Comparison of Acoustic Channel Characteristics for Direct and Multipath Models in Shallow and Deep Water

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Abstract. The primary objective of this study is to compare the acoustic channel characteristics between direct and multipath models in shallow and deep-water environments. Moreover, the study delves into the influence of temperature and salinity on sound speed propagation and absorption. These factors are affected by various chemical compositions present in the underwater medium. The assessment of these effects is conducted for both shallow and deep-water scenarios. Lastly, comprehensive scrutiny and comparison of transmission losses have been conducted for both the direct and multipath models. The simulation results clearly demonstrate that the transmission losses in deep water for the multipath model are significantly higher than those in shallow water. This difference can be attributed to the increased pressure and sound reflections experienced in the deep-water environment. Each 1 °C decrease in temperature results in a 3.5 m/s increase in acoustic velocity when sound travels from the water's surface to the bottom. In contrast, deep water maintains a constant acoustic velocity of 1545 m/s regardless of changes in salinity. However, in shallow water, there are significant variations in acoustic velocity due to salinity changes. Comparing deep water to shallow water, there is a considerable attenuation reduction of 20 dB in deep water. Specifically, at lower frequencies (0–100 kHz), the transmission losses for direct paths in deep water are almost negligible. In contrast, for multipath transmission, there is an increase of 93%. In shallow water, the transmission loss increases by 66% for direct path models and as much as 97% for multipath models.

Keywords: Absorption · Attenuation · Acoustic Channel · Deep water · Shallow water · Sound Speed · Temperature · Transmission Loss · Salinity

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1 Introduction

Underwater Acoustic Sensor Networks (UASNs) are systems composed of interconnected underwater sensor nodes that communicate using acoustic signals [1]. Sound waves are used for communication in UASNs because underwater environments are highly attenuative to electromagnetic waves. Acoustic waves travel through the water medium as pressure variations, propagating in all directions from the source [2]. They experience absorption, scattering, and refraction as they interact with the water, seabed, and other objects in the underwater environment. Despite the advantages, acoustic communication in UASNs also has some challenges, such as limited bandwidth, vulnerability to noise, multipath propagation, and lower data rates compared to electromagnetic communication [3].

Multiple reflections, refractions, and diffractions, resulting in multiple propagation paths between the source and receiver among acoustic signals. This phenomenon is known as multipath propagation and can cause interference and distortion of the transmitted signals. In addition, the medium properties such as; temperature and salinity also influence the sound speed in various underwater regions such as shallow and deep water [4]. In shallow water environments, multipath propagation is attained through the interaction of sound waves with the various boundaries and objects present [5]. Factors that contribute to multipath propagation in shallow water includes: reflection (Sound waves can bounce off the water surface, seafloor, and other reflecting objects, leading to multiple paths for signal propagation); refraction(it occurs when sound waves pass through regions with varying water properties, such as temperature or salinity gradients. These gradients cause changes in the speed of sound [6], resulting in the bending of sound waves. As sound waves bend and change direction, they can reach the receiver along different paths, contributing to multipath propagation); and scattering [7].

Whereas, in deep water environments, multipath propagation is primarily achieved through the phenomenon of sound wave scattering and refraction [8]. Unlike shallow water, deep water lacks significant seafloor interaction, and the primary factors contributing to multipath propagation are as follows: scattering(in deep water, sound waves encounter various scatterers present in the water column, such as suspended particles [9], microorganisms, and other small objects); surface reflections [10] (in deep water, sound waves can reach the water surface, where they undergo reflection); and boundary interactions [11]. Understanding and modeling the multipath propagation in both shallow and deep-water environments are crucial for designing communication systems and signal processing techniques that can effectively mitigate the effects of multipath interference and enhance the reliability of communication.

