Reliability Evaluation of Underwater Sensor Network in Shallow Water Based on Propagation Model

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Abstract. Underwater wireless sensor networks are composed of numerous vehicles/sensors that are deployed in precise acoustic vicinity to execute collaborative monitoring and data assembling tasks. These sensor nodes establish an acoustic communication link among them and the surface station. The unpredictable variations in the underwater parameters (depth; temperature; salinity; pH) introduce changes in signal speed randomly, which affect the link formation. Hence, designing a feasible channel model is essential to estimate the effect of underwater parameters and their losses (absorption loss, spreading loss) on the connectivity of underwater networks. In this work, an acoustic channel model has been considered which distinguishes the effect of frequency and the aforementioned parameters on link formation. A methodology for evaluating the reliability of the underwater sensor network deployed in shallow water scenarios based on the acoustic propagation model has been proposed. The network is deployed as 3D reference architecture, where the nodes are randomly deployed in a fixed scenario depth and the source node is deployed with an adjustable buoy length. The influence of underwater parameters, network parameters, and simulation time on the two-terminal reliability of underwater sensor networks has been analyzed. The simulation results indicated that the maximum reliability is achieved at lower frequencies when compared to higher frequencies.

Keywords: Acoustic Channel; Network Reliability; Propagation Model; Shallow Water; Underwater Sensor Network

1. Introduction

Basically, underwater acoustic sensor networks are formed by group of sensors and/or autonomous underwater vehicles deployed underwater and networked through wireless links (either single hop or through multi-hop) by means of acoustic signal to perform collaborative monitoring tasks over a given deployment scenario [1]. The nodes in UASN are intended to set up to facilitate applications for oceanographic information gathering, pollution monitoring, offshore explorations, calamity management, assisted navigation, and tactical surveillance [2]. The communication techniques used for information transmission in underwater should absorb and resist with the environmental conditions to enable a reliable communication among the nodes.

Wireless sensor networks for underwater communication essentially uses three basic approaches for transmitting information based on acoustic, Electro Magnetic (EM), and optical signals [3]. Each one of these approaches has advantages and disadvantages mainly due to their physical constraints [4] such as; propagation delay, Line of Sight, absorption, scattering, multipath etc. The communication technologies (optical, radio-frequency) have been proposed for short range communications (1-100m).
In fact, radio waves propagate long distances through conductive sea water only at extra low frequencies (30-300Hz), which requires either high transmission power or large antenna size [5]. These signals are attenuated rapidly within few meters (radio) or in tens of meters (optical) due to attenuation and scattering phenomenon respectively [6].

However, the optical signals do not suffer much from high attenuation but are affected by scattering. Whereas, the acoustic technology for information transmission in underwater offers long range (1-10km) due to low attenuation (signal reduction) of acoustic signals in underwater [7]. The conventional techniques (RF, optical) for information transmission in terrestrial environments provide broad communication range (0-100km) at high bandwidths (KHz-10MHz) with less power requirements [8]. Whereas, in underwater environment water absorbs the EM frequencies over long distances which makes the acoustic waves a preferred choice for information transmission over long distances [9-10]. Majority of the researchers has worked on the UWSNs, which uses the acoustic signals for information transmission and proved that acoustic technology has been considered as best suitable technology for UWSNs [11]. On the other hand, the acoustic signals are extremely influenced by the underwater medium such as; temperature gradients, surface ambient noise, and multipath propagation due to reflection and refraction. In addition, the much slower speed (1500 m/s) of acoustic signals in underwater has an impact on the efficient communication and networking [12]. The typical physical characteristics of the acoustic waves include propagation velocity, absorption, multipath, and ambient noise causes the propagation path loss along the acoustic links. These characteristics of acoustic waves can adversely affect the link formation among the nodes.

The communication link among the nodes is a function of distance, and the nodes are randomly moved in underwater due to node mobility and water currents. Based on the node movement, the distance required to establish the link among the nodes is altered. Hence, a channel model, which considers the effect of physical constrains on acoustic signal propagation is required to enable reliable communication links among the sensor nodes. The acoustic channels are modelled by considering of path loss. The path loss in underwater depends on the distance between transmitter and receiver and also on the signal frequency. As the frequency increases, the acoustic energy transfers into heat which results in absorption loss [13].

Moreover, higher frequencies experience more absorption loss resulting in the limit of usable bandwidth. Underwater acoustic communication channel exhibits challenges in many aspects [14] which are quite different from the terrestrial radio communication channel due to the acoustic propagation characteristics such as transmission loss, multipath propagation and multipath fading, Doppler spreading, ambient noise, time-dependent channel variations and variable delay. These fundamental propagation characteristics make the UASN deployment a challenging task for researchers. This necessitates studying the propagation characteristics of the acoustic channel in order to facilitate the efficient deployment of sensor nodes and development of higher layer communication protocols for UASNs to ensure effective and reliable communication.

