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Design and Implementation of Short Range Underwater Acoustic Communication Channel using UNET

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***Abstract*— Over the past few years, there has been significant developments in the underwater technologies. Particularly, technologies like underwater wireless sensor networks (UWSNs) and autonomous underwater vehicles (AUVs) require an underwater efficient wireless communication system. In this paper, we model an efficient underwater acoustic communication channel. By modeling the propagation loss and noise, we determine the frequency at which the losses are minimum, also known as optimal frequency. We also find the required transmission bandwidth. Modeled optimal frequency is then used to design and simulate a water environment monitoring system on a real time simulation environment provided by the software UNET.**

Keywords*— Underwater wireless communication, acoustic communication channel, optimal frequency

I. INTRODUCTION

With sixty percent of the Earth's surface covered with oceans, seas, rivers etc, civilian and military systems have been using water as a transportation mode and there is a need for efficient communication. Thus over the past few years study of underwater wireless communication networks has been a field of intense research interest. The last decade has witnessed a rapid development in the technologies related to underwater activities [1], [2], [3]. Like the terrestrial communication, development of the underwater communication networks involves the selection of a suitable carrier and the design of a high performance channel.

Radio signals, optical signals and acoustic signals are the common carrier choices for underwater communication networks. Radio signals require a larger antenna with higher transmission power in order to achieve long range communication [4], [5] and are impractical for underwater communication networks. While optical signals have tremendous speed, they suffer largely from reflection, refraction and scattering [5]. Thus acoustic waves become the best choice for short range and long range underwater communication. In addition, compared to optical and radio waves, acoustic waves require a smaller transmission power.

Though acoustic frequencies are suitable over radio and optical modes, not all frequencies can be employed as a carrier as some of the frequencies (higher frequencies) suffer larger attenuation. Thus designing an efficient acoustic communication channel by suitably modeling the channel parameters is necessary for minimizing the loss and achieving higher performance [6].

Loss of the acoustic signals as they propagate through the water depends on the distance and the transmission frequency. The transmission frequency determines the signal attenuation and absorption. It is found that the effects of ambient noise from the ocean also depend on the transmission frequency, [7, 8, 9, 10]. Thus for a particular distance of transmission, it becomes important to select a suitable frequency of transmission which suffers minimum loss.

Bandwidth and power are the two important requirements for any communication system. UWSNs demand a larger bandwidth and lower transmission power. Capacity of the network can be found after obtaining the bandwidth as a function of distance. For a given distance, there exists an optimal frequency of transmission at which the losses are minimum. The bandwidth is set around the optimal frequency and the transmission power is adjusted to obtain the desired SNR. This paper mainly focuses on modeling the parameters of underwater acoustic communication channel and determining optimal frequencies for different distances. The mathematical models are used to design and simulate a sensor network for data transmission. As an example, typical water parameters such as temperature and *pH* are processed and transmitted.

MATLAB is the popular and suitable tool used for mathematical modeling. Hence in our approach, we employ MATLAB for modeling the channel parameters. However real time simulation of a deployed sensor network cannot be realized effectively using MATLAB. Thus in order to accomplish this task and to determine the efficiency of the communication, we employ a real time simulation software named UNET [11].

In section 2, we look upon the theory associated with channel modeling. Propagation delay, attenuation, multipath effects, SNR, noise effects and the method to obtaining the optimal frequencies are discussed in detail. Section 3 has the description of software simulation of the deployed sensor network using UNET. In section 4, we analyze the obtained results. The final conclusions drawn are summarized in section 5.

II. CHANNEL MODELLING

A. *Propagation loss*

Speed of the sound in water is approximately five times that of in air and is around 1500 *m/s*. However as the parameters such as temperature, salinity and depth vary, speed of the sound changes. Thus it is important to determine the effects of these parameters on sound's speed in water. The Mackenzie's formula [12] shown in Equation 1 provides a better estimate of speed of sound.

$$c\,(D, S, T) = 1448.96 + 4.591T - 5.304 * 10^{-2}T^{2} + 2.374 * 10^{-4}T^{3} + 1.340\,(S-35) + 1.630 * 10^{-2}D + 1.675 * 10^{-7}D^{2} - 1.025 * 10^{-2}T(S - 35) - 7.139 * 10^{-13}TD^{3} \qquad (1)$$

