Optimal Node Placement in Underwater Acoustic Sensor Network

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ABSTRACT

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Muhamad Felemban

Almost 70% of planet Earth is covered by water. A large percentage of underwater environment is unexplored. In the past two decades, there has been an increase in the interest of exploring and monitoring underwater life among scientists and in industry. Underwater operations are extremely difficult due to the lack of cheap and efficient means. Recently, Wireless Sensor Networks have been introduced in underwater environment applications. However, underwater communication via acoustic waves is subject to several performance limitations, which makes the relevant research issues very different from those on land. In this thesis, we investigate node placement for building an initial Underwater Wireless Sensor Network infrastructure. Firstly, we formulated the problem into a nonlinear mathematic program with objectives of minimizing the total transmission loss under a given number of sensor nodes and targeted volume. We conducted experiments to verify the proposed formulation, which is solved using Matlab optimization tool. We represented each node with a truncated octahedron to fill out the 3D space. The truncated octahedrons are tiled in the 3D space with each node in the center where locations of the nodes are given using
3D coordinates. Results are supported using ns-3 simulator. Results from simulation are consistent with the obtained results from mathematical model with less than 10% error.
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Chapter 1

Introduction

Water covers almost 70% of the planet Earth. Most of the underwater environment is still unexplored. Recently, the interest of exploring and monitoring aqueous environment has been growing in both science and industry. However, it is extremely difficult to conduct submarine operations due to the lack of an easy way to monitor and collect data at the bottom of the oceans. One way to conduct such operations is to exploit Autonomous Underwater Vehicles (AUV) at the bottom of the oceans. AUVs can be operated without the need of tethers or cables. However, underwater communication has many challenges that limits the performance of the AUVs operations. Some of the challenges are:

- Limited Bandwidth because of the low frequency band used in underwater communication channels.
- Underwater channel is highly susceptible to path loss due to the physical characteristics of the underwater communication channels.
- High propagation delay that is almost five times higher than the propagation of Radio Frequency (RF) terrestrial signals.
- High Bit Error Rate (BER) due to high probability of connectivity loss under-
These challenges can be tackled by introducing sensor nodes that transmit the control data over multi-hop routes wirelessly to the vehicles. The vehicles are intended to work in relative independence of human interaction. The sensor nodes forward the control packets from the surface to the AUVs while the gathered monitoring data packets are forwarded backwardly.

1.1 Research Problem Overview

Underwater Wireless Sensor Network (UWSN) is a mature research field which attracted the research community over the past decade. Underwater nodes placement and localization are the fundamental initial challenges in building a UWSN. Number of techniques have been proposed for optimal deployment of such network [3, 4, 5, 6]. However, there is no optimal deployment strategy that considers physical characteristics of acoustic channels and the covered volume in underwater space. Work in [7] tackles the coverage and connectivity of 3D UWSN in geometry. The inter-node distance needs to be carefully chosen in such it limits the effect of acoustic channels to build a robust and reliable UWSN.

1.2 Research Methods and Goals

In this thesis, we focus on finding the optimal positioning strategy for sensor nodes which supports AUVs mission critical operation. The placement problem is formulated into an optimization problem as follows: There exists a volume of interest $V$ with a single or multiple AUVs operating for a mission critical task. UWSN is required to relay control packets from the surface nodes to AUVs and the data packets from AUVs to surface nodes. Our main objective is to define the optimal number
of nodes and their locations such that it attains maximum coverage with minimum power consumption by reducing transmission loss between the nodes. The inter-node distance depends on the transmission loss at a given depth and temperature. The minimum inter-node distance can be found by finding the optimal transmission loss between the nodes. From this problem, we have also obtained the minimum number of nodes to cover a certain volume and the maximum coverage volume for a given number of nodes.

1.3 Thesis Preview

The rest of this thesis is organized as follows. Chapter 2 provides an overview of the general background necessary for this thesis. We discuss the behavior and characteristics of acoustic communication underwater. Then, we provide a review of Underwater Sensor Network and some challenges and practical designing issues. We also present some previous work in optimal node placement underwater. Chapter 3 presents the network model and the problem formulation. Chapter 4 discusses the analytic and simulation results. Thesis is concluded by the conclusion and future direction in Chapter 5.
Chapter 2

Background and Related Work

2.1 Overview

Wireless Sensor Networks (WSN) have been a revolutionary emerging technology for many fields in science and industry. This is because of their ability to form a vast network of small sensing devices, called nodes, distributed in a sparse area to observe and act on the environment. Each node is not only capable of sensing, actuating, and forwarding data, but also is capable of carrying out simple computation and filtering out transmitted data. Thus, wireless sensor networks are suitable for deployment in many fields [8]. For example, habitat monitoring [9] [10] [11], health monitoring [12], industrial applications [13], and simple home applications [14] [15]. WSNs have also been used in underwater environment for ocean-floor monitoring and data sampling [16].

In the rest of this chapter, we discuss the underwater acoustic channels behavior and characteristics. Then, we provide a broad overview of UWSN and some practical issues and challenges. Next, we present an overview of previous work done in underwater node placement.
2.2 Underwater Acoustic Communication

Underwater communication has been a research focus since 1945 when sUS tried to develop an underwater telephony system during World War II to establish communication between submarines [17]. However, it was only until the past two decades where acoustic communication was mainly used for communication in many underwater applications such as habitat monitoring, data sampling, and underwater explorations. Acoustic communication is the typical physical medium for underwater applications that provides reliable communication between nodes. Acoustic waves are not the only available medium for underwater wireless signal transmission. Electromagnetic (EM) waves can also be used for transmitting wireless signals underwater. However, EM waves in the high frequency range (i.e., 2.4 GHz), are highly vulnerable to attenuation in sea and fresh water. It was shown in [18] that the attenuation for seawater with average connectivity of 4 mhos/meter and fresh water with average connectivity of 0.05 mhos/meter are 1695 dB/meter and 189 dB/meter, respectively. Lanbo et al. [19] study the relation between EM waves frequency and attenuation. It is shown that attenuation in seawater exponentially increases with frequency. Such attenuation is impractical for underwater wireless communication. As a result, EM waves need to operate on extra low frequency ranges (30 - 300 Hz). However, this requires a large transmission power, large transducer antennae, and very restricted seawater conditions. Optical waves are another option for wireless transmission.Unlike EM waves, optical waves offer extremely high data rate. However, optical signals are also susceptible to water absorption and scattering, which makes it impractical to use underwater [20]. The following subsections discuss the physical fundamentals and propagation properties of acoustic waves as well as major challenges of using acoustic waves as communication medium in underwater environment.
2.2.1 Propagation Speed

Acoustic waves have a relatively slow propagation speed through water compared to EM propagation. The speed of sound near the ocean surface is around 1520 m/s, which is four times faster than speed of sound in the air, but five times smaller than speed of light. Such slow propagation speed will impact the communication performance and hence requires proper design of the network to achieve good connectivity. Moreover, efficiency of network protocols is reduced due to the inaccuracy of estimating round trip time (RTT) [21]. Temperature, depth, and salinity have an impact on the propagation speed of acoustic waves underwater. In general, acoustic waves propagate faster in warm water than cold water. Approximately, the speed increases 4.0 m/s as the temperature increases 1 °C. On the other hand, the speed of sound increases roughly 17 m/s as the depth of water increases 1 km. At the same time, the temperature decreases as the depth of water increases. In fact, the relation between temperature, depth, and sound speed is nonlinear. The overall relation can be illustrated in Figure 2.1(a). The relation gets more complex if the pressure effect is also accounted, as illustrated in Figure 2.1(b). Salinity does not have a great impact on the speed of sound especially in the open ocean. However, it has some impact near the shores where the speed changes around 1.4 m/s every 1 Practical Salinity Unit (PSU) [19].