2. Literature Review

The numerous of challenges (absorption, propagation delay, transmission loss, multi-path, noise etc.) encountered by the acoustic channel in underwater makes it an interesting research area to work on. The growth in sensor technology and wireless technologies, UASNs has attracted a lot of researchers and has contributed significantly to this field. The underwater acoustic channel has been modelled by considering the acoustic propagation characteristics such as velocity of sound propagation, absorption and multipath phenomenon’s. An extensive amount of literature has provided by various authors corresponds to the underwater acoustic network architectures [15]; research challenges and applications [16-17]; deployment issues [18-22]; localization [23]; protocols [24]; clustering [25]; connectivity [26]; network life time, transmission range, and propagation delay etc [27].

In addition, an extensive amount of has been done in modelling of acoustic channels [28] to estimate the effect of physical constraints on acoustic signal propagation. Majorly, the underwater acoustic communication influenced by the fundamental physical properties such as; temperature,
pressure (depth), salinity, pH, wave speed etc. The sound travels with different speeds in underwater because the speed of a sound is a function of temperature, depth, salinity. An underwater acoustic propagation model [28] has developed to identify the variation of sound speed variation in underwater. In underwater environment, the propagation parameters are altered in time which leads to reduction in signal strength when compared to the nominal value predicted by a deterministic propagation model.

A statistical propagation model has proposed in [29] to facilitate a large-scale system design in such conditions (e.g., power allocation), in which the transmission loss is treated as a random variable. The large-scale path loss among the acoustic communication links has been evaluated by considering the underwater environmental parameters such as; surface height; wave height; node displacements etc. The UASNs and terrestrial sensor networks have major architecture issues mainly due to medium of transmission (air and water medium) and technique used for information transmission (RF and acoustic) respectively. However, the terrestrial sensor network is exhibit different network requirements [30-39] in terms of propagation delay, topology, power requirements, mobility, network life time, data rate etc. Hence, the design of specific network architecture for UWSN is a challenging task for researchers by considering entire underwater medium characteristics. A channel model has provided in [40], which estimate the behaviour of the underwater parameters and analyze their behaviour in the design of UASNs. The focus on UASNs has been rapidly gaining attention which explores the underwater environment to enable the wide variety of applications such as; monitoring; explorations; surveillances etc. Moreover, each of these applications may differ in requirements such as; architecture; node density; protocol; energy; power etc. The channel model should be aware of the different requirements specifications for various applications needs. An energy-aware underwater channel model [41] based on passive sonar equation, has established which considers the transmission losses; ambient noise level and detection threshold.

A simple acoustic channel model [42] has proposed which generates a reliable prediction of the transmission loss that increases in proportion to the acoustic frequency. A channel model [43] has proposed in which the transmission losses are evaluated by considering the effect of absorption and spreading among the communication links. A Rayleigh fading channel model for shallow water has proposed in [44], in which the transmission loss is evaluated by considering the shallow water parameters and effect of sound speed. An acoustic channel model [45] based on Rice fading model has proposed in which the propagation path to the receiver has identified based on Eigen paths and poison distribution. This channel model considers the spreading and absorption losses due to surface and bottom reflections. However, in deep water scenario they do not consider the real time effect of different propagation phenomena such as; surface duct; convergence zones; deep sound channel; and reliable acoustic paths.

The literature has provided the various channel models for modelling the underwater parameters for UASNs. But there is no literature available by considering the acoustic channel characteristics to determine the network reliability of UWSNs. However, a little contribution of literature [46-48] available for reliability evaluation based on head nodes, throughput, inter vehicular communication respectively. Hence, in this work a mathematical model considering the underwater channel characteristics (temperature, depth, salinity, pH, absorption, spreading losses and transmission loses) in shallow water has been developed. The network reliability has been evaluated by varying all the underwater propagation parameters and network parameters (network size, coverage area, transmission range etc.).

3. Assumptions
   - UWSN is identical and functioning at the start of the mission time and all the sensors have same transmission range \((R_t)\) and sensing range \((R_s)\).
   - The source node with a buoy is positioned at a fixed depth \((SN_z)\).
   - The node transmission range is always greater than sensing range of the nodes \((R_t > R_s)\).
   - The movement of nodes in underwater is modelled by RWPM with zero pause time, node velocity \((V_{max}, V_{min})\), and node direction \((\theta, 2\phi)\).
• The node failure during mission time pursues Weibull distribution with scale parameter ($\theta$) and shape parameter ($\beta$).
• The failure of a node in mission time is statically independent, and once the node fails it will be considered as a failed for entire mission duration.
• All the communication links ($L$) are acoustic and bidirectional.
• No interference, overlapping among the nodes was considered.

