# THREE DIMENSIONAL TARGET TRACKING WITH UNDERWATER ACOUSTIC SENSOR NETWORKS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

NOVEMBER 2009

Approval of the thesis:

# THREE DIMENSIONAL TARGET TRACKING WITH UNDERWATER ACOUSTIC SENSOR NETWORKS

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# ABSTRACT

## THREE DIMENSIONAL TARGET TRACKING WITH UNDERWATER ACOUSTIC SENSOR NETWORKS

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November 2009, 50 pages

Sonar is the traditional method of underwater target detection and tracking. However, using traditional sonar arrays may be difficult and impractical in some mission-critical scenarios as they require a ship or a submersible to be mounted on or towed by. Alternatively, Underwater Acoustic Sensor Networks (UW-ASN) offer a promising solution approach. In this thesis, a target tracking algorithm for UW-ASN, Three-Dimensional Underwater Target Tracking (3DUT) is presented. The objective of 3DUT is to collaboratively accomplish accurate tracking of underwater targets with minimum energy expenditure. Based on the time-of-arrival (ToA) of the echoes from the target after transmitting acoustic pulses from the sensors, the ranges of the nodes to the target are determined, and trilateration is used to obtain the location of the target. The location and the calculated velocity of the target are then exploited to achieve tracking. In order to realize energy-effective target tracking, 3DUT incorporates a new target movement-based duty cycle mechanism. To avoid rapid depletion of energy resources of boundary nodes due to continuous surveillance, 3DUT employs an adaptive procedure to find, designate, and activate new boundary nodes. Performance evaluation shows that 3DUT is a promising alternative to the traditional sonar based target tracking approaches especially for on-demand surveillance applications.

Keywords: Underwater Acoustic Sensor Networks, Target Tracking

# ÖZ

## SU ALTI AKUSTİK SENSÖR AĞLARI İLE ÜÇ BOYUTLU HEDEF TAKİBİ

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Kasım 2009, 50 sayfa

Su altı hedef tespit ve takibi için sonar kullanılmaktadır. Ancak sonar dizilerinin gemi ya da su altı araçlarına monte edilmesi ya da bu araçlar tarafından çekilmeleri gerekmesi, kritik görevlerde sonar dizilerinin kullanımını zor ve pratik olmayan bir hale getirmektedir. Alternatif olarak su altı akustik sensör ağları (SASA) ümit verici ve gelecek vaat eden bir çözüm yaklaşımıdır. Bu tezde, su altı akustik sensör ağları ile üç boyutlu su altı hedef takibi algoritması (3BSAT) sunulmaktadır. 3BSAT'ın amacı su altı hedeflerinin takibini sensör düğümlerinin birlikte çalışması ve düşük enerji harcaması ile, doğru şekilde başarmaktır. Sensör düğümlerinin sinyal göndermeleri sonucu, bu sinyallerin hedeften yansıyan ekolarının geliş zamanlarına göre sensör düğümlerinin hedefe uzaklıkları belirlenir ve hedefin konumu geometrik olarak hesaplanır. Hedefin konumu ve hesaplanan hız bilgileri kullanılarak izleme gerçekleştirilir. Optimum enerji harcanarak hedef takibini gerçekleştirmek için hedefin yörüngesine dayalı yeni bir doluluk-boşluk oranı mekanizması kullanılır. Sınırdaki düğümlerin sürekli gözetleme sonucu enerjilerinin diğer düğümlere göre daha çabuk bitmesini engellemek için, 3BSAT yeni sınır düğümlerini bulmak, görevlendirmek, ve aktif hale getirmek için uyarlamalı bir prosedür kullanır. Başarım değerlendirmesi 3BSAT'ın klasik sonara dayalı hedef takibi yaklaşımlarına, özellikle talep üzerine gözetleme uygulamalarına, ümit vaat eden bir alternatif olabileceğini göstermektedir.

Anahtar Kelimeler: Su Altı Akustik Sensör Ağları, Hedef İzleme

# ACKNOWLEDGMENTS

I would like to express my gratefulness and deepest respect to my advisor, Dr. Özgür B. Akan. I am indebted to Dr. Akan for his constant support during my graduate study. This thesis would not be completed without his mentorship and trust.

I also thank Dr. Semih Bilgen, Dr. Kemal Leblebicioğlu, Dr. Şenan Ece Schmidt, and M.S. Talha Işık who kindly agreed to serve in my M.S. Examining Committee.

I also would like to thank all the members of the Next-generation Wireless Communications Laboratory (NWCL) for their support during my graduate study.

I am also grateful to my chiefs Eric Wander and Paul Pianu for their support at the very last phase of my studies.

Finally, I am extremely grateful to my parents, Recep and Necla İşbitiren, and my brother Taylan İşbitiren, for their love, support and encouragement.

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| | |
|---|---|
| 3D | Three Dimensional |
| SONAR | Sound Navigation and Ranging |
| 3DUT | Three Dimensional Underwater Target Tracking |
| ToA | Time of Arrival |
| UW-ASN | Underwater Acoustic Sensor Network |
| DoA | Direction of Arrival |
| TDoA | Time Difference of Arrival |
| RSSI | Received Signal Strength Indication |
| SAS | Synthetic Aperture Sonar |
| GPS | Global Positioning System |
| UWB | Ultra Wide Band |
| ML | Maximum Likelihood |
| AUV | Autonomous Underwater Vehicle |
| DT | Detection Threshold |
| SL | Source Level |
| PL | Propagation Loss |
| IL | Intensity Level |
| BND | Boundary Node Designation |
| RR | Receive Response |
| MAC | Medium Access Control |

# CHAPTER 1

# INTRODUCTION

Detecting, classifying and tracking underwater targets are indispensable parts of modern underwater defense systems. Thus far, various types of sonar (sound navigation and ranging) arrays have been used for this purpose [34]. These sonar arrays are generally mounted on or towed by a ship or a submersible [10], [26], which makes them unsuitable for most of the on-demand tracking missions. Moreover, the platform towing the array or on which the array is mounted is a single point of failure for the entire system. On the other hand, when sonar arrays are used standalone, they need to be deployed prior to the application [9], [25] which is inconvenient for temporary on-demand missions.

In terms of surveillance, reconnaissance, and targeting, sensor networks stand as one of the promising technologies due to their rapid deployment, self-organization and fault-tolerance characteristics [1]. A specific case of sensor networks, i.e., underwater sensor networks (UWSN), are envisioned to enable applications for oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications [2].

## 1.1 Underwater Acoustic Sensor Networks

Since the studies on underwater networking have been done since World War II, it is an unexplored subject. The traditional approach for the underwater monitoring is to deploy the sensors and collect them at the end of the application. However, in this case, the reported data cannot be reached until the sensor nodes are collected.

Since there is no communication between the sensor nodes during the monitoring, there is no online reconfiguration [2]. In this case, adaptive tuning of the instruments and reconfiguration of the system in case of some events are not possible. Besides, there is no online failure detection so if the sensors fail during the mission, the whole mission can fail. Moreover, the storage capacity of the nodes are limited. Therefore, a networking solution which enables real-time monitoring of selected areas by means of wireless links is necessary.

Recent advances in electronics and wireless communications have lead to the realization of the underwater sensor networks to be used in applications such as ocean sampling in which they can be used for synoptic, cooperative adaptive sampling of ocean environment.

Moreover, environmental monitoring such as monitoring biological, chemical and nuclear pollution are possible with underwater acoustic sensor networks. Observing the climate change, doing improved weather forecast, monitoring the activities some of the fish species, analyzing the effect of human activities to underwater ecosystem are some of the environmental monitoring applications. For example, in [41], temperature gradients detection is achieved.

Furthermore, measuring seismic activities, disaster prevention by providing tsunami alarms are also some of the underwater sensor network applications. Additionally, underwater sensor networks can identify hazards on sea bed, locate dangerous rocks or shoals in shallow water [2].

## 1.2 Underwater Target Detection and Tracking

The traditional underwater detection and tracking mechanisms employ sonar arrays which are mounted to and pulled by the surface vehicles and underwater platforms, or placed under the surface of the water prior to the application. Surface ship hull-mounted sonar, submarine hull-mounted sonar, side-scan sonar and towed arrays can be given as examples of sonar applications. The transducers are assembled as arrays to increase the source level of the acoustic pulse [34]. For a single projector which is a transducer operating in the transmit mode, to have a better detection performance, it requires a large surface area, which is not very practical. Besides, using several projectors is more reliable because some of the projectors may fail.

The hydrophones which are the transducers operating in receive mode are assembled as arrays to increase the signal to noise ratio. Besides, as they are assembled as arrays, their response in a desired direction improves.

However, since these arrays must be mounted on or towed by a vessel, this vessel can be a single point of failure of the entire system.

There are also some studies for underwater target detection and tracking with underwater sensor networks [43], [12], [38], [20]. However, there is no unified target tracking solution. Instead of proposing a complete tracking scheme, only location estimation is discussed in [43]. The energy expenditure, which is very important for underwater sensor networks, is not taken into account in [12]. Kalman filtering and duty cycles are utilized in [38] for locating the target and for energy expenditure. However, high number of uniformly distributed static sensors are utilized, which requires prior deployment of the sensors. In [20], a maximum-likelihood (ML) estimation algorithm is proposed for underwater target size detection and a complete tracking mechanism is not provided.

## 1.3 Challenges of Underwater Communications

In order to achieve underwater target detection and tracking, the challenges of underwater communications must be taken into account. Electromagnetic waves have very high underwater propagation loss so they must be used at very low frequencies. However, even in order to use very low frequencies, very large antennas must be used, which is not practical for underwater communications. Moreover, optical signals require high precision which is hard to obtain under the surface of the water. Therefore, acoustic communication is a promising solution. However, the propagation delay in underwater is five orders of magnitude higher than the delay in terrestrial radio frequency channels. Moreover, the delay is very variable, which causes some of the communications mechanisms to fail.

Furthermore, there is path loss which is the combination of attenuation and geometric spreading. Attenuation is the absorption of the acoustic energy into heat energy, which increases with distance and frequency and occurs through viscosity and molecular relaxation [34]. Geometric spreading is the spreading of the sound energy as a result of the expansion of the wavefronts [2].

The propagation of underwater sound follows multiple paths in the vertical plane [34]. This causes differences between the arrival times and propagation losses along multiple paths. Besides it causes inter-symbol interference [2].

In order to address the issues introduced above, we present the *Three Dimensional Underwater Target Tracking* (3DUT) algorithm. Since 3DUT does not depend on the number of nodes and the algorithm runs even if the number of the nodes changes, it is a scalable. Furthermore, since it does not necessitate large sonar arrays and surface vessels to pull the nodes, it is cost-effective. Tracking starts when the acoustic noise of a target is detected by the sensor nodes. The distances of the sensor nodes to the target are estimated by transmitting acoustic pulses (ping), and employing time-of-arrival (ToA) of the pings and the echoes. The location of the target is then obtained by employing trilateration. In order to achieve tracking, the velocity and the projected location of the target are calculated. Based on these calculations, the nodes along the path of the target are activated. This process continues until there is no signal received from the target. We assume that 3DUT tracks one target at a time. Tracking more than one target at a time necessitates differentiating the targets, which requires extra signal processing, which is left as a future study.

One of the most important features of 3DUT is *three dimensional* localization and tracking of the target. In order to continue tracking, the number of nodes collecting information from the target must be at least four in order to be able to geometrically localize the target. The total number of nodes necessary for tracking which is a function of the volume of the region to be detected and the sensing radius of the sensors, is discussed in Chapter 4. 3DUT utilizes a tracking-aware adaptive duty-cycle mechanism based on the three dimensional movement pattern of the target for minimum energy expenditure. Moreover, 3DUT exploits a boundary node designation (BND) mechanism to minimize the time to detect the target when it enters into the sensing region by keeping it surrounded with higher duty-cycled nodes. Furthermore, time synchronization among the sensor nodes is not necessary.

The deployment of an UW-ASN could be achieved by a helicopter or a surface platform. The sensor nodes are regarded as disposable. As the sensor nodes can drift under the surface of the water, the localization algorithm is run during the tracking process to update the locations of the nodes. After deployment, an UW-ASN can be easily incorporated into a network-centric warfare system which is the combination of networking sensors, decision makers, and shooters for the aim of high shared awareness [3]. By using 3DUT, a patrol mission can be achieved in an underwater area by easily deploying the sensors without endangering a ship and its crew.

## 1.4 Organization of the Thesis

This thesis is organized in five chapters. In Chapter 2, we present a review of related work on target detection and tracking algorithms in both UW-ASN and terrestrial sensor networks. In Chapter 3, at the beginning, a 3DUT overview is given, and then the steps of the algorithm is described in detail. In Chapter 4, first, possible reasons of errors are provided, then simulation results of 3DUT are presented. Finally, the thesis is concluded in Chapter 5.

# CHAPTER 2

# RELATED WORK

Target detection and tracking applications are studied in both terrestrial and underwater networks. As mentioned in Chapter 1, terrestrial sensor networks can be used for surveillance, reconnaissance, and targeting. For underwater target detection and tracking, sonar arrays and underwater sensor networks can be used. Hence, we investigate the existing work about tracking in two main categories, i.e., terrestrial and underwater target tracking.

