



Ray Tracing Techniques for Multipath Channel Modelling: Overcoming Challenges and Solutions

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Abstract—Understanding and building effective communication systems in underwater environments requires the use of multipath channel modelling. However, there are substantial difficulties in adequately characterising the intricate propagation behaviour of underwater acoustic channels. In order to address these issues and offer solutions for more precise multipath channel modelling, this study focuses on the use of ray tracing techniques, in particular using the BELLHOP approach. The paper begins by outlining the difficulties with multipath channel modelling in underwater acoustics, such as multipath propagation, the channel's time-varying and dispersive characteristics, and the lack of extensive measurement data. It then looks at how ray tracing methods, notably those that employ the BELLHOP approach, overcome these issues and make it possible to depict the underwater audio channel in more depth and with more realism. The ray theory-based BELLHOP method is a potent tool for modelling sound propagation in aquatic environments. It takes into account beam reflection, refraction, and scattering phenomena and enables the strength and timing of multipath arrivals. The BELLHOP approach captures the complicated multipath propagation characteristics and offers insights into the spatial and temporal properties of the underwater channel by tracking individual rays and taking into account their interactions with the environment. The BELLHOP method for ray tracing in underwater acoustic channels is covered in detail in this publication. It looks at methods for tracking rays and simulating the effects of various environmental conditions. The research also discusses difficulties in dealing with range-dependent settings, various seabed compositions, and

sound speed profiles. In order to evaluate the precision and dependability of the ray tracing models, the research also provides validation procedures and comparisons with measurement data. It addresses the benefits and drawbacks of BELLHOP and normal mode approaches as well as how they might be used in different underwater communication systems. By demonstrating the power of ray tracing methods using BELLHOP and normal mode approaches

Keywords— Multipath, underwater acoustics, ray tracing, bellhop.

I. MULTIPATH CHANNEL MODELLING CHALLENGES IN UNDERWATER ACOUSTICS

In the interdisciplinary field of underwater acoustics, sound in water and how it interacts with the environment are studied. Sonar, imaging systems, and underwater communication are just a few of its many uses. Understanding how sound waves behave underwater requires the use of multipath channel modelling. In the presence of reflections, refractions, and scattering, the pathways that sound waves can take as they go from a source to a receiver are referred to as the multipath channel. Sonar and underwater communication systems are challenged by multipath channels, which can lead to interference and signal distortion[1][8].

Due to the complicated way that sound propagates in the aquatic environment, underwater acoustics poses a special set of difficulties. Multipath propagation is one of the core concepts in underwater acoustics. When sound waves take many paths to get from one place to another, bouncing off different objects along the way and meeting various media,

this phenomenon is known as multipath. This phenomenon causes the original signal to arrive at the receiver in many delayed and distorted forms [2].

Multipath creates several significant obstacles for underwater acoustics research and applications. For a variety of fields, such as underwater communication, sonar systems, environmental monitoring, and marine biology research, it is essential to comprehend and address these issues.

The occurrence of echoes, in which the primary signal is interfered with by delayed replicas of the original signal, is one of the main effects of multipath propagation. Signal deterioration, elevated mistake rates, and worsened communication or detection performance may follow. Echoes can also compromise the precision of target localization and sonar imaging, making it difficult to derive useful information from the signals that were received.

Additionally, a variety of elements, including characteristics of the bottom, variations in the water column, surface reflections, and gradients in temperature and salinity, have an impact on multipath propagation in underwater acoustics. Accurate modelling and prediction of the behavior of multipath channels are made much more difficult by the added complexities and uncertainties that these elements impose.

Diverse signal processing methods, sophisticated modelling tactics, and adaptive communication or sensing techniques are needed to address the difficulties caused by multipath propagation in underwater acoustics. Researchers and engineers are always working to provide effective solutions to reduce the effects of multipath, increase the reliability of communications, improve imaging capabilities, and comprehend the underwater acoustic environment better [18-26].

This paper intends to analyze the multipath issues in underwater acoustics, investigate existing mitigation solutions, and offer unique ideas to enhance the performance and reliability of underwater acoustic systems. We can realize the full potential of underwater acoustics for a variety of applications and scientific advancements by comprehending and overcoming these difficulties.

In the discipline of underwater acoustics, ray tracing methods have proven to be useful tools for reducing the difficulties caused by multipath propagation and enhancing multipath channel modelling. Accurate and effective methods for comprehending and forecasting the behavior of acoustic signals are required due to the complexity of sound transmission in the underwater environment.