4. Methodology

4.1. Deployment Model
The deployment strategies of UWSNs should meet the requirements of fundamental network services such as topology control, routing, and boundary detection to build an underwater application. Hence, the node deployment is the primary task and played a critical role in justifying the requirements of underwater applications (monitoring, exploration, disaster prevention, and tactical surveillances etc.). Based on the sensor node movements, the deployment strategies are classified into three types, such as static, self-adjusted, and movement-assisted deployments. In addition to the deployment strategies, various network architectures (1D, 2D, 3D, & 4D) are available for deploying the sensor network in underwater. In this work, the sensor nodes are deployed using the 3D reference architecture, where the sensor nodes are deployed in a monitored underwater region and altered their depths according to the node movements [49]. The proposed deployment model for evaluation the network reliability of UWSNs is represented in figure 1.

Figure 1. Deployment Model of Underwater Sensor Network.

The network is composed with n number of sensor nodes and each node have the same transmission range ($R_t$). The sensor nodes are deployed randomly in underwater scenario and the source node along with its buoy deployed of adjustable depth. The reliability analysis has been evaluated for shallow water conditions by taking into the effect of depth (source node depth, scenario depth) on sensor node locations, acoustic transmission losses among the sensor nodes, temperature, salinity, and pH of water. According to [50] the sensing range ($R_s$) of each deployed sensor is considered exactly half the value of node transmission range ($R_t$) (i.e., $R_s = R_t / 2$) for maintaining the connectivity among the sensor nodes. From figure 1, the link status is defined by considering the transmission losses among the sensor nodes as well as their transmission ranges. The dotted lines represent the link status, which is unable form the link with source node through single hop or multi-hop due to the transmission losses and based on their transmission and sensing range respectively.

4.2. Network Model
The UWSN should be modelled in order to evaluate the network characteristics and performance. At any moment of mission duration, the UWSN can be characterized as a fixed arbitrary graph $G (U, L, r)$ with n number of nodes altering their locality according to RWPM, and set of L communicating links. The failure nodes follow a known failure distribution and links are formed either single hop or multi-
hop manner based on the transmission range ($R_t$), sensing range ($R_s$) and 3D Euclidean distance ($d_{mn}$) by considering the propagation losses of acoustic communication links among the nodes respectively. In UWSN the probability $R_G(\tau)$ has assumed for the successful communication among set of nodes with an assumption that all the nodes in network are operational at any instant of time (\tau). In UWSN, the (s, t) pair should be operational at every instant of time duration (\tau) for the existence of communication link among the designated node pairs. Hence the reliability of the network will be equal to the product of the reliability of the (s, t) pair and the reliability of the network with perfect (s, t) pair of nodes [51]. Mathematically, the reliability of the network by utilizing factorial theorem can be expressed as (10) by authoring that the failure of node will certainly leads to UWSN failure. The reliability of the UWSN at a particular instant of time duration (\tau) can be evaluated by using (1).

$$R_G(\tau) = \left(\prod_{u_{p}} R_{u_{p}}(\tau)\right) R_{G/p}(\tau), \text{ where } p = \{u_1, u_2, \ldots, u_p\}$$

(1)

4.3. Acoustic Channel Model

The ocean is an extremely complicated and dynamic acoustic medium with the characteristic feature of inhomogeneous nature. Regular and random are two kinds of heterogeneities observed in the ocean which cause fluctuations in the sound field. Hence, the speed of sound amends with depth, temperature, salinity, location, time of the day and season. Basically, ocean acoustic channel is divided into two channels: Shallow water channel and deep-water channel. Shallow water refers to water column with depth 100m and below whereas deep water refers to water column with depth above 100m [52]. The sound propagation in underwater has played vital role and should be aware of sound speed characteristics for perspective of signal transmission in underwater based on acoustic channel. Sound propagation in the ocean is influenced by the physical and chemical properties of the seawater and by the geometry of the channel itself [53]. Sound propagates in the ocean with variable sound velocity. Sound velocity varies with variations in temperature, salinity and depth. Variations of the sound velocity are relatively small. However, even small changes can significantly affect the propagation of sound in the ocean. The sound speed in underwater by taking into the account of temperature, salinity, and depth is defined using (2).

$$c(T, S, z) = a_1 + a_2T + a_3T^2 + a_4S + a_5z + a_6S^2 + a_7T(S - 35) + a_8Tz^3$$

(2)

where, $C$ is the sound speed articulated in m/s, $T$ is temperature expressed in °C, salinity $S$ is salinity uttered in parts per thousand (ppt) and $D$ is depth expressed in meters. An underwater acoustic signal experiences attenuation due to spreading, scattering and absorption [54].