2.2.2 Transmission Loss

Transmission loss in acoustic waves is caused by two phenomena: energy spreading and waves absorption. Energy spreading, also called geometric spreading, depends mainly on the transmission range of the acoustic waves. As the wave propagates for longer distances, it occupies larger surface area. As the surface area increases, the energy per unit surface area becomes less. There are two types of geometric spreading for acoustic waves underwater: spherical and cylindrical spreading. The energy
loss caused by spherical spreading is proportional to the square of the transmission range, while for the cylindrical spreading is proportional to the distance \([22]\). Waves absorption, on the other hand, is frequency-dependent. High-frequency signals are more vulnerable to absorption loss because of the transference of the acoustic energy to heat. This limits the available bandwidth of the acoustic channels. The overall attenuation \(A(r,f)\) of acoustic signal with transmission range \(r\), in meters, and frequency \(f\), in Hz, is given by \([23]\),

\[
A(r, f) = A_0 \kappa^{\alpha(f)} r
\]

(2.1)

where \(\alpha(f)\) is the absorption coefficient and \(\kappa\) is the spreading factor caused by the energy spreading. Common used values for the factor is \(\kappa = 1\) for spherical spreading, \(\kappa = 2\) for cylindrical spreading and \(\kappa = 1.5\) for practical spreading. The absorption coefficient of the seawater can be expressed using Thorp model in dB/km as follows \([24]\),
\[ \alpha(f) = 0.11 \frac{f^2}{1 + f^2} + 44 \frac{f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \] (2.2)

Where \( f \) is the signal’s frequency. Fisher & Simmons model is a more accurate absorption coefficient model, which takes into account temperature and depth [25]. The model takes the following form,

\[ a(d, t, f) = A_1 P_1 \frac{f^2 f_1}{f_1^2 + f^2} + A_2 P_2 \frac{f^2 f_2}{f_2^2 + f^2} + A_3 P_3 f^2 \] (2.3)

Where \( A \) coefficients represent the effect of temperature on the signal absorption, \( P \) coefficients represent the effects of the depth and \( f \) represent the relaxation frequencies introduced due to the absorption caused by boric acid and magnesium sulphate. This model holds for maximum depth of 8 km and is restricted to the average observed water salinity of 35 ppt and acidity level of 8 pH [26].

### 2.2.3 Ambient Noise

Ambient noise in oceans can be modeled by four components of noise sources: water turbulence, surface-ship, thermal noise, and breaking waves. Those sources can be described using Gaussian statistics and power spectral density (p.s.d) in dB re \( \mu \) per Hz using the following formula [27],

\[ N(f) = N_t(f) + N_s(f) + N_{th}(f) + N_w(f) \] (2.4)
where \( N_t, N_s, N_{th}, \) and \( N_w \) are given by the following formulae,

\[
10 \log(N_t(f)) = 17 - 30 \log(f) \tag{2.5}
\]
\[
10 \log(N_s(f)) = 40 + 20(s - 0.5) + 26 \log(f) - 60 \log(f + 0.03) \tag{2.6}
\]
\[
10 \log(N_{th}(f)) = -15 + 20 \log(f) \tag{2.7}
\]
\[
10 \log(N_w(f)) = 50 + 7.5w^\frac{1}{2} + 20 \log(f) - 40 \log(f + 0.4) \tag{2.8}
\]

Turbulence noise \( N_t(f) \) only affects the very low frequency region of \( f < 10 \) kHz. Surface-ship noise \( N_s(f) \) influences the frequency region from 10 kHz to 100 kHz, and is modeled through the shipping activity factor \( s \) in the equation. The value of \( s \) ranges between 0 and 1 which represents high and low activity, respectively. Thermal noise \( N_{th}(f) \) dominates the region of \( f > 100 \) kHz, where noise caused by breaking waves \( N_w(f) \) majorly contributes in the region from 100 Hz to 100 kHz and driven by the wind-speed \( w \) in m/s. The overall p.s.d of the ambient noise can be illustrated in Figure 2.2(a) [23] and its components in Figure 2.2(b).

### 2.3 Underwater Wireless Sensor Network

UWSN have been extensively used in many submarine applications for data sampling, environmental monitoring, disaster prevention, and other military applications. UWSNs provide many advantages over the traditional approach, in which an underwater sensing device is deployed to record data during the monitoring period and then nodes are collected for data processing [28]. UWSN provide the following advantages for submarine applications [29]:

- **Real-time monitoring**: The sampled data can be directly forwarded and processed on the fly during the monitoring session.

- **Online system configuration**: Monitoring nodes can be interactively controlled
(a) Power spectral density (p.s.d) of ambient noise in dB re μ Hz

(b) Components of ambient noise in dB

Figure 2.2: Ambient noise in underwater

by the controlling system out-water to tune and reconfigure the nodes.

- *Failure detection*: failures can be instantly detected.

- *Unlimited storage capacity*: sampled data is forwarded and stored in a uncon-
strained storage capacity.

In the following subsections we will show the differences between UWSNs and WSNs in terms of network architecture, protocol stack, and applications.

2.3.1 Network Architectures

The topology of UWSN is a crucial factor that affects the energy consumption, capacity, and reliability of the network [1]. Network topology should be carefully designed to achieve good throughput. Moreover, post-deployment optimization should be performed to ensure optimal network throughput. Nodes in a vast UWSN that cover a sparse area need to be placed optimally to reduce per node energy consumption. As the distance between the nodes increases, more energy is required to maintain a reasonable Signal-to-Noise (SNR) value over longer distances.

In general, underwater missions are expensive due to the high cost of underwater sensor devices. Hence, it is important to design a highly reliable network to avoid failures of underwater nodes. For example, the network should be designed to avoid single points of failure that could affect the overall performance of the network. Moreover, due to the limited capacity of the communication channel, as discussed in Section 2.2, the nodes should be organized in a prudent way to avoid communication bottlenecks. Akyildiz et al. [1] propose two comprehensive communication architectures and discuss the associated challenges for each architecture. The following subsections briefly discuss the pros and cons of each architecture and the associated challenges.

Two-dimensional UWSN

In this architecture, the underwater sensor nodes are anchored to the bottom of the ocean using deep ocean anchors. The nodes are connected wirelessly using acoustic
channels to one or more sinks forming a 2D network at the bottom of the ocean as shown in Figure 2.3 [1].