## 2.1 Target Detection and Tracking in Terrestrial Sensor Networks

There are different methods for finding the location of the target such as direction of arrival (DoA), time difference of arrival (TDoA) and received signal strength indication (RSSI). After obtaining the distances between the target and the sensor nodes by using these techniques, triangulation is used for target localization calculations [39], [37], [35]. In [39], a sensor senses the environment and communicates its readings periodically to the server which resides on a computationally superior sensor node. The server triangulates the location of the object using the readings. The signal attenuation of the target source power $P$ is governed by equation $I = \frac{P}{4\pi r^2}$, where $r$ is the Euclidean distance between the object and a sensor node. This relation is the basic equation used in triangulation. A protocol providing a distributed mechanism for locally determining the optimal set of sensors suitable for tracking is used in [37] and only these nodes are activated, minimizing the energy spent on tracking. In [35], the location of the target is obtained by analyzing the differences of the target's sound arrival times among the sensors, and using triangulation.

Furthermore, for target detection and tracking applications signal processing and estimation techniques are used [30], [18], [5]. Non-Gaussian probability density function of target locations are represented by a discrete set of particles by using particle filter in [30]. The positions of these particles are propagated sequentially using known state transition equation, and updated using new location estimates via the observation equation. Leader nodes perform an improved particle filter algorithm to estimate the target state based on the selected nodes' acoustic energy measurements in [18]. If there is no prior information on the target, it requires the use of a large number of particles and therefore more computation. Therefore, first the optimal linear combination algorithm is used to obtain the initial estimation point. A maximum a posteriori (MAP) estimation mechanism is used in [5] to track a moving target using acoustic bearings only data from sensors with unknown positions. Moreover, there are some studies emphasizing the efficient resource usage in target tracking [14], [42], [24], [19]. In [14], the real-time design and analysis of VigilNet, a large-scale sensor network system which tracks, detects and classifies targets in a timely and energy efficient manner, is presented. The main idea in [42] is to determine participants in a sensor collaboration by dynamically optimizing the information utility of data for a given cost of communication and computation. In [24], two algorithms are described, one of which is called rare-area which ensures that only nodes that receive a given quality of data participate in tracking. The other is called rare-node in which any node with redundant information cannot participate in tracking. The number of messages and the number of message collisions are reduced in [19], while providing refined accuracy because communication is the most energy-consuming operation.

Even if there are many studies focused on target detection and tracking in terrestrial sensor networks, these studies do not address the challenges of underwater acoustic communications. A mechanism that uses RSSI has to deal with problems caused by large variances in signal strength reading, multi-path fading, irregular signal propagation patterns and background interference. Such mechanisms may not be useful in the underwater scenario due to the large variances in RSSI [7]. Besides, TDoA requires time synchronization which is hard to achieve underwater. Angle-of-arrival (AoA) systems are expensive and obtaining precise estimates is often difficult [15]. 3DUT uses the time of arrival (ToA) which is a technique suitable for underwater communication for ranging purposes [7].

## 2.2 Underwater Target Detection and Tracking

Underwater target detection and tracking can be achieved by using sonar arrays which can be mounted on or towed by the surface vessels. Furthermore, underwater target detection and tracking can be achieved by using underwater sensors which are deployed prior to the application. Therefore, we review the approaches to the underwater target detection and tracking in two main parts, i.e., centralized and distributed, as follows.

### 2.2.1 Centralized Target Detection and Tracking

The traditional underwater detection and tracking mechanisms employ sonar arrays which are mounted to and pulled by the surface vehicles and underwater platforms, or placed under the surface of the water prior to the application. Surface ship hull-mounted sonar, submarine hull-mounted sonar, side-scan sonar and towed arrays can be given as examples of sonar applications.

There are different applications of sonar for object detection and tracking. In [26], a method to combine synthetic aperture sonar (SAS) imaging of stationary targets with moving target detection and imaging is presented. Defocussing and detection of moving targets are investigated and both the trajectory and the location of the moving target are given by mathematical expressions. By using space time adaptive processing the spatial correlated noise from the stationary targets can be suppressed while all the non-stationary such as moving target will be detected. The technology of multi-sensor state estimation in underwater distributed system is studied in [11]. The state estimation based on bearing sequences of multisensor is fused to improve the tracking performance. A method for sensor-adaptive control of autonomous marine vehicles in an autonomous oceanographic sampling network is described in [10]. Besides, the advantage of multiple cooperating sensor platforms over single sensor platforms is presented. Data fusion techniques for localizing and tracking the targets are explained in [9] and [25], respectively. Range estimation is performed by electric field sensors and bearing is obtained by acoustic sensors. However, all these applications require the sensors communicating with each other so they are mounted to or pulled by a submersible which can be a single point of failure for the entire system. They can be also mounted to the sea floor prior to the application, which is not appropriate for on-demand missions.

In underwater domain, there are some studies which use data processing and fuzzy systems for target detection and tracking. In [17], robotics vision-based control strategy for underwater pipeline tracking system is introduced. A vision guidance system for autonomous underwater vehicle that can track and inspect the underwater installation is shown in [4]. Two dimensional bearings-only target motion analysis is used in [27] and an observer monitors noisy sonar bearings from a target in passive listening mode, processes the measurements and finds out target motion parameters.

The traditional sonars are large, generally require a ship pulling them, and difficult to deploy, which make them inconvenient for fast deployment and temporary missions. Since some of the traditional sonar arrays are towed by a ship, in order not to disturb the collaboration of the sensors on the array, the vessel should move straight. Besides, the cable which connects the sonar array to the vessel limits the maneuver capabilities of the vessel. Mounted arrays are susceptible to the pitch/roll of the vessel [8]. 3DUT offers a solution which is easy to deploy, distributed and autonomous, which does not necessitate surface vessels or underwater platforms.

### 2.2.2 Distributed Target Detection and Tracking

There are very few existing proposals for distributed underwater acoustic communication systems for tracking an underwater target. In [12], undersea navigation via a distributed acoustic communication network is introduced. The location of the target is calculated by the intersection of range circles of two sensors. However, the energy expenditure of the sensor nodes are not considered. In [29], the aim is to investigate the feasibility of fusing data from a distributed field of global positioning system (GPS) sonobuoys for computation of error of range in case of target being detected by one sonobuoy. However, as stated in [29], the computation of the range using the propagation loss profile and the data of one sonobuoy usually leads to inaccurate target localization. Moreover, in real underwater target tracking procedures, it is difficult to detect the same target at the same time by two or more sonobuoys. It is presented in [20] that an ultra-wide band (UWB) channel can be used for underwater channel modeling. Besides, it proposes a maximum-likelihood (ML) estimation algorithm for underwater target size detection using collaborative signal processing within a cluster in UW-ASN. However, target localization or target tracking is not proposed. In [16], the problem of tracking the motion of a submarine in shallow waters using adaptive planning for the positioning of passive sonobuoys is analyzed. As stated earlier, obtaining information from the target may not be always possible using the sonobuoys. In order to obtain more accurate and reliable data, the information about the target must be collected at a short distance to the target.

The work in [38] is the closest work to our study. The predicted area of the target is estimated and appropriate processing nodes are selected. Moreover, wake-up / sleep mechanism is used to select several nodes whose information about the target is used among all the nodes to decrease communication overhead. Furthermore, valid measurement selecting mechanism is used to reduce the number of awake sensor nodes. In the performance analysis, energy efficiency is not considered and in simulations an extremely high number of uniformly distributed sensors with very short sensing radius are used, which is not realistic. It will take a huge amount of time to deploy so many sensors uniformly under the surface of the water and the prices of the underwater sensors are not too low to use such a great amount. Besides, tracking is considered in 2-dimensions, which is limited in real applications.

To address these problems, Three Dimensional Underwater Target Tracking (3DUT) is proposed, which enables target tracking with easily deployable sensor nodes in a distributed manner. Starting when a target enters into the sensing region of the network, the three dimensional location of the target is calculated by the information from the sensors close to the target. The sensors on the path of the target are discovered and utilized for continuous tracking. In order to keep the surveillance, high duty-cycled boundary nodes are used and these nodes are designated by boundary node designation mechanism.

# CHAPTER 3

# 3DUT ALGORITHM

The objective of 3DUT algorithm is to detect, localize and track submersibles such as submarines, torpedoes and autonomous underwater vehicles (AUV) in an accurate and energy-efficient manner. A possible deployment of a 3D UW-ASN is shown in Fig. 3.1. The specific terms used in Fig. 3.1 are described below in Section 3.1, in the context of the 3DUT algorithm. At least three anchor nodes float at the surface of the water to accomplish the localization of the underwater nodes [15]. One of these nodes is the sink which collects the information from underwater sensor nodes and carries out the calculations. Additionally, there are a number of sensor nodes deployed randomly under the surface of the water. The nodes pointed out as dark circles are the ones which collect and send information from the target to the sink. the hexagon shaped node is projector node and this projector node can change during tracking process.

## 3.1 3DUT Algorithm Overview

3DUT is a two phase algorithm. During the first phase, sensor nodes listen to the underwater environment for potential targets. We call this phase as *Passive Listening*.

Once the noise radiated from a target is detected, the second phase of the algorithm, *Active Ranging*, is initiated. During this phase, a sensor node, which is called *projector* whose selection mechanism is described in Section 3.2, broadcasts pings to be reflected by the target. The target is assumed to be a point target so that the echoes are radiated isotropically and reach to the sensors at the vicinity of the target. During

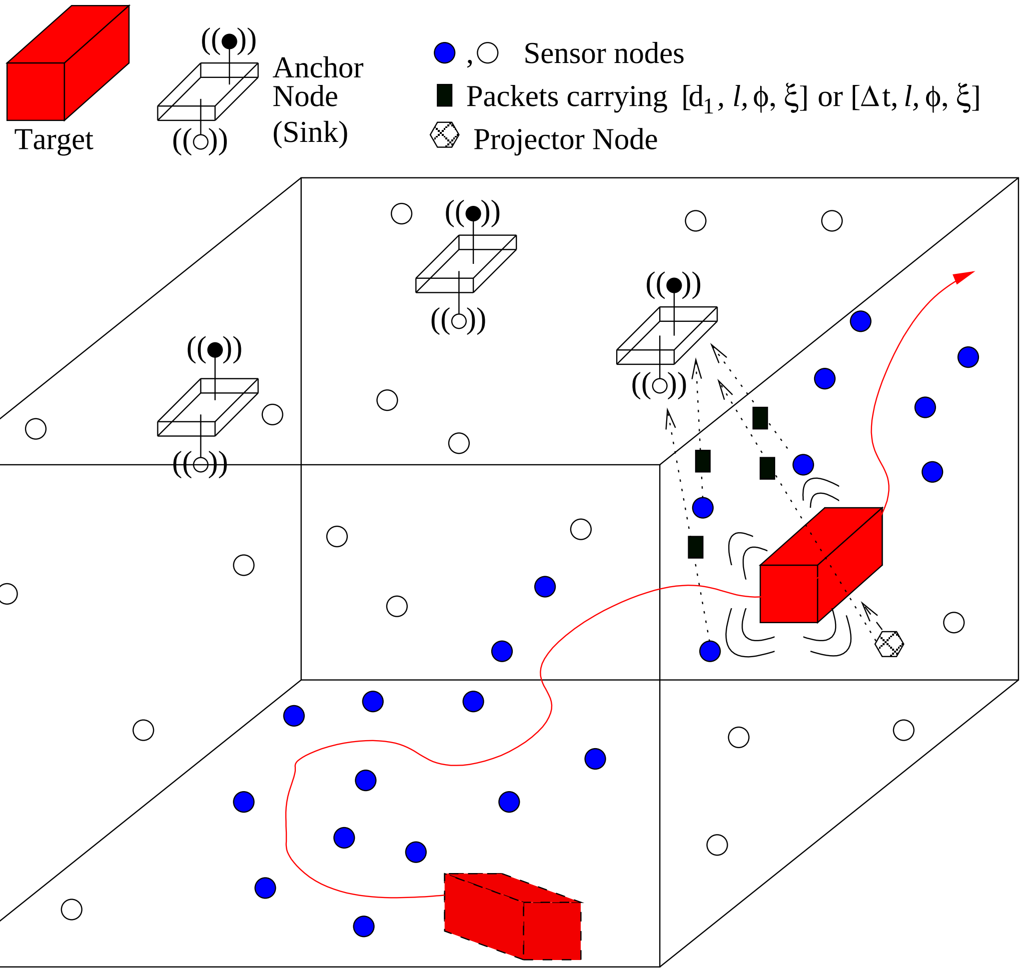

Figure 3.1: A network model for an underwater acoustic sensor network implementing 3DUT.

tracking, there is only one designated projector node which can change with respect to the movement of the target. The ping contains ping label ($l$) which is used to identify the ping used in ranging calculations as explained in Section 3.3. Once the echo is received by the projector, it calculates its distance to the target ($d_1$). Then, it sends $d_1$, $l$, its remaining energy ($\xi$) and coordinates ($\Phi$) to the sink. All nodes have their location information through the localization algorithm. There is no specific relation between 3DUT and the employed localization algorithm, i.e, one of the underwater localization algorithms in literature [15], [44] can be used to achieve localization. Upon reception of the echo by the *hydrophone nodes*, they calculate the time difference ($\Delta t$) between the arrival of the ping and the echo and send $\Delta t$, $l$, $\xi$ and $\Phi$ to the sink. We call the nodes which do not send but can receive the ping as *hydrophone* *nodes*. Throughout the tracking, if the target gets out of the sensing region of the projector node, another projector is selected out of the hydrophone nodes. Therefore, throughout tracking, projector and hydrophone nodes can change dynamically. The sink has two important duties: First, it calculates the location, direction and the speed of the detected target as explained in Section 3.3 and 3.4. Second, depending on the results of these calculations, it selects a new projector node and activates those nodes that are located near the future estimated trajectory of the target. Activating the nodes means sending activation message which includes higher duty cycle ($\delta$) and new cycle period ($\tau$) which are determined based on the speed of the target as explained in Section 3.4.