4.3.1. Spreading Loss.

Spreading loss is a quantity of reduction in signal strength due to the effect of geometrical spreading when a sound wave transmits away from the source. Spherical spreading and Cylindrical spreading are two kinds of spreading in underwater acoustics: The spreading loss is calculated using (3).Where $L_{sp}$ is the path loss expressed in dB, $R_t$ is the transmission range in meters and $k$ is the spreading factor ($k = 1$ for cylindrical spreading and $k = 2$ for spherical spreading).

$$L_{sp} = k \times 10 \log_{10} \log_{10} R_t$$

(3)

4.3.2. Absorption Loss.

In underwater environment, the acoustic signal energy may convert into other forms (heat) while signal propagation. The losses occurred due to absorption are influenced by material imperfections which varies with the type of physical wave transmitted through it. The absorptive loss for acoustic wave propagation is frequency dependent. In addition to the absorption, the sound signal is attenuated in underwater due to two main mechanisms named viscous absorption and ionic relaxation effects. These effects are encounter in underwater due to the presence of minuscule quantities of boric acid and magnesium sulphate salts in sea water [55]. At high frequencies (above 100 kHz), the influence of
viscous absorption is significant at high frequency, the ionic relaxation effects due to boric acid affect at low frequency (say up to few kHz), whereas at intermediate frequencies (up to a few 100 kHz) the magnesium sulphate affect is significant. The total absorption coefficient is represented by using (4).

\[
\alpha = \frac{A_1 P_1 f_1^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2^2}{f^2 + f_2^2} + A_3 P_3 f^2
\]  \tag{4}

The absorption loss represents the energy loss of sound due to the transformation of energy in the form of heat due to the chemical properties of viscous friction and ionic relaxation in the ocean and this loss is range dependent and can be expressed by using (5). Where, \( L_{ab} \) is the path loss expressed in dB, \( R_t \) is transmission range in meters and \( z \) is the absorption coefficient in dB/km.

\[
L_{ab} = \alpha \times R_t \times 10^{-3}
\]  \tag{5}

4.3.3. Transmission Loss.
Transmission loss (TL) is defined as the accumulated diminish in acoustic intensity when an acoustic pressure wave transmits away from a source. The total transmission losses can be obtained by summing the losses due to absorption and spreading losses respectively. The signal strength of received signal and the optimum threshold signal strength required for a signal to establish a perfect communication link is derived from the TL value [55]. Acoustic signals in shallow water experienced cylindrical losses as the sound signal reflects from boundaries of the cylinder. The transmission loss (direct path model) caused by cylindrical spreading and absorption can be expressed using (6).

\[
TL_{dp} = 10 \log_{10} R_t + \alpha R_t \times 10^{-3}
\]  \tag{6}

4.4. Depth Calculation
The depth calculation [56] of each deployed sensor is crucial for defining the connectivity and link status amid the sensor nodes in the network. Each deployed sensor nodes maintain the connection to the surface or source node either direct or through intermediate nodes. With reference to the source node, the unknown depths of each deployed sensor node are evaluated using (7).

\[
Z_k = D - \left( SN_z + d_{ij} \right)
\]  \tag{7}

where \( k = 2 \ldots n \), \( Z_k \) represents the depth information of all deployed nodes expect source node, \( D \) is the scenario depth (SD), \( SN_z \) is the depth of source node (SN), and \( d_{ij} \) is the Euclidean distance among the deployed nodes with reference to source node and is given by using (8). Where \((x_s, y_s)\) are the random locations of source node and \((x_d, y_d)\) are the random locations of deployed nodes other than source node. After calculating the unknown depths of each sensor nodes, the deployed nodes got their 3D coordinates \((X, Y, Z)\) respectively.

\[
d_{ij} = \sqrt{(x_s - x_d)^2 - (y_s - y_d)^2}
\]  \tag{8}

4.5. Node Status
The sensor nodes in the UWSN are defined by a vector \( U \) and their entity status is defined by \( u_i \), where \( i = 1, 2 \ldots n \) and \( u_i \in U \). Due to the harsh underwater environment and node mobility’s the sensor nodes in an UWSN are not forever operational or reliable. It is very crucial to be aware of the distribution of the sensor node failure in underwater for designing the network for specific applications. Hence, considering assumption # 5, the reliability of sensor node is defined as (9) and the entity status defined as (10).