Sinks are special nodes that are capable of relaying the data from the ocean bottom to the surface station. Each sink is equipped with two transceivers: vertical and horizontal. The horizontal transceiver is used to communicate with the anchored nodes performing two functions: (1) send control commands to sensor nodes and (2) receive data from sensor nodes. The vertical transceiver is used by the sink to relay data and receive control commands from surface stations. Based on the application, vertical transceiver should be capable of transmitting long range signals as deep as 10 km. The surface station is equipped with long range acoustic transceiver capable of handling parallel communication with one or more sinks. It is also equipped with RF transmitter to communicate with other surface stations or on-shore sinks.

The anchored nodes at the bottom of the ocean can be connected to the sinks via direct or multi-hop paths. Direct path, i.e., star topology, is simple yet energy inefficient. In this scenario, each node establishes a dedicated communication channel
with the sink. The further the node, the higher transmission power is required.\[28\] proved that transmission power may decay with distance with powers greater than two. Moreover, overall network throughput is very likely to be reduced due to high power acoustic channels. Multi-hop topologies, on the other hand, are more energy efficient as the transmission distances are kept low and hence require lower transmission power. Network capacity is also more likely to be increased due to limited acoustic channel interference. The main drawback of multi-hop paths is its complexity in setting up and maintaining multi-hop routes, which will be discussed later in Section 2.3.3. In conclusion, multi-hop paths address the main concerns of a UWSN: energy and capacity. However, the routing functionality should be carefully determined to achieve network reliability.

**Three-dimensional UWSN**

In 3D UWSN networks, sensor nodes float at different depths covering a 3D volume of interest to observe a given phenomena from the surface to the bottom. Floating nodes are vulnerable to sea currents that could drift the nodes from their original locations. One solution is to anchor the nodes to the bottom of the ocean. The depth of the node can be regulated by adjusting the length of the wire that connects the sensor. The node can be also attached to a floating buoy on the surface to make length adjustment simpler. Another approach is to equip the node with an air pump that inflates and deflates to adjust the depth of the node \[30\]. Figure 2.4 \[1\] depicts the general layout of a 3D UWSN.

The main challenge in 3D UWSN is to ensure connectivity between nodes. Data is forwarded in a multi-hop manner since there are no sink nodes. Thus network devices should coordinate their depth to assure network connectivity. Moreover, nodes depth should be regulated in order to attain 3D sensing coverage of the monitored area according to the nodes sensing ranges. The nodes should be distributed properly
to cover the column from the surface to the bottom of the ocean, as some applications require data sampling among multiple levels of depth. However, connectivity and coverage need to be compromised. Revelmoanana [31] investigates the relation between sensing range and communication range to obtain optimal network coverage and connectivity. Three measures are introduced to assess connectivity and coverage: diameter, degrees of reachability, and degrees of connectivity. The first two are derived as a function of the communication range while the last one is derived as a function of the sensing range.

2.3.2 Protocol Stack

Protocol stack in underwater networking differs from terrestrial wireless network. This is due to the differences in communication media, underwater environment, and applications. Acoustic communication is characterized by high propagation delay, high noise, and transmission loss. Thus the design of the network layers protocols have to be tailored to optimize efficiency in underwater networking. In the following
subsections, we will discuss the advances in underwater networking protocol stack over the past decade.

**Data Link Layer**

Channel access control for multiple access poses unique challenges in UWSN due to the differences in the underwater and terrestrial environment. The characteristics of the acoustic channels, i.e., limited bandwidth and high delay, are the main challenges. Medium Access Control (MAC) protocol defines the mechanism of channel sharing between the nodes. In wireless networks, collision domain is occurred if two or more nodes are sharing the same channel media. When two nodes in the same collision domain are simultaneously attempting to access the communication channel, contention occurs. Severe media contention causes message collision and hence data loss which impacts the performance of the network. In general, MAC protocols are of two types: contention-free and contention based. We will discuss each type and discuss theirs suitability for UWSNs.

**Contention-free MAC protocols**

Contention-free MAC protocols prevent contentsions between nodes by providing a dedicated channel frequency, time slot, or unique coding scheme. The traditional contention-free MAC protocols are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA).

FDMA divides the available frequency band into smaller coherent sub-bands and assigns individual sub-band to different users. FDMA is not suitable for UWSN because of the narrow channel bandwidth, i.e., less than 100 kHz, fading, and multi-path characteristic of the acoustic channel [32]. TDMA, on the other hand, divides the time interval into time slots. Each time slot is assigned to an individual user, in which it can access the entire frequency band. Packet collision between two adjacent
time slots is prevented by introducing a proportional guard times between each slot. The major advantage of TDMA is its flexibility in assigning time slots to users, hence increasing the data rate of individual users on demand. However, TDMA requires a very precise time synchronization between nodes. One way to synchronize nodes is to broadcast probe signals using a predetermined time reference. However, this task is challenging due to the high difference in propagation delays between different underwater paths [33]. CDMA is favored over FDMA and TDMA in underwater networking because of its ability to provide the entire frequency band for individual user with minimal overhead and less complexity. CDMA exploits pseudo-noise (PN) to code the signals in order to distinguish them, allowing users to fully utilize the entire frequency band simultaneously. There are two spreading techniques: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). In DSSS, the signals are linearly modulated using the PN code, while in FHSS the carrier frequencies are changed according to a specified pattern obtained from the PN code. Each user in the system is assigned with a unique PN code.

**Contention-based MAC protocols**

The main drawback of contention-free MAC protocols is the division of the resources between the nodes which reduces the efficiency of the entire network. In TDMA for example, a time slot may be assigned to an inactive node. This assignment leads to a waste of available resources. Contention-based MAC protocols attempt to share the resources between nodes in an efficient yet fair manner. In the following paragraphs, we will discuss some contention-based MAC protocols and their suitability in underwater networking.

The most simple contention-based MAC protocol is ALOHA. ALOHA protocol allows random access of users to the medium. A user will send the information immediately when it is available. An acknowledgment (ACK) is sent back by the
receiver if the packet is received correctly. A collision may occur when two users simultaneously transmit packets. If collision occurs, packet is lost and ACK is not received. The user will retransmit the packet after backing-off for a random amount of time to reduce the probability of a collision. It is proved that a simple implementation of ALOHA achieves only 18% of the maximum achievable throughput [34]. This percentage can be improved up to 36% by dividing the time into time slots and restricting the transmission to be at the beginning of each time slot. This protocol is called Slotted-ALOHA [35]. ALOHA and Slotted-ALOHA, however, are inefficient in underwater networking because of the high power consumption due to high rate of packet retransmissions.