2 Literature Review

Underwater Acoustic Sensor Networks (UASN) have gained significant attention in recent years due to their potential applications in underwater monitoring, environmental sensing, marine exploration, and military surveillance. Transmission losses in UASNs are a crucial aspect to consider for reliable and efficient communication in underwater environments. Several research papers and studies have explored various factors affecting transmission losses in UASNs, including: path loss models; absorption and scattering; multipath propagation; channel estimation and equalization; network topology and routing. In [12], the authors have investigated the fundamental physics of wave propagation, specifically focusing on acoustic, electromagnetic (EM), and optical communication carriers. In [13], the authors have extensively studied the impact of propagation characteristics on underwater communication. In [14], the authors have focused on the relationship between propagation loss, ambient noise, and channel capacity in underwater communication. To address inaccuracies in acoustic velocity estimation, a mathematical model [15] has been proposed.

This model provides a conversion framework between atmospheric pressure and depth, as well as depth and atmospheric pressure, aiding in sound speed determination. In [16], the authors have presented an experimental setup that investigates the impact of underwater medium parameters. A method [17] has been proposed to enhance localization accuracy in underwater environments. To simulate underwater networks effectively, a specifically developed acoustic channel model [18] is employed. In [19], researchers have conducted real-time measurements of route loss in underwater acoustic channels. In [20], a deep learning-based framework has been introduced to enhance accuracy and throughput in channel modeling. The authors have provided a detailed account of the statistical properties of the channel model in [21]. Moreover, a novel technique for frame boundary estimation in UASN has been proposed in [22]. In [23], the authors especially address the clustering in UASN by focusing on the integration of three essential approaches in the context of IoT applications. In [24], the authors investigated how water absorption affected the hybrid phenol formaldehyde (PF) composites' mechanical characteristics.

3 Methodology

This comprehensive approach provides valuable insights into the complex acoustic environment of shallow and deep water, and enabling better understanding and modeling of underwater acoustic propagation.

3.1 Sound Speed

The transmission of sound through water differs significantly from electromagnetic (EM) waves, primarily due to its slow speed. Mackenzie's empirical formula, denoted by (1), provides a means to calculate sound velocity [26].

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

3.2 Acoustic Propagation Loss

Propagation loss of sound refers to the reduction in the strength or intensity of sound waves as they travel through a medium or propagate in a given environment [27]. The loss associated with cylindrical spreading is expressed using Eq. (2), while spherical spreading loss is represented by Eq. (3).

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

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

3.3 Absorption Loss

Sound waves in a medium, such as air or water, experience absorption, where the energy of the sound wave is converted into heat [28]. The absorption is frequency-dependent, with higher frequencies generally being absorbed more rapidly which is represented using (4). Where, α is absorption coefficient in underwater and is represented using (5). The slackening frequency for boric acid, denoted as f_1 (in kHz), is given by Eq. (6). In Eq. (6), S represents salinity (in parts per 1000), and T represents temperature in degrees Celsius. The relaxation frequency for magnesium sulfate, denoted as f_2 (in kHz), is given by Eq. (7).

$$L_{ab} = (\alpha \times R_t) \times 10^{-3} \tag{4}$$

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \tag{5}$$

$$f_1 = 2.8\left(\frac{S}{35}\right)^{0.5} \times 10^{[4-1245/(273+T)]} \tag{6}$$

$$f_2 = \frac{8.17 \times 10^{[8-1990/(273+T)]}}{1 + 0.0018(S - 35)} \tag{7}$$

3.4 Transmission Losses in Shallow Water

In shallow water, sound travels a long way by repeatedly reflecting off the bottom and surface, a process known as multipath propagation [29]. This phenomenon introduces transmission losses. The equation employed in this analysis accounts for the horizontal separation distance (r) between the sound source and receiver, specifically when r is within a range of up to 1 times H (skip distance). In this context, H represents the average water depth of the acoustic study area, which serves as a conservative definition for the purposes of this analysis (skip distance). The skip distance H can be defined by using (8). The transmission losses due to multipath in shallow water is defined using (9) for the case, when r is within the range of H, (10) for the case when $H \leq r \leq 8H$ and (11) when $r > 8H$. Where, d is the mixed layer depth, z is the scenario depth,

K_L is the near field anomaly, α_T is the shallow water attenuation coefficient. Whereas, assuming direct path between source and receiver (with R_t as node transmission range), the transmission losses are evaluated using (12).

