Performance Evaluation of Path Loss Models For Mobile Underwater Acoustic Sensor Networks

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***Abstract* - To advance the state of the art in developing the protocols for Ubiquitous Underwater Acoustic Sensor Networks (UU-ASN) relies on the use of computer simulations to evaluate protocol performance. To simplify the complexity in implementation, physical environment characteristics are not implemented in detail in simulation ensuring a logical simulation runtime performance. Understanding the subject in relevance to path loss, the development of a standardized, precise *underwater path loss model* has become an elusive goal.**

The proposed path loss model is based on the fundamental ocean acoustics which computes the capacity of an acoustic network (i.e. Energy and bandwidth) and the efficiency of scalable channel sharing protocols. Further simulations were carried out to assess the performance of the various *path loss models with Underwater Acoustic model* based on the bit error rate effects, latency and the packet delivery ratio of the customized physical layer. The effect of weather season and the variability of ocean environmental factors such as water temperature on the communication performance are also considered. The mathematical analysis and simulations highlight important considerations for the deployment and operation of UU-ASN to examine different underwater acoustic networking protocols.

***Index Terms* - Ubiquitous Underwater Sensor networks, Acoustic Communications, Physical layer simulation, QualNet.**

I. INTRODUCTION

Acoustic underwater communications is a well-established field that has been used by the military for almost half a century. Recently, civilian applications for underwater communications have emerged, including oil prospecting and water quality monitoring [1]. Acoustic communication in Underwater Wireless Communication Networks (UWCNs) has several challenges due to the presence of fading, multipath and refractive properties of the sound channel which necessitate the development of precise underwater channel models. Underwater acoustic channels are generally recognized as one of the most difficult communication media in use today.

Acoustic propagation is best supported at low frequencies, and the bandwidth available for communication is extremely limited [2]. For example, an acoustic system may operate in a frequency range between 10 and 15 kHz. Although the total communication bandwidth is very low (5 kHz), the system is in fact ultra-wideband, in the sense that bandwidth is not negligible with respect to the centre frequency. Sound propagates underwater at a very low speed of 1500 m/s, and propagation occurs over multiple paths[2][4]. Delay spreading over tens or even hundreds of milliseconds results in a frequency selective signal distortion, while motion creates an extreme Doppler effect.

The design of underwater communication systems has so far relied on expensive specialized hardware for acoustic communication and modulation. The conventional reliance on hardware acoustic modulation has stemmed from low processing speeds that did not allow the modulation of acoustic signals in software. Software modulation and demodulation is a recent alternative approach which overcomes most of the drawbacks of hardware modems. For E.g. The target network application's system architecture is shown in Fig.1.

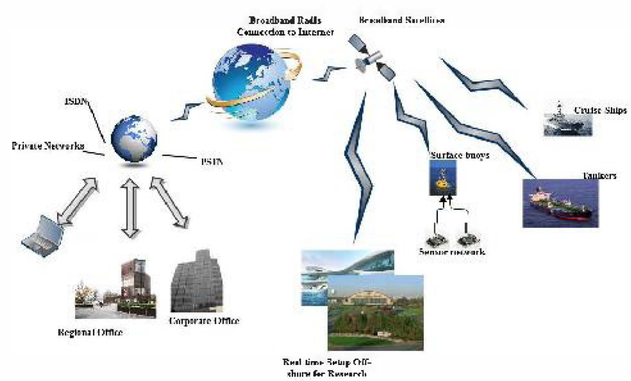

Fig.1 Overall System Architecture

We expect the network deployment to consist of tens to hundreds of sensor modules in a shallow water environment. The sensor modules can communicate acoustically through wireless multi-hop links. The modules periodically sample their sensor, collecting physical indicator data such as temperature and salinity, which influence pollution levels in the water. The nodes report their data to a surface node nearby.