\[
R_{u_i} = \Pr \left( u_i (\tau) = 1 \right) = e^{\left( \frac{-\tau}{\theta} \right)^\beta}
\]  \tag{9}
\[ u_i(\tau) = \begin{cases} 1 & \text{if } i^{th} \text{ node is operational at time } \tau \\ 0 & \text{if } i^{th} \text{ node is fails at time } \tau \end{cases} \] (10)

### 4.6. Link Status

The nodes in UWSNs are connected with the source node either through direct links or multi-hop links. These acoustic links among the sensor nodes are affected by the underwater parameters (temperature, salinity, pH, and depth) and introduce a path loss owing to absorption and spreading. The path loss in UASNs is a function of frequency and distance. Hence, the link formation among the nodes is a function of path loss, which is directly proportional to the 3D Euclidean distance among the sensor nodes. Therefore, the link formation in underwater is a function of path loss and their transmission and sensing ranges respectively. The sensor nodes which are in the transmission range \( R_t \) of source nodes are connected directly to the source node, if the transmission loss exhibited by any perfect \((s, t)\) pair in the network is below the maximum allowable loss, which is obtained from its maximum transmission range \( R_t \). Similarly, the nodes which are not in the range of \( R_t \), then the source node form a multi-hop links based on their sensing range \( R_s \), if the transmission loss exhibited by any perfect \((s, t)\) pair in the network is below the maximum allowable loss, which is obtained from its maximum sensing \( R_s \). The link status as a function of path loss among the deployed nodes is defined using (11) & (12) respectively.

\[
L_{mn} = \begin{cases} 1 & \text{if } d_{mn} \leq R_t \text{ and } d_L \leq TL_{R_t} \\ 0 & \text{otherwise} \end{cases} \] (11)

\[
l_{mn} = \begin{cases} 1 & \text{if } d_{mn} \leq R_s \text{ and } d_L \leq TL_{R_s} \\ 0 & \text{otherwise} \end{cases} \] (12)

where, \( L_{mn} \) represents the direct link formation among the nodes, \( l_{mn} \) represents the intermediate link status among the nodes, \( d_L \) represents the path loss distance and \( TL_{R_t} \) is the maximum transmission loss due to transmission range, \( TL_{R_s} \) is the maximum transmission loss due to sensing range and \( d_{mn} \) is the 3D Euclidean distance among the nodes, and it is represented as (13).

\[
d_{mn} = \sqrt{(x_s - x_d)^2 + (y_s - y_d)^2 + (z_s - z_d)^2} \] (13)

### 4.7. Connectivity

With the prior information about the link formation among the sensor nodes, at any instant of time duration \( \tau \), the UWSN can be signified by a connectivity matrix \( A(\tau) \) of size \( n \times n \) with link status as its elements. This connectivity matrix is developed to determine the connectivity between source and destination pair \((s, t)\) and the connectivity is defined by using (14).

\[
C_q(\tau) = \begin{cases} 1 & \text{if network connected} \\ 0 & \text{if network is not connected} \end{cases} \] (14)

### 4.8. Node Mobility

The underwater environment is unpredictable in nature; hence to deploy a network and analyze the network characteristics is an exigent task. The nodes are movable in any UASN and one should know the location of the node in order to analyze the networking properties among the sensor nodes. Hence, it is crucial to adopt a mobility model that considers the fluid nature of the medium in which they move. The node movements of underwater sensors are independent to each other. Almost all models in the mobile sensor networks assume that each sensor moves independently from the others. Typically, the path of each sensor is taken as an independent realization of a given stochastic process, such as a random walk, or a random way point process [57]. In our approach, RWPM model is used to find the \((X, Y)\) coordinates of the deployed sensor nodes and the variation in \( Z \) coordinate is evaluated.
for every simulation run. The sensor nodes move within the defined boundary periphery according to the RWPM model [58]. The sensor nodes randomly select the velocity between \((V_{\text{min}}, V_{\text{max}})\) and direction \((0, 2\phi)\) for their new location. The updated node positions with respect to time are determined at regular time intervals \(\Delta \tau\). At every incremental time interval \(\Delta \tau\) the updated node locations are evaluated as a utility of velocity and direction using (15).

\[
\begin{align*}
x_i(\tau + \Delta \tau) &= x_i(\tau) + \Delta V_i(\tau) \cos \phi_i(\tau) \\
y_i(\tau + \Delta \tau) &= y_i(\tau) + \Delta V_i(\tau) \sin \phi_i(\tau)
\end{align*}
\] (15)

4.9. Reliability Evaluation
The reliability \(R_G(\tau)\) of the UWSN is a function of time, and can be evaluated by averaging the results for \(Q\) (number of iterations) simulation runs at every rise in time interval \(\tau\) in the mission duration [59, 60]. Mathematically, the reliability of the UWSN can be defined as (16).

\[
R_G(\tau) = \left( \prod_{n=p}^R G_{n}(\tau) \right) \sum_{q=1}^Q C_q(\tau)
\] (16)

5. Algorithm
Based on the methodology provided in section IV, an algorithm has been proposed and developed in MATLAB R2018a with a processing speed of 3.9 GHz. The step-by-step procedure is as follows.