The locations of the sensor nodes continuously change due to the dynamic nature of the underwater environment. Therefore, we assume that the localization algorithm runs periodically and the locations of the sensors are known subject to a certain amount of localization error as its effect is analyzed in Section 4.3.1.

In order to save energy, the nodes which are not located at the network edge have low duty cycles. The nodes which are at the boundary of the sensing region have higher duty cycles in order to detect the target entering into the sensing region immediately. Throughout the tracking process, the boundary nodes might become non-functional due to energy depletion. Therefore, the sensors, which are at the boundary of the network and are about to run out of energy, send a message to the sink notifying their energy depletion status. Since the sink has the location information of the sensors in the network through localization algorithm, it finds out the new boundary nodes and sends a designation message to them. By this way, 3DUT continuously achieves seamless surveillance of the sensor network zone. The details of boundary node designation are described in Section 3.5.

### 3.2 Passive Listening

After deployment, the sensor nodes begin to passively listen to their environment.

The sensor nodes check whether the intensity level ($IL$) caused by the received signal which is radiated from an underwater target is above a predefined detection threshold

(DT) value. Let SL be the source level of the target, which is the radiated noise in the frequency band of interest, and PL be the underwater propagation loss of the acoustic signal. By incorporating the basic sonar principles [34], the intensity level (IL) due to the target at the nodes is given by:

$$IL = SL - PL \tag{3.1}$$

where the units of $IL$, $SL$, and $PL$ can be given as dB re 1 $\mu$Pa (micro Pascal) where 1 $\mu$Pa is the reference pressure of the underwater sound. The difference between the $IL$ and the underwater noise ($N$) must be greater than $DT$, i.e., $IL - N > DT$, to be able to detect the target.

In order to obtain the value of $PL$, we consider the propagation loss of the sound under the surface of the water which is given by:

$$PL = 20 \log r + \alpha r \cdot 10^{-3} \tag{3.2}$$

where $\alpha$ is the attenuation coefficient in dB/km and $r$ is the distance in meters [34]. In order to be able to compare the difference between the intensity level caused by the target and the underwater noise with a predefined $DT$ to understand whether there is a target or not, noise component must be determined. The underwater noise can be modeled as turbulence, shipping, waves and thermal noise [33]. Surface motion caused by the wind driven waves is the major factor contributing to the noise in the frequency region 100 Hz - 100 kHz (which is the operating region used by the majority of acoustic systems) [33]. Therefore, noise parameter can be calculated as:

$$10 \log N_{\omega}(f) = 50 + 7.5\omega^{1/2} + 20 \log f - 40 \log (f + 0.4) \tag{3.3}$$

where $\omega$ is the wind speed in m/s and $f$ is the frequency in kHz [33].

The relation between the $IL$ at a commercial underwater transducer [28] and the voltage ($V_{out}$) at the terminals of the transducer caused by the sound is given as:

$$IL = 20 \log(V_{out}) - RR \tag{3.4}$$

where $RR$ is the receive response (pressure sensitivity) of the hydrophone, which is the magnitude of the open-circuit voltage per unit magnitude of plane wave pressure incident on the hydrophone [6]. In order to be able to detect the target, the voltage reading at the transducer must be higher than the voltage caused by the underwater noise. We assume that if the voltage reading at the hydrophone due to a target is $\eta$ times as the voltage reading due to the underwater noise, then that target can be detected, where $\eta$ is a real number greater than 1. To achieve this, a $DT$ of $20\log(\eta)$ dB at the hydrophone is sufficient according to (3.4). The value of $\eta$ must be selected such that $20\log(\eta)$ is smaller than the sound pressure levels of the targets to be detected. If a source has a lower sound level than the threshold, then this source cannot be detected by the sensor nodes. For example, submarines have the lowest noise level of around 90 dB re 1 $\mu$Pa at 1 m [34] among the possible targets which are noisy torpedoes, frigates, quiet torpedoes between the frequency range of 100 Hz to 10 kHz, which is a suitable range for underwater communications. The unit dB re 1 $\mu$Pa at 1 m is the intensity level relative to the intensity of a plane wave with an rms-pressure of 1 $\mu$Pa taken at the reference distance 1 m from the source [28]. Therefore, we can select the value of $\eta$ up to 10.000. However, to obtain a more sensitive network, low threshold values must be selected. The detailed results for passive detection performance can be found in Section 4.2.1.

Initially, when the sensor nodes detect the target, they send a message to the sink node indicating the detection of a target. Then, the sink node assigns the first node from which it received the message as the projector and broadcasts a message indicating the new projector node. The sink node does not make calculations until it receives an acknowledgment (ACK) from the designated projector node. If the sink node does not receive an ACK from the designated projector node, it waits for a timeout and sends the designation message again. The sink node repeats this process three times and if it still does not receive an ACK, it designates another projector node and conducts the same procedure.

After reception of a message from one of the boundary nodes, if the number of nodes detecting the target is less than 4, the sink sends direct activation messages to the nodes which are as close as two times the sensing radius of the sensor nodes to this boundary node. By this way, the boundary nodes and the activated nodes can detect the target at the same time and localization of the target can begin. The number of nodes to be activated is determined such that the total number of active nodes is at least 4. The active nodes are the nodes that can collect information from the target. Since by sending pings and receiving the echoes, the projector node collects information about the target, it is already an active node. The nodes that can detect the target among the hydrophone nodes are also the active nodes.

Note that the number of the active nodes, the nodes collecting information from the target, must be at least 4 to be able to make the trilateration calculations in three dimensions. If there are only 2 active nodes, then the intersection of their sensing regions is a circle. If there is another node detecting the target, the intersection of the sensing region of this node with the circle resulting from the intersection of the sensing regions of the first two nodes, can be one of the two points on the circle. Therefore, in order to locate the target uniquely, another node is necessary so there needs to be at least 4 nodes detecting the target. In order for this assumption to hold, at least one of the nodes must be on another plane than the other nodes. For example, if the four nodes are on the same line, many points can be found at the intersection of the sensing regions of the nodes so a unique location of the target cannot be found. If the four nodes are on the same plane, the location of the target can be calculated at two different places. This is called flip ambiguity which occurs for a graph in a d-dimensional space when the positions of all neighbors of some vertex span a $(d-1)$ dimensional space. In this case, the neighbors create a mirror through which the vertex can be reflected [22]. If the number of nodes collecting information is greater than 4, least squares method can be used to obtain the location of the target because the method of least squares is applied for the solutions of overdetermined systems, i.e., the system of equations in which there are more equations than unknowns.

Upon selection of the projector sensor, this node broadcasts pings and 3DUT algorithm moves to the *Active Ranging* phase.

## 3.3 Active Ranging

During this phase, the projector node sends pings to the target and the transmission rate of the ping is assumed to be $\gamma\ s^{-1}$ where $s$ is in seconds.

In active sonar, the intensity level $(IL)$ at the transmitter due to the target can be described as:

$$IL = SL + TS - 2 \cdot PL \tag{3.5}$$

where $SL$ is the source level, $PL$ is the propagation loss, and $TS$ is the target strength which refers to the echo returned by an underwater target [34]. The difference between the $IL$ and underwater noise ($N$) must be greater than the $DT$ for detection, i.e., $IL - N > DT$.

The nodes that receive the ping from the projector node and the echo from the target, include the time difference of reception of the ping and the echo ($\Delta t$), whereas the projector node includes the distance between itself and the target ($d_1$) in the messages which they send to the sink. For $\Delta t$ calculations, the timestamps at medium access control (MAC) layer are used to obtain correct reception and transmission times. The messages also contain the locations of the nodes ($\Phi$) for the sink to be able to make target localization calculations, the ping label ($l$) for ping signal differentiation and the remaining energies of the nodes ($\xi$) to let the sink node be able to select the nodes to activate in tracking process. The sink then calculates the location, direction and the speed of the target as explained in this Section and in Section 3.4.

In order to calculate the target-to-node distances, the time of reception of the pings and echoes are utilized. As explained earlier, the target is assumed to be a point target so that the echoes are radiated isotropically and reach to the sensors at the vicinity of the target. Fig. 3.2 illustrates the target-to-node distance calculation scheme.

Let $N_t$ be the projector node and $t_{Nt_1}$ and $t'_{Nt_1}$ are the times of sending the ping and reception time of the echo from the target, respectively. The distance between the target and $N_t$ is calculated as:

$$d_1 = \frac{C \cdot (t_{Nt_1} - t'_{Nt_1})}{2} \tag{3.6}$$

where $C$ is the speed of the sound under the surface of the water. Each time a hydrophone node receives a ping with a label which is not received previously, it presets its timer. When the hydrophone node receives an echo with a label received previously, it timestamps it. This way, the node obtains the difference of reception time of the ping and the echo. This difference is a function of the target-to-node distances

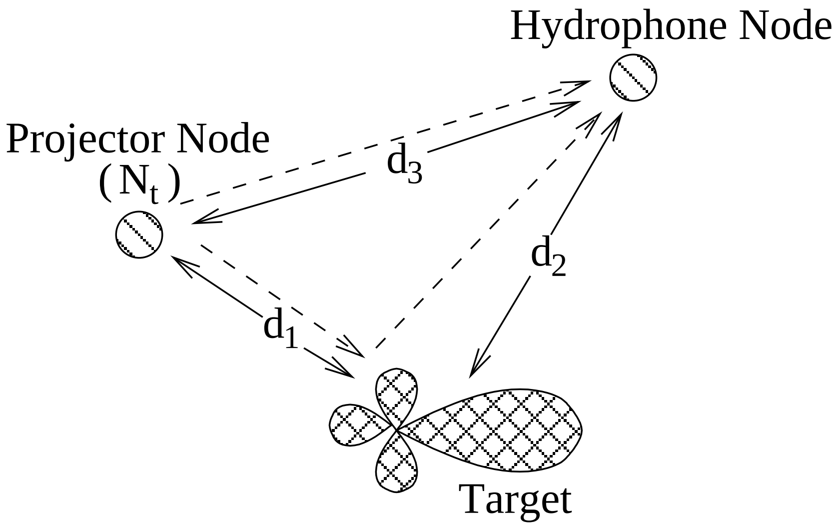

Figure 3.2: Target-to-node distance calculation by utilizing ping message.

and the speed of the sound under the surface of the water and can be given as:

$$\Delta t = \frac{d_1 + d_2}{C} - \frac{d_3}{C} \tag{3.7}$$

where $d_1$, $d_2$ and $d_3$ are the distances between the projector node and the target, the hydrophone node and the target, and the projector node and the hydrophone node, respectively, as shown in Fig. 3.2. The distance between the hydrophone nodes and the target ($d_2$) in (3.7) can be calculated as:

$$d_2 = \Delta t \cdot C + d_3 - d_1 \tag{3.8}$$

$N_t$ sends the distance between itself and the target and the hydrophone nodes send $\Delta t$ to the sink node where the target-to-node distances are calculated. The sink node has the location information of the sensors through the localization of the nodes so it calculates $d_3$. The projector node sends the distance between itself and the target to the sink which, by this way, has $d_1$ information. By utilizing $d_1$, $d_3$, $C$ and $\Delta t$ in (3.8), the sink node calculates $d_2$. The same process is conducted for the other sensor nodes to calculate their distances to the target upon their reception of the ping and the echo.

After obtaining the distances between the nodes and the target, the sink node analyzes if there is a unique solution by using four distances between four different sensors and the target. If there is, it calculates the location of the target. The algorithm in the sink node uses the geometrical equation given by:

$$(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 = d_i^2 \tag{3.9}$$

where $(x_i, y_i, z_i, d_i)$ are the coordinates of the node $i$, and the distance between the node and the target respectively and $(x_0, y_0, z_0)$ are the coordinates of the target. When the sink node receives 4 messages from 4 different sensors, the algorithm will have 4 different equations with 4 different $(x_i, y_i, z_i, d_i)$. By exploiting 4 equations obtained by the information from 4 different sensor nodes, the location of the target is computed.

Note that the calculation of the location of the target must be done continuously in order to achieve tracking. The tracking mechanism is presented in detail in the next section.

### 3.4 Target Tracking Mechanism

In order to be able to track the target, the sensor nodes on its path should have higher duty cycles. As the information from the sensor nodes arrive to the sink, the location and the velocity of the target are continuously calculated.

When the number of active nodes which provide information about the target to the sink node is at least 4, the location of the target is calculated by trilateration as explained in Section 3.3. After trilateration, the sink node calculates the velocity of the target by using its previous locations:

$$V_x = \frac{x_2 - x_1}{t_2 - t_1} \tag{3.10}$$

where $V_x$ is the x-coordinate component of velocity $(V_t)$ of the target, $(x_2, x_1)$ are the locations of the target at x-coordinate at $(t_2, t_1)$, and y and z components are calculated similarly. If the target is about to leave the sensing region of at least one of the active nodes and the number of active nodes is not greater than 4, the sink node finds the total number of active nodes, $N_a$, whose sensing region the target is going to leave. The objective is to find the necessary number of nodes to activate to have at least 4 active nodes to be able to continue tracking. The sink node concludes that the target is about to get out of the sensing region of the active nodes if the distance between the boundary of the sensing region of the active nodes and the target is less than $\chi$

and the target is moving away from the node. Then, the sink calculates the path of the target by using its velocity and finds the nodes whose sensing regions intersect with the path of the target. The sink node sorts the nodes with respect to their distances to the target and selects the first $N_a$ of the nodes for activation which means increasing their duty cycles. However, if all the nodes are at the boundary, there is no need for changing the duty cycles of the nodes because they have all high duty cycles initially. If the difference of the distances of some of the nodes to the target are less than $\zeta$, then the sink node sorts these nodes with respect to their remaining energy.

