments and find that the proposed algorithm works effectively under extreme surroundings.

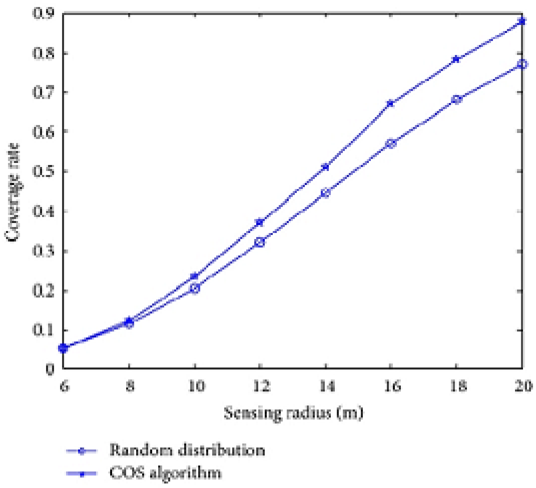


Figure 2.23: Coverage versus the sensing radius for 60 nodes [22]

The authors mention that the performance of the COS algorithm is affected by two aspects:

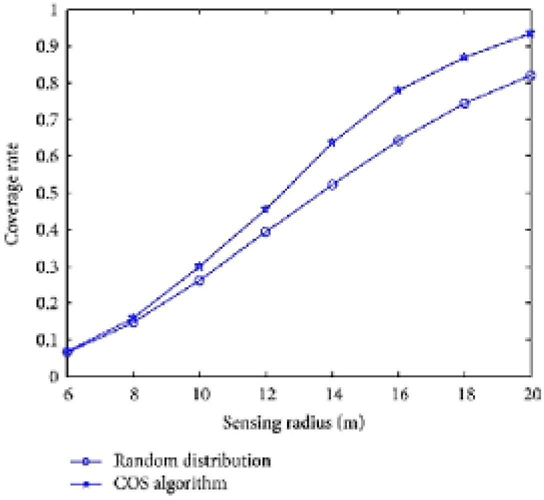


Figure 2.24: Coverage versus the sensing radius for 80 nodes [22]

1. for the limitation of the network model, the coverage cannot be significantly improved when the wireless sensor nodes are nonuniformly distributed,

2. the COS algorithm is performed on each sample plane alone because the authors do not consider the relativity between the adjacent sample planes. Also we can see from Figure 2.21 and 2.22 that the optimization is not quite satisfactory. The sampling plane coverage rate of the COS algorithm outperforms the random approach by approximately 10% (Figure 2.23 and 2.24) which is not a significant improvement.

CHAPTER 3

COMPARATIVE STUDY

3.1 Comparative Study Table

The given comparison table presents an overview of some issues found on the papers that we have discussed previously. The rows represent each issue and the columns represent the papers referenced. Each of the referenced works typically address several of the issues given and the table can be used for comparison and for a quick reference. We have tried to cover as many papers as possible to give a current overview of the state of the research into Underwater sensor network coverage.

3.2 Summary of the Table

We find that “area coverage” is discussed in all of the four research work we discussed previously. “Mobile node” is only used in [19]. In [20] and [21] “Deterministic deployment” is used. “Random deployment” is used in [19], [20] and [22]. “Heterogeneous nodes” are only used in [22]. [19], [20] and [21] uses “Homogeneous nodes”. “Energy constraint” is used in [19] and [22]. The term “K-coverage” is covered in [19] and [20]. Both “Three-dimensional coverage” and “Coverage with connectivity” is covered in all of the four papers. “Voronoi diagram” is only used in [19] and [21]. In [19], [20] and [21] “Worst or best Coverage” is covered.