The surface node, known as the base station, includes a water-immersed acoustic transceiver that communicates with the underwater nodes [10]. It is also equipped with a long range wireless broadband communication card that uses a cellular or satellite connection to stream the network data towards a central server. The server includes a data repository that archives historical data from the monitored area.

The network deployment will stream near-real time data from the aquatic environment into the data repository, providing professionals in the water management and

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research communities with access to sizeable and timely data from the water. The application will also leverage existing environmental information management platforms for providing the tools necessary for analysing, displaying, and sharing the collected data.

In this paper, we compare existing path loss models with the proposed underwater acoustic path loss model which are used for large scale three dimensional UU-ASNs. These models are Two-Ray, Free Space and Underwater acoustic path loss models. The underwater acoustic channel is usually evaluated from statistical propagation models: no specific terrain data is considered, and channel parameters are modelled as stochastic variables. Moreover, two ray and free space path loss models are appropriate for terrestrial applications than in underwater scenarios.

Underwater acoustic path loss model is based on the fundamental ocean acoustics which computes the capacity of an acoustic network (i.e. Energy and bandwidth) and the efficiency of scalable channel sharing protocols. We use Qualnet Network Simulator for our simulations. Our performance metrics are latency, energy consumption per node and the packet delivery ratio of the customized physical layer.

The remainder of this paper is organized as follows. Section II describes the Mobile UWSN and its applications. Section III describes the physical layer considerations including acoustic propagation velocity, multipath, ambient noise and Doppler effects. Section IV analyses physical layer design using QualNet. Simulation results that have to be considered, is evaluated in section V and some concluding remarks along with future work is deliberated in section VI.

II. MOBILE UWSN

In comparison to the static, a mobile UWSN is a self-organizing network. Underwater sensor nodes are mobile due to the aqueous process. After transport by the currents and dispersion, the sensors must reorganize as a network in order to maintain communication. Fig. 2 depicts the mobile underwater sensor network environment

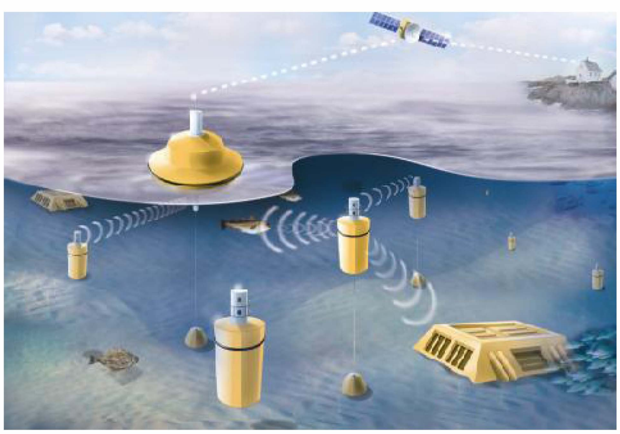

Fig. 2 Mobile Underwater Sensor Network

Two classifications for mobile underwater sensor networks:

1) Mobile UWSNs for long-term non-time-critical aquatic monitoring.

2) Mobile UWSNs for short-term time-critical aquatic exploration.

TABLE I
COMPARISON BETWEEN TERRESTRIAL AND UNDERWATER ACOUSTIC SENSOR NETWORKS

Parameters	Terrestrial Sensor Networks	Underwater Acoustic Sensor Networks
Protocols	Can estimate the network dynamics & Reliable data transfer	Distinct network dynamics & Unreliable data transfer
Communication Method	Radio Frequency communication	Physical Means: RF waves, Optical Waves, Acoustic waves
Deployment	Largely Populated nodes to gather information	Sparsely deployed - Challenges & high cost of Deployment
Power	Comparatively low power consumption	High Power Consumption with respect to distance, medium is being used.
Node Mobility	Predictable	Difficult to Predict

III. PHYSICAL LAYER DESIGN CONSIDERATIONS

Physical Layer Research Issues

Building on the acoustic fundamentals of ocean acoustics, we proceed to the design of our software-driven wireless acoustic communication system[5]. Underwater acoustic communications are mainly influenced by *transmission loss*, *noise*, *multipath*, *Doppler spread*, and *high and variable propagation delay*. All these factors determine the *temporal and spatial variability* of the acoustic channel, and make the available bandwidth of the underwater acoustic channel limited and dramatically dependent on both range and frequency.

