Abstract—Underwater acoustic networks have attracted great attention in the last few years because of its numerous applications. High data rate can be achieved by efficiently modeling the physical layer in the network protocol stack. In Acoustic medium, propagation speed of the acoustic waves is dependent on many parameters such as temperature, salinity, density, and depth. Acoustic propagation speed cannot be modeled using standard empirical formulas such as Urick and Thorp descriptions. In this paper, we have modeled the acoustic channel using real time data of temperature, salinity, and speed of Bay of Bengal (Indian Coastal Region). We have modeled the acoustic channel by using Mackenzie speed equation and real time data obtained from National Institute of Oceanography and Technology. It is found that acoustic propagation speed varies between 1503 m/s to 1544 m/s as temperature and depth differs. The simulation results show that temperature, salinity, depth plays major role in acoustic propagation and data rate increases with appropriate data sets substituted in the simulated model.

Keywords—Underwater Acoustics, Mackenzie Speed Equation, Temperature, Salinity.

I. INTRODUCTION

UNDERWATER SENSOR NETWORKS (UWSN) play an important role in the development of aquaculture, marine monitoring, pollution monitoring, military applications, offshore exploration, monitoring of flora and fauna and natural disasters like cyclones, tsunamis [1]. To construct such potential applications, terrestrial sensor network features and its parameters are not applicable for underwater acoustics sensor networks. UWSN exhibits several organizational and architectural challenges with respect to terrestrial sensor networks mainly due to its transmission medium characteristics and acoustics signals employed to transmit data [2]. Underwater acoustic channel differs from terrestrial wireless radio channels in many ways; for instance, the propagation speed of acoustic wave is at least five orders of magnitude lower than that of wireless radio channels. Only when we have a complete understanding of acoustic channel characteristics, it is possible to design a proper acoustic transmission system that can match the real-time marine environment. While designing the underwater communication environment the following problems like limited bandwidth, extended multipath, refractive properties of the medium, fading [3] needs to be addressed. In any wireless communication, designing an efficient and reliable communication channel is not an easy task. It is worth mentioning the same, as according to author’s literature work, lot of research work in routing and MAC Protocols in UWSN are based on the characteristics of underwater acoustic channel [4]. Sound Field Model mainly includes the normal wave model, radiation model, fast sound field model, and the parabolic equation model [5]. The models of underwater acoustic channel mainly contain the deep vertical channel model and the shallow-water multi-path channel model. While the shallow-water multipath channel model can be divided into multi-path model based on ray theory, random time varying filter channel model and random statistical channel model [6]-[8]. Researchers simulate the underwater acoustic channel by establishing suitable mathematical models and then study the various properties using software simulation. Furthermore, the usable bandwidth of an underwater sound channel is typically a few kHz at large distances. In this research work, we have modeled the physical channel of underwater acoustics communication layer, as this layer serves as the foundation for the remaining layers and protocols in the ISO/OSI model [9]. We have considered the underwater physical layer channel parameters such as propagation speed, propagation loss, background noise, transmission loss, received power; propagation delay also needs to be considered. The existing work in literatures, model the acoustic propagation speed as 1500 m/s. This refers to empirical relation of the speed of sound. However, the speed of sound in water differs from the speed of sound in air medium; similarly acoustic wave propagation speed differs from sea to sea and from ocean to ocean. The bathymetry data shows that sound velocity in Pacific Ocean is around 1450 to 1485 m/s and in Atlantic Ocean, it varies from 1450 to 1500 m/s and in the Indian Ocean, Arabian Sea, and Bay of Bengal, it varies between 1490 to 1540 m/s. Therefore, the velocity of sound variation depends on parameters like temperature, salinity, depth, and pressure. In existing models, propagation speed is set to 1500 m/s whereas [10] proposed the nine-parameter equation to calculate the propagation of sound in water based on the parameters mentioned such as temperature, density, salinity, and depth. However, this work went unnoticed as researchers modeled the acoustic channel using the approximate speed velocity as 1500 m/s. In this work, we have modeled the acoustic link using Mackenzie propagation speed equation. Parameters such as temperature, density are obtained from real-time data in Bay of Bengal provided by National Institute of Ocean and Technology, India and Bathymetric data of Oceans for simulation purposes.
In this paper, we have modeled the acoustic link using Mackenzie equation and real-time data like depth, temperature, and salinity. Propagation speed values change with respect to depth and temperature. Therefore, we have modeled acoustic propagation with the real-time values obtained from Bathymetry data. The results show acoustic propagation speed plays a vital role in the transmission of data.