Sound waves can encounter different barriers, such as the water's surface, the seafloor, and other objects in the water column, and experience multipath propagation as a result. These interactions cause the original signal to arrive at the receiver in several delayed and distorted forms. For the purpose of developing reliable underwater communication systems, sonar imaging methods, and environmental monitoring applications, proper modelling and simulation of these multipath channels is essential [30-32].

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Multipath propagation in underwater acoustics presents a number of issues that call for novel signal processing methods, sophisticated modelling methodologies, and adaptive communication or sensing systems [8-10]. In order to reduce the impacts of multipath, increase communication dependability, improve imaging capabilities, and learn more about the underwater acoustic environment, researchers and engineers are always working to develop reliable solutions.

In light of the foregoing, this paper aims to analyze the multipath difficulties in underwater acoustics, investigate current mitigation solutions, and offer novel ideas to enhance the performance and reliability of underwater acoustic systems. Understanding and overcoming these difficulties will enable us to fully utilize underwater acoustics for a variety of applications and scientific advancements.

Ray tracing methods have been extensively employed in underwater acoustics to model multipath channels. By following the path of sound waves as they travel through the environment, ray tracing is a technique used to simulate the spread of sound waves. It offers a precise and effective method for simulating the behaviour of sound waves in challenging underwater environments. However, utilising ray tracing techniques for multipath channel modelling has its drawbacks. This article offers a thorough analysis of the problems and potential solutions associated with multipath channel modelling in underwater acoustics [1].

II. MULTIPATH CHANNEL MODELLING CHALLENGES

The time-varying nature of the channel, the requirement for precise modelling of sound wave reflection, refraction, and scattering, and the existence of diverse obstructions including rocks, reefs, and abnormalities in the seafloor are just a few of the problems discussed in this section. The section includes citations to earlier studies that examined similar problems and suggested remedies for them.

Due to the distinctive features of the underwater environment, modelling multipath channels in underwater acoustics presents a number of difficulties [1][5]. The following are some of the main difficulties:

Reverberation and multipath propagation: Sound waves are subjected to repeated reflections and scattering off the seafloor, the water's surface, and other objects in the water column in underwater environments, which are recognized for their high levels of multipath propagation. As a result, there are overlapping and time-varying echoes in the propagation environment, which is complex. Accurate modelling and characterization of these multipath components is difficult.

Underwater acoustic channels have a time-varying and dispersive nature as a result of the water's fluctuating sound speed, temperature gradients, salinity fluctuations, and other environmental conditions. Time-variant channel responses might result from propagation conditions that can vary quickly. Accurately capturing this dynamic behavior is difficult in a model.

Lack of thorough measurement data: The complexity of deploying measurement equipment in deep water and the size of the underwater domain make it difficult to get thorough and representative measurement data for underwater acoustic channels. The creation and validation of precise channel models are hampered by the scarcity of high-quality measurement data [2][14].

2.1 Time-Varying Nature of the Channel:

Because of the fluid nature of the undersea environment, the medium's characteristics may alter over time. The propagation route of sound waves can alter as a result of interactions with the environment. The term "temporal variability" refers to differences in the signal that the receiver receives as a result of this. Understanding the behaviour of sound waves in underwater environments requires accurate modelling of the channel's time-varying properties.

Past studies have suggested remedies for the channel's time-varying characteristics. Dynamic ray tracing, which simulates sound wave propagation by following sound waves across the environment while accounting for changes in medium properties over time, has been suggested for use in several investigations. Some research have suggested modelling the temporal variability of the channel using statistical techniques like autoregressive models.

2.2 Reflection, Refraction, and Scattering:

The reflection, refraction, and scattering of sound waves are key phenomena that need to be precisely described in multipath channel modelling. These occurrences can happen when two different media come together or when sound waves come into contact with objects like rocks, reefs, and abnormalities in the seafloor. Understanding how sound waves behave in aquatic environments depends on accurate modelling of these phenomena.

2.3 Presence of Obstacles:

Multipath channels can be introduced in underwater environments by the presence of obstructions like rocks, reefs, and abnormalities in the bottom. These obstructions can cause sound waves to scatter and reflect, creating various routes and delaying the arrival of the received signal. To comprehend the behaviour of sound waves in intricate underwater environments, accurate modelling of the interaction of sound waves with barriers is required.

The existence of difficulties has been addressed in previous research publications with suggested remedies. The use of geometric ray tracing, which entails following sound waves through the environment while taking into consideration the geometrical characteristics of the obstacles, has been suggested in several investigations. In other studies, it has been suggested to accurately represent the interaction of sound waves with barriers using a technique called hybrid

ray tracing, which combines geometric ray tracing and physical optics [24].