Physical Layer

A typical speed of acoustic waves near the ocean surface is about 1500m/s, more than four times faster than the speed of sound in air but five orders of magnitude smaller than the speed of electromagnetic in air [6]. And the speed of sound v in water can be calculated according to the empirical formula as

$$v = 1450+4.21T -0.037T2 + 1.14(S -35) + 0.175P \qquad (1)$$

where T, S and P respectively represent the temperature, salinity and depth (the pressure).

Significance of the variables

Temperature	- 1 Degree C	= 3 m/s
Salinity	- 1 ppt	= 1 m/s
Pressure	- 10 m	= 0.17 m/s

The slow propagation speed of sound impacts the performance of communication system and network protocol design in a number of ways.

We briefly analyse the factors that influence acoustic communications in order to state the challenges posed by the underwater channels for sensor networking which is shown in Fig. 3.

A. Transmission loss

It consists of *attenuation* and *geometric spreading*. The attenuation is mainly provoked by absorption due to conversion of acoustic energy into heat, and increases with distance and frequency.

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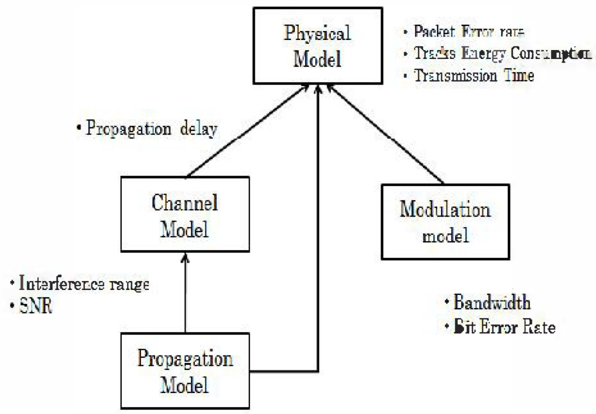

Fig.3 Physical Layer Model

Attenuation or path loss that occurs in an underwater acoustic channel over a distance l for a signal of frequency f *[6]* is given by

$$A(l, f) = l^* ka(f)l \qquad (2)$$

where k is the spreading factor, and $a(f)$ is the absorption coefficient. Expressed in dB, the acoustic path loss is given by

$$10 \log A(l, f) = k * 10 \log l + l * 10 \log a(f) \qquad (3)$$

The first term in the above summation represents the spreading loss, and the second term represents the absorption loss. The spreading factor k describes the geometry of propagation, and its commonly used values are $k = 2$ for spherical spreading, $k = 1$ for cylindrical spreading, and k=1.5 for the so-called practical spreading.

B. Ambient Noise

It can be classified as *man-made noise* and *ambient noise*. The ambient noise in the ocean can be modelled using four sources: turbulence, shipping, waves, and thermal noise. Most of the ambient noise sources can be described by Gaussian statistics and a continuous power spectral density (p.s.d.). The following empirical formulae give the p.s.d. of the four noise components in dB per Hz as a function of frequency in kHz[6]:

$$\begin{aligned} 10 \log Nt(f) &= 17 - 30 \log f \\ 10 \log Ns(f) &= 40 + 20(s - 0.5) + 26 \log f - 60 \log(f + 0.03) \\ 10 \log Nw(f) &= 50 + 7.5w1/2 + 20 \log f - 40 \log(f + 0.4) \\ 10 \log Nth(f) &= -15 + 20 \log f \end{aligned} \qquad (4)$$