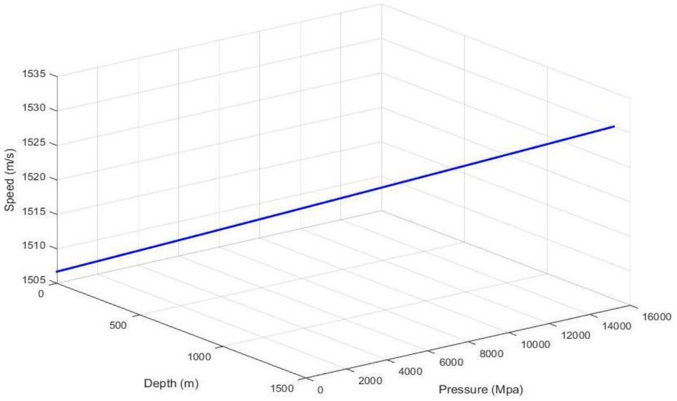


Figure 1: Velocity profile of sound

In Equation 1, *T* is the temperature in °C, *S* is the salinity in parts per trillion, *D* is the depth in meters and *c* is the speed of sound in *m/s*. The equation is valid up to a depth of 8 *km* and provides a better velocity profile in water. This could be used for studying propagation delay.

B. *Attennuation*

As acoustic signal propagates through the water, they endure from a debasement of amplitude called as attenuation or path loss. Absorption of sound by the dissolved salts like $MgSO_4$,, boric acid etc present in the sea water [13] and geometrical spreading [14] mainly contribute for the attenuation of the acoustic signal. Attenuation over a distance *l* for a signal frequency f is given by

$$A(l, f) = l^{k}a(f)^{l} \qquad (2)$$

where *k* is the spreading factor and a(*f*) is the absorption coefficient. The value of *k* depends on the geometry of propagation: typical values are *k* = 2 for spherical spreading, *k* = 1 for cylindrical spreading and *k* = 1.5 for practical spreading. The absorption coefficient can be expressed using the Throp's formula [7] which is given by:

$$10 log\,a(f) = 0.11\frac{f^{2}}{1+f^{2}} + 44\frac{f^{2}}{4100+f} + 2.75 * 10^{-4}f^{2} + 0.003 \qquad (3)$$

The variation of absorption coefficient with respect to frequency is shown in Figure 1. It can be seen that absorption coefficient rapidly increases with frequency.

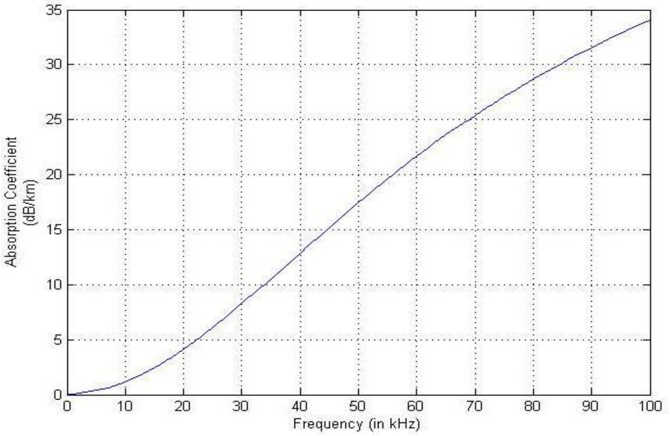


Figure 2: Absorption coefficient, a(*f*) as a function of frequency

C. *Multipath effects*

Equation 1 describes the attenuation on a single obstructed path. If there are multiple propagation paths, say *p* propagation paths, for a single of frequency f and power P, channel transfer function is given by:

$$H(l, f) = \sum_{p=0}^{P-1} \Gamma p \,/\sqrt{A(lp, f)}\, e^{-j2\pi f\zeta p} \qquad (4)$$

where l = l_o is the distance between transmitter and receiver and $\Gamma_p = l_p/c$ is the delay [9], [10]. However in our approach to determine optimal frequency, we consider only the basic path loss assuming that the transmission is directional.

D. *Noise*

Acoustic studies [10] have shown that ambient noise in the ocean can be modeled using four sources: turbulence, shipping, waves and the thermal. These noise sources can be described by Gaussian statistics and continuous power spectral density (p.s.d). The empirical formulae for the four noise components in dB re *μ* Pa per Hz as a function in kHz is given by:

$$10 \log N_t(f) = 17 - 30 \log f$$

$$10 \log N_s(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log (f + 0.03)$$

$$10 \log N_w(f) = 50 + 7.5w^{1/2} + 20 \log f - 40 \log (f + 0.4)$$

$$10 \log N_{th}(f) = -15 + 20 \log f \qquad (5)$$

In the above equation, *w* represents the speed of wind in *m/s* and *s* represents shipping factor which has value between 0 and 1. The ambient noise in the ocean is colored and hence different factors have pronounced effects in specific frequency regions. Turbulence noise is dominant below 10 Hz. Noise due to shipping activities influences in the frequency region of 10 Hz – 100 Hz. and is determined by the shipping factor s. Surface motion caused by the wind driven waves is the major factor contributing to the noise in the frequency region 100 Hz – 100 kHz. Lastly, thermal noise becomes dominant for frequencies above 100 kHz [10].