III. RAY TRACING TECHNIQUES IN MULTIPATH CHANNEL MODELLING

The many ray tracing methods, such as geometric, hybrid, and dynamic ray tracing, that are utilized in multipath channel modelling in underwater acoustics are covered in this section. The section includes citations to earlier studies that examined these strategies and their drawbacks.

Underwater networks' key limitations are that they must function underwater and that they rely on underwater sound transmission rather than radio frequency communication. Underwater acoustic communication has several drawbacks in addition to the typical issues with wireless sensor networks, such as variable sound speed, acoustic link capacity restrictions, shadow zones, lengthy propagation times, high transmission losses, high bit error rates, and frequent node failures [8].

Owing to the pricey underwater tests and unidentified underwater acoustic modem infrastructures, these restrictions not only present additional challenges for testing the suggested network protocols in network simulators, but they also highlight the need for and significance of a reliable network simulator. The underwater sound propagation method used in channel modelling is one of the aspects that affects how trustworthy a network simulator is for undersea networks. Although there are various underwater sound propagation methods, ray tracing is the most effective one.

Ray tracing methods fall into two categories: deterministic and stochastic. Whereas stochastic ray tracing uses statistical techniques to predict the pathways based on the chance of reflection and refraction, deterministic ray tracing entails estimating the precise paths of the sound waves. Both approaches are employed in various applications and each has merits and disadvantages[15-17].

Deterministic Ray Tracing:

The method of deterministic ray tracing calculates the precise pathways of sound waves. Its foundation is in the laws of geometrical optics, which presuppose that the wavelength of sound is substantially smaller than the size of the surrounding objects. The process is breaking down the environment into smaller components or cells, and then determining the sound waves' paths through each cell. At each cell-to-cell interaction, the Snell's law is solved to determine the sound wave's path. The behaviour of sound waves in the environment can be studied by using a set of rays that depict the wave's course.

Stochastic Ray Tracing:

Stochastic ray tracing is a method for calculating the trajectories of sound waves using statistical techniques. It is based on the principles of probability, which consider the wave's travel to be random. The likelihood of reflection and refraction at each interface between two cells can be calculated to estimate the wave's journey. The process entails producing a lot of rays and then following their courses as they go across the surroundings. Based on the geometry of the surrounding objects and the physical characteristics of the water, it is possible to calculate the likelihood of reflection and refraction at each interface. The method creates a

statistical distribution of the sound wave trajectories that can be used to study how sound waves interact with their surroundings.

3.1 Ray Theory:

We follow a heuristic method based on Snell's law, which is represented as, "The ray acoustics theory can be found in most literature and will not be duplicated here

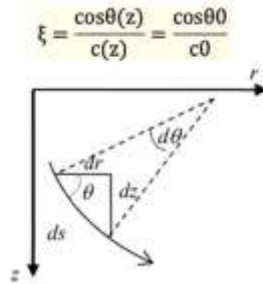


Figure III:1 radius of curvature

Figure shows that the radius of curvature is

$$R = \frac{1}{\sin\theta} \frac{dz}{d\theta}$$

Snell's law states that the ray angle is a function of depth when the sound speed varies with depth. The ray's radius of curvature at depth z is given by taking the derivative of the previous equation with respect to

$$R(z) = - \frac{dz}{dcos\theta} \frac{1}{dz} = - \frac{1}{\xi g(z)}$$

The ray parameter and the regional value of the sound speed gradient g , thus, determine the ray curvature at every point in space (z). The gradient's positive or negative sign controls whether R 's sign is positive or negative, and consequently, whether the ray path curves downhill or upward.

3.2 Geometric Ray Tracing:

By following the rays of sound across the environment while taking into consideration the geometrical characteristics of the environment, geometric ray tracing is a ray tracing technique used to simulate the propagation of sound waves. It has been frequently utilized in multipath channel modelling in underwater acoustics and is a computationally efficient method.

The constraints of geometric ray tracing have been examined in earlier research works. According to several research, the interaction of sound waves with barriers is not adequately modelled by geometric ray tracing, which causes errors in the multipath channels that are predicted. According to other research, geometric ray tracing fails to effectively capture the channel's time-varying characteristics, which results in errors in the expected received signal.

3.3 Hybrid Ray Tracing:

Hybrid ray tracing is a ray tracing method that precisely models the interaction of sound waves with obstructions by combining geometric ray tracing and physical optics. It accounts for the diffraction and scattering of sound waves, which geometric ray tracing cannot effectively simulate.