The rest of this article is as follows, Section II shows the existing physical channel modeling, and Section III explains the parameter metrics needed for modeling an acoustic channel using a standard equation followed by its simulations using industrial popular network simulator OPNET. Section V shows the result analysis and discussions followed by conclusions and future work.

II. EXISTING MODELS FOR ACOUSTIC COMMUNICATION

Designing an efficient and reliable communication channel is a major challenge in any wireless communication. Several models in literature models the underwater acoustic link taking into account environment parameters such as salinity, temperature, depth, environmental noise, etc. The first implemented model was by [11]. In this model, the authors proposed a simple physical acoustic model based on the fundamentals of underwater physics. This model has failed to address the important parameters such as sensor's node density and depth. AUVNet Sim [12] model simulates the underwater acoustic channel by considering few underwater environment parameters, but the Physical Layer of the network is simple, and it considers only the Throp equation [13] in the channel. To implement a reliable and efficient model, the acoustic parameters must be taken into consideration, and moreover, the Throp formula addresses only the physical environment parameters such as salinity, temperature, depth, environmental noise, etc.

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III. PERFORMANCE METRICS FOR MODELING UNDERWATER ACOUSTIC COMMUNICATION

In this section, we present the performance metrics used in modeling underwater acoustic channel. The propagation of acoustic communication will change in salinity, temperature, and the pressure. As per the Bathymetric data and the data from the National Institute of Oceanography and Technology, India's acoustic propagation speed will range from 1503 to 1544 m/s in the Bay of Bengal Ocean. Fig. 1 explains the propagation speed in water with respect to depth.

A. Propagation Speed

Propagation speed or velocity is considered to be the critical parameter in the acoustic link modeling. As mentioned earlier, propagation speed of acoustic waves differs from sea to sea and from ocean to ocean and it is necessary to set the
appropriate value in the acoustic channel to obtain efficient simulation results. Acoustic Propagation speed can be calculated using the following model proposed by Mackenzie [10];

\[ c = 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \]
\[ + 1.340(S - 35) + 1.630 \times 10^{-5}D + 1.675 \times 10^{-7}T^2 - 1.025 \times 10^{-9}T(S - 35) - 7.139 \times 10^{-11}T \]

where, \( T \) = Temperature in Celsius (2 to 30); \( S \) = Salinity parts per thousand (25 to 40 PPM); \( D \) = Depth of Sea in meters (0 to 800 m).

**B. Transmission Loss**

Acoustic Transmission Loss (ATL) is reduction of sound intensity from the transmitter to the receiver. There are many underwater acoustic signal-modeling techniques [26] used for modeling Underwater Communication. The acoustic signals used for underwater communication are subjected to fading due to a) Spreading and b) Attenuation. Transmission loss can be measured based on empirical expressions as

\[ ATL = cr \cdot 10 \log r + cr \cdot 10^{-3} \]  

where \( cr = 1 \) for spherical spreading loss, \( cr = 2 \) for cylindrical spreading loss in deep water. However, since sound energy is not perfectly contained by reflection (reflection coefficients less than 1) and refraction, the true spreading is often somewhere between the predictions given by \( cr = 1 \) and \( cr = 2 \). Thus, a practical spreading equation which represents an intermediate spreading condition between spherical and cylindrical spreading that is \( cr = 1.5 \). \( r \) is the range in meters \( \alpha \) is the attenuation factor given as

\[ \alpha = \frac{0.11f^2}{1 + f^2} + \frac{44f^2}{4100 + f^2} + 2.75 \times 10^{-4}f^2 + 0.003 \]  

where \( \alpha(f) \) is given in dB/km, \( f \) is the center frequency of the transmitted signal in kHz.