Unlike ALOHA, Carrier Sense Multiple Access (CSMA) tries to sense the medium for existing transmission before attempting to transmit [36]. CSMA improves the throughput over ALOHA and Slotted-ALOHA; however, it fails to operate in the presence of hidden node and exposed node problems. Referring to Figure 2.5a, hidden node problem occurs when node A begins transmission to middle node B. Since node C is out of node’s A range and can not sense the carrier, it may transmit at the same time leading to a collision at B. The exposed node problem is shown in Figure 2.5b. B is sending a packet to node A. Since node C is in the node’s B range, it can not transmit packets to node D.
As an alternative to CSMA, Karn et al. \cite{37} propose Multiple Access with Collision Avoidance (MACA) protocol. MACA uses two-way signaling packets called request-to-send (RTS) and clear-to-send (CTS). This approach overcomes hidden and exposed terminal depicted in Figure 2.5. When node A wants to send a packet to node B, it sends a RTS packet containing the length of the message. Node B upon receiving RTS replies with CTS packet that reserves the medium for the duration of the transmission. As soon as node A receives CTS, it begins transmission of the data packet. Any node overhears node B’s CTS, including node C, will defer its transmission for the length of the data packet specified by CTS to avoid collision. Due to the high propagation delay of underwater communication, MACA is impractical for underwater networking for the following reasons: (1) it is more likely that the channel is sensed idle and (2) it will be difficult to predict the start and finish time of the transmission thus it leads to low throughput.

In conclusion, the high propagation delay of underwater communication limits throughput of the network. CDMA is the most promising MAC technique because of its ability to increase channel reuse and reduce packet retransmission \cite{28}. Salvaá-
Garau et. al propose a combined TDMA and CDMA based protocol to mitigate the high propagation delays and high channel interference in acoustic channels [38]. The scheme is formed by clustering the network in small adjacent nodes. TDMA is used within the cluster with a long band guards. Nodes in the same cluster are assumed to be close to one another, hence the effect of high underwater propagation delay is minimized. Interference among clusters is then minimized by assigning different spreading codes to each cluster.

2.3.3 Network Layer

The main function of network layer is to determine the path between the source and the destination nodes in an efficient and reliable way. There is a significant interest in developing new routing protocols for terrestrial WSN [39]. However, the different nature of underwater environment engenders many drawbacks in employing existing routing protocols for underwater networking. The existing routing protocols can be categorized into three types: proactive, reactive, and geographical routing protocols. We will discuss the applicability of each type to underwater networking.

Proactive routing protocols establishe routes at the beginning of network operation and every time the topology is modified because of node mobility or node failure. This scheme overcomes the delay induced by route discovery in each packet transaction by maintaining an up-to-date routing information at each node. Each node, then, can establish a path to any other node based on predetermined criteria. This is done by exploiting a broadcast control packet that updates the routing table at each node. Examples of this protocol scheme are Destination-Sequence Distance Vector (DSDV) protocol [40] and Optimal Link State Routing (OLSR) protocol [41]. The disadvantage of this scheme is the large signaling overhead each time the topology changes. Moreover, some of the paths are never used but are still maintained. Therefore, proactive protocols may not scale for large underwater networks.
Reactive protocols (e.g., Ad Hoc On-Demand Distance Vector (AODV) protocol \cite{12} and Dynamic Source Routing (DSR) \cite{13}) establish a path only when a node initiates a route discovery process to a destination in response to a pending transmission. The discovered path is maintained by a maintain route procedure until the path is no longer needed. Although this scheme results in high latency due to route discovery, it is efficient for large dynamic networks. However, underwater networks are unlikely to move rapidly. Similar to proactive protocols, there is still a large amount of exchanged control packets between nodes. Moreover, due to the asymmetrically in underwater communication links, most of the reactive protocols are not suitable for underwater networking.

Geographical routing protocols, such as Greedy-Face-Greedy (GFG) \cite{44} and Partial Topology Knowledge Forwarding (PTKF) \cite{45}, use the geographical positions to establish routes between nodes. These schemes generate low control signaling overhead. In terrestrial wireless networks, Global Positioning System (GPS) can be used to determine the location of the nodes. However, GPS can not be utilized to localize nodes underwater. Hence, nodes localization techniques are required to estimate the 3D locations of the node underwater. This is a challenging problem for nodes with limited power resources.

Default terrestrial routing protocols are not efficient for underwater networking. Hence, researches have proposed tailored routing protocols specifically for underwater acoustic networks. Xie and Gibson propose a novel centralized routing protocol for Underwater Acoustic Network (UAN) that autonomously establishes network topology, controls network resource, and establishes network flows \cite{46}. The manager, which runs on the surface station, implements network management using distributed network agents by probing underwater network characteristics periodically. This information is retrieved and used by the manager to initiate data delivery paths to avoid bottlenecks and provide quality of service in the networks. Xie et al. also propose
an underwater networking routing protocol based on geographical routing approach called Vector-Based Forwarding (VBF). In VBF, each packet carries the position of the sender, the destination, and the forwarder. The packet traverses from the source to the destination in a virtual routing pipe. Each node, upon receiving the packet, computes its position relatively to the forwarder position by measuring the distance and the angle of arrival. Based on routing vector, i.e., determined vector that connects source to destination, each node determines if it is close enough to that routing vector. If the node decides it is close enough, it stores its own position in the packet and forwards it, otherwise it simply discards it. Practically, all nodes that are positioned close to the routing vector are potential forwarders for the packet. This provides redundancy and network robustness against packet loss and node failure. However, such redundant transmissions are not energy and bandwidth efficient. A self-adapting algorithm is proposed to evaluate the benefit of forwarding the packet.

In conclusion, routing protocols for terrestrial WSN are not suitable for underwater networking. Routing protocol underwater networking is application-driven. Tailored protocols exist in the literature survey that can be slightly modified to meet the specific requirements of underwater application.

2.3.4 Transport Layer

Transport layer protocol has a significant importance in designing wireless networks. The main functionality is to perform flow and congestion control. Reliable transport protocol is needed to preserve the scarce underwater networks resources and assure efficiency. Congestion control is required to prevent network congestion and any subsequent packet loss. Flow control assures that a receiver is not overwhelmed with data transmission. The most common transport layer protocol, i.e., Transmission Control Protocol (TCP), is not suitable for underwater networking. This is because TCP is based on window-based mechanism that depends on accurately measuring RTT. Due
to the characteristics of underwater environment, RTT is long and hence will affect the throughput of TCP implementations \cite{29}. User Datagram Protocol (UDP) is a commonly used transport protocol for real-time service networks. However, it does not provide any reliability and thus may not be suitable for underwater networking.

Xie et al. \cite{48} propose a transport layer protocol for underwater networking called Segmented Data Reliable Transport (SDRT). SDRT addresses the unique challenges of underwater communication, \textit{i.e.}, high propagation delay, low bandwidth, energy efficiency, and high dynamic of underwater networks. SDRT is based on recovering reordered transmitted packets using Tornado codes \cite{49}. Although SDRT is an early attempt to design a reliable transport protocol for underwater networking that addresses the aforementioned challenges, it is still evolving work. The following design principles should be the guidelines for designing a complete transport layer solution for underwater environment \cite{29}:

- \textit{Minimizing energy consumption}
- \textit{Forwarding out-of-sequence packets}
- \textit{Prompt reaction to network congestion}
- \textit{Reliability}

