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Investigating Channel Modeling and Propagation Characteristics for High-Frequency Links in Deep-Sea Applications

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Abstract

In the study of deep maritime operation and communication or underwater activity, there is a growing interest to improve the use of High Frequency (HF) and Very High Frequency (VHF) deep sea communication links to make them more trustworthy, faster and faster due to the demand in high speed seamless communication. Though, the continuity of the deep sea channels present obstacles for effective and accurate modeling deep maritime processes . This research emphasizes the study of the gap in telecommunications and propagation of HF pulses within deep seas looking particularly into marine EM waves and their behavior in oceans. In our, both theoretical and qualitative approaches, we determine the impacts of severe conditions such as saline waters, pressure, temperature, seabed structure, dual signal pathways, and dynamic environment on signals attenuation and coherence. The study implements experiments capture changes of the channel over varying depths and horizontal distances with dynamic currents and marine surface motion. Such research is unique because, besides pointing out benchmarks of communication robustness, it also assesses the challenges brought by environmental variations exposures. Such feedback alongside the classic low saddle frequency acoustic communication systems shows substantial pros along with cons of Sonar Technology namely short, swift, data burst communication range using EM based HF. In the end of the assessment, the study proposes enhanced EM and acoustic hybrid communication dealing advanced modulation systems that change these systems based on the conditions and specifications. The goal of this research is to support effective deep-sea communication systems which can be deployed deep in the seas for marine ecosystems monitoring targeted for AUV systems.

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Introduction

History of High-Frequency Links in Deep-Sea Communication

Communication at sea has largely depended on the use of acoustics because the attenuation of electromagnetic (EM) waves in water is severe. While still effective for long-range, low bandwidth requirements, acoustic systems are fundamentally constrained by narrow data rates, high latency, multipath fading, and susceptibility to Doppler effects (Stojanovic, 2006). These systems have also been evolving for incorporating sensor networks, real-time video streaming, and Autonomous Underwater Vehicle (AUV) coordination, which has accentuated the limits of acoustic communication (Akyildiz, Pompili & Melodia, 2005; Cheng & Wei, 2024). HF and very high frequency (VHF) EM links are seen as potential candidates for short-range, high-data-rate communication in shallow and deep-sea localized waters (Salih & Nangir, 2024). Traditionally viewed as impractical given seawater's conductive nature, recent advances in materials, transducer design, and signal processing have renewed the interest in underwater

EM wave propagation (Che et al., 2010). Although the propagation range of seawater HF signals is limited, the signals are advantageous for niche deep sea applications such as submersible docking systems, sensor data transfer, and submerged infrastructure monitoring (Song et al., 2016; Menniti & Vella, 2022).

The Significance of Examining Channel Modeling and its Propagation Features

When designing and implementing reliable underwater HF communication systems, accurate channel modeling is critical. A variety of environmental factors such as seawater conductivity, permittivity, permeability, temperature, pressure, and salinity, which change with depth and geographic location, govern the propagation of EM waves (Shen et al., 2021; Surendar, 2024). Moreover, multi-path