$$H = \sqrt{\frac{1}{3}(d + z)} \quad (8)$$

$$TL_{Multipath} = 20 \times \log(r) + \alpha \times r + 60 - K_L \quad (9)$$

$$TL_{Multipath} = 15 \times \log(r) + \alpha \times r + \alpha_T(r/H - 1) + 5 \times \log(H) + 60 - K_L \quad (10)$$

$$TL_{Multipath} = 10 \times \log(r) + \alpha \times r + \alpha_T(r/H - 1) + 10 \times \log(H) + 60 - K_L \quad (11)$$

$$TL_{Directpath} = 10 \times log_{10} \times R_t + \alpha \times R_t \times 10^{-3} \quad (12)$$

3.5 Transmission Losses in Deep Water

These reflections result in energy being redirected away from the desired propagation path, leading to a decrease in received sound level. The transmission loss (assuming direct path) can be mathematically expressed using (13). The transmission loss due to surface reflections can be expressed using (14) by considering the wind speed (w) and angle of incidence (θ). Finally, the transmission losses can be represented using (15). Equation (16), demonstrated the transmission losses due to convergence zones in deep water [30].

$$TL_{Direct\,path} = 20\,log_{10} R_t + \alpha R_t \times 10^{-3} \quad (13)$$

$$TL_{SR} = 10 \times \log\left[\frac{1 + \left(f/f_1^2\right)}{1 + \left(f/f_2^2\right)}\right] - (1 + (90 - w)/60)\left(\frac{\theta}{30}\right)^2 \quad (14)$$

$$TL_{Multi-path} = TL_{dp} + TL_{SR} \quad (15)$$

$$TL_{Convergence\,Zones} = 20\log(r) + \alpha \times r \times 10^{-3} - C_Z\_Gain \quad (16)$$

4 Simulation Parameters

To simulate the transmission losses of an UASN, several parameters need to be considered for the simulation model which helps in accurately predicting the transmission losses. Table 1 provides the detailed list of parameters used for simulation along with their ranges.

Table 1. Execution Parameters

Parameter	Range
Depth of shallow water (meters)	0–100
Depth of deep water (meters)	100–8000
T ($^{\circ}$C)	30–22 (shallow), 22–4 (deep)
S (ppt)	30–33 (shallow), 23–37 (deep)
F(kHz)	0.1–100
pH	7.8
R_t (meters)	100
MLD (meters)	10–95
K_L(dB)	7–20
W (m/s)	4–12.5
Theta	20–36

5 Simulation Results

The transmission of underwater acoustics is profoundly affected by the speed of sound in both shallow and deep water. Shallow water exhibits abrupt variations in sound speed, contrasting with the more gradual changes observed in deep water. As illustrated in Fig. 1, temperature variations exert a dominant influence on acoustic velocity in shallow water, while in deep water, sound speed increases linearly with decreasing temperature, eventually reaching a constant value when the temperature reaches 4 °C and below. Likewise, the variations in salinity also play a significant role in acoustic propagation in both shallow and deep water.

The impact of salinity variations on sound speed in both shallow and deep-water environments has been illustrated in Fig. 2 when compared to temperature, the change in sound speed due to salinity variations has less influence on sound propagation. The acoustic velocity is gradually decreased in shallow water as the salinity increases, but in deep water it rises linearly and attained study state. At a particular value of temperature and salinity, the attenuation of sound wave due to absorption has been evaluated which is depicted in Fig. 3.

The transmission losses due to surface reflections are purely depends on frequency, windspeed and angle of incidence. Figure 4, shows the comparison of transmission losses due to surface reflections and convergence zones of multipath acoustic channel model and direct path model at a particular depth in deep water.