\section{2.4 Underwater Node Placement}

Akkaya et al. present a distributed node deployment technique for Underwater Acoustic Sensor Networks \cite{3}. The proposed solution is an iterative-based algorithm that adjusts the nodes depth after the initial deployment until no further improvement can be done. It does not find an optimal solution, neither the minimum number of nodes. It tries, however, to achieve maximum network connectivity and sensing coverage with the available number of nodes and maintain minimum number of nodes.
movement and number of messages. Pompili et al. study different node deployment strategies for two-dimensional and three-dimensional architecture for underwater sensor network [4]. The objective of the analysis is to determine the minimum number of nodes that achieves optimal sensing and coverage range. In the 2D architecture, a triangular-grid deployment is proposed where nodes are placed on the vertices of equilateral triangles to cover a rectangular area on the surface of the ocean. They study the trajectory of sinking objects by calculating the average x-axis and y-axis displacements as the node sinks in the water. The proposed model allows tracking the node’s final location at the bottom of the ocean taking into account the effects of water currents. In the 3D architecture, three strategies are proposed to deploy nodes that obtains 1-coverage: 3D random, bottom-random and grid random. Alam et al. [2] propose nodes placement strategy that achieves a full sensing coverage in 3D space using the minimum number of nodes. The strategy is based on Voronoi tessellation of certain polyhedrons of a 3D space. A metric called volumetric quotient is introduced to measure the ratio of the volume of the polyhedron to the volume of the node’s sensing range circumsphere of radius $R$. A high volumetric quotient means that the polyhedron is completely space-filling the circumsphere of radius $R$ of the node and hence less number of nodes is required to cover the 3D space. Hence the problem can be reformulated as finding the best polyhedron that has the highest volumetric quotient given the radius $R$. The volumetric quotients of four polyhedrons are compared: cube, hexagonal prism, rhombic dodecahedron, and truncated octahedron. The 3D coordinates of each polyhedron are given in terms of $R$. Moreover, the ratio between the sensing range and transmission range is studied and found to be at least 1.7889 times the sensing range to achieve full connectivity.

Optimal placement of gateway nodes on the water surface can improve the overall performance of the underwater network. Ibrahim et al. [50, 51, 6] present deployment strategies for multiple surface gateways radio-capable nodes. The problem is modeled
as a 3D graph optimization problem where the nodes represent the underwater sensors and the candidate positions of the surface gateways. The objective function is to find the subset of candidate positions for the gateways to satisfy certain constraints. In [50], the objectives are to minimize the expected time delay and energy consumption. The optimization problem is solved using a heuristic approach. While in [51], the same problem is solved using Integer Linear Programming (ILP). In both papers, all nodes are assumed to be with relatively fixed locations and has the same communication range. Furthermore, the interference model is assumed to be simple where each node can only transmit packets when no other neighboring nodes are directing packets to it. In [6], the same problem is modeled with objective function of increasing the lifetime of the underwater network. The set of candidate positions is given as 2D mesh that covers the required water surface in the underwater sensor deployment. However, the large set of candidate positions affect the practicality of the deployment problem. In [52], authors propose an algorithm to define a smaller set of candidate positions based on the geometric properties of the deployed network. The proposed algorithm reduces the problem formulation’s complexity. Badia et al. develop an optimization framework that joins nodes deployment, link scheduling, and routing in underwater sensor network [5]. The network is modeled using a directed graph where nodes are the candidate positions of the sensor nodes in the 3D space. The actual sensor locations will be decided by the outcome of the integer linear programming model. The network model is capable of capturing acoustic channel propagation underwater as well as the interference condition at the receivers. The path loss model between two acoustic transceivers is modified to better seize the correct behavior of the acoustic channel underwater. Four metrics are investigated in the experiments: end-to-end delay, time, average energy needed to deliver a packet to the sink, and total energy consumption. Pashku et al. develop a sensor placement optimization framework for underwater threat detection networks [53]. The proposed framework
joins sensors placement with threat detection algorithm for single-period and multi-period models. The sensor placement algorithm uses a quasi-regular placement model where sensors are placed forming regular shapes like triangles, squares and so on. In [54], Domingo tackles the problem of placing wireless nodes in Shadow Zones. The optimal placement of affected nodes is found using a mathematical model to minimize the transmission loss while maintaining the network connectivity. If the node is located within the area of a shadow zone, it is uncoupled to two wired-connected nodes across the zone. The problem of finding the new location of the introduced node is formulated as a nonlinear programming problem. The objective function is to find the optimal location that minimizes the transmission loss between the two nodes.
Chapter 3

Network Model and Problem Formulation

In this chapter, the proposed network model is presented. Then, the problem is formulated as nonlinear programming model that captures the acoustic signals characteristics underwater.

3.1 Network Model

We consider a 3D UWSN where a certain number of nodes are deployed to cover certain underwater volume. The underwater network consists of two entities: Surface Gateways (SG) and Relay Nodes (RN). SGs are static nodes attached to buoys on the surface. They are equipped with two types of interfaces: acoustic and electromagnetic. SGs connect the underwater network to the Internet via electromagnetic interface. SG forwards and receives packets to the underwater network using acoustic interface. Each SG can be connected to one or more RNs. RNs are placed at multiple depths inside the water to relay the packets from SGs to the operating AUVs at the ocean floor and vice versa. In our network model, we assume,
• All RNs are equipped with homogenous transceivers and have a sphere-based communication with radius of $r_c$. $r_c$ is assumed to be constant for all nodes. We further assume that all nodes in the network transmit with a uniform transmission power.

• Two nodes are connected if the node inter-distance is less than or equal $r_c$.

• A RN has a sphere-based sensing model with a sensing range of $r_s$. We assume all RNs have the same $r_s$.

• The network is fairly large and there is no boundary effect. The number of RNs is inversely proportional to the volume covered by the RNs.

• The ocean is divided horizontally into different regions based on the depth. The propagation characteristics of acoustic waves are different in each region.

• Each RN can be statically deployed in any position at any depth. Furthermore, RNs can maintain their location using various means of depth and location adjustments.

The target is to find an optimal placement strategy that achieves full coverage and full connectivity with all direct neighboring RNs using the minimum number of RNs and minimum transmission loss. Full coverage and connectivity can be achieved by utilizing the solution suggested in [7]. The solution starts with finding a space-filling polyhedron that best approximate the sensing sphere. This is measured by the volumetric quotient, which measures the ratio of the volume of the polyhedron to the volume of the communication sphere of radius $r_s$. It is found that Truncated Octahedron (TO) has the highest volumetric quotient among all other polyhedrons. A TO has 14 faces, 8 of them are hexagonal and 6 are square as shown in Figure 3.1. The length of the edge in the hexagonal and the square is $a$. The volume of a TO is $8\sqrt{2}a^3$ and the radius of its circumsphere is $\frac{\sqrt{10}a}{2}$. The volumetric quotient of TO is,
The placement algorithm then finds the locations where RNs should be placed to tessellate the space-filling polyhedron, i.e., TOs. The input of the algorithm is distance $R$ and the co-ordinates of a seed point, e.g., $(x, y, z)$. The output is the coordinates of the locations where RNs are to be placed. The coordinates of the RNs locations with an arbitrary seed-point $(cx, cy, cz)$ are as follows,

$$(cx + (2u + w)rac{2R}{\sqrt{5}}, cy + (2v + w)rac{2R}{\sqrt{5}}, cz + wrac{2R}{\sqrt{5}})$$

(3.1)

where $u \in Z$, $v \in Z$, $w \in Z$; $Z$ is the set of integers. $R$ is the radius of the circumsphere of TO. To achieve full coverage and connectivity of the network, $R$ should be set to $r_s$. However, $r_c/r_s$ should be greater than or equal $4/\sqrt{5}$. Since the distance between any two nodes should be less than or equal $r_c$, we reduce the problem to be finding the optimal value of $r_c$ that minimizes the number of nodes and the transmission loss. The SNR of an emitted underwater acoustic signal at the receiver can be expressed in dB by the passive sonar equation [22].
\[ SNR = SL - TL - NL + DI \] (3.2)

where \( SL \) is the signal level of transmission power, \( TL \) is the transmission loss (represented by \( \delta \) in our model), \( NL \) is the noise level, and \( DI \) is the directivity index.