Turbulence noise influences only the very low frequency region, $f < 10$ Hz. Noise caused by distant shipping is dominant in the frequency region 10 Hz -100 Hz, and it is modelled through the shipping activity factor s, whose value ranges between 0 and 1 for low and high activity, respectively. Surface motion, caused by wind-driven waves is the major factor contributing to the noise in the frequency region 100 Hz to 100 kHz. Finally, thermal noise becomes dominant for $f > 100$ kHz. The overall p.s.d. of the ambient noise,

$$N(f) = Nt(f) + Ns(f) + Nw(f) + Nth(f). \qquad (5)$$

C. Signal To Noise Ratio

Since the transmission loss in a uw channel depends both on frequency as well as the transmission distance, let it be represented by A(l, f). Using attenuation $A(l, f)$ and noise PSD N(f) , the signal to noise ratio (snr) at the receiver at a distance l and frequency f for a transmitted power of p and receiver noise bandwidth df is given by

$$\mathrm{SNR}(l,f) = P/A(l,f)/\,(N(f)^*\,df) \qquad (6)$$

It may be noted that the optimum transmission band depends on link distance. Further, for each l, there exists an optimal frequency *fo(l)* for which maximum SNR is obtained. This is the frequency for which the term 1/ $A(l, f)$* $N(f)$ becomes maximum .

D. Multipath

It may be responsible for severe degradation of the acoustic communication signal, since it generates Inter Symbol Interference (ISI). The multipath geometry depends on the link configuration. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have long multipath spreads. The extent of the spreading is a strong function of depth and the distance between transmitter and receiver.

E. High delay and delay variance.

The propagation speed in the UW-A channel is five orders of magnitude lower than in the radio channel. This large propagation delay (0.67 s/km) and its high variance can reduce the throughput of the system considerably.

F. Doppler spread

The Doppler frequency spread can be significant in UW-A channels, causing degradation in the performance of digital communications: transmissions at a high data rate cause many adjacent symbols to interfere at the receiver. The Doppler spreading generates two effects: a simple frequency translation and a continuous spreading of frequencies, which constitutes a non-shifted signal.

When acoustic waves propagate in multipath, the power spectrum of receiving signals spread as is called Doppler spread. Time selective fading has significant impact on the bit error rate (BER) performance of digital signal, so in order to reduce its impact; the symbol rate has to be much greater than the rate of the fading beat. This is more difficult for a receiver to compensate for this effect.

G. Modulation

Since higher rate modulation can encapsulate more bits into one symbol (*e.g.*, two bits can be encapsulated in one symbol for QPSK), under the same symbol rate, it takes less time to transmit a single data frame, which leads to less energy consumption assuming the transmission power is constant and the total energy consumption is proportional to the duration of transmission [7]. However, higher rate modulation makes transmitted signals more susceptible to channel noise which requires higher received SNR for successful reception.

The adaptive scheme implemented a *probing* method for transmitters to measure the recent performance of the acoustic channel. Both the probe message and the probe response message are modulated by BPSK to reduce the chance of failed reception [9]. With good channel condition, the transmitter uses higher rate modulation to reduce transmission duration. Otherwise, lower rate modulation is used to make the transmitted signals less susceptible to channel noise.

IV. Physical Layer Framework using QualNet

Due to both logistical and technical difficulties of deploying realistic underwater acoustic networks, research involving underwater networks has primarily been limited to either theoretical analysis or simulation study [3]. This paper describes how the real time measurements were programmed into a custom underwater acoustic channel model for the QualNet 5.0.2 simulator. Fig. 4 depicts the customized architecture of the QualNet simulator. As acoustic waves from a transmitter propagate through the ocean, they are reflected by the sea surface and bottom which causes a multipath channel to a receiver. Moreover, the heterogeneous medium scatters the waves and generates numerous micro-paths to the receiver.