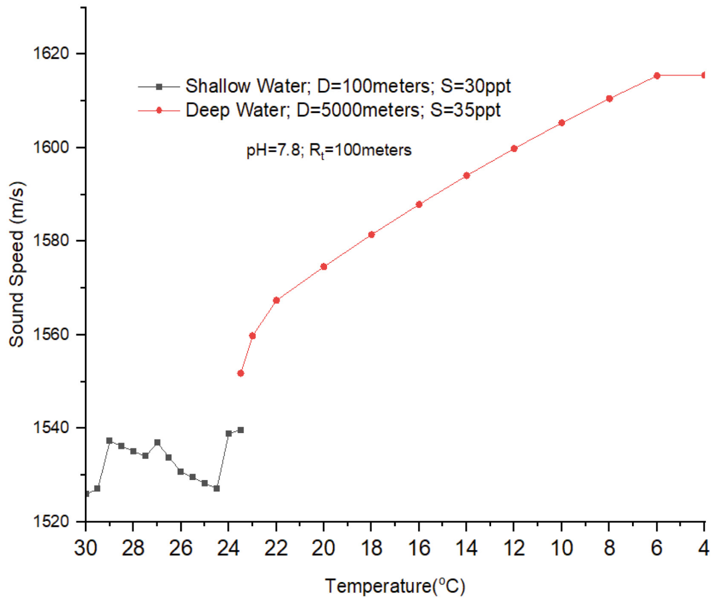

Fig. 1. Variation of acoustic velocity in accordance to temperature.

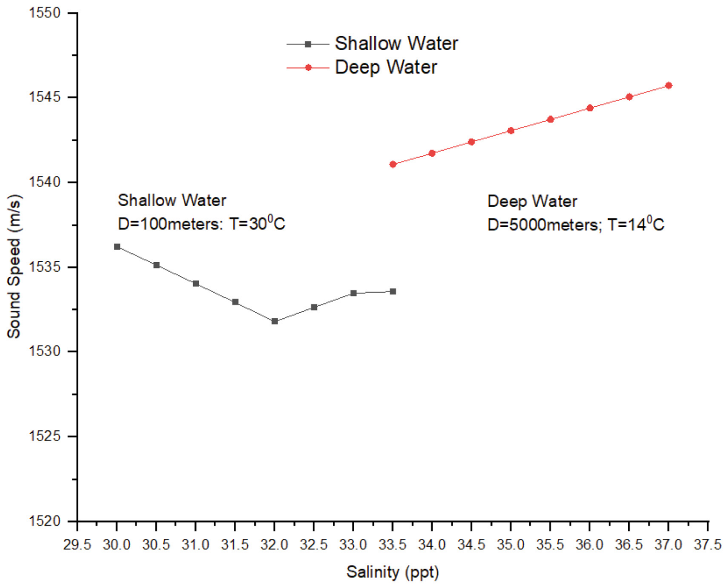

Fig. 2. Variation of acoustic velocity in accordance to salinity.

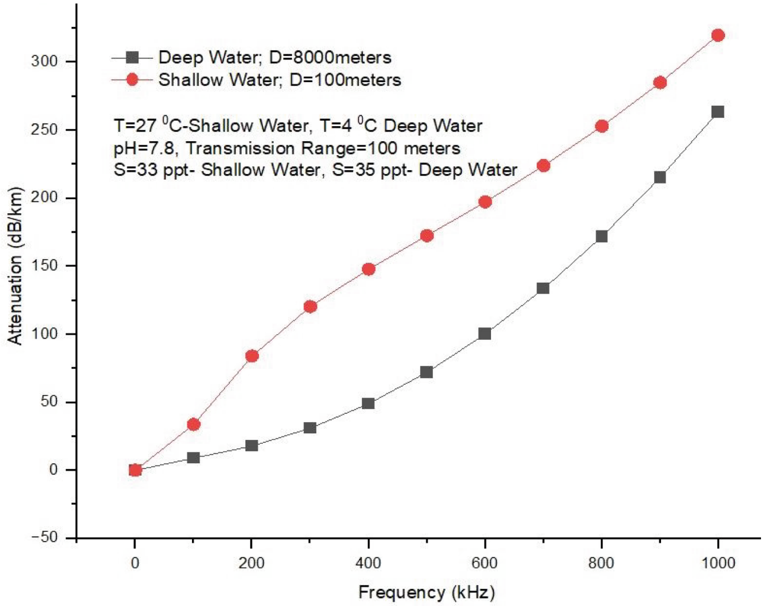

Fig. 3. Attenuation *vs* frequency.