The signal level \( SL \) is related to the transmission power intensity \( I_t \) and hence to the transmission power \( P_t \) of the transceiver. The intensity \( I_t \) in shallow water is given in \( Watts/m^2 \) as follows,

\[ I_t = \frac{P_t}{2\pi \times 1m \times z} \] (3.3)

where \( z \) is the depth in meters. In deep water Eq. (3.3) becomes,

\[ I_t = \frac{P_t}{4\pi \times 1m \times z} \] (3.4)

and \( SL \) is given as,

\[ SL = 10\log\left(\frac{I_t}{0.67 \times 10^{-18}}\right) \] (3.5)

\( NL \) is given by Eq. (2.4) and \( DI \) is set to zero.

Transmission loss, \( \delta \), of an acoustic signal between two nodes depends on two factors: energy spreading and attenuation. Path loss is calculated by Equation (2.1) and can be expressed in dB as the following,

\[ \delta = 10\kappa \log(r) + \alpha(f)r10^{-3} \] (3.6)

where \( \kappa \) is the geometric spreading factor, and \( \alpha \) is the absorption coefficient which is a function of frequency, temperature, and depth. Equation (2.3) expresses the Fisher & Simmons model of absorption coefficient. However, a simpler yet accurate formula is presented by Ainslie and McColm [55, 56] as follows,
\[\alpha(f) = \gamma_1 \frac{f_1 f^2}{f_1 + f^2} + \gamma_2 \frac{f_2 f^2}{f_2 + f^2} + \gamma_3 f^2\] (3.7)

where,
\[
\begin{align*}
f_1 &= 0.78(S/35)^\frac{1}{2} e^{\frac{T}{35}} \\
f_2 &= 42e^{\frac{T}{37}} \\
\gamma_1 &= 0.106 e^{\frac{pH - 8}{0.56}} \\
\gamma_2 &= 0.52(1 + \frac{T}{43})(\frac{S}{35})e^{-\frac{d}{17}} \\
\gamma_3 &= 0.00049e^{-\left(\frac{T}{27} + \frac{d}{17}\right)}
\end{align*}
\]

where \(T\) is the temperature in \(^\circ\)C, \(d\) is the depth in m, \(pH\) is water acidity, and \(S\) is the water salinity. The default values of \(pH\) and \(S\) are 8 and 35, receptively.

Since \(r_s = \sqrt{10}a/2\) and \(r_c = 4\sqrt{5}\), then the volume of TO in terms of \(r_c\) is

\[
V = 8\sqrt{2}a^3 = 8\sqrt{2}\left(\frac{2r_s}{\sqrt{10}}\right)^3 = \frac{64\sqrt{2}}{10\sqrt{10}}\left(\frac{\sqrt{5}r_c}{4}\right)^3 = \frac{r_c^3}{2}
\] (3.8)

### 3.2 Problem Formulation

Let the network consist of \(N\) number of RN’s with the same acoustic propagation characteristics at a given depth and temperature. The goal of the optimization problem is to find the optimal distance between nodes, i.e., \(r_c\), for a fixed value of \(f\). The optimization problem \(P\) can be formulated as nonlinear programming problem.

Given, \(\kappa, d, T, V_{th}, f, R_{max},\) and \(N\)

Minimize,

\[
\delta = 10\kappa\log(r) + \alpha(d, f)r \times 10^{-3}
\] (3.9)

subject to:

\[
r < R_{max}
\] (3.10)
\[ 0 < f < 10^6 Hz \quad (3.11) \]

\[ V_{th} \leq \frac{Nr_c^3}{2} \quad (3.12) \]

Constraint (3.10) assures that the transmission distance is within the transmission capability of the acoustic modem. Constraint (3.11) ensures that frequency is in the valid range for Eq. (3.7). Constraint (3.12) assures that the total volume covered by \( N \) nodes is greater than or equal to a predetermined threshold volume.

This model can be extended to compute the optimal transmission range using the free space path loss in EM waves [57]. In this case, the objective function is,

\[ \delta = 32.4 + 20\log(f_c) + 20\log(R_k) \quad (3.13) \]

where \( f_c \) is the signal’s frequency in MHz and \( R_k \) is the range in Km. Constraints (3.11) will be changed according to the frequency band of the EM waves. Eq. (3.2) can be substituted with the SNR equation in EM wave as the follows,

\[ SNR = \frac{P_R}{P_N} \quad (3.14) \]

where \( P_R \) is the received signal power and \( P_N \) is the noise power in Gaussian distribution.
Chapter 4

Results and Discussion

This chapter presents the results of the mathematical model developed to obtain the optimal inter-node distances. First, we solve the optimization problem $P$ and obtain the transmission ranges that minimize transmission loss. Then, we compute the largest possible volumes for a given number of nodes $N$ that retains a transmission loss threshold $\delta_{th}$ which is defined as follows,

$$\delta_{th} = SL - SNR_{th} - NL \quad (4.1)$$

The transmission loss threshold is essential to maintain certain SNR values which is necessary to compute the number of nodes in certain volume. Finally, we validate the results using simulation.

4.1 System Setup

The parameters used in our model are shown in Table 4.1. The values follow the specifications of the commercial underwater acoustic modem HAM.NODE [58]. We assume that the volume of interest is $V_{th}$. In this model, we divide the area into four levels with depth of 2500 m each.
We assume using Orthogonal Frequency Division Multiplexing (OFDM) as an encoding technique. OFDM is a multi-carrier encoding technique which divides the carrier into orthogonal sub-carriers. The data is divided into parallel channels and each is carried over a sub-carrier. OFDM is efficient because noise is spread over a large portion of available bandwidth [1]. The amplitude and the phase of the sub-carrier are calculated using the Quadrature Amplitude Modulation (QAM) scheme [59]. Scalable OFDM with 16-QAM modulation provides the highest Bit Error Rate (BER) performance compared to other modulations [60]. Assuming we consider 16-QAM modulation with OFDM transmission in our model, we can compute BER as follows,

\[ P_{16QAM} = \frac{3}{2k} \text{erfc}(\sqrt{\frac{k}{10} \frac{E_b}{N_0}}) \]  

(4.2)

where \( k \) is \( \log_2 16 \) and \( E_b/N_0 \) is the energy per bit to noise power spectral density ratio and is calculated as follows,

\[ E_b/N_0 = \text{SNR} \frac{B_N}{R} \]  

(4.3)

where \( B_N \) is the noise bandwidth in Hz, \( R \) is the data rate in bps and SNR is \( 10^{\text{SNR}(d,f)/10} \). Using Equations 4.2, 4.3, and parameter values given in Table 4.1 we compute SNR values for BER of \( 10^{-1}, 10^{-3}, 10^{-6}, \) and \( 10^{-9} \). The SNR values are shown in Table 4.2. It is obvious that lowering the BER requires higher SNR values.

