Analysis of Acoustic Channel Model Characteristics in Deep-Sea Water

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Abstract. Undersea acoustic communications have drawn a lot of attention recently as their uses start to transition from military to commercial. The acoustic properties of the ocean are characterized by their tremendous complexity and dynamic nature. The parameters such as; depth, temperature, salinity, location, time of day, and season of the underwater medium influences the acoustic signal propagation. However, these medium parameters are varying arbitrarily depending upon shallow and deep-water divisions of the ocean. In addition to the medium parameters, the characteristics of the acoustic channel (transmission loss, absorption and multi-path) are affected by variation in the acoustic signal speed in underwater. The influence of the aforementioned parameters alters the velocity of acoustic transmission, which affects network connectivity. Because research in the undersea environment is expanding rapidly, proficient channel modelling is required to demonstrate the effect of sound speed variations with respect to medium parameters. As a result, an acoustic channel has been modelled in this work, which analyses the sound speed variation in deep water with respect to underwater medium parameters. In addition, the proposed model evaluates absorption and transmission losses in a deep-water scenario.

Keywords: Absorption · Acoustic Channel · Deepsea · Sound Speed · Temperature · Transmission Loss · Salinity

1 Introduction

In the scientific community, underwater acoustic sensor networks (UASN) are becoming more significant due to their function as enabling technology for a variety of applications. The underwater acoustic sensor networks (UASN) are composed of submerged sensors and are used to gather information on the parts of rivers and oceans that have not previously been explored. These networks are dispersed across a study region and contain a configurable number of vehicles, anchored sensors, and floating sensors [1]. These nodes establish a communication channel with one or more hops between them. Optic, radio, electromagnetic, and acoustic waves are all capable of being used by underwater equipment to communicate with one another [2]. Since it can transmit digital data

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through an underwater channel and has a large range, acoustic communication is the preferred method among researchers. The network characteristics of the UASN (node mobility, transmission range, power), as well as the characteristics of the underwater medium (temperature, pressure, salinity, and pH), introduce significant research challenges, such as limited bandwidth, multipath fading, limited battery, and limited data capacity [3].

The main factors that matter in an underwater environment are temperature, salinity, and sound speed with respect to depth [4]. Due to a variety of characteristics, such as wave height, turbid currents, water pressure, water chemical compositions, and wave speed, the undersea environment is also unpredictable [5]. The proposed channel model must be able to recognize changes in underwater medium characteristics and network parameters in order to build a reliable network. Usually, in underwater, the acoustic channel model performance is influenced by its operating frequency and the speed sound [6]. Temperature, salinity, depth, and pH are all factors that affect sound speed in underwater [7]. The sound speed changes as temperature and salinity change with regard to depth in the water. Seawater salinity varies according to both water depth and geographic location. Salinity have been measured as a part per thousand and calculated from the ocean dissolved salt concentrations (ppt) [8–10].

In Polar Regions, salinity is less than 30 ppt, despite the fact that the average salinity is between 31 and 37 ppt. On the other hand, salinity, temperature, transmission distance, and frequency of operation all affect how well sound travels through sea water [11]. These irregular differences in sound speed (depending on temperature, salinity, water depth, and pH) and absorption affect the formation of linkages between the sensor nodes (dependent on acoustic frequency, transmission distance). The connectedness of UASN also depends on the development of efficient communication links between the sensor nodes. An effective acoustic channel model that takes into account the effects of sound speed, absorption losses, and transmission losses must be included in order to provide reliable communication between the sensor nodes in a deep underwater network.

2 Related Work

The marine environment has a significant impact on wireless acoustic signal propagation across a water body as the channel of propagation. The Doppler shift, strong multi-path propagation, high attenuation, constrained bandwidth, severe fading, lengthy delay spread, fast time variation of the channel, route loss, and noise are only a few of the challenges the acoustic channel faces [12]. Therefore, in order to build and create efficient underwater communication systems, it is essential to do research and have a thorough understanding of how the underwater environment affects the communication signal in both the regions (shallow and deep water) of marine. Even though, the terrestrial networks have attained significant attention in the research groups, the implementations of these networks in underwater is a challenging task due to excessive absorption of electromagnetic waves in underwater. In addition, the terrestrial networks are differed from underwater in many network constraints [13–24] such as; propagation delay, topology, power needs, mobility, network life, data rate, etc. The foremost parameter that affects the performance of acoustics is variable sound speed. Usually, the temperature changes have been reduced in Deepsea water locations when compared to shallow water. The authors in [12] have provided and investigated the underlying physics of fundamental wave propagations using the fundamental physics concepts before contrasting the problems and effects of using various communication carriers (acoustic, EM, and optical).