**C. Propagation Loss**

The Monterey Miami Parabolic equation model [24] provides a better framework to predict and calculate the underwater acoustic propagation loss using a parabolic equation. This model replicates the Helmholtz wave equation [25] and is based on Fourier analysis. By implementing a dynamic propagation loss calculation, this model proves that small changes in the acoustic parameters such as node distance, depth can result in wide differences in the acoustic propagation loss. The acoustic propagation loss formula for MMPE model is as

\[ PL(t) = m(f, s, d_A, d_B) + w(t) + e() \]

**D. Propagation Delay**

Mobility plays an important role in the underwater sensor nodes. Nodes deployed underwater cannot be in static position as factors like strong currents, winds, waves makes it tough to deploy. So while calculating the propagation delay for mobile nodes, the following formula needs to be addressed

\[ T_F = \left( d_{\text{start}} / \bar{v} + d_{\text{end}} / \bar{v} \right) / 2 \]

where \( d_{\text{start}} \) = Distance between transmitter and receiver at the beginning of the simulation (meters); \( d_{\text{end}} \) = Distance between transmitter and receiver at the end of the simulation (meters); \( \bar{v} \) = Velocity of Sound, from Mackenzie (1).
(SNR) of the receiver and largely determines the transmitting power. Ocean Ambient noise is complex and changeable and it is described using Wenz Model. However, Thermal Noise of the Wenz model does not simulate the thermal noise generated by transmitting and receiving equipment.

\[ N_{Thermal} = (r_{x_temp} + b_{r_{x_temp}}) \times r_{x_bw} + BOLTMANN \]

The total Noise is calculated as

\[ N_{Total} = N_{Turbulence} + N_{Shaping} + N_{Wind} + N_{Thermal} + e(f) \]  

\[ N_{Turbulence} = \text{Turbulent Noise; N}_{Wind} = \text{Surface Noise; f: Center Frequency of the transmitted Signal (in kHz); w: Is the Ocean Surface Wind Speed (in m/s); D: Is the Shipping Density values ranges between 0 to 1; rx_temp: Device temperature; bkg_temp: Background Temperature; rx_bw: Receiver Bandwidth; BOLTMANN: Boltzmann Constant; r}_{x_{noisefig}: \text{Noise Figure; e(f): Random noise function calculated from MMPE Model.}} \]

**F. Received Power and Signal-to-Noise Stage**

The received power signals obey the exponential distribution, as for all arriving packets, whether valid or invalid, the average power level of the received signal is computed by the sonar equation which takes account of the transmitted power, the path loss and receiver and transmitted antenna gains. The final receiver power is calculated as:

\[ p = SL - TL + TS + DI \]  

\[ SL = \text{Source Level; TL = Transmission loss; TS = Transducer gain; DI = Receiving Transducer Gain (Values 0-1)} \]

At this point, the power difference between \( P_s \) and \( p \) is caused by time varying multipath and Doppler Effect and Signal to Noise stage is expressed as

\[ \text{SNR} = \frac{p}{N(f)B} \]  

\( p \) is the Received Power, \( N(f) \) is single noise power spectral density. \( B \) is the system bandwidth.

**G. Bit Error Stage Model**

Acoustic Bit error rate, BER is a key parameter that is used in assessing systems that transmit digital data from one location to another.

**IV. Modeling Acoustic Channel**

We have modeled the acoustic channel using well-known popular industrial software OPNET. The fourteen Stage Transceiver Pipeline used by the Simulation Kernel (SK) to evaluate the characteristics of wireless communication, with the first 6 pipeline stages implemented in the transmitter node and remaining 8 in the receiver node. To implement an efficient acoustic link model, an accurate underwater channel model need to be implemented in the transmitter node and receiver node.