4.2 System Evaluation

The absorption coefficient \( \alpha \) is calculated using Ainslie and McColm model due its simplicity and accuracy. It holds for frequencies in the range of \( 0 < f < 1000 \text{ KHz} \). Figure 4.1 shows absorption coefficient at different depths. The absorption coefficient
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$</td>
<td>1.5</td>
</tr>
<tr>
<td>Noise bandwidth ($B_n$)</td>
<td>1KHz</td>
</tr>
<tr>
<td>Wind speed (w)</td>
<td>0 m/s</td>
</tr>
<tr>
<td>Shipping activity factor (s)</td>
<td>0.5</td>
</tr>
<tr>
<td>Water Acidity (pH)</td>
<td>8</td>
</tr>
<tr>
<td>Water salinity (S)</td>
<td>35 ppt</td>
</tr>
<tr>
<td>Date rate (R)</td>
<td>3.4 Kpbs</td>
</tr>
<tr>
<td>Temperature (T)</td>
<td>15° C</td>
</tr>
<tr>
<td>$R_{Max}$</td>
<td>30 km</td>
</tr>
<tr>
<td>BER</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>$V_{th}$</td>
<td>$10000 \times 10000 \times 10000$</td>
</tr>
<tr>
<td>N</td>
<td>25</td>
</tr>
<tr>
<td>$P_t$</td>
<td>100 Watts</td>
</tr>
</tbody>
</table>

Table 4.1: Parameter values

<table>
<thead>
<tr>
<th>BER</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>4.8919</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>13.532</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>17.4120</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>19.4711</td>
</tr>
</tbody>
</table>

Table 4.2: BER Vs. SNR

rapid increase with frequency limits the use of larger frequencies for acoustic links at given distance. It is also clear that absorption coefficient decreases as depth increases.

Consequently, as the operating frequency increases, the absorption loss affects the transmission loss. Figures 4.2(a), 4.2(b), and 4.2(c) show the total transmission loss at the depths of 10, 5000, and 10000 m for up to transmission range of 1 km for different frequencies. Transmission loss steeply increases as transmission range increases. However, the impact of the distance is limited in low frequencies because of the low absorption loss. It is also notable that transmission losses decrease as the depth increase because of the low absorption loss deep in the water.

We solved the nonlinear programming problem $P$ using Optimization Toolbox in MATLAB [61]. The function $fmincon$ is used with Active Set algorithm to find the
Figure 4.1: Absorption coefficient $\alpha$ using Ainslie and McColm model at different depths for $T = 15^\circ$, $pH = 8$ and, $S = 35$

feasible solution of the problem. Transmission loss threshold in Equation (3.2) can be calculated using parameters values in Table 4.1. Table 4.3 shows threshold values for frequencies 1, 10, 100, and 1000 KHz at depths 10, 2500, 5000, 7500 m in dB/km.

<table>
<thead>
<tr>
<th>Depth</th>
<th>1 KHz</th>
<th>10 KHz</th>
<th>100 KHz</th>
<th>500 KHz</th>
<th>1000 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10m</td>
<td>118.9</td>
<td>134.93</td>
<td>139.15</td>
<td>125.3</td>
<td>119.28</td>
</tr>
<tr>
<td>2500m</td>
<td>91.92</td>
<td>107.94</td>
<td>112.16</td>
<td>98.32</td>
<td>92.3</td>
</tr>
<tr>
<td>5000m</td>
<td>88.91</td>
<td>104.93</td>
<td>109.15</td>
<td>95.3</td>
<td>89.2</td>
</tr>
<tr>
<td>7500m</td>
<td>87.15</td>
<td>103.17</td>
<td>107.39</td>
<td>93.54</td>
<td>87.52</td>
</tr>
</tbody>
</table>

Table 4.3: Transmission loss threshold for 1, 10, 100, and 1000 KHz at depths 10, 2500, 5000, 7500 m to maintain BER of $1^{-9}$

Since the objective function has a logarithmic behavior as shown in Figure 4.2, the solver will always obtain the lower bound value determined by Equation (3.12). In other words, the optimal transmission range $r_c$ is the one which solves the equation. The minimum number of nodes that gives the highest volume at each depth with minimum total transmission loss is computed. The minimum number of nodes and the corresponding transmission ranges are given in Table 4.4 and 4.5 respectively.
Figure 4.2: Transmission loss of deep and shallow water
Table 4.4: Minimum number of nodes at different depth levels

<table>
<thead>
<tr>
<th>Depth</th>
<th>100 KHz</th>
<th>500 KHz</th>
<th>1000 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2500 m</td>
<td>40</td>
<td>2282</td>
<td>35855</td>
</tr>
<tr>
<td>2500-5000 m</td>
<td>37</td>
<td>3158</td>
<td>62715</td>
</tr>
<tr>
<td>5000-7500 m</td>
<td>15</td>
<td>1853</td>
<td>44211</td>
</tr>
<tr>
<td>7500-10000 m</td>
<td>6</td>
<td>1082</td>
<td>29969</td>
</tr>
</tbody>
</table>

Table 4.5: Maximum transmission range at different depth levels

<table>
<thead>
<tr>
<th>Depth</th>
<th>100 KHz</th>
<th>500 KHz</th>
<th>1000 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2500 m</td>
<td>2320.8 m</td>
<td>602 m</td>
<td>239.32 m</td>
</tr>
<tr>
<td>2500-5000 m</td>
<td>2381.9 m</td>
<td>541.27 m</td>
<td>199.77 m</td>
</tr>
<tr>
<td>5000-7500 m</td>
<td>3218.3 m</td>
<td>646.2 m</td>
<td>224.46 m</td>
</tr>
<tr>
<td>7500-10000 m</td>
<td>4367.9 m</td>
<td>773.12 m</td>
<td>255.82 m</td>
</tr>
</tbody>
</table>

The number of nodes increases with the frequency because of the rapid increase in transmission loss, and hence the inter-node distance decreases. As the depth increases, less number of nodes are required, thus increases the inter-node distance for the same frequency.

Alternatively, the maximum volume of certain number of nodes $N$ that holds the transmission loss constraint is computed. Using transmission loss threshold values in Table 4.3, the corresponding transmission range from Equation (2.1) is obtained. The maximum volume of $N$ nodes is calculated by Equation (3.8).