The times when these nodes are expected to detect the target and the times to send the activation messages to these sensors are calculated. These times are called expected reception time, $T_{Er}$, and expected activation time, $T_{Ea}$. The nodes are started being activated $\kappa$ seconds (s) before they are assumed to start detection. In other words, there is $\kappa$ s difference between $T_{Er}$ and $T_{Ea}$. The reason for calculation of these times is to avoid the activation of the nodes earlier than they are expected to detect the target so that they do not consume energy unnecessarily.

The sink node has an activation node list for the nodes to be activated. Each time it receives a message from a node in the list, it deletes these nodes from the list. Moreover, if the number of active nodes are at least 4 and $N_a$ is zero, then there is no need to send activation messages to the new nodes. In this situation, the activation node list is cleared.

At $T_{Ea}$, the sink node sends activation messages to the nodes which are expected to detect the target. If at $T_{Er}$, the sink does not receive any messages from the nodes which are expected to detect the target, it activates 4 new sensors. These 4 new sensors are selected such that they are the closest nodes to the nodes which are expected to receive noise from the target.

The new $\tau$ is calculated by the sink node with respect to the speed of the target. The aim is to employ the new sensors such that they can receive signals from the target in 4 different active periods. Therefore, the new $\tau$ is the $\frac{1}{4}$th of the time the target will stay in the sensing region of the sensor node. By this way, 3 different velocity calculations can be made by using the data from the new active sensors. Since data is collected in each active period, then the sensors will obtain at least 4 data in 4 active periods. By using the data from the consecutive active periods, the velocity can be calculated. Therefore, with the collected data in 4 different active periods, 3 velocity calculations are done.

In order to calculate a new $\tau$ for a sensor node, the sink node calculates the time during which the target will be in the sensing region of that node. For this purpose, the sink node calculates the coordinates of the node's sensing region from where the target will enter and exit. Since the sink node calculates the velocity of the target, it can calculate the duration of the target in the sensing region described as:

$$t = \frac{\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2 + (z_1 - z_0)^2}}{V_t} \tag{3.11}$$

where $(x_0, y_0, z_0)$ and $(x_1, y_1, z_1)$ are the coordinates from which the target enters into and exits from the sensing region of the sensor, respectively.

The duty cycle, $\delta$ of a sensor is dependent on its distance to the target. We use the sensing radius of the sensors to calculate the new $\delta$ which is selected to be the ratio of the time for the sound to travel a distance of $r$ meters under the surface of the water to $\tau$ and can be given as:

$$\delta = \frac{0.67 \cdot 10^{-3} \cdot r}{\tau} \tag{3.12}$$

where 0.67 is the propagation delay in s/km [2] and $r$ is sensing radius of the node. With this new duty cycle value, the node is ensured to receive a signal during its active period from the target when the target is in the sensing region of the node. The reason is that the target can be maximum $r$ m away from the node if it is in the sensing region of the node. In this case, it takes $0.67 \cdot 10^{-3} \cdot r$ seconds for the underwater acoustic signal from the target to reach to the sensor node.

The sink node selects another projector node when the target leaves the sensing region of the current projector node. It assigns the node which is the closest to the target as the new projector and sends a broadcast message indicating the new projector. Then, it waits for the ACK from the designated projector. If it does not receive an ACK, it sends another broadcast three times and if the sink still does not receive an ACK, it will designate another sensor node as projector. 3DUT algorithm operations are outlined in Algorithm 1.

It is very important to sense the target as soon as it enters into the sensing region

**Algorithm 1** Algorithm of 3DUT protocol operation. $(x_{t_1}, y_{t_1}, z_{t_1})$ and $(x_{t_2}, y_{t_2}, z_{t_2})$ are the positions of the target at different times, $L_{1,2,3,4}$ are the locations of the sensor nodes, $d_{1,2,3,4}$ are the distances of the sensors to the target, R is the sensing radius of the nodes. $d_s$ is the distance the target will traverse in sensing region of new active sensor. $N'$ are the nodes whose sensing regions overlap with the calculated path of the target. Activation message includes $(\delta, \tau)$.

```
if $(SL - PL) - N \geq DT$ then
    projector selection
end if
if projector node then
    send ping periodically
    if Reception of an echo then
        calculate its distance to the target and send to the sink
    end if
end if
if hydrophone node then
    if Reception of a ping then
        preset timer
    end if
    if Reception of an echo then
        stop timer and send the $\Delta t$ to the sink
    end if
end if
if Number of active nodes$\geq 4$ then
    $Trilateration(d_1, d_2, d_3, d_4, L_1, L_2, L_3, L_4)$
    $Vx_t = \frac{(x_{t_2} - x_{t_1})}{\Delta t}, Vy_t = \frac{(y_{t_2} - y_{t_1})}{\Delta t}, Vz_t = \frac{(z_{t_2} - z_{t_1})}{\Delta t}$
else
    $\tau = \frac{d_s}{4 \cdot V_t}$
    $\delta = \frac{0.67 \cdot 10^{-3} \cdot R}{\tau}$
    activate $N'$
end if
if target exits from the sensing region of a projector node then
    select a projector node
end if
if Localization then
    run BND
end if
if Boundary nodes send a failure alarm message then
    run BND
end if
```

of the sensor network. In order to achieve this, the sensors at the boundary of the sensor network have higher duty cycles than the other sensors. However, this causes faster energy consumption for them than the other sensors. In this case, the boundary nodes may become non-functional due to energy depletion and the sensing region is not bounded with high duty cycled sensors. In order to mitigate this problem, 3DUT incorporates *Boundary Node Designation* algorithm.

## 3.5 Boundary Node Designation

The main objective of using Boundary Node Designation (BND) algorithm is to detect the target as soon as it enters into the sensing region of the network by first finding out the nodes at boundary of the network, then assigning high duty cycles to these nodes instead of assigning high duty cycles to all the nodes in the network. In Section 3.5.1, we analyze the tradeoff between using and not using BND, then in Section 3.5.2, we describe the mechanism in detail.

### 3.5.1 Energy Consumption with High Duty-cycled Boundary Nodes

3DUT assigns higher duty cycles to the nodes at the boundary in order to detect the target as soon as it enters into the sensing region of the sensor network. However, in this case, after each localization, every node must send their locations to the sink node so that the sink can find out the boundary nodes. Then, the sink node sends messages to the nodes at the boundary to inform them that they are the boundary nodes. This brings a communication overhead which results in energy consumption. On the other hand, if the boundary nodes are not differentiated, every node must have high duty cycles not to miss the target.

If the boundary nodes are differentiated, the energy consumption of the network can be given as:

$$E = [(N \cdot (E_T + E_R)) + (B \cdot (E_T + E_R))] \cdot \Lambda + (\delta_b \cdot B + \delta_r \cdot R) \cdot P_I \cdot T \qquad (3.13)$$

where $N$ is the number of nodes except the sink node in the network, $E_T$ is the energy consumed for transmission, $E_R$ is the energy consumed for reception, $B$ is the number of boundary nodes, $\Lambda$ is the number of localization employed during the whole tracking process, $\delta_b$ is the duty cycle for boundary nodes, $\delta_r$ is the duty cycle for non-boundary nodes, $R$ is the number of non-boundary nodes, $P_I$ is the consumed power in idle state, and $T$ is the time of the tracking process. The term $(N \cdot (E_T + E_R)) \cdot \Lambda$ stands for the energy consumption when all the nodes send their location information to the sink node. The term $(B \cdot (E_T + E_R)) \cdot \Lambda$ is the energy consumption when the sink node sends the message to the boundary nodes indicating that they are the boundary nodes.

On the other hand, if the boundary nodes are not specified, the energy consumption of the network can be given as:

$$E = \delta_b \cdot N \cdot P_I \cdot T \tag{3.14}$$

We can check if using BND is more energy-efficient or not by comparing the energy consumptions given in (3.13) and (3.14). We conclude that the following relation must hold in order for the case in which boundary nodes have high duty cycles and non-boundary nodes have low duty cycles to be more energy-efficient:

$$0 < (\delta_b - \delta_r) \cdot R \cdot P_I \cdot T - [(N \cdot (E_T + E_R)) + (B \cdot (E_T + E_R))] \cdot \Lambda \tag{3.15}$$

Observing (3.15), we see that BND algorithm becomes more advantageous if the time of tracking increases and the number of running of localization algorithm is decreased. At the first glance, it is not very clear to compute the tradeoff and to conclude if it is advantageous to use the boundary node designation. However, by fixing some of the variables, and changing the tracking time and number of runs of localizations, we can obtain the cases in which BND is advantageous. The solution of this problem is left as a future work.

### 3.5.2 BND Procedure

The aim of boundary node designation is to keep the sensor network closed and bounded by the high duty cycled sensors in case of a failure of the boundary nodes. The objective is to maintain seamless surveillance in sensor network zone.

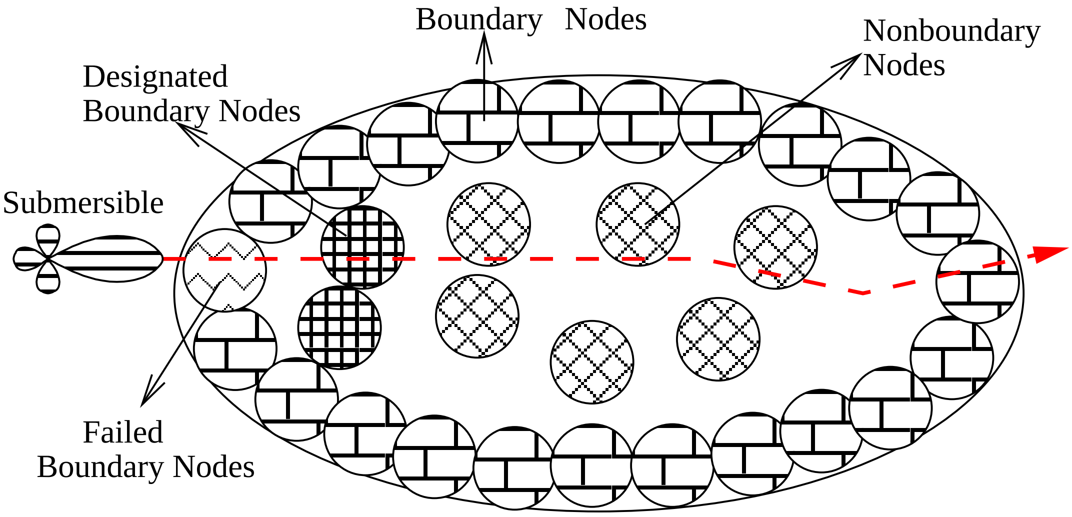

Figure 3.3: When a boundary node fails, new boundary nodes are designated.

If this mechanism is not utilized, there can be some scenarios in which the targets enter into the sensing region of the network and pass through it without being detected. As shown in Fig. 3.3, if the nodes are not designated and assigned as boundary nodes, the sensor network may not detect the target, nor track it, because the duty cycles of the non-boundary nodes are low.

When a boundary node is about to run out of energy, it sends a failure alarm message to the sink node. After this message is received or after localization algorithm is run, the sink node runs BND algorithm to find the new boundary nodes.

In the first phase of BND algorithm, 3DUT divides the sensing region into smaller cubes which are called voxels. The dimensions of the voxels are selected with respect to the dimensions of the targets. The reason is, we assume that the sensing regions of two sensors intersect if the distance between the boundaries of their sensing regions is smaller than the minimum width of the target. We assume the dimensions of the voxels are $v$, which can be selected with respect to a practical value for minimum width of a submarine [13].