The authors in [25] has explored the effects of propagation characteristics on underwater communication, including sound speed, channel latency, absorption, scattering, multipath, waveguide effects, and ambient noise. The authors in [26] used increased propagation loss and ambient noise models to examine the dependence of the channel capacity on depth and temperature. For reducing the mistakes in the sound speed in oceans and seas, a mathematical model [27] that offers the conversion of atmospheric pressure to depth and depth to atmospheric pressure has been presented. In, [28] authors have described an experimental setup that shows how salinity, temperature, and pressure affect the physical properties of the deployed environment and sound speed fluctuations. A method [29] for increasing the localization accuracy in the water by estimating the sound speed at a specific spot with time. For network simulation in underwater environments, an acoustic channel model has been developed [30]. A real-time measurement of the route loss for an underwater acoustic channel has been made [31]. To improve accuracy and throughput, modelling underwater acoustic channel characteristics has been applied recent breakthroughs in deep learning and artificial intelligence. To increase the accuracy of channel models, a deep learning-based framework for underwater channel modelling has been presented [32]. The main statistical characteristics of the channel model have been outlined and examined in [33].

The literature has shed light on how changes in the properties of the underwater medium affect underwater sound propagation. The impact of temperature, salinity, absorption, and transmission losses caused by changes in the sound speed must therefore be addressed and taken into account. The link development in the network is altered by these fluctuations in sound speed caused by the unpredictability of the undersea environment. As a result, the proposed work objective is to analyses the acoustic channel properties in the Deepsea water region while taking transmission losses and absorption into account.

3 Channel Model

An acoustic channel that considers the effects of temperature, salinity, absorption, and transmission losses on sound speed has been designed for simulating an underwater acoustic channel in shallow and Deepsea water. In a Deepsea water scenario, the sound speed has first been measured at various depths by adjusting salinity and temperature, and then the losses resulting from the change in sound speed have been determined. In addition, the transmission losses and absorption with respect to frequency and distance has been evaluated for deep water scenario.

3.1 Sound Velocity

The incredibly slow pace at which sound moves through water is one of the main differences between acoustic waves and EM transmission. Undersea sound speed is influenced by conditions including pressure, salinity, and temperature. The speed of sound near the ocean surface is normally around 1520 m/s, which is four orders of magnitude faster than the speed of sound in air but five orders of magnitude slower than the speed of light. The sound speed in water is directly impacted by environmental changes (temperature, salinity, and depth). Mackenzie provides an empirical formula [34] for calculating sound velocity as a function of temperature, salinity, and depth is represented using (1).

$$c(T, S, z) = a_1 + a_2 T + a_3 T^2 + a_4 T^3 + a_5 (S - 35) + a_6 z + a_7 z^2 + a_8 T (S - 35) a_9 T z^3 \tag{1}$$

3.2 Propagation Loss of Sound

Spreading, dispersion, and absorption all contribute to the attenuation in undersea acoustic signals. Spreading loss is a metric for signal deterioration brought on by the geometrical spreading effect that occurs as a sound wave moves away from its source. Cylindrical and spherical spreading in underwater acoustics, are two different types of spreading mechanisms. For cylindrical and spherical spreading the loss is expressed using (2) and (3) respectively. L_{CS} represents loss due to cylindrical spreading, L_{SS} represents loss due to spherical spreading and R_t represents the transmission range [35].

$$L_{CS} = 10\log(R_t) \tag{2}$$

$$L_{SS} = 20\log(R_t) \tag{3}$$

3.3 Absorption Coefficient

For the frequency range of 100 Hz to 1 MHz, an empirical formula [35] for the absorption coefficient has been expressed using (4). It changes with frequency, pressure (depth), and temperature.

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

3.4 Absorption Loss

The absorption loss, which is range-dependent and calculated using (5), represents the energy loss of sound as a result of the transformation of energy into heat due to the chemical features of viscous friction and ionic relaxation in the ocean.

$$L_{ab} = (\alpha \times R_t) \times 10^{-3} \tag{5}$$

3.5 Transmission Loss

Transmission loss [36], which is defined as the cumulative loss of acoustic strength caused by an acoustic pressure wave as it moves away from its source which is represented by using (6).

$$TL_{Deepsea} = L_{SS} + L_{ab} \tag{6}$$

4 Implementation Parameters

The parameters considered for analyzing the transmission loss, absorption loss, spreading loss and sound speed has been listed in Table 1.