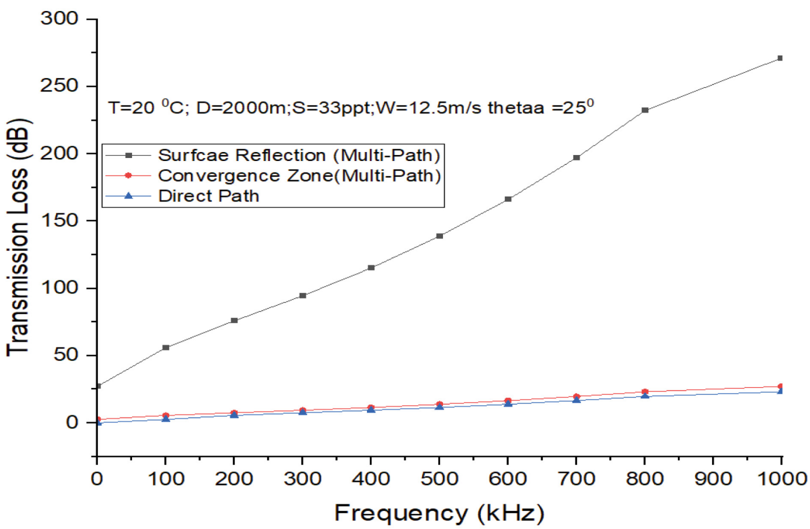

Fig. 4. Comparison of transmission losses for direct and multipath models in deep water.

It is observed that, the transmission losses are directly proportional to wind speed and frequency. Similarly, the angle of incidence at which the acoustic wave reflected back from the surface also had an impact on transmission losses. Figure 4 vividly illustrates that surface reflections result in considerably higher transmission losses compared to the convergence zones in deep water. Whereas, in shallow water the multipath propagation due to mixed layer has less transmission losses when compared to surface reflections. It is evident from Fig. 5, that the transmission losses due to mixed layer depth attained high values when compared to near field anomaly and direct path models.

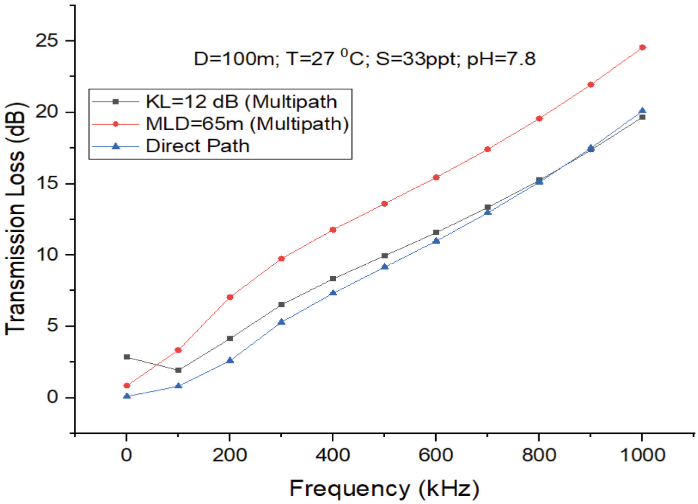

Fig. 5. Comparison of transmission losses for direct and multipath models in shallow water.

6 Conclusion

This work focuses on comparing the acoustic channel characteristics between direct and multipath propagation models in both shallow and deep-water environments. The investigation begins by introducing the fundamentals of acoustic propagation in water, including the effects of absorption, scattering, and refraction. The simulation results unequivocally demonstrate that the transmission losses experienced in deep water for the multipath model are notably higher than those encountered in shallow water. This discrepancy can be attributed to the heightened pressure and sound reflections that occur in the deep-water environment. Furthermore, the study reveals that for every 1 °C decrease in temperature, there is a corresponding 3.5 m/s increase in acoustic velocity when sound propagates from the water's surface to the bottom. Conversely, deep water maintains a consistent acoustic velocity of 1545 m/s, regardless of changes in salinity. On the other hand, in shallow water, the acoustic velocity varies significantly due to changes in salinity. When comparing deep water to shallow water, a substantial attenuation reduction of 20 dB is observed in deep water. Particularly, at lower frequencies (0–100 kHz), the transmission losses for direct paths in deep water are nearly negligible. However, for multipath transmission, there is a significant increase of 93% in transmission losses. In shallow water, the transmission loss increases by 66% for direct path models and as much as 97% for multipath models.

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