The sink node first finds the coordinate limits of the region sensed by the nodes. By coordinate limits, we mean the maximum and minimum x, y and z coordinates sensed by the sensors. As an example, the surfaces of the big cube in Fig. 3.4 are

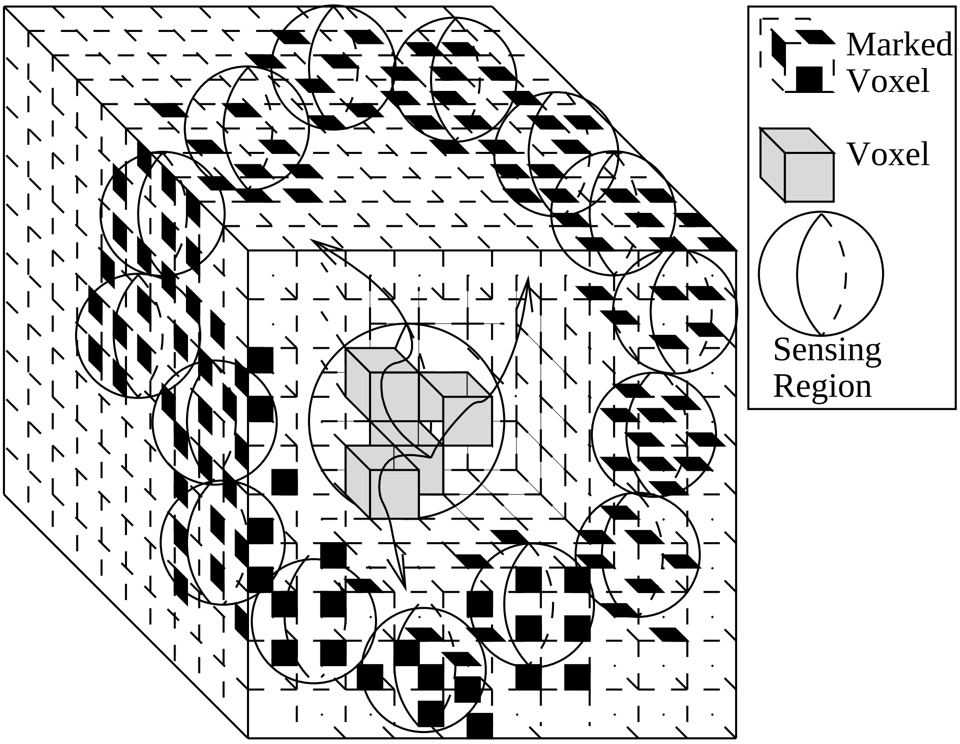

Figure 3.4: The Boundary Node Designation algorithm. If boundary of the sensing region is reached by always passing through neighboring non-marked voxels intersecting with $S_1$ one by one, then $S_1$ is a boundary node.

the limits of the region sensed by the nodes. Then, to check if a sensor, e.g., sensor 1 ($S_1$), is at the boundary of the sensing region, the sink node finds the voxels which intersect with the sensors other than $S_1$ and marks them. Then, the sink finds the voxels which intersects with $S_1$. In order for $S_1$ to be at boundary of the sensing region, the voxels intersecting with $S_1$ must not be marked by other sensors and they must not be enclosed by the voxels which are marked by other sensors. To check this, the sink starts from a voxel intersecting with only $S_1$, i.e., which is not marked by the other sensors. Then, the sink checks if it is possible to reach to the voxels at the boundary of the sensor network by selecting the non-marked neighbors of this voxel. If it is possible, the $S_1$ is at the boundary because it is not enclosed by the other sensors. This process is conducted for every sensor and the boundary nodes are found.

# CHAPTER 4

# PERFORMANCE EVALUATION

We analyze the performance of 3DUT algorithm with respect to different metrics and present the results of the simulations which mainly evaluate the accuracy of tracking with respect to the speed of sound, localization error, errors in distances between the nodes and the target, number of nodes and duty cycle. We deploy a simulation environment using ns-2 [23] and distribute 50 sensors to an area of 600 m x 600 m x 600 m. We set the signal propagation speed to 1500 m/s. The attenuation of the underwater acoustic signal is adopted as explained in Section 3.3. As explained before, the target is assumed to be a point target so that the echoes are radiated isotropically and reach to the sensors at the vicinity of the target. The parameters which are mentioned while describing the algorithm are shown in Table 4.1.

Table 4.1: The parameters used in simulations (s : second, m : meter)

| | |
|---|---|
| *Ratio between the target noise and the ambient noise* : $\eta$ | 2 |
| *Ping transmission rate* : $\gamma$ | 1 $s^{-1}$ |
| *Distance to check if a target is getting out of the sensing region of a sensor node* : $\chi$ | 10 m |
| *Minimum distance for the sink to sort the sensor nodes with respect to their distance to target* : $\zeta$ | 10 m |
| *Difference of activation time and target detection time of the nodes* : $\kappa$ | 5 s |
| *Voxel dimension* : $\nu$ | 25 m |

## 4.1 Preliminary Analysis

In this section, we analyze the required number of nodes to be able to continue tracking and the sources of errors in 3DUT calculations.

### 4.1.1 Required Number of Nodes for Accurate Tracking

In order to be able to track a target in the sensing region of sensors, all the subregions forming the whole sensing region must be covered by at least 4 sensors, i.e., it must be 4-covered. Before tracking process takes place, the sensors are distributed randomly to the region. The random deployment of the sensors is considered as a Poisson process and in this case inter-sensor distance is exponentially distributed [40]. Consequently, reformulating the results in [40] for three dimensional space, the probability of full coverage in a three dimensional arbitrary volume ($V_{arbitrary}$) becomes:

$$P_{cov}{}^{3D} = 1 - e^{\frac{-8r^3\lambda}{V_{arbitrary}}} \tag{4.1}$$

where $\lambda$ is the number of nodes. The term $8r^3$ comes from the fact that in order to ensure 1-coverage, the distance between two neighboring sensors should be less than $2r$ on x, y and z axis. Hence the total volume between two neighboring sensors should be less than $8r^3$.

The probability that $k$ sensors will be present in the sensing region of a sensor is given by [40]:

$$Pr_k = \frac{(\rho\frac{4}{3}\pi r^3)^k e^{-\rho\frac{4}{3}\pi r^3}}{k!} \tag{4.2}$$

where $\rho$ is the node density. Combining (4.1) and (4.2), we obtain the probability that the specified arbitrary volume is covered by $k$ or more sensor nodes, which is given by:

$$Pr = [1 - \sum_{k=0}^{k-1} \frac{(\rho\frac{4}{3}\pi r^3)^k e^{-\rho\frac{4}{3}\pi r^3}}{k!}][1 - e^{\frac{-8r^3\lambda}{V_{arbitrary}}}] \tag{4.3}$$

In Fig. 4.1, the probabilities of 4-coverage with respect to sensor numbers and sensing radius in different volumes are shown. As shown in Fig. 4.1, the sensing radius has an important effect on the coverage. If we double the sensing radius, the required number of sensor nodes decreases down to around $\frac{1}{10}$ of its previous value.

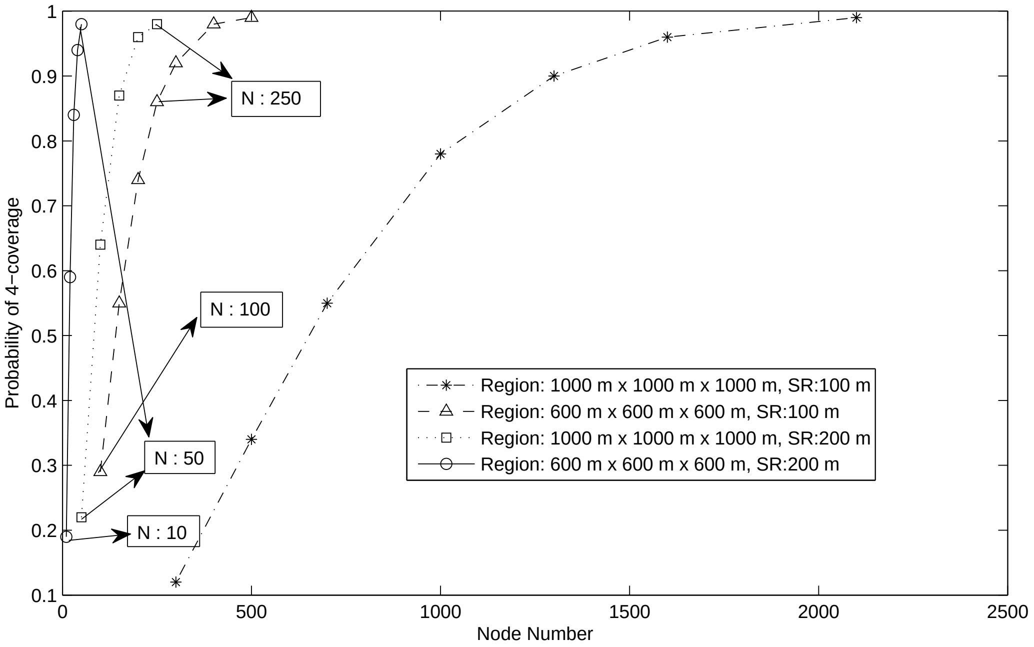

Figure 4.1: The probability that any point in the region is covered by at least 4 sensors vs. the number of nodes for different sensing radius (SR).

### 4.1.2 Preliminary Error Analysis

In this section, we analyze the sources of errors in calculated target location and find out error bounds for the components used in target localization calculation. By finding the error bound for each of the component and using them in simulations, we obtain an overall error bound for 3DUT. We first analyze the error in underwater sound speed and use this error to analyze the error in calculated distance between the nodes and the target.

#### 4.1.2.1 Sound Speed Error

The practical assumption for $C$ is 1500 m/s. However, $C$ varies with respect to the temperature, pressure (depth), and salinity. By exploiting the empirical formula for the calculation of the speed of the sound under the surface of the water [34], we compute $C$ as:

$$\begin{aligned} C(T,h,s) = 1492.9 + 3(T-10) - 6\cdot 10^{-3}(T-10)^2 - \\ 4\cdot 10^{-2}\cdot(T-18)^2 + 1.2(s-35) - \\ 10^{-2}(T-18)(s-35) + \frac{h}{61} \end{aligned} \tag{4.4}$$

where $T$ is the temperature in Celsius, $h$ is depth in meters and $s$ is salinity in parts per thousand (ppt). The error in $C$ can be given as:

$$\begin{aligned} \Delta C &\leq \tfrac{\partial C}{\partial T}\Delta T + \tfrac{\partial C}{\partial h}\Delta h + \tfrac{\partial C}{\partial s}\Delta s \\ &= [3 + 6\cdot 10^{-3}(2T-20) - (4\cdot 10^{-2})(2T-36)]\Delta T \\ &- 10^{-2}(s-35)\Delta T + [1.2 - 10^{-2}(T-18)]\Delta s + \tfrac{\Delta h}{61} \end{aligned} \tag{4.5}$$

In [32], it is stated that $\Delta s$ and $\Delta T$ can be assumed to be 0.75 ppt and 0.1 °C. The temperature and the depth can be obtained by CTD (conductivity, temperature, depth) sensors which are used for determining essential physical properties of the sea water [36]. Assuming $\Delta h = 2$ m, we obtain the upper bound for $\Delta C$ as 1.35 m/s at 10 °C and for a salinity of 35 ppt. This error in $C$ affects the accuracy of the estimation of the distance between the projector node and the target and the distance between the hydrophone nodes and the target.

#### 4.1.2.2 Target-to-Node Distance Accuracy

As explained in Section 3.3, the target-to-node distance calculations are based on the time during which the ping travels between the nodes and the target. 3DUT calculates $d_1$ and $d_2$ by employing (3.6) and (3.7). The error bound in distance between the projector node and the target can be computed by

$$\Delta d_1 \leq \frac{\partial d_1}{\partial C}\Delta C + \frac{\partial d_1}{\partial(t_{Nt_1} - t'_{Nt_1})}\Delta(t_{Nt_1} - t'_{Nt_1}) \tag{4.6}$$

$$= (t_{Nt_1} - t'_{Nt_1})\frac{\Delta C}{2} + \frac{C}{2}\cdot\Delta(t_{Nt_1} - t'_{Nt_1}) \tag{4.7}$$

where $C$ is the speed of the sound under the surface of the water, $(t_{Nt_1} - t'_{Nt_1})$ is the time difference between the transmission of the ping and reception of the echo. Contribution of $\Delta(t_{Nt_1} - t'_{Nt_1})$ can be neglected, hence $\Delta d_1$ is due to $\Delta C$, meaning that it changes with respect to the distance between the projector node and the target. The dependency of $\Delta d_1$ to $d_1$ at different $\Delta C$ can be seen in Fig. 4.2. As it can be seen from Fig. 4.2, $\Delta d_1$ increases as the distance between the projector node and the target increases because in this case the propagation time of the signal to travel between the projector node and the target increases which amplifies the effect of $\Delta C$.

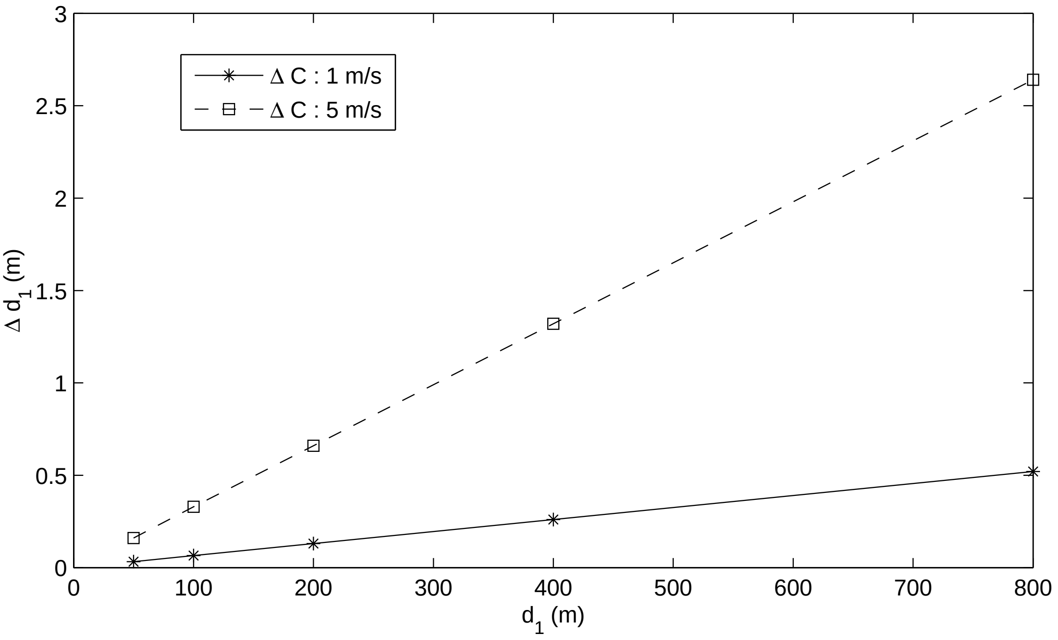

Figure 4.2: $\Delta d_1$ vs. $d_1$ for different $\Delta C$.