**Step1:** Initialize all the network parameters such as \((U, D, t\text{Mission})\), node parameters (time to failure pdf \((\theta, \beta)\)), node velocity \((V_{\text{min}}, V_{\text{max}})\), direction \((0, 2\phi\)), \(R_t, R_s\) node positions \((X_i, Y_i)\), \(q = 1, C_q(\tau) = 0, Q\), underwater parameters (temperature, salinity, \(pH\), Source node depth \((\text{SND})\), Scenario depth \((\text{SD})\), and frequency \((f)\).

**Step2:** Generate \((X_i, Y_i)\) random locations for the deployed nodes.

**Step3:** Calculate the unknown depth of each deployed node with respect to source buoy node using (7)

**Step4:** Simulate the node status using (9)

**Step5:** Acoustic channel is modeled by considering sound propagation (2), absorption (3), spreading losses (4), and path loss (5).

**Step6:** The transmission loss for acoustic links is evaluated (6)

**Step7:** Check for link existence as per (11) and (12)

**Step8:** The connectivity is obtained by considering the transmission losses among the sensor nodes with the help of connectivity matrix. If the network is connected then increment \(C_q(\tau)\) by one and update \(\tau = \tau + \Delta \tau\).

**Step9:** Generate the new node locations according to RWPM (15)

**Step10:** Repeat step2 to step9 until \(\tau\) reaches \(t\text{Mission}\)

**Step11:** Repeat step2 to step10 for \(Q\) number of simulations runs

**Step12:** Evaluate network reliability (16).

6. Simulation Parameters
The USWN is simulated under shallow water condition with varying network parameters by considering acoustic channel model having the frequencies 100Hz and 1000Hz respectively at given salinity and temperature conditions. The parameters considered are provided in Table 1.

| Table 1.Simulation Parameters |
|-------------------------------|
| **Simulation Parameter**      | **Specification** |
| Deployment Dimension          | 3D               |
| Environment Scenario          | Shallow water    |
| Scenario Depth (SD)           | 20 to 100m       |
| Source Node Depth (SND)       | 5 to 100m        |
7. Simulation Results
The underwater mobile network has been simulated in a shallow water environment (20 to 100m) considering acoustic channel propagation with a network size (9 nodes to 100 nodes) and the frequency (100-1000Hz). Transmission range of all nodes is homogeneous ranging between 10m to 3000m. The network has been deployed such that it covers the geographical area to a maximum of 5000 x 5000 Sq. m. The node movements are modelled in accordance with random waypoint mobility model moving with a minimum velocity of 3m and maximum velocity of 6m. The underwater ad hoc network reliability has been evaluated using MATLAB and the effect of several parameters on the network performance has been studied. The simulation has been performed over 10 000 simulation runs. The obtained results are explained in details in the subsequent paragraphs.

The effect of acoustic channel parameters (frequency, temperature, salinity) and the network parameters by varying coverage area, network size and transmission range at various SD (20, 50 and 100m). The source node is initially deployed at 5m and subsequently the depth is incremented in steps of 5m up to 100m. The study clearly indicates that the reliability decreases as the frequency increases from 100Hz to 1000Hz with the salinity (30ppt) and the temperature (30°C) maintained constant. Whereas, the reliability decreases with the increasing coverage area and increases with the increasing node transmission range and network size (number of nodes in the network).

It is observed that at any moment of mission duration, the reliability is a function of frequency due to acoustic channel that exhibits more absorption at higher frequencies, and has adverse impact on the connectivity among the nodes. The fall in reliability with the increasing coverage area is due to nodes distributed in larger area, which requires large propagation distance among the nodes to form a communication link. As the propagation distance among the nodes increases, the path loss associated with the propagation distance is also high. Due to this phenomenon the nodes fail to satisfy the condition of the connectivity. That is, the probability of establishments of the links (direct connectivity) in small coverage area is better than the one in large area. The reliability has improved with increase in SD is observed because when the acoustic signal propagated deep into the water; the effect of underwater parameters (temperature, salinity) on acoustic signal is low when compared to the surface. However, the reliability decreases with increases in SND due to the pressure level in underwater. Hence, an optimum buoy length should be considered to achieve maximum reliability of network.