Table 1. Implementation Parameters

Parameter	Range
Depth	100–8000 m
Temperature	30–4 °C
Salinity	30–37 ppt
Frequency	100 Hz–100 kHz
pH	7.8
R_t	100 m

5 Simulation Results

The acoustic medium is the primary means of wireless data communication in marine environment, and the speed of sound is the most fundamental characteristic that influences the data rates that can be achieved, as well as the quality of service, latency, and other crucial network parameters in this channel. The sound speed has unpredictable variations in underwater due to abnormal changes in temperature, salinity, depth and pH with respect to the season, time and location of the ocean.

In addition, the sound speed also influenced by numerous factors, including wave height, turbid currents, water pressure, chemical compositions of the water, and wave speed. Whereas, the variation in aforementioned parameters has different profiles in shallow and deep-water divisions of the ocean. The sound speed profile exhibits abnormal variations in shallow water because of drastic change in temperature gradients of the water column across the water depth. Whereas, the temperature is almost constant (4 °C) at the deep water scenarios, where the sound speed profile has minimal variations. It is clearly depicted in Fig. 1, that the sound speed is varying with temperature and depth. When the depth is extended to 7000 m and the temperature is lowered to 4 °C, the sound

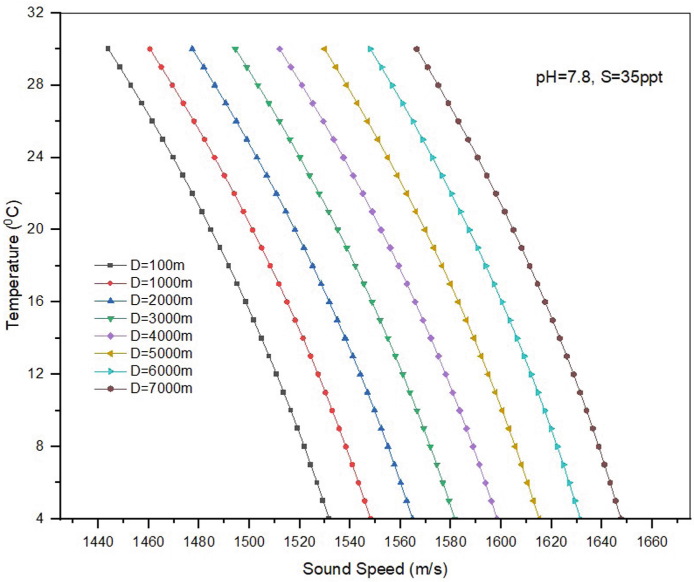

Fig. 1. Effect of Temperature variations on sound speed in deep-water

speed increases to 1650 m/s (see Fig. 1) from the initial value of 1450 m/s at a certain temperature and depth ($T = 30$ °C, $D = 100$ m). Similarly, salinity of the ocean water

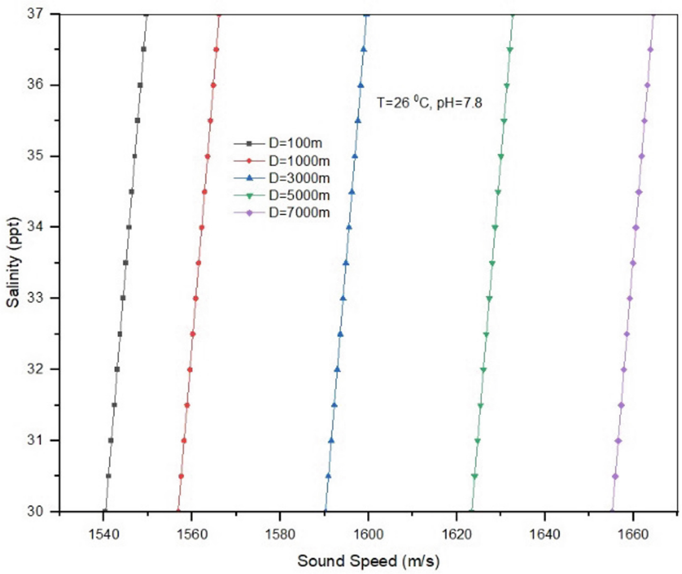

Fig. 2. Effect of salinity variations on sound speed in deep-water

increases along the depth, which also influences the sound speed in deep water. This is clearly depicted in Fig. 2, that the sound speed increases with increase in depth as well as salinity. At a particular salinity (S = 33 ppt), the sound speed attained different profiles (varying from 1540 m/s to 1650 m/s) along the depth (see Fig. 2).