The benefits and drawbacks of hybrid ray tracing have been examined in earlier studies. According to several research, hybrid ray tracing may accurately forecast multipath channels, especially in challenging situations with barriers. Longer simulation times are a result of hybrid ray tracing's higher computing cost compared to geometric ray tracing, according to other studies [24].

3.4 Dynamic Ray Tracing:

By simulating the propagation of sound waves through the environment while considering the changes in the medium's properties over time, dynamic ray tracing is a ray tracing technique that takes into account the time-varying nature of the channel.

The benefits and drawbacks of dynamic ray tracing have been examined in earlier studies. According to some studies, dynamic ray tracing may accurately forecast multipath channels in settings that change over time. Longer simulation times are a result of dynamic ray tracing's higher processing cost compared to geometric ray tracing, according to other studies.

3.5 Bellhop:

For forecasting acoustic pressure fields in ocean environments, the BELLHOP beam tracing model is used. An especially straightforward algorithm is produced by the beam tracing structure. With both physics- and geometry-based spreading principles, several different forms of beams, including hat-shaped and Gaussian beams, are implemented.[8]

To create reliable communication protocols, underwater acoustic communication systems rely on precise modelling and simulation of multipath propagation phenomena. A popular software programme for multipath channel modelling in underwater acoustics is BELLHOP (Boundary Element Limited-Area Model for High-frequency Acoustic Propagation). This review article gives a thorough summary of BELLHOP's features, uses, and contributions to solving multipath channel modelling problems. The examination covers the fundamental ideas, significant innovations, and developments in BELLHOP as well as the difficulties in simulating underwater multipath channels. It also emphasizes the value of BELLHOP in assessing system effectiveness and developing effective underwater communication systems.

Transmission loss, eigenrays, arrivals, and received time-series are just a few of the useful outputs that BELLHOP can generate. The top and bottom bounds (altimetry and bathymetry), as well as the sound speed profile, might be range dependent. The setting of directed sources and geoacoustic parameters for the boundary media is made possible by additional input files. Also available may be top- and bottom-reflection coefficients.[48]

Utilized across several operating systems (Mac, Windows, and Linux), BELLHOP is implemented in Fortran, MATLAB, and Python.

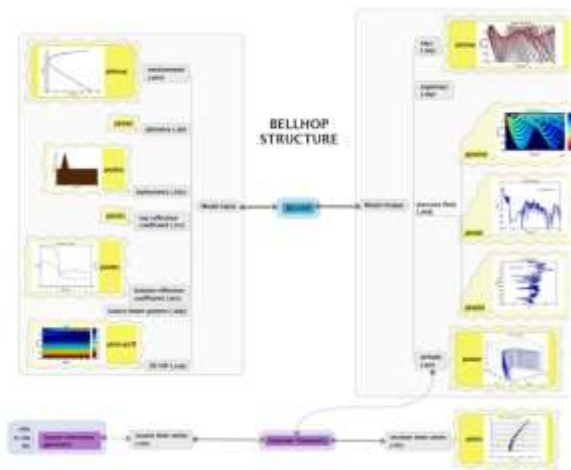


Figure III:2 Bellhop Structure

IV. SOLUTIONS

The difficulties in multipath channel modelling utilising ray tracing methods in underwater acoustics have been addressed in a number of ways. These solutions consist of:

1. Hybrid Models:

In order to increase the model's accuracy, hybrid models integrate ray tracing with other simulation techniques like finite element or boundary element methods. Hybrid models may depict both the scattering and diffraction effects as well as the wave-like character of sound propagation.

2. Data Assimilation:

The measured data can be incorporated into the model to increase model accuracy using data assimilation techniques like inverse modelling. Techniques for data assimilation can decrease the amount of data needed and increase the model's dependability.

3. Adaptive Ray Tracing:

Adaptive ray tracing techniques reduce computing time while preserving accuracy by adjusting the number of rays dependent on the complexity of the environment. The model's effectiveness can be increased while the computational cost is decreased by using adaptive ray tracing techniques.

4. Calibration:

A careful calibration of the model can increase its accuracy and guarantee that it faithfully mimics the real world. Calibration calls very precise measurements and thorough analysis, yet it can greatly increase the model's dependability.

V. CONCLUSION

Underwater acoustics' multipath channel modelling with ray tracing methods is a potent tool for comprehending the behaviour of sound waves there. The technique must overcome several obstacles, including those related to calibration, data needs, model correctness, and environmental complexity. However, several methods, such as hybrid models, data assimilation, adaptive ray tracing, and calibration, have been put forth to address these issues. These techniques have the potential to increase the multipath

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