7.1. Case 1: The influence of Network Coverage Area on UWSN Reliability
The network reliability is almost zero when the node coverage area goes beyond 4 000 000 Sq. m, the network is still reliable as the communication happens through multi-hop manner as seen in the figures 2(b) and 2(c). The network coverage area from 10 000 Sq. m to 250 000 Sq. m provides a maximum
reliability of 0.9621 and further the reliability falls by 20% beyond 100 000 Sq. m. Thereafter the network reliability falls down by 60% (see figure 2(a)). The network reliability beyond the 1 000 000 Sq. m is insignificant irrespective of the SD and SND (see figure 2(a) - figure 2(d)-figure 2(e)). The increase in network reliability is observed with increase in scenario depth (see figure 2(b)). For example, the network reliability when SD 20m with coverage area 1 000 000 Sq. m is 0.7383; whereas, for SD 100m the network reliability with same coverage is about 0.7719. The network reliability is increases almost by 3.3 % when SD increases from 20m to 100m.

For example the network reliability achieved (see figure. 2(e)) is 0.7285 and 0.7565 with SD=20 and 100 mts respectively at frequency of 1000Hz, whereas the network reliability achieved (see figure 2(d)) is 0.7311 and 0.7569 with network having same scenario metrics with an operating frequency of 100Hz. It is observed from the figure 2(c), the network with SD 100m and SND 50m achieves a maximum reliability (0.9621) with a coverage from 64 Sq. m to 25 000 Sq.m irrespective of the influence of frequency, thereafter the reliability falls down by 20% beyond 1 000 000 Sq.m and almost reaches to zero beyond 4 000 000 Sq.m. Whereas, the same network with SND 20m achieves maximum reliability with coverage from 2 500 Sq.m to 25 000 Sq.m (see figure 2(c)). This is due to
the selection of optimal source buoy length for a given scenario depth. It is evident that, the network reliability achieves a maximum value when the choice of SND is considered exactly half or 1/3rd of SD (i.e., for SD 100m, the choice of SND is either 50m or 40m).

7.2. Case 2: Influence of Network Size on UWSN Reliability

The effect of network size (i.e., number of nodes varying from 9 to 100 deployed with coverage area 1000 000 Sq. m and transmission range=500m, SND varies 5m to 100m and SD varies 20m to 100m) on two terminal reliability of UWSN has been analyzed. The network reliability is gradually falls down as the SND increases. Whereas, the 2TR is gradually increasing with increase in SD is observed (see figure 3(d)–figure3 (e)).

Figure 3: Influence of (a), (b) NS (c) SND (d) SD on Two Terminal Reliability

At the surface (say 20m) the effect of temperature and salinity is high on the sound speed which decreases the network reliability. The sound speed alters randomly at the lower depths. This random change in the sound speed will affect the link formation among the nodes at surface depths (20m) when compared to deep depths (say 100m). At the higher depths the sound speed is a function of depth (effect of temperature and salinity is low), therefore increase in SND will alters the link formation...
among the nodes. As the SND increases, the pressure level on the source node may increases, and further increase in SND may introduce isolation of source node in the network. It is also observed from the figures 3 (d) and 3(e), the network reliability is a function of frequency, and it is decreases with increase in frequency due to absorption. As seen in figure 3(a) – figure 3(b) -figure 3(c), the graph depicts that the effect of frequency on 2TR with respect to NS; the reliability is decreases with increase in frequency is observed at DSN 40m and SD 100m (see Fig. 3(c)).

The network reliability is increasing with respect to NS (see figure 3(a) - figure 3(b)), but as the frequency of the acoustic signal increases the network reliability decreases when compared to lower frequencies. For example, the reliability (for NS 18) frequency 100Hz is 0.8245; whereas at a frequency 1000Hz the reliability is 08210. The network at SD 100m with a frequency change from 100 Hz to 1000Hz, the reliability falls down by 0.35%. Hence, at higher frequencies the network reliability is falls down due to absorption caused by the acoustic signal while forming the link among the nodes. The results also show that the two terminal reliability increases with an increase in SD and network size as seen in figure 3(a) - figure 3(b). The network deployed with more number of nodes in a fixed NCA and TR leading to increase in reliability due to improved connectivity (direct connection between (s-t) node pairs) when compared to network composed with less number of nodes(multi-hop connection between (s-t) node pairs).

7.3. Case 3: Influence of Transmission Range on UWSN Reliability

As discussed in the case 2, the effect of transmission range on two terminal reliability of the UWSN is similar to the effect of network size on 2TR. The network reliability has increased with an increase in SD and TR is observed in figure 4(a) and figure4(d).