Table 3.1: Comparison Table based on some issues

	HierarHierarchical and Non-hierarchical 3-Dimensional UWSN[19]	Deployment Analysis in UWSN[20]	Coverage and Connectivity in 3D UWSN[21]	Coverage Optimization Algorithm Based on Sampling for 3D UWSN[22]
Area coverage	✓	✓	✓	✓
Mobile nodes	✓			
Deterministic deployment		✓	✓	
Random deployment	✓	✓		✓
Heterogeneous nodes				✓
Homogeneous nodes	✓	✓	✓	
Energy Constraint	✓			✓
K-coverage	✓	✓		
Three-dimensional coverage	✓	✓	✓	✓
Voronoi diagram	✓		✓	
Worst or best case coverage	✓	✓	✓	
Coverage with connectivity	✓	✓	✓	✓

CHAPTER 4

CONCLUSION

An underwater network is typically made up of many autonomous and individual sensor nodes that perform data collection operations as well as store and forwarding operations to route the data that has been collected to a central node. The main challenges of deploying such a network are the cost, the computational power, the memory, the communication range and most of all the limited battery resources of each individual sensor node. Thereby to determine the minimum number of nodes required to build a UWSN with least possible energy consumption and high nodes longevity is really typical.

Research had been going on for years on this very arena and significant advancement had been achieved in past one or two decades. There used to be different area where the researchers had been working to improve upon that includes, network strategies both in 3D and 2D environment, energy consumption, coverage and connectivity, etc.

In this thesis, we have brought a rough discussion regarding two-dimensional and three dimentional deployment strategies. We also have provided two different network architectures for 3D underwater wireless sensor networks, which are hierarchical network and nonhierarchical network. We also have investigated the coverage and the connectivity issues in three-dimensional networks, where nodes are placed in a 3D space.

Our prime goal in this thesis was to define different deployment strategies and finally bring a comparative analysis between the papers we have discussed early in this paper. For doing so, four survey papers namely “Hierarchical and Nonhierarchical Three Dimensional UWSN”, “Deployment Analysis in UWSN”, “Coverage and Connectivity in 3D UWSN” and “Coverage Optimization Algorithm Based on Sampling for 3D UWSN” are discussed.

After analyzing it was found that for deployment of sensor nodes in UWSN, different fields had to be explored. Some deployment strategy may have advantageous arena in some fields but may fall short in some other.

We have brought comparison between the papers in chapter 3 basing on the fields which includes Area coverage, Mobile nodes, Deterministic deployment, Random deployment, Heterogeneous nodes, Homogeneous nodes, Energy Constraint, K-coverage, three-dimensional coverage, Voronoi diagram, Worst or best case coverage and Coverage with connectivity.

Though the work is done in an amature way but it would be helpful as a future reference for further studies in UWSN where the future researchers will find a easy and comprehensive analysis among the researches taken place early.

REFERENCES

[1] *http:// www.ece.gatech.edu/research/labs/bwn/UWASN/*, 12/28/2013.

[2] A. Quazi, W. Konrad, “Underwater acoustic communication”, *IEEE Communications Magazine*, vol. 20, issue 2, pages 24-30, 1980.

[3] M. Stojanovic, “Acoustic (underwater) communications”, *Encyclopedia of Telecommunications*,J.G. Proakis (Ed.), Wiley, New York, 2003.

[4] J.G. Proakis, J.A. Rice, E.M. Sozer, M. Stojanovic, “Shallow water acoustic networks”, *Encyclopedia of Telecommunications*, J.G. Proakis (Ed.), John Wiley and Sons, 2003.

[5] J.G. Proakis, E.M. Sozer, J.A. Rice, M. Stojanovic, “Shallow water acoustic networks”, *IEEE Communications Magazine*, vol. 39, issue 11, pages 114-119, November 2001.

[6] L. Freitag, M. Stojanovic, “Acoustic communications for regional undersea observatories”, In *Proc. Oceanology Intl*, March 2002.

[7] E.M. Sozer, M. Stojanovic, J.G. Proakis, “Underwater acoustic networks”, *IEEE Journal of Oceanic Engineering*, vol. 25, issue 1, pages 7283, 2000.

[8] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless sensor networks: A survey”, *Computer Networks*, vol. 38, issue 4, pages 393422, 2002.

[9] E. Cayirci, H. Tezcan, Y. Dogan, V. Coskun, “Wireless sensor networks for underwater surveillance systems”, *AdHoc and Sensor Networks (Elsevier)*, vol. 4, issue 4, pages 431-446, July 2006.

[10] V. Ravelomanana, “Extremal properties of three-dimensional sensor networks with applications”, *IEEE Transactions on Mobile Computing*, vol. 3, issue 3, pages 246257, 2004.