The overall power spectral density of the ambient noise shown in the Figure 2 is given by:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$$

(6)

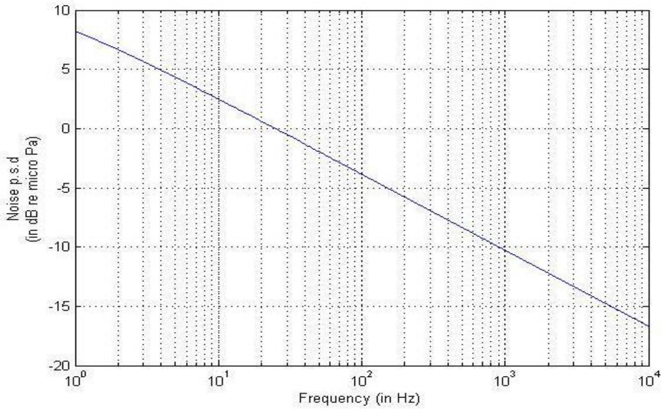


Figure 3: Noise power spectral density

E. SNR

The SNR observed at the receiver is determined using the knowledge of signal attenuation A (*l*, *f*) and the noise p.s.d., N (*f*) and is given by:

$$SNR(l, f) = \frac{P/A(l, f)}{N(f)\Delta f} \tag{7}$$

where SNR (*l*, *f*) is the SNR over a distance *l* and transmission center frequency *f*, *P* is the signal power and Δ f represents receiver noise bandwidth [10]. If the transmission bandwidth, B (*l*) over a distance is known along with the transmission power P (*l*), then Equation 7 can be modified as:

$$SNR(l, B(l)) = \frac{\int_{B(l)} S_l(f) A^{-1}(l, f)\, df}{\int_{B(l)} N(f)\, df} \tag{8}$$

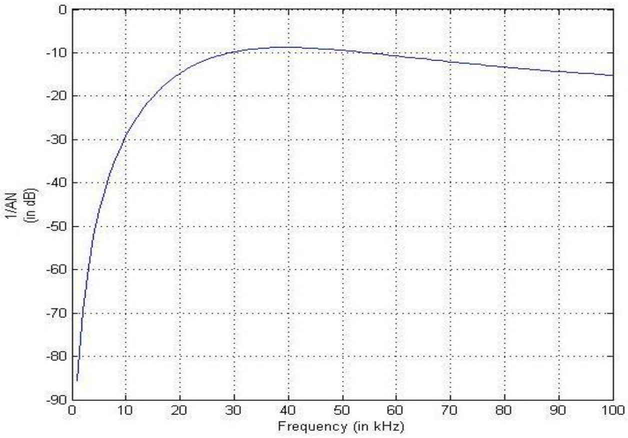


Figure 4: 1/AN as a function of frequency for *l* = 1.5 km

F. Optimal transmission frequency

The attenuation – noise product, also known as AN product is given by A (*l*, *f*) N (*f*). From Equation 7, it becomes evident that AN product determines the frequency dependent part of SNR. For every transmission distance *l*, there exists an optimal frequency $f_0(l)$, for which the narrow band SNR becomes maximum. At the optimal frequency, AN product has a minimum value. In practice, transmission bandwidth is chosen around $f_0(l)$ and the transmission power is adjusted to obtain the desired SNR.

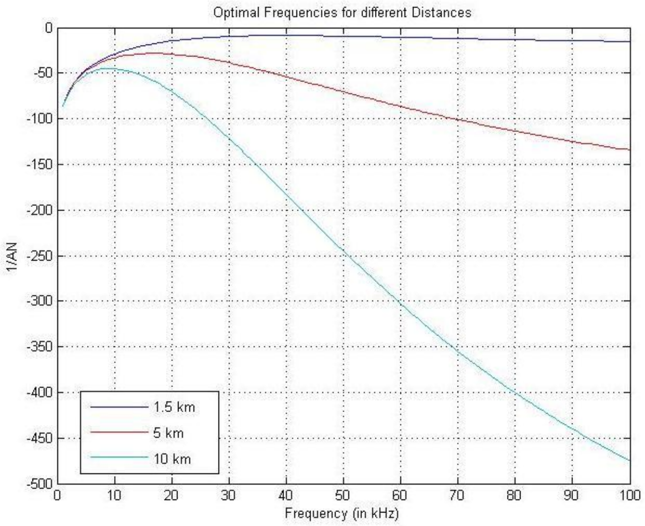


Figure 5: Plots of 1/AN product as a function of frequency for different distances