The error bound in distance between the hydrophone nodes and the target can be computed by

$$\begin{aligned}\Delta d_2 &\leq \tfrac{\partial d_2}{\partial c}\Delta C + \tfrac{\partial d_2}{\partial (t_T - t_P)}\Delta(t_T - t_P) + \Delta d_3 + \Delta d_1 \\ &= (t_T - t_P)\cdot\Delta C + C\cdot\Delta(t_T - t_P) + \Delta d_3 + \Delta d_1\end{aligned} \tag{4.8}$$

where $t_T$ is the time of reception of the echo from the target and $t_P$ is the time of reception of the ping from the projector node by the hydrophone nodes. Contribution of $\Delta(t_T - t_P)$ can be neglected. The error in $d_2$ is composed of the error in the speed of the sound under the surface of the water, $\Delta d_1$ and $\Delta d_3$. $\Delta d_3$ is the error in employed localization algorithm. The average error in the localization algorithm described in [15] is 3.75 m in deep water and 6.23 m in shallow water, hence, we assume an average localization error of 5 m. Since $d_3$ is the distance between two nodes, we assume the maximum $\Delta d_3$ to be 10 m. In Fig. 4.3, the change of $\Delta d_2$ with respect to $d_2$ at different $\Delta C$ and $d_1$ can be seen.

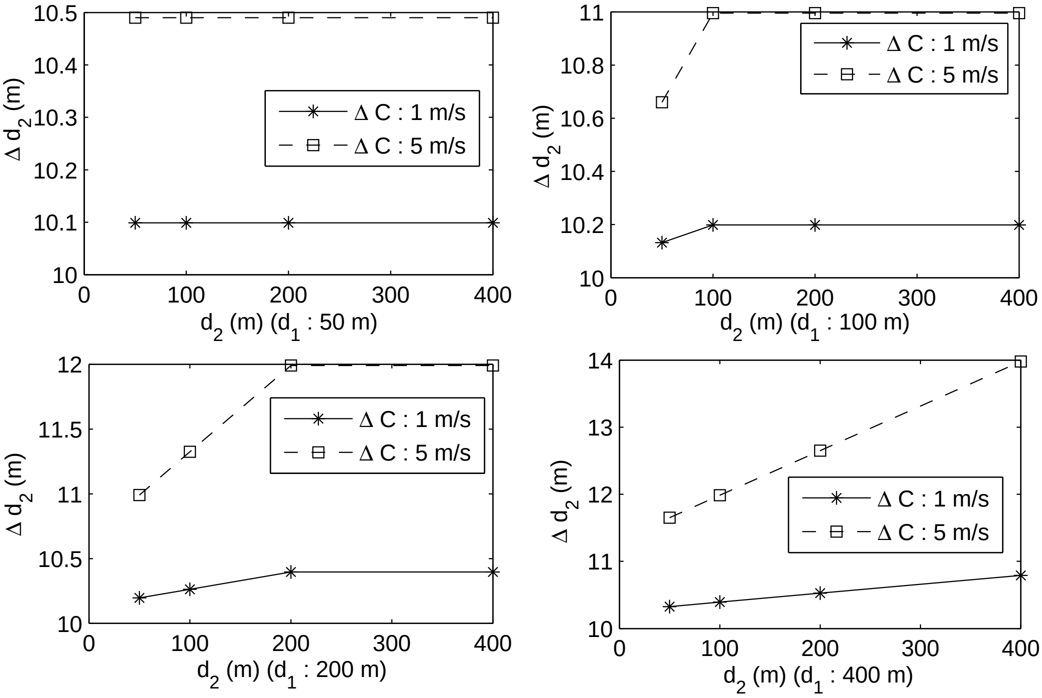

Figure 4.3: $\Delta d_2$ vs. $d_2$ for different $d_1$ and $\Delta C$.

In order to find the error bound for $d_2$, the projector node, hydrophone node and the target are assumed to be situated as shown in Fig. 4.4 because $t_T - t_P$ is maximum in this case. As it can be seen from Fig. 4.3, $\Delta d_2$ increases with $d_2$ increases until $d_2$ is equal to $d_1$. When $d_2$ exceeds $d_1$, the maximum $t_T - t_P$ value which can be obtained in the case shown in Fig. 4.4 is constant.

The target is localized by using the coordinates of the nodes and the distances between the nodes and the target. Therefore, the tracking error is a function of the errors in distances between the nodes and the target, localization error and the coordinates of

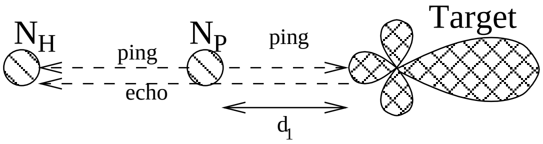

Figure 4.4: Positions of hydrophone node ($N_H$), projector node ($N_P$), and target to obtain the maximum $t_T - t_P$ where $t_T$ is the time of reception of the echo and $t_P$ is the time of reception of the ping by the hydrophone nodes.

the nodes. We obtained the error bounds for the distances between the nodes and the target and we use the error bound found in [15] for localization of the nodes. By using these values in simulations, we compute an overall error bound.

Even if the overall error boundary for trilateration can be computed by using the error in distances between the nodes and the target, due to the ambiguity in trilateration, the error boundary computed is meaningless. For the problem of finding Euclidean positions for the vertices of a graph, knowing the length of each graph edge does not guarantee a unique realization, because vertex positions may change preserving the edge lengths. It is possible to realize the graph with almost the same inter-vertex distances and having less error in the distances between the vertexes in the alternate realization of graph [22]. In order to resolve this ambiguity, 3DUT checks the distances between the calculated locations of the target if they are below the distance that can be traveled by the target between each calculation.

## 4.2 Detection Performance

In this section, we analyze the passive and active detection distances so that we can use practical distances in simulations. We analyze the detection distances with respect to frequency and wind speed for different possible targets.

### 4.2.1 Passive Detection Performance

As described in Section 3.2, detection of a target is dependent on the environment noise and frequency. The behavior of detection distances of the sensors which can be calculated by (3.1), (3.2), (3.3) with respect to underwater noise and frequency is shown in Fig. 4.5. The radiated noise values of the vessels mentioned in Fig. 4.5 with respect to frequency can be found in Table 4.2 [34]. The reason why we used the noise values of submarine, torpedo and frigate is that these are the possible targets which 3DUT is designed to track.

Table 4.2: The radiated noise of the vessels at different frequencies

| *Frequency (kHz)* | *Submarine (dB)* | *Quiet torpedo (dB)* | *Frigate (dB)* |
|---|---|---|---|
| *f = 1* | 110 | 120 | 135 |
| *f = 3* | 100 | 110 | 123 |
| *f = 5* | 95 | 105 | 118 |
| *f = 10* | 90 | 100 | 113 |

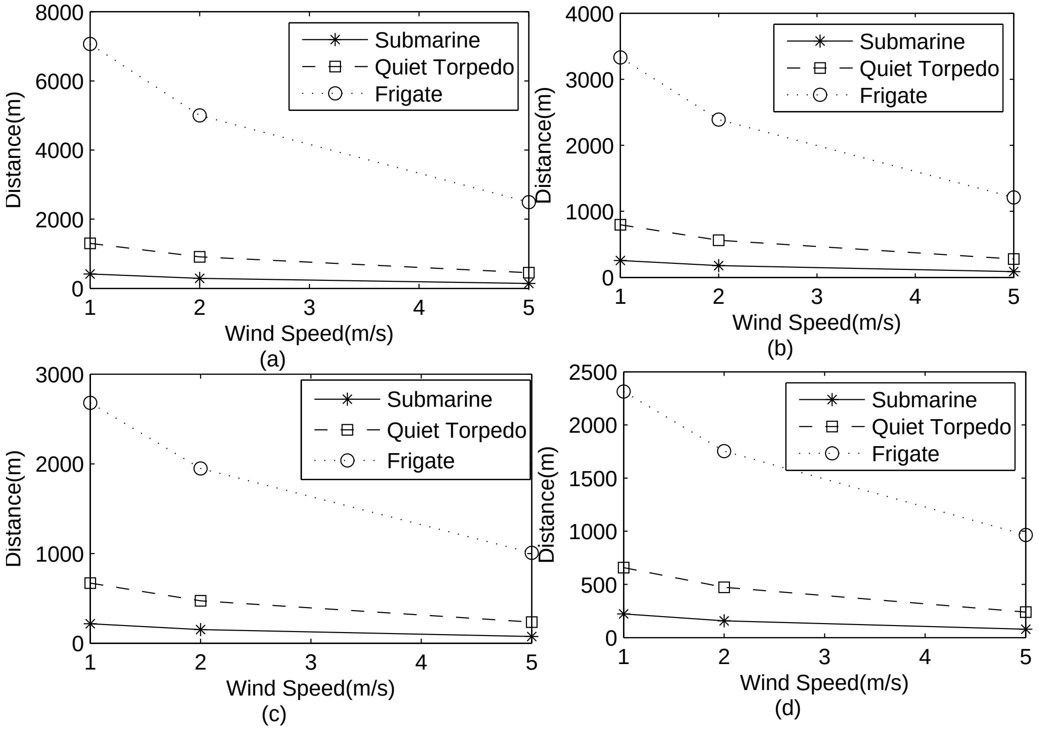

Figure 4.5: Passive detection distance vs. wind speed for different underwater vehicles at frequencies (a) $f$ = 1 kHz, (b) $f$ = 3 kHz, (c) $f$ = 5 kHz, (d) $f$ = 10 kHz.

As it can be seen from Fig. 4.5, the detection distance decreases as wind speed increases because underwater ambient noise increases as wind speed increases as described in (3.3). Furthermore, since the noise radiated by the submarine is lower than the other vehicles, its detection distance is the shortest. As the frequency increases, the noises of the devices decrease and propagation loss increases which causes the detection distance to decrease. However, as the frequency increases, the underwater ambient noise also decreases which causes the detection distance to increase.

### 4.2.2 Active Detection Performance

As described in Section 3.3, active detection of a target is dependent not only on environment noise and frequency but also on target strength. The behavior of active detection distance calculated by (3.5) is given in Fig. 4.6.

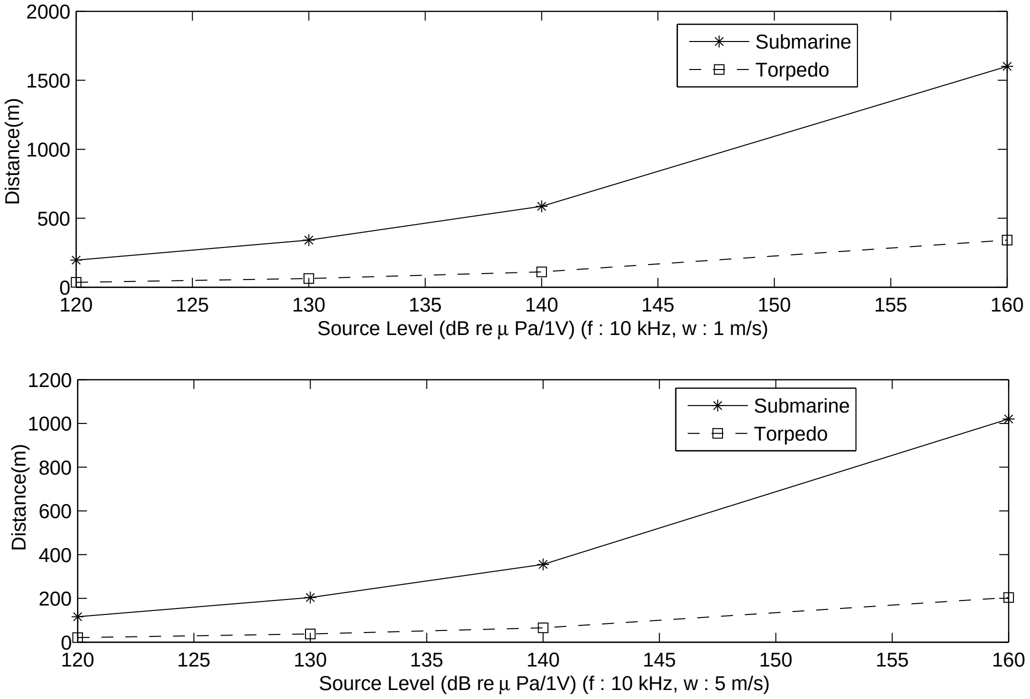

Figure 4.6: Active detection distance vs. source level at 10 kHz for different wind speed (w) values.

As it can be seen from Fig. 4.6, the detection distance of submarine is higher than the torpedoes because the target strength of a submarine is greater than that of torpedoes. The target strengths of a submarine and a torpedo are assumed to be 15 dB and -15 dB [34], respectively. Depending on the type of transducer mounted to the sensor nodes and the voltage level applied for the pings, the detection distance of a target changes as follows:

$$SL = TRV + 20\log(V_{in}) \tag{4.9}$$

where $TRV$ is transmitting response to voltage (transmitting sensitivity) which gives the pressure in the medium per unit of electrical excitation as a function of frequency [31]. Therefore, by mounting one of the commercial transducers [28] on the sensor nodes, it is possible and feasible to use them as projector node in order to be able to obtain the same detection performance as passive detection. The relation between the input voltage and source level is given in (4.9).