[11] *http://auvlab.mit.edu/*, 12/28/2013.

[12] *http://www.mbari.org/aosn/MontereyBay2003/MontereyBay2003Default.htm*, 12/28/2013.

[13] B.M. Howe, T. McGinnis, H. Kirkham, "Sensor networks for cabled ocean observatories", *Underwater Technology, 2004. UT '04. 2004 International Symposium on*, pages 113,120, 20-23, April 2004.

[14] J. Jalbert, D. Blidberg, M. Ageev, "Some design considerations for a solar powered AUV: Energy management and its impact on operational characteristics", *Unmanned Systems*, vol 15, issue 4, pages 26-31, 1997.

[15] M. Hinchey, "Development of a small autonomous underwater drifter", In *Proceedings of IEEE NECEC'04*, St. John's, NF, Canada, October 2004.

[16] R. Davis, C. Eriksen, C. Jones, "Autonomous buoyancydriven underwater gliders", In "*G. Griffiths (Ed.), The Technology and Applications of Autonomous Underwater Vehicles*, Taylor and Francis, London, 2002.

[17] P. Ogren, E. Fiorelli, N.E. Leonard, "Cooperative control of mobile sensor networks: Adaptive gradient climbing in a distributed environment", *IEEE Transactions on Automatic Control*, vol. 49, issue. 8, pages 12921302. 2004.

[18] E. Fiorelli, N. Leonard, P. Bhatta, D. Paley, R. Bachmayer, D. Fratantoni, "Multi-AUV control and adaptive sampling in Monterey Bay", In *Proceedings of IEEE Autonomous Underwater Vehicles 2004: Workshop on Multiple AUV Operations (AUV04)*, June 2004.

[19] S. M. Nazrul Alam, Zygmunt J. Haas , "Hierarchical and Nonhierarchical Three-Dimensional Underwater Wireless Sensor Networks", *eprint arXiv:1005.3073*, 2010.

[20] Pompili, D, Melodia, T, and Akyildiz, I.F, "Three-dimensional and Two-dimensional Deployment Analysis for Underwater Acoustic Sensor Networks", *Ad Hoc Networks (Elsevier) Journal*, vol. 7, no. 4, pages 778-790, June 2009.

[21] S. M. Nazrul Alam and Z. Haas, "Coverage and Connectivity in Three-Dimensional Underwater Sensor Networks", *Wireless Communication and Mobile Computing*, vol.8, pages 995-1009, October 2008.

[22] Du Xiaoyu, Sun Lijuan, and Liu Linfeng, "Coverage Optimization Algorithm Based on Sampling for 3D Underwater Sensor Networks", *International Journal of Distributed Sensor Networks*, vol. 2013. Article ID 478470, 12 pages, 2013.

[23] I. F. Akyildiz, D. Pompili, and T. Melodia, “Underwater Acoustic Sensor Networks: Research Challenges”, *Ad Hoc Networks (Elsevier)*, vol. 3, no. 3, pages 257-279, March 2005.

[24] S. M. Nazrul. Alam and Z. Haas, “Coverage and Connectivity in Three-Dimensional Networks”, *In MobiCom*, pages 346-357, 2006.

[25] M. Stojanovic, “Design and Capacity Analysis of Cellular Type Underwater Acoustic Networks”, *IEEE Journal of Oceanic Engineering*, vol. 33, issue 2, pages 171-181, April 2008.

[26] Steinhaus, Hugo. *Mathematical Snapshots*, 3rd edition, Oxford University Press, 1969.

[27] Wells, D. *The Penguin Dictionary of Curious and Interesting Geometry*, London: Penguin, 1991.

[28] Thomson, Sir William (Lord Kelvin), “On the division of space with minimum partition area”. *Philosophical Magazine*, vol. 24, pages 503-514, 1887.

[29] *http://http://etc.usf.edu/clipart/43100/43130/prism-hex6_43130.htm*, 12/28/2013.

[30] M. Naderan, M. Dehghan, and H. Pedram, “Sensing task assignment via sensor selection for maximum target coverage in WSNs”, *Journal of Network and Computer Applications*, vol. 36, no. 1, pages 262-273, 2013.