There exists an optimal frequency that holds the transmission threshold and gives the largest transmission range at certain depth, transmission power, and BER. This is due to the behavior of the ambient noise model as shown in Figure 2.2(a) where the ambient noise approach a minimum value at frequencies around 40 KHz. Figure 4.3 shows that the transmission range increases as the depth increases. The optimal frequency increases with depth because of the limited effect of absorption in deep water. Low BER values limit the transmission range for the same frequency at the same depth. Figures 4.5(a) and 4.5(b) show the optimal frequency with different values of the desired BER at depths 100 and 1000 m, respectively. The figures also
show that for a desired BER value $ber_1$, a maximum transmission range $r_1$ can be obtained. For any $ber_2 < ber_1$, the transmission range $r_2$ should be less than $r_1$ to compensate the SNR threshold value. Increasing the transmission power level improves SNR and thus increases the inter-node distance as shown in Figures 4.6(a) and 4.6(b). Modulation scheme is an important factor that has an impact on SNR in underwater communication channels. Binary Phase-Shift Keying (BPSK) and Quadrature Phase-Shifting Keying (QPSK) are modulation schemes that use Phase-Shift Keying technique to convey data with 1 bit per symbol and 2 bits per symbol, respectively. BER of BPSK and QPSK can be computed as follows,

$$P_{b}^{PBSK,QPSK} = \frac{1}{2} \text{erfc}(\frac{E_b}{N_0})$$

(4.4)

Figures 4.7(a) and 4.7(b) demonstrate the effect of modulation scheme on the inter-node distance at the optimal frequency at depths of 100 and 10000 m, respectively. BPSK and QPSK provide larger transmission ranges because they use less number of bits of modulation compare to 8-QAM and 16-QAM. Low data rate networks, i.e., UWSN, are more susceptible to transmission loss and hence using lower bits per symbols improves the acoustic channel throughput.

## 4.3 Placement Strategy

Once $r$ is obtained, the coordinates of the node in 3D space are computed using Equation (3.1). The nodes are placed next to each other forming tiled TOs that cover certain volume. Figures 4.8(a) and 4.8(c) depict the placement of 9 and 13115 nodes in 3D space with transmission ranges of 11157 and 984 m, respectively.
Figure 4.3: Maximum transmission range for different depths with $P=100$ W and $BER=10^{-9}$

4.4 Simulation Setup and Results

We validate the results obtained from the mathematical model using NS-3 simulator [62]. NS-3 supports underwater acoustic networks using the available UAN framework. The framework consists of three main components: medium channel, physical (PHY), and MAC. We modified the framework as follows. The modified medium channel supports different absorption models, i.e., Fisher and Simmons, Ainslie and McColm, and Thorp models. We use Ainslie and McColm model in the simulation. Moreover, we modified the PHY layer such that it uses passive sonar equation to calculate SNR threshold as in Equation (3.2). We use the provided MAC ALOHA protocol in the framework. However, it has been adjusted to work with UDP socket provided in NS-3 in order to work with UDP client and server application.

The parameters used in the simulation are listed in Table 4.1. A node sends a dummy packet of size 25 bytes at data rate of 2 Kbps. We targeted two nodes with a distance of 10 m from each other as shown in Figure 4.4. The right node is moving
Figure 4.4: Two nodes distanced 10m from each other. The arrow shows movement of the node away at constant velocity of 10 meters per minute. Left node continuously sends UDP packets to the right node. The packet is correctly received with probability greater than 90% if the SNR is greater than the cut-off threshold. This threshold is calculated using Equation (4.3) to maintain a channel BER of $1^{-9}$. Figures 4.9, 4.10, 4.11, and 4.12 show the Packer Error Rate (PER) over the distance as node is moving away at different depths and frequencies. PER drops to 0 after certain transmission range because the SNR values degraded below the cut-off threshold value. The dashed vertical lines show the maximum transmission ranges obtained from the mathematical model in Table 4.6.

<table>
<thead>
<tr>
<th>Depth</th>
<th>100 KHz</th>
<th>500 KHz</th>
<th>1000 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>10m</td>
<td>2334.5 m</td>
<td>602.93 m</td>
<td>237.95 m</td>
</tr>
<tr>
<td>2500m</td>
<td>2393 m</td>
<td>541.28 m</td>
<td>199.46 m</td>
</tr>
<tr>
<td>5000m</td>
<td>3232.3 m</td>
<td>646.23 m</td>
<td>235.63 m</td>
</tr>
<tr>
<td>7500m</td>
<td>4394.7 m</td>
<td>773.16 m</td>
<td>255.52 m</td>
</tr>
</tbody>
</table>

Table 4.6: Transmission range corresponding to transmission loss threshold
(a) Maximum transmission range at depth 100 m and transmission power of 100 W varies with the desired BER

(b) Maximum transmission range at depth 10000 m and transmission power of 100 W varies with the desired BER

Figure 4.5: Optimal frequency with different BER values
(a) Maximum transmission range at depth 100 m and BER= $10^{-9}$ with different transmission power

(b) Maximum transmission range at depth 10000 m and BER= $10^{-9}$ with different transmission power

Figure 4.6: Optimal frequency with different transmission power level
(a) Maximum transmission range with different modulation schemes at depth 100 m, transmission power of 100 W, and BER = $10^{-9}$

(b) Maximum transmission range with different modulation schemes at depth 10000 m, transmission power of 100 W, and BER = $10^{-9}$

Figure 4.7: Optimal frequency with different modulation schemes
Figure 4.8: Placement of truncated octahedron in 3D space
Figure 4.9: Maximum transmission range to maintain a cut-off SNR threshold of 19.47 dB at depth of 10 m with frequencies 100, 500 and 1000 KHz

Figure 4.10: Maximum transmission range to maintain a cut-off SNR threshold of 19.47 dB at depth of 2500 m with frequencies 100, 500 and 1000 KHz
Figure 4.11: Maximum transmission range to maintain a cut-off SNR threshold of 19.47 dB at depth of 5000 m with frequencies 100, 500 and 1000 KHz

Figure 4.12: Maximum transmission range to maintain a cut-off SNR threshold of 19.47 dB at depth of 7500 m with frequencies 100, 500 and 1000 KHz
Chapter 5

Conclusion and Future Direction

In this thesis, we presented an optimal node placement strategy for underwater wireless sensor networks that considers the characteristics of underwater acoustic channels. We formulated the problem as a nonlinear programming model. The objective is to obtain the transmission range that minimizes the transmission loss for a given frequency at certain depth. We also considered two objective factors which are finding the largest volume for a given number of nodes and finding the minimum number of nodes to cover a certain volume. We computed transmission loss threshold by varying the values of BER and transmission power levels. We found that there exists an optimal frequency in which it gives the maximum transmission range. This optimal frequency is around 40 KHz for different values of BER and transmission power levels.

Results showed that the operating frequency affects the number of nodes required to cover a definite volume. As frequency increases, more nodes are required with short inter-node distance to maintain a transmission loss threshold. Inter-node distance is expanded as the transmission power increases at the same water depth. We also observed that the modulation schemes have an important impact on the inter-node distance for the BER. It is shown that schemes that use lower bit per symbols increase channel throughput as well as transmission range. We validated the results obtained
from the mathematical model using NS-3. Results showed that transmission ranges obtained from the analytical model match the results in the simulation with 10% error.

As a future work, we will consider extending the objective function to include the channel capacity. Channel capacity is an important factor that improves the overall performance of the underwater network. This model can be used as an initial infrastructure for future researches in UWSN.
References