## 4.3 Tracking Accuracy

In this section, we present the accuracy performance as the tracking error with respect to different metrics such as node number, underwater speed of sound, channel error rate, delay variance, localization error, errors in distances between the nodes and the target. The tracking error is given as the average mean square error of the calculated locations of the target, which can be given as

$$E_{Avg} = \sum_{i=1}^{N} \frac{\sqrt{(x_i' - x_i)^2 + (y_i' - y_i)^2 + (z_i' - z_i)^2}}{N}$$

where $E_{Avg}$ is the average error, $N$ is the number of target location data collected, $(x_i, y_i, z_i)$ is the real location of the target, and $(x_i', y_i', z_i')$ is the calculated location of the target.

### 4.3.1 Accuracy vs. Node Number

Since the information from the nodes are used to calculate the location of the target, intuitively, as the number of nodes increases, the accuracy of tracking is better. However, this is not valid for every case because 3DUT calculates the location of the target by the information from 4 different nodes. During tracking, even if the target is in the sensing region of more than 4 nodes, the information from some of the nodes is not used. The tracking results of some sensor networks with different node numbers whose boundary nodes and non-boundary nodes have 50% and 25% duty cycles are shown in Fig. 4.7. The average tracking error is 4.53 m when there is 50 nodes and

9.61 m when there is 20 nodes. Therefore, the number of nodes does not have a huge impact on the accuracy, hence, it is not necessary to deploy many sensors to achieve accurate tracking. As discussed in Section 4.1.1, the probability of tracking is dependent on the sensor number, sensor radius and the volume of the region and deploying many sensors might be unnecessary if there is already enough number of sensors.

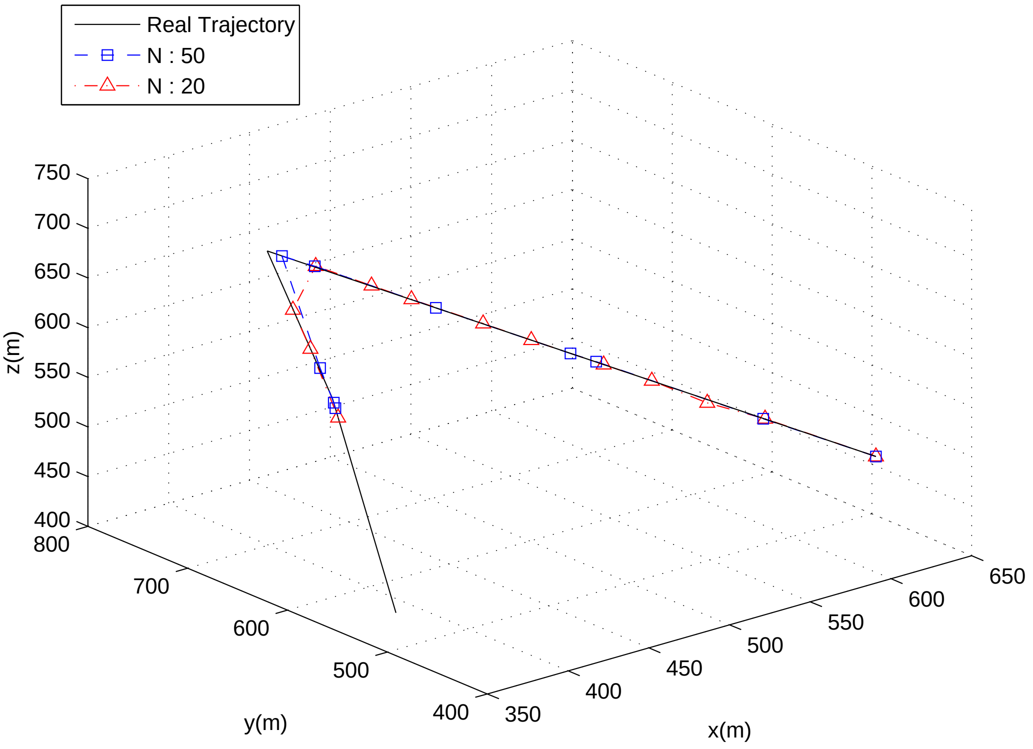

Figure 4.7: Calculated target trajectory for varying network size (N is the number of nodes deployed).

### 4.3.2 Accuracy vs. Underwater Speed of Sound

In our calculations, we assume that the speed of the sound under the surface of the water is 1500 m/s. However, as explained in Section 4.1.2.1, the speed of the sound may vary with respect to temperature, pressure (depth), and salinity. Therefore, we set an underwater sound speed error of 5 m/s and observed the effect of this change to accuracy. The tracking result when there is an error in underwater sound speed can be seen in Fig. 4.8, and the average error is 7.94 m.

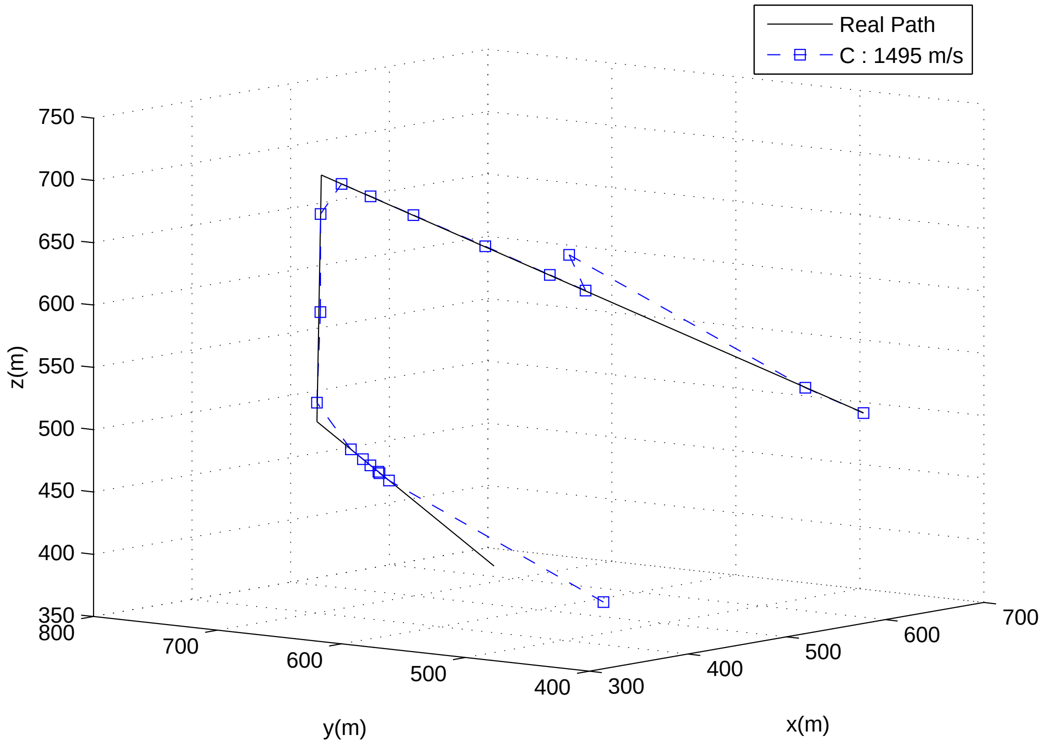

Figure 4.8: Calculated target trajectory for varying underwater sound speed.

### 4.3.3 Accuracy vs. Channel Error Rate

In order 3DUT to calculate the location of the target, the nodes send the information they collected to the sink node. However, due to the characteristics of underwater channel the communication is prone to failures. We analyze the effect of rate of packet loss to the tracking error. The result can be seen in Fig. 4.9. As it can be seen from the figure, the accuracy decreases as the channel error rate increases. The channel error rate has more impact if the packets sent by the projector node are corrupted because in this case the distance between the nodes and the target cannot be calculated. If there are more than 4 sensors providing information to the sink about the target, corruption of the packets of some of these nodes may not have a huge impact in target localization because the sink can use the information from the other sensors.

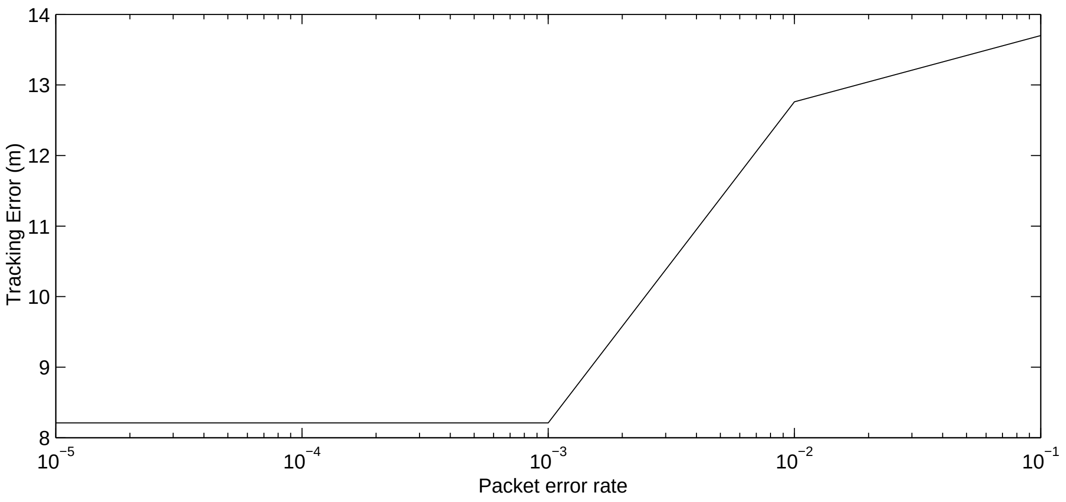

Figure 4.9: Tracking error vs. packet error rate

### 4.3.4 Accuracy vs. Delay Variance

The underwater acoustic communication channel has a variable delay, which results in error in target location calculations because, in order to calculate the distances between the nodes and the target, the difference of transmission time of ping and the reception time of ping and echoes are used. The effect of delay variance to tracking error can be seen in Fig. 4.10. As the delay variance increases, the tracking error also increases. Since the distances between the nodes and the target are calculated based on the speed of the sound under the surface of the water, the localization of the target is affected greatly with small changes in delay variance. The reason is that the delay variance is multiplied by the speed of sound under the surface of the water and the error values caused by the delay variance is on the orders close to the distances between the sensors.

### 4.3.5 Accuracy vs. Error in Localization of the Nodes

In order 3DUT to calculate the location of the target, it is assumed that the locations of the nodes are known a priori. However, the node localization error has an impact on the accuracy. As shown in Fig. 4.11, when there is a localization error ($E_L$) of

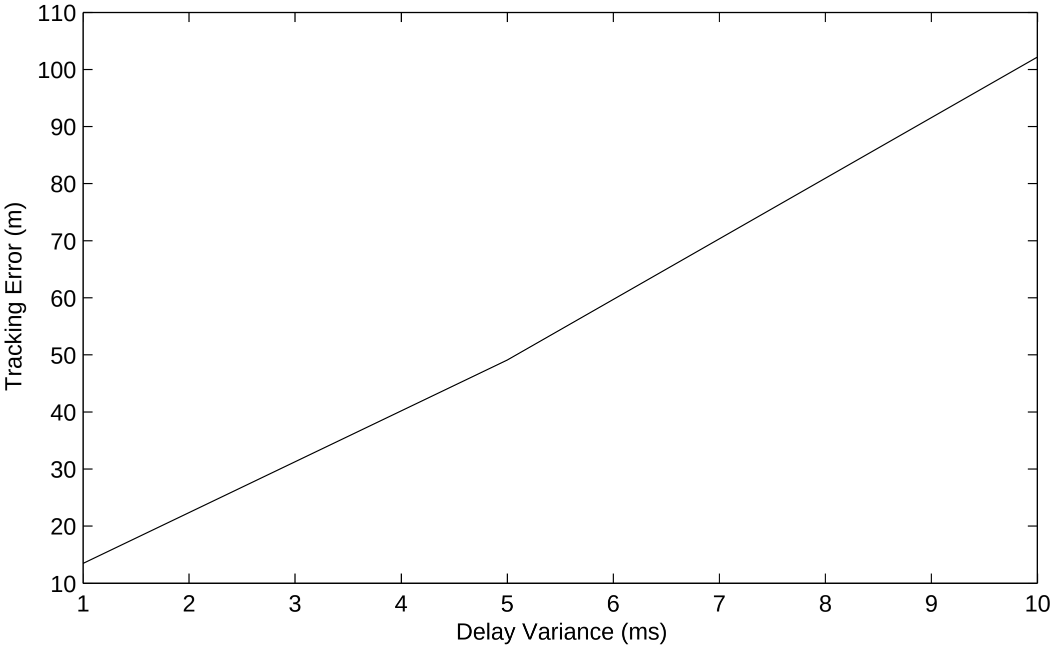

Figure 4.10: Tracking error vs. delay variance

5 m, the tracking accuracy is seriously affected. As it can be seen in Fig. 4.11, the sensor network missed a part of the path of the target. The average tracking error is computed to be 12.8 m. Therefore, in order to obtain an accurate tracking, an accurate localization algorithm must be utilized and this algorithm must be run periodically to obtain the locations of the nodes during tracking because the locations of the nodes may change due to the underwater tides and currents. The period of running the localization algorithm is important for accuracy because the nodes drift due to underwater currents which results in change of location of the nodes. Between each running of localization algorithm, the sink does not have the exact locations of the nodes. However, running the localization algorithm results in energy consumption. Therefore, there is a tradeoff between accuracy and energy consumption with respect to the frequency of running the localization algorithm. The analysis of this tradeoff is left as a future work.