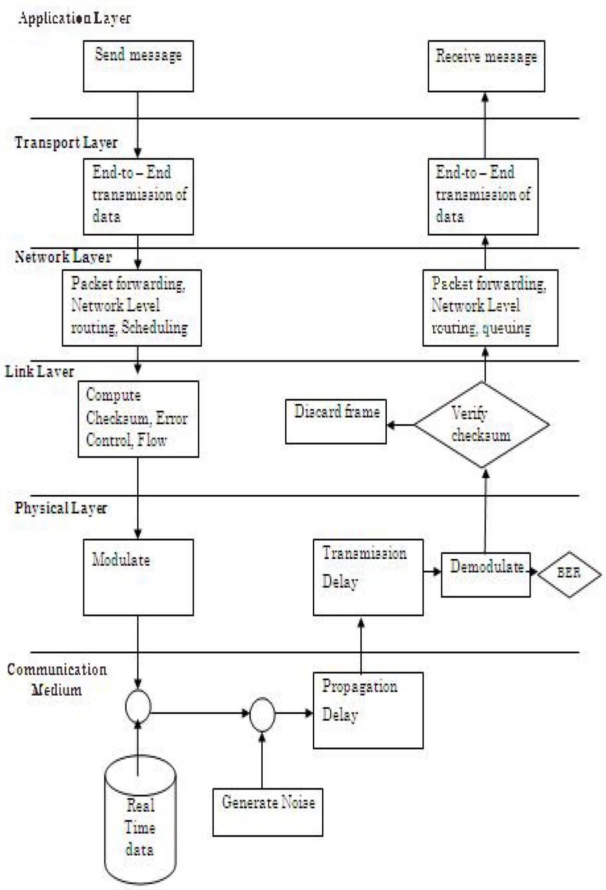

Fig. 4 Architecture of QualNet simulator

Because the sea surface and the medium are moving continuously, the channel impulse response is changing and hard to be estimated. In the point of underwater acoustic communication this makes us to consider various ocean conditions for the development of underwater acoustic modems. Therefore, we need to gather channel data as much as possible and analyze them precisely.

The measured values and sound velocity profile of the channel is used to calculate the propagation delay. Packets are converted into modulated waveforms which are convolved with the measured channel impulse response. Then recorded noise is added and a formula for transmission loss applied to approximate the SNR with which a packet is received.

Finally, the distorted signal is demodulated and its BER is computed. The higher layers above the physical layer are implemented using QualNet. Fig. 5 shows the implementation of UWA Path loss model using QualNet simulator. The simulator currently offers BPSK and QPSK modulation. Fig.6 depicts the implementation of Underwater Acoustic Radio Type (Physical layer) using QualNet simulator. It is also possible to adjust the sampling rate, carrier frequency, and symbol rate as well as many other configuration parameters.

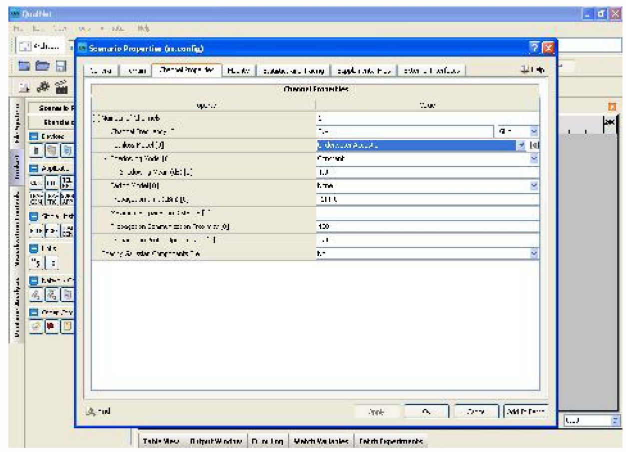

Fig.5 Implementation of Underwater Acoustic Path loss model using QualNet simulator.