Absorption, which results from the transformation of acoustic energy into heat, is the principal cause of attenuation. As the distance and frequency rise, the attenuation grows. The influence of different absorption due to various chemical compositions of the underwater medium has been depicted in Fig. 3. It is clear that boric acid (H_3BO_3), magnesium sulphate ($MgSO_4$), and pure water are the main contributors to attenuation at frequencies below 1 kHz, between 1 kHz and 100 kHz, and above 100 kHz, respectively (see Fig. 3). It is also obvious that the orders of magnitude vary widely and that attenuation rises sharply with frequency. For frequencies of 1 kHz and below, attenuation is less than a few hundredths of a dB/km; hence, it is not a limiting factor. Approximately 1 dB/km of attenuation occurs at 10 kHz, restricting ranges of more than a few tens of kilometres. The transmission losses are frequency and range dependent. According to Fig. 4, transmission losses increase as frequency increases, while transmission losses decrease as depth increases.

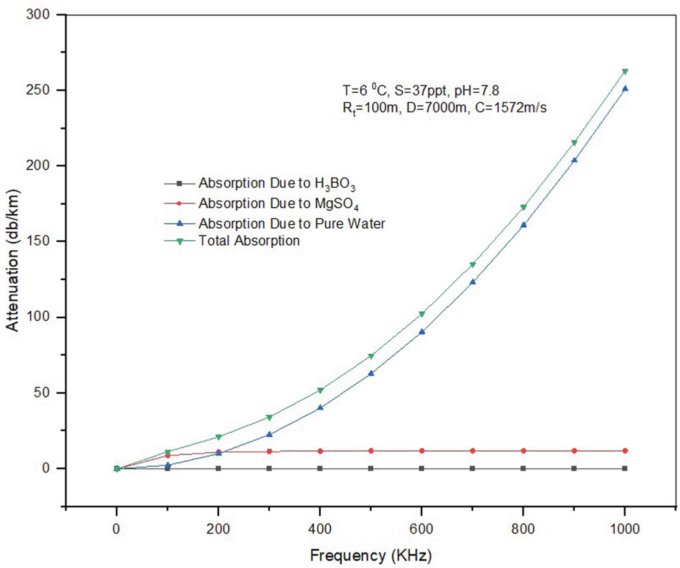

Fig. 3. Attenuation in deep water due to absorption

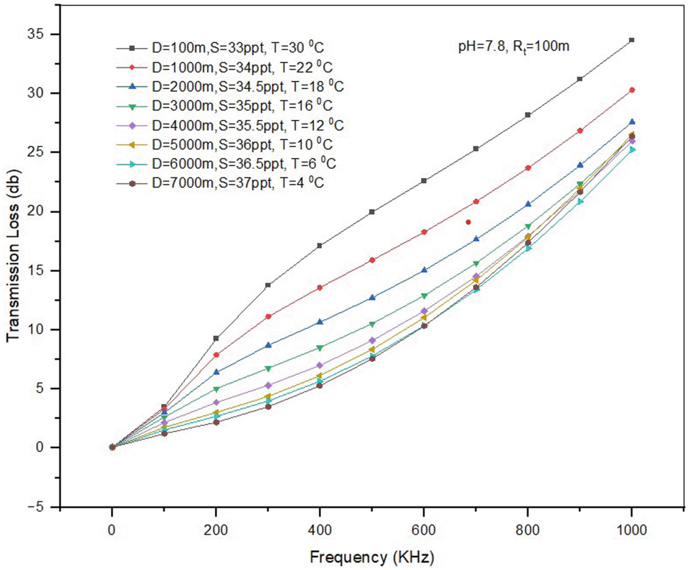

Fig. 4. Transmission losses with respect to frequency in deep-water

6 Conclusion

This study proposes an acoustic channel model that investigates the effect of underwater medium factors such as temperature and salinity on sound speed. By varying different depths in a deep-water scenario, the proposed channel model investigates the effect of salinity and temperature at a fixed pH. The proposed channel model also investigates the effect of absorption due to different chemical compositions of water with respect to the frequency of the acoustic signal. Finally, the transmission losses have been estimated at various depths in deep-water with respect to the frequency at a fixed transmission range. The simulation results show that transmission and absorption losses are frequency dependent. These two losses have increased in proportion to the frequency. As the temperature and salinity decrease gradually and along the depth, the sound speed increases in deep-water.

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