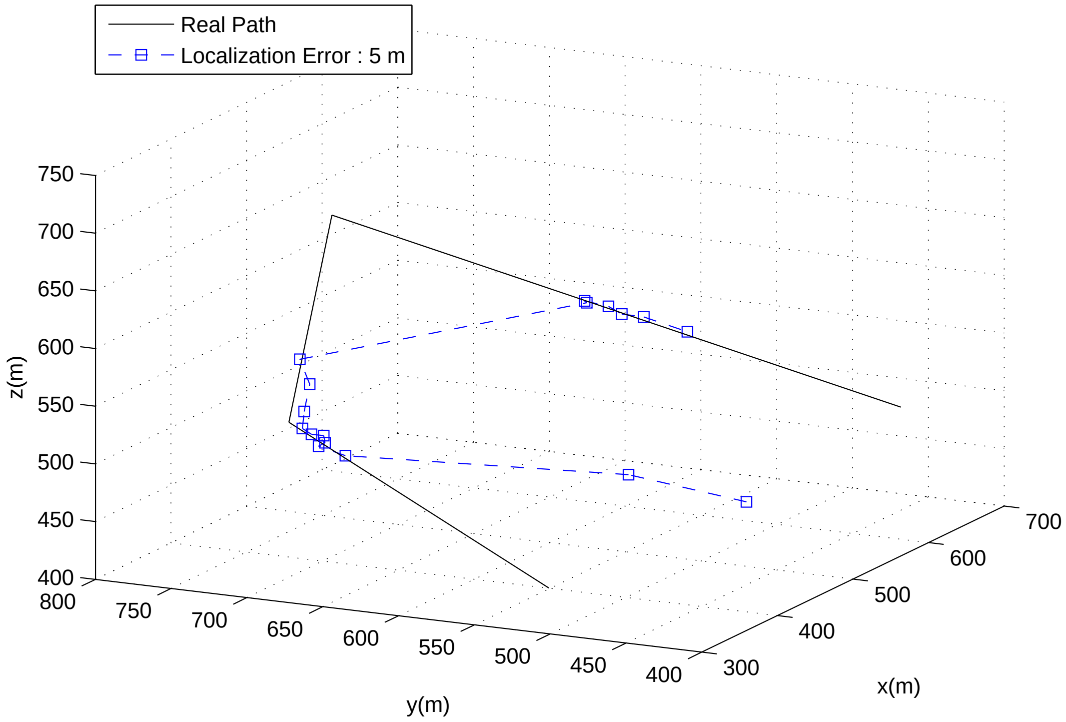

Figure 4.11: Calculated target trajectory in case of localization errors.

Table 4.3: The accuracy (Average Tracking Error) vs. $E_L$, $\Delta d_1$ and $\Delta d_2$

| *Accuracy vs. $E_L$* | |
|---|---|
| | *Average Tracking Error* |
| $E_L$ : 5 m | 12.87 m |
| *Accuracy vs. $\Delta d_1$* | |
| | *Average Tracking Error* |
| $\Delta d_1$ : 1 m | 8.54 m |
| $\Delta d_1$ : 3 m | 17.09 m |
| *Accuracy vs. $\Delta d_2$* | |
| | *Average Tracking Error* |
| $\Delta d_2$ : 2 m, $E_L$ : 5 m | 12.89 m |

### 4.3.6 Accuracy vs. $\Delta d_1$

In order 3DUT to calculate the location of the target, it calculates $d_1$. Furthermore, $d_2$ is calculated by using $d_1$. Therefore, tracking accuracy is dependent on $\Delta d_1$. The average tracking error with respect to $\Delta d_1$ can be seen in Table 4.3. In order to reduce $\Delta d_1$, the error in underwater sound speed must be minimized.

### 4.3.7 Accuracy vs. $\Delta d_2$

In order 3DUT to calculate the location of the target, it calculates $d_1$ and $d_2$. In trilateration, the distances between the nodes and the target are used. Therefore, $\Delta d_2$ has a direct effect on the tracking accuracy. Therefore, we must minimize $\Delta d_2$. To achieve this, as shown in Fig. 4.3 and Fig. 4.4, the distance between the projector node and the target must be minimized. 3DUT employs the nodes which are the closest to the target to be able to obtain information and minimize $\Delta d_2$. The average tracking error with respect to the $\Delta d_2$ can be seen in Table 4.3. Running the simulations by inserting the errors in different ways, we obtain an average error of 12.89 m for $\Delta d_2$.

When we apply the maximum errors for the components such as $\Delta d_1$, $\Delta d_2$, $\Delta L$, and packet loss probability which causes the overall error in tracking and run the simulation, we obtain a maximum average error of 29.96 m. When compared to large submarine sizes such as 175 m [21], this error is acceptable for localization of the target.

## 4.4 Energy Consumption

In this section, we analyze the average energy consumption of the nodes ($E_{avg}$) with respect to different metrics.

### 4.4.1 Effect of BND Algorithm

The objective of BND algorithm is to keep the high duty cycled nodes at the boundary of the network so that the targets entering into the sensing region of the network are detected immediately. In order to achieve the detection of the target immediately, all the sensors can be given high duty cycles which results in higher energy consumption. We analyze this situation by considering the cases with and without BND. In the first case, we use BND algorithm and we assign 50% and 25% duty cyle to the boundary nodes and non-boundary nodes, respectively. In the second case, we do not use BND algorithm and assign 50% duty cycles to all the nodes. We run the simulations for different durations of tracking to compare the cases with and without BND and the effect of time to the result. As shown in Fig. 4.12, for varying durations, we always observed that using BND results in less energy consumption. The energy consumption decreases by an average value of 6 %. Therefore, we conclude that BND is a promising approach to reduce energy consumption in target tracking with underwater sensor networks.

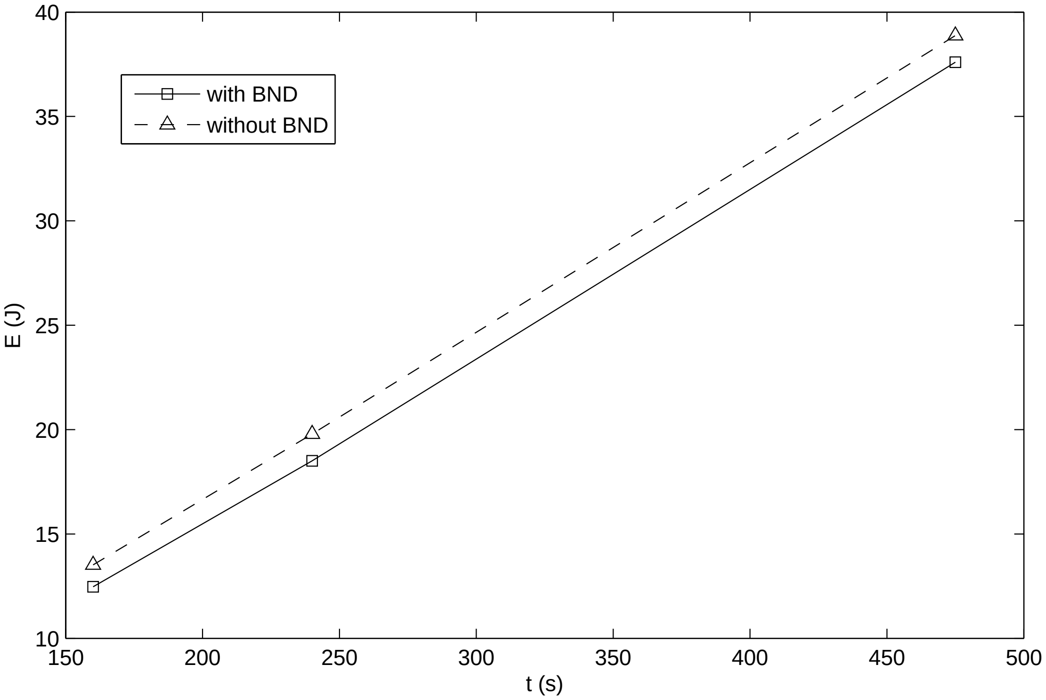

Figure 4.12: Average energy consumption vs. duration of tracking with and without BND.

### 4.4.2 Energy Consumption vs. Duty Cycles

The sensor nodes have duty cycles to decrease energy consumption. 3DUT assigns high duty cycles for boundary nodes and lower duty cycles for non-boundary nodes. In order to analyze the effect of the duty cycles on energy consumption, different duty cycles are assigned to the non-boundary nodes. As it can be seen from the results in Fig. 4.13, the energy consumption decreases when lower duty cycles are used. The reason of the decrease in the energy consumption is the fact that the sensing times of the nodes are decreased. When the nodes have high duty cycles, they sense the environment for longer time and consume more energy even if they are not used in tracking.

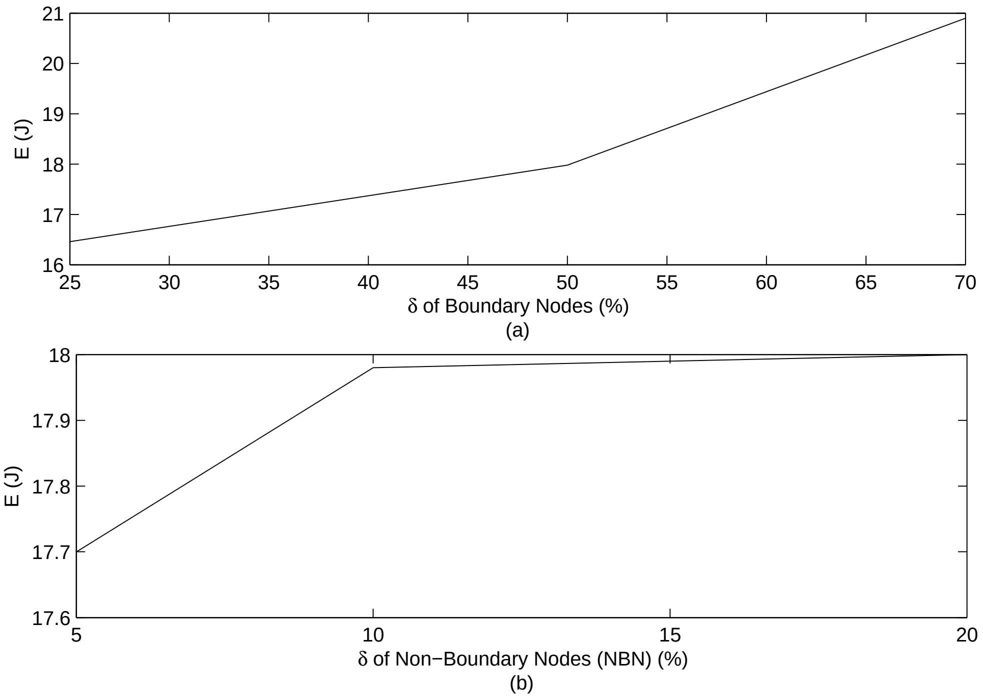

Figure 4.13: Average energy consumption vs. duty cycles, BN : Boundary Node, NBN : Non-boundary Node. (a) $\delta_{NBN}$ : 10 % (b) $\delta_{BN}$ : 50 %.

# CHAPTER 5

# CONCLUSION

Target tracking is an important and mission-critical capability. Under the surface of the water, the tracking problem becomes harder and more costly due to the dynamic nature of the underwater environment and the challenges of underwater acoustic communications. In this thesis, Three Dimensional Underwater Target Tracking (3DUT), a target tracking algorithm for UW-ASN, is presented. 3DUT is a distributed and energy-aware solution for target tracking problem for underwater domain. The algorithm starts when the nodes at the boundary of the sensor network receive signals from the target and appropriate nodes are assigned with appropriate duty cycles for energy consumption. Trilateration is used to calculate the location of the target and target movement pattern-based duty cycles are used to increase the energy efficiency. Furthermore, a mechanism, Boundary Node Designation procedure, to designate the new boundary sensors is used so that the surveillance is sustained in sensing region. Through analysis and simulations, we presented that 3DUT can track the targets in an accurate and energy-efficient manner.

We presented the performance evaluation results of 3DUT in terms of tracking error and energy consumption. The behavior of 3DUT under the surface of the water is analyzed by employing specific underwater characteristics. We analyzed the effect of delay variance and as the delay variance increases, the tracking error increases. Due to the channel error rate, some of the packets can be lost, which results in tracking error. The tracking error is 12.5 m at a packet loss rate of 1 %. The target localization calculations are based on the locations of the sensors so the accuracy of the employed localization algorithm is very important. At an average localization error of 5 m, the tracking error is 12.9 m. During tracking, the locations of the nodes can change due to the underwater currents and tides, so the localization algorithm must run periodically, which results in energy consumption. In the case of running the localization algorithm more frequently, the tradeoff between the accuracy gain and energy consumption is left as a future analysis. We compared the cases with and without boundary node designation and concluded that by using BND the average energy consumption decreases by 6 %. We calculated the maximum errors for the distances between the nodes and the target and used these values to compute the track error. The simulation results show that the average track error is around 7 m and maximum track error is less than 30 m. As explained earlier, compared to large submarine sizes such as 175 m [21], this error is acceptable for localization of the target.

As future work, the underwater channel characteristics can be analyzed in detail and the detection performance can be improved. Besides, the effects of target Doppler can be analyzed. Moreover, optimization for the duty cycles based on the target mobility can be implemented. Furthermore, instead of assuming the target as a point, the behavior of more practical reflections from the target can be analyzed. In order to achieve this, a Kalman Filter can be adopted to obtain more accurate estimates by integrating the underwater signal analysis.

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