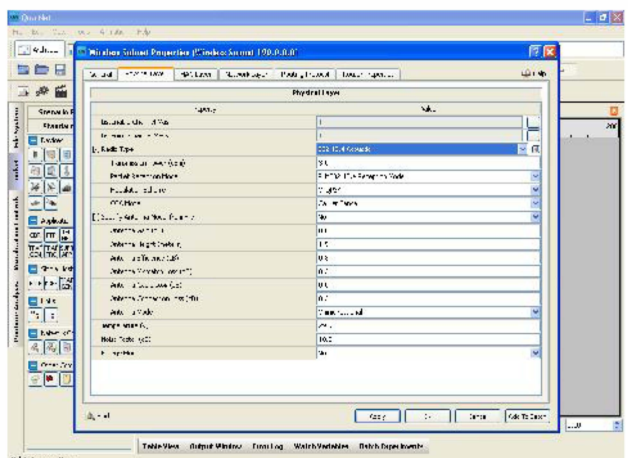

Fig.6 Implementation of Underwater Acoustic Radio Type using QualNet simulator.

V. Simulation Results

We use the Qualnet 5.0.2 simulator to compare the performance of two ray, free space and underwater acoustic path loss model. Existing protocol stack of the Qualnet simulator is modified in order to make the simulation environment suitable for underwater sensor networks while the harshness of the environment dictates systems that are neither small nor easily deployable, and certainly not inexpensive or disposable [11]. The underwater acoustic channel is implemented as follows. The attenuation over a distance d for a signal of frequency f can be modeled by A(f).

The geometry of propagation is described using the spreading factor ($1 < k < 2$), and we use $k = 1.5$ (corresponding to most practical scenarios). The absorption loss a(f) is described by the Thorp's formula [6]. In our physical layer implementation, the receiver node successfully receives a packet if the Signal-to-Noise Ratio (SNR) is above a threshold, where noise is assumed to be a function of the noise factor, bandwidth and temperature. Table II, represents the simulation parameters to be configured in QualNet Simulator.

TABLE III
SIMULATION PARAMETERS

Parameters	Values
Domain Area	1000 * 1000 * 600
Simulation Time	6000 s
No. of nodes	250
Transmission range of each node	180 m
Path loss Model	Underwater Acoustic, Two-Ray, Free Space
Speed of Sound	1500 m/s
Packet Size	400 bits
Data Rate	50 kbps
Routing Protocol	AODV, DSR

We set the data rate of the acoustic channel to 50 kbps with a channel frequency of 100 kHz. The speed of sound is set as 1500 m/s. Nodes are placed in a (1000, 1000, 600) volume. The transmission range is set to 180 m. There are 250 nodes and the average node degree is 9. To calculate the bit error rates and delay, for each topology (generated with a different seed), we run an application protocol. We analyze the performance of the protocols for varying number of nodes as 100, 250, 500 and 1000.

In the mobile USN, nodes are allowed to drift in a 20 km * 20 km domain. Simulations last 6000 s and the domain is large enough to contain all the mobile nodes during the simulation time.

A. Energy consumption

In Fig. 7, we give the energy consumption of two ray, free space and UAP. In sensor networks, energy consumption is related with several parameters.

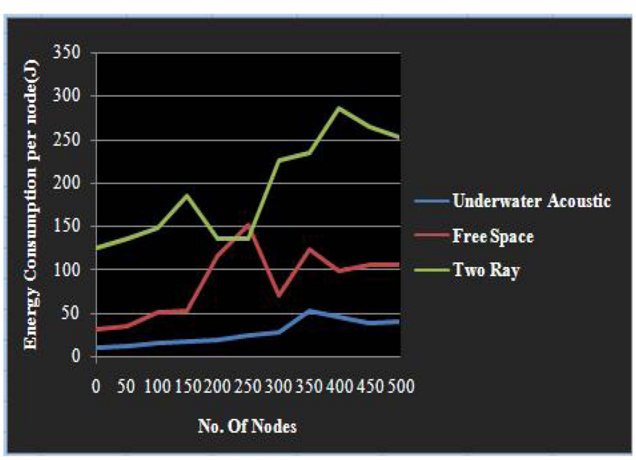

Fig 7. Energy consumption per node

Here, we assume that a significant portion of energy is spent during packet transmission. Therefore, energy consumption is related with the number of transmitted bits.