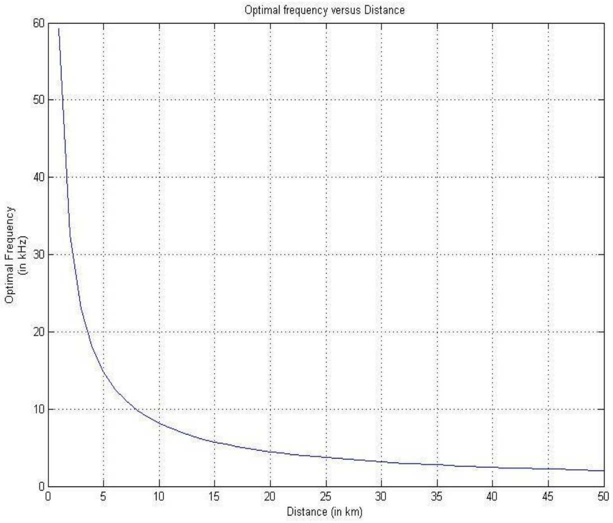


Figure 6: Optimal frequency as a function of distance

It can be seen from the Figs.5-6 that optimal frequency decreases exponentially with distance. Thus as the distance between the transmitter and the receiver increases, available bandwidth decreases. As channel capacity is a function of bandwidth [10], with increase in distance between the communicating nodes, capacity decreases.

III. REAL TIME SIMULATION USING UNET

The mathematical models designed using MATLAB were employed for the design and simulation of a water monitoring system which was capable of measuring water temperature and *pH*. The system consisted of sensor nodes, each being capable of transmitting the measured values of temperature and *pH* periodically to a buoy floating at the surface of the water. The sensor network was simulated in a real time environment using the software UNET.

UNET simulator [11] uses the UnetStack implementation to simulate an underwater network. UnetStack is an agent based underwater network stack that defines agents with services, messages, capabilities and parameters. Agents are the basic building of UnetStack. The UnetStack is implemented in Java or Groovy.

The simulated sensor network consisted of five nodes deployed at different depths but equidistant (1.5 km) from a buoy located at the surface of the water. Therefore, the placement profile of the five nodes will be nearly hemispherical. The diagrammatic representation of the simulated sensor network is as shown in Figure 7. The optimal frequency determined from the mathematical modeling was used as the carrier frequency. Values of the other parameters like salinity, water depth etc was also assigned.

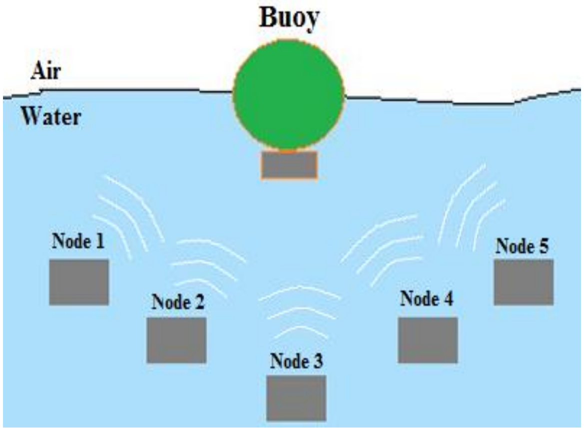


Figure 7: Diagrammatic representation of the sensor network

For the simulation, temperature and *pH* values at each node locations were stored in buffer. These initialized values were randomly retrieved at regular intervals of time and transmitted to the buoy. The network so designed was simulated for five hours. The loss was calculated by determining the values of the total number of transmitted packets and received packets. Simulations were repeated by changing the values of carrier frequencies to determine its effect on data throughput.

IV. RESULTS AND DISCUSSIONS

The velocity profile shown in Figure 1 was plotted assuming that water has a constant temperature of 15 ^{0}C and a salinity of 35 ppt. The profile shows that velocity increases with an increase in the depth. Since delay is a function of velocity, velocity profile becomes important for determining the acoustic signal delay at different depths.