**A. Propagation Speed**

Propagation speed is calculated using the Mackenzie [10] nine parameters speed propagation mentioned in (1). Propagation delay is the sixth stage in the radio transmitter stage in OPNET and it is mentioned as propel model. The default propagation delay model for radio links, dra propel calculates delay based on the distance separating the transmitter and receiver, and the propagation velocity of radio waves. We need to replace the propagation velocity of radio waves with propagation velocity of acoustic waves 1503-1540 m/s. Therefore; the following modifications should be done in this stage.

### TABLE I

**UWA_PROPDEL.PS.C**

```c
#include "opnet.h"
#include "math.h"
#define T 18
#define S 27
#define D 4500
UWA_PROPDEL_MT(OP_SIM_CONTEXT_ARG_PUSH: Packet * pkptr) {
    //Mackenzie equation for Propagation speed */
    double PROP_VELOCITY=(1448.96+4.591*T)-(5.304*pow(10,-2)*T+1.675*pow(10,-7)*T*T-1.025*pow(10,-2)*T*T+2.374*pow(10,4)*T*T*T+1.340*S-35)+1.630*TS-35-7.139*pow(10,-13)*T*D*D*D;
    // Computing propagation delay to start of reception. */
    start_prop_delay = start_prop_distance / PROP_VELOCITY;
    // Propagation delays in Packet transmission data attributes. */
    pp_td_set_dbl (pkptr, OPC_TDA_RA_START_PROPDEL, start_prop_delay);
    pp_td_set_dbl (pkptr, OPC_TDA_RA_END_PROPDEL, end_prop_delay);
    FOUT; }
```
B. Transmission Loss

Transmission Loss is implemented in the receiver node of the model. For all arriving packets, whether valid or invalid, the average power level of the received signal is computed by (2). This computation is a link budget, which takes into account of transmitter power, the path loss and receiver and transmitter antenna gains. The transmission loss for underwater channel is defined as the accumulated decrease in acoustic intensity when an acoustic pressure wave propagates outwards from a source. Transmission loss can be implemented in the sixth stage of the transmitter node. The attenuation factor for shallow water is calculated by (3).

\[
\text{path_loss} = \text{path_loss} + n \cdot 10 \log(\text{prop_distance}) + b \cdot \text{prop_distance}
\]

\[
b = 0.1 \cdot a/(1+a) + 40 \cdot a/(4100+a) + 0.000275 \cdot a + 0.003
\]

\[
a = \text{pow(tx_center_freq,2)}
\]

\[
\text{plW} = \text{addWavePL} (\text{pLoss}, \text{wavePL})
\]

\[
\text{plr} = \text{getRandompl(Distance)}
\]

\[
\text{FIN} (\text{pLoss} (\text{frequency}, \text{Source depth}, \text{Distance}, \text{receiver depth}, \text{waveP}, \text{waveH}))
\]

\[
\text{pLoss} = \text{getWaveFL} (\text{waveLenght}, \text{op_sim_time}(), \text{waveP}, \text{waveH}, \text{receiver depth})
\]

\[
\text{plW} = \text{plW} + \text{plr}
\]

\[
\text{FIN} (\text{MT} (\text{uwa_power} (\text{pkptr})))
\]

\[
\text{uwa_power}_\text{mt} (\text{OP_SIM_CONTEXT_ARG_OPT_COMMA Packet } \text{pkptr})
\]

\[
\text{FIN}_\text{MT} (\text{uwa_power} (\text{pkptr}));
\]

\[
a=pow(tx_center_freq*2) ;
\]

\[
\text{b} = 0.1 \cdot a/(1+a) + 40 \cdot a/(4100+a) + 0.000275 \cdot a + 0.003 ;
\]

\[
\text{path_loss} = \text{path_loss} + n \cdot 10 \log(\text{prop_distance}) + b \cdot \text{prop_distance} \cdot 0.001 ;
\]

\[
\text{FOUT}
\]