Since we assume an acoustic network, the underwater nodes use acoustic modems [8][10]. Most of the off-the-shelf acoustic modems have large range values because they are designed to work in applications where the distance between nodes are in kilometers. However short range modems are preferred in USNs to achieve higher data rates.

B. Packet Delivery Ratio

Packet delivery ratio can be calculated as the ratio between the number of data packets that are received by the sink and the number of data packets that are sent by the source. Fig. 8, represents the underwater acoustic path loss model provides the maximum PDR.

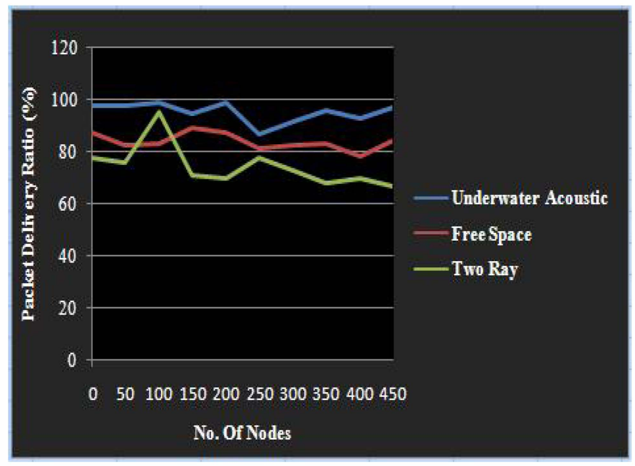

Fig. 8 Packet Delivery Ratio in Underwater Acoustic sensor network scenario

C. Average End- to- End Delay

Average End-to-end delay refers to the time taken for a packet to be transmitted across a network from source to destination. $\mathbf{d_{end-end} = N\ [\ d_{trans}+d_{prop}+d_{proc}]}$, where $d_{end-end}$= end-to-end delay, d_{trans}= transmission delay, d_{prop}= propagation delay, d_{proc}= processing delay, N= number of links (Number of routers + 1). Herewith, Fig. 9 depicts the average end-to-end delay in underwater acoustic sensor network scenario.

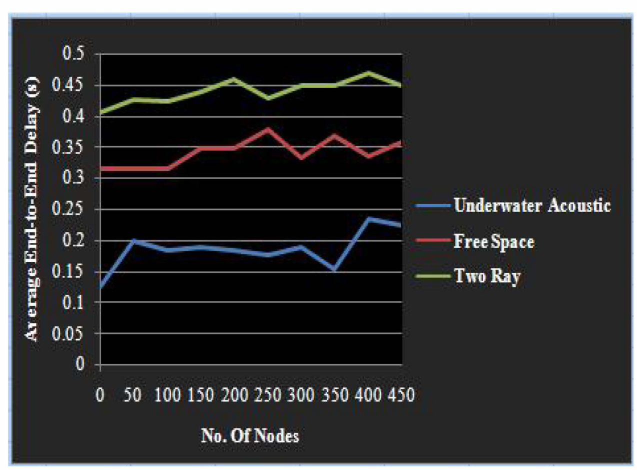

Fig. 9 Average End-to-End Delay in Underwater acoustic sensor network scenario

Free space and two ray path loss models has lower PDR and higher average end- end delay compared to underwater acoustic path loss model. Hence, the performance of underwater acoustic path loss model is not affected by increasing scalability with dynamic ocean currents.

VI. CONCLUSIONS

The research issues related to physical layer design with respect to path loss model for performance enhancement is studied in detail. A detailed design flow for the entire environment is formulated based on the physical properties of underwater acoustic environment. Setting up of infrastructure for a UU-ASN using an underwater acoustic path loss model is simulated using QualNet simulator successfully.

As a future work, we plan to integrate the Energy Efficient Localization technique along with above mentioned physical environment to build an accurate, fast and reliable environment suitable for underwater sensor network applications could affect the performance of the routing protocols.

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