The plot of absorption coefficient versus frequency for a propagation distance of 1.5 *km* is given in Figure 2. It can be seen from the plot that absorption coefficient rapidly increases with frequency. Thus we can deduce that lower frequencies experience lesser attenuation compared to higher frequencies. The noise power spectral density is shown in Figure 3. It is obtained by considering the speed of wind to be 10 *m/s*. The shipping factor is set to 0.5. It can be observed that noise p.s.d. decays linearly on a logarithmic frequency scale.

The plot of 1/AN product versus frequency for a transmission distance of 1.5 km is shown in Figure 4. It is seen that 1/AN product has a maximum value near to 40 kHz. Thus we determine the optimal frequency as 40 kHz. Plots of 1/AN products for different distances are shown in Figure 5. From Figures 5 - 6, it is evident that optimal frequency decreases with increase in distance between the transmitting and receiving nodes and thereby decreasing the available bandwidth. The available bandwidth for distances above 100 km is less than 2 kHz. To summarize, 40 kHz was obtained as the optimal frequency for a distance of 1.5 km.

TABLE I.
PARAMETRIC VALUES CONSIDERED FOR SIMULATION

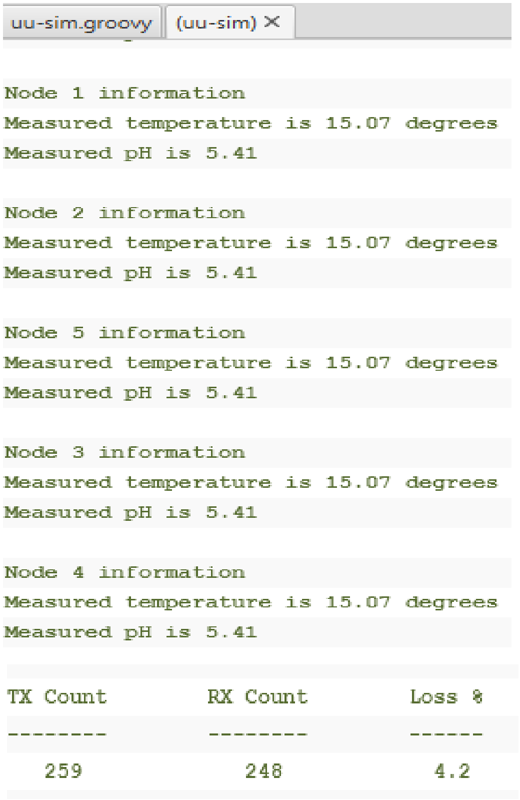
Parameters	Values
Temperature (^{0}C)	15
pH	5.4
Salinity (*ppt*)	35
Wind speed (*m/s*)	10
Shipping factor	0.5
Noise level (dB re μ Pa per Hz)	4

TABLE II.
CARRIER FREQUENCIES AND OBTAINED LOSSES

Carrier frequency (kHz)	Loss (%)
10	4.6
40	4.2
100	4.3
200	4.9

For the real time simulation using UNET, obtained optimal frequency of 40 kHz was used as the carrier frequency. The values of the salinity, wind speed, shipping factor and noise level were initialized as given in the Table I. The node locations are set such that all the nodes are at a distance of 1.5 km from the buoy. The initial values of the temperature and *pH* at the node locations were also initialized as given in Table I. The simulation was carried out for a time of five hours and results are as shown in Figure 8.

The simulation was also repeated by varying the carrier frequency. Table II lists the losses obtained for different carrier frequencies. It can be seen that the network exhibits the best performance when operated in the region near to the optimal frequency of 40 kHz.



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Node 1 information
Measured temperature is 15.07 degrees
Measured pH is 5.41

Node 2 information
Measured temperature is 15.07 degrees
Measured pH is 5.41

Node 5 information
Measured temperature is 15.07 degrees
Measured pH is 5.41

Node 3 information
Measured temperature is 15.07 degrees
Measured pH is 5.41

Node 4 information
Measured temperature is 15.07 degrees
Measured pH is 5.41

TX Count        RX Count        Loss %
--------        --------        ------
  259             248            4.2
```

Figure 8: Real time simulation result

V. CONCLUSIONS

In this paper, we have successfully modeled acoustic communication channel which can be used to implement efficient underwater wireless communication. We found that for a given transmission distance; there exists an optimal frequency at which the losses are minimum. We learnt that optimal frequency and bandwidth decreases with the increase in the distance between the communicating nodes. Thus it can be deduced that larger bandwidth is available for short distances. For longer distances, performance can be enhanced by the use of relays. The theoretical model was used to design a sensor network which was simulated using UNET. The network exhibited the best performance in the region around the optimal frequency.

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