C. Propagation Delay

Propagation loss mainly describes the loss in the medium of the wireless channel. In our case it is acoustic medium. During the process of transmitting the acoustic signal from the acoustic source to the acoustic receiver, the signal energy is prone to the propagation loss, which influences the signal-to-noise ratio in the receiver side. When the sound wave frequencies are above 1kHz, seawater acoustic absorption is the main factor causing acoustic wave attenuation and is proportional to the square of the wave frequency. After integrating a large number of measure results, the propagation loss for acoustic transmitting medium is given by the Monterrey-Miami Parabolic Equation (MMPE Model) in (4)-(7). This model exactly simulates the propagation loss in acoustic medium. Since the proposed model considers appropriate underwater acoustic parameters such as temperature, density, depth, salinity it results in more efficient outcomes.

D. Propagation Delay

Concerning the mobility of the acoustic node, the pipeline mechanism calculates two delays namely, the delay to start of reception and the delay to the end of reception. In addition to the transmission delay, the propagation delay is another delay when there is acoustic packet transmission through the acoustic wireless channel. In the acoustic wireless simulation, considering the movement of the acoustic station, the distance between the transmitter and receiver could be changing all the time. Therefore, there is a need for a calculation in relation to the delays, namely, the start of the propagation delay and the end of the propagation delay and calculated using (8).

\[
\text{propDelay} = \text{propDelay} + \text{propDelay} \cdot \text{PROP_VELOCITY} ;
\]

\[
\text{compute_prop_delay} = \text{start_prop_delay} \cdot \text{PROP_VELOCITY} ;
\]

\[
\text{end_prop_delay} = \text{end_prop_delay} \cdot \text{PROP_VELOCITY} ;
\]

\[
\text{start_prop_delay} = \text{start_prop_delay} \cdot \text{PROP_VELOCITY} ;
\]

\[
\text{end_prop_delay} = \text{end_prop_delay} \cdot \text{PROP_VELOCITY} ;
\]

\[
\text{x}
\]

\[
\text{y}
\]

\[
\text{z}
\]

E. Background Noise

Acoustic signals are corrupted because of fading and noise. The overall noise in the underwater acoustic channel
The receiver power stage is the crucial aspect of the acoustic channel modulation as the received power reveals how the correctness and validates acoustic channel that has been modeled. This computation is a link budget, which takes into account the initial transmitted power, the path loss, and receiver and transmitter antenna gains. It can be calculated by using (10).

### G. Bit Error Rate and Signal to Noise Ratio

The next stage is calculating the signal-to-noise ratio for the acoustic packets. Acoustic signal modeling must consider appropriate mathematical modeling tools [27]. This is because,
BER and SNR can be eliminated, if modeling is done using appropriate modeling tools. The value of the SNR directly reflects the received power, background noise and interference noise. The SNR of the value is calculated individually in various periods. Finally after calculating the values in different period these are added together to provide the SNR value. The effective SNR can be calculated using (11). Bit error rates are computed the based on the modulation curve or modulation attribute could be set to different values and the modulation attribute is related to the channel model.

V. MODEL IMPLEMENTATION AND RESULT ANALYSIS

This section will provide the model implementation and result analysis. As mentioned in the existing work, there are few acoustic model available that addresses the node parameters issues like density, mobility, depth, and node scalability. In our work, we have modeled the acoustic link by considering the above parameters and using accurate speed of acoustic waves obtained from real time data.

<table>
<thead>
<tr>
<th>TABLE VIII</th>
<th>SIMULATION PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Values</td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>40 kHz</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Node Count</td>
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</tr>
<tr>
<td>Temperature</td>
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<tr>
<td>Salinity</td>
<td>27</td>
</tr>
<tr>
<td>Depth</td>
<td>4500 m</td>
</tr>
<tr>
<td>Density</td>
<td>50 m</td>
</tr>
</tbody>
</table>

A. Propagation Delay Stage

In this stage, the dra_propdel radio transceiver is modified with the acoustic parameters model. The default propagation velocity is replaced with acoustic propagation velocity using Mackenize equation. The necessary functional block code added in this stage is explained in Table I. This replaces the propagation velocity of light waves with the propagation velocity of acoustic waves. In order to implement the mobility in the nodes, trajectory needs to be set for each node. Trajectory will set the path for the nodes to traverse and propagation delay is implemented in this stage using the coding mentioned in Table IV. Source snippets in Table I and IV are implemented in this stage to calculate the propagation speed and propagation delay in our simulation model.

B. Receiver Power Stage

This receiver power stage is the eight stage of the acoustic transceivers and this stage computes the average power level of the received signal. This stage becomes important as the transmission loss is implemented in this stage. Apart from the acoustic transmission loss from Table II, propagation loss based on MMPE model from Table III is being implemented to compute the loss models. The final received power is calculated based on the Table VI coding. This computation takes into the account of the initial transmission power, the path loss, and receiver, transmitter antenna gains. The acoustic transmission loss for the underwater acoustic channel can be defined as the accumulated decrease in acoustic intensity, when an acoustic pressure wave propagates outwards from the source.

C. Background Noise Stage

The overall noise in the acoustic transmission involves turbulence noise, ambient noise, shipping noise, wave noise and thermal noise. The total power spectral density can be implemented in this channel by using the coding from Table V. This computes the overall noise generated in the acoustic transmission. The network topology for simulation model is shown in Fig 2.

D. Signal to Noise Ratio

In this stage, the value of the signal-to-noise ratio for the given packet is calculated. The received SNR is calculated in Table VII. This value is affected by the received power and the sum of the background noise and interference noise. In a whole packet reception process, there might be many packets arriving at the same time.
Because of new interference, the signal to noise ratio should be evaluated again and again. Therefore, the SNR value is calculated separately in different periods. These are then added together to provide the final SNR.

E. Bit Error Rate (BER)

In this stage, BER is calculated based on modulation curve. According to the BER value, the error bits are put into the packet randomly. The specific calculation method is to calculate the bit errors probability and then compare this with a random number from 0 to 1. If it is bigger than the random number, this bit is an error bit. Fig. 3 shows the BER calculated in the receiver level. Fig. 4 shows the acoustic link model transmission loss as a function of distance between the nodes in various frequencies. From this graph it is clear that, the transmission loss increases as distance between nodes increases. We have modeled the acoustic link with different frequencies. This proves that propagation speed (Mackenzie) in water and distance (depth) plays vital role in carrying the information. Fig. 5 explains shows, when the transmitted power and carrier frequency are fixed, the SNR and BER decrease with distance increases and it also fluctuates with time.

![Graph](image)

**Fig. 4 Transmission loss vs distance**

![Graph](image)

**Fig. 5 BER vs SNR**

It is noted clearly that the significant time-varying effect of underwater acoustic channel is modeled and average SNR obtained from the simulation decreases with distance. Even though there is complexity of underwater acoustics channel, delay is calculated in appropriated manner. This shows that the sound velocity is stable, when we compute using proper mathematical equation (Mackenzie equation) rather than assuming the propagation speed as 1500 m/s.

VI. CONCLUSION AND FUTURE

In this research paper, we have studied, designed and implemented underwater acoustic communication model with accurate speed equation model. The model serves best for upper layer protocols, as we have modeled the acoustic link propagation with corresponding to real time data like temperature, salinity and depth. This model is based on the characteristics of underwater acoustic channel. In-order to define an appropriate acoustic channel modeling slight changes in propagation model is needed and this will significantly affect the final results obtained in our simulation model. Since propagation speed differs in different geographic regions, there is need to model the propagation speed with real time data obtained. As future work, we will consider improving the model with various propagation speed equations like Del Grosso model, Chen and Millero Model, Coppens Model and Medwin Model.

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