Figure 4: Influence of (a) SND (b), (c) TR (d) SD on UWSN Reliability

This is because, as the transmission range of the nodes increases, the nodes have a capability of establishing single-hop (direct) links among themselves which, leads to achieve the greatest connectivity irrespective of the absorption and path losses. Hence, at the higher transmission ranges the network reliability achieves its maximum value (0.9621) irrespective of the effect of frequency and network scenario metrics. Similarly with respect to SD the network reliability increases with increase
in SD is observed in figure 4(a) and figure 4(d), which is due to the effect of temperature and salinity is high on link formation at the upper surfaces when compared to lower surfaces. Similarly, the transmission range beyond 1000m has no significant effect on the network reliability with a coverage of 1 000 000 Sq. m irrespective of SD and SND has been observed (see figure 4(a) - figure 4(d)). It can be depicted from figures 4(b) and 4(c) that the effect of frequency on network reliability; at higher frequency (say 1000Hz) the network reliability is decreased when compared to lower frequency (say 100Hz) due to absorption. For example, the network reliability with frequency 100Hz is 0.7401; whereas the reliability with frequency 1000Hz is 0.7365 at TR 500m (see figure 4(b)). Hence, for a network with a fixed coverage area and network size; the optimal choice of transmission range required to achieve efficient network reliability. To have an optimal choice, the designer can think of consider a transmission range between 250m-400m to achieve a optimal reliability.

7.4. Case 4: Influence of Mission Time on UWSN Reliability

Based on the assumptions consider in developing the algorithm for evaluating network reliability of UWSN, the discussions are made in the previous cases (case 1 to case 3). Based on the assumption #5, the failure of a node during mission time follows Weibull distribution. There are several reasons that cause node failure – node mobility, out-of-coverage, low transmission range, surface reflections, speed, absorption, path loss, physical damage due to underwater environment, and the list goes on. The reliability concepts define reliability of a component or system or network deteriorates with operation time. As ad hoc networks are application specific and short duration network, the present study considers, the mission time of 72 hours. The change in reliability with respect to mission time by varying network size has been depicted in figure 5(a). It is identified that the maximum reliability (0.9621) achieved with a network consists of nodes higher than 50.

![Figure 5: Influence of Mission Duration varying (a) NS (b) NCA (c) TR on UWSN Reliability](image)

The network reliability by varying NCA with respect to mission time has been illustrated in figure 5(b), which shows the maximum reliability (0.9621) achieved with NS=18 with NCA=1 000 000 Sq.m and beyond this the reliability falls down drastically. To achieve the maximum reliability even beyond 1 000 000 Sq.m, then NS and TR should be greater than 50m and 500m respectively. Similarly the
network reliability achieved its maximum value (0.9621) at the transmission range greater than or equal to 500 mts (see figure 5(c)). There is no significant effect on network reliability is observed beyond the transmission range of 500 m irrespective of the network scenario metrics. The graphs show the maximum reliability of 0.9621 is achieved for a NCA (1 000 000 Sq. m); TR (500 m); NS (50) deployed at 100 m and fixed source depth of 50 m with an operating frequency of 100 Hz (see figure 5(a) - figure 5(b) - figure 5(c)).

8. Conclusion
Based on the acoustic channel model, the USWN has been as 3D network using geometric random graphs. The proposed algorithm is best suitable for simulating the USWN in shallow water scenario of 20 m to 100 m. The algorithm also takes into consideration the source node depth 5 m to 100 m deployed in a square simulation boundary with defined transmission and large set of nodes, operating frequency, temperature, salinity and pH of the underwater environment. From the results it is understood that the reliability is a function of frequency, which is obtained maximum at lower frequencies (100 Hz), when the network size and transmission range is high in large area or nominal transmission range in small coverage area.

The network with operating frequency 100 Hz with network metrics of NS=22; TR=500; NCA=1 000 000 Sq. m; SD=100 m; SND=40 m, the reliability achieved is 0.8210 (see figure 3(a)). The fall in network reliability has been observed (0.8080) with operating frequency 1000 Hz with the same network conditions (see figure 3(b)). For the study considered with TR=500 m, NS=18 deployed in 1000000 Sq. m with (SD=100 m, SND=40 m, F=1000 Hz, T=30°C, S=30 ppt, and pH=8), the maximum reliability achieved was 0.7402. Whereas, the same study considered for binary model (no propagation), the reliability achieves its maximum value 0.9621 with TR=100 m. This shows the impact of underwater environment and frequency of acoustic channel on two terminal reliability analysis of UWSN. The network reliability falls down by 22% by using acoustic propagation model when compared to binary model. This value can be reduced by 10% if the TR becomes 1000 m or more and similarly changing the NS to 22 nodes or more, and about 15% increase in reliability can be achieved with frequency reduced from 1000 Hz to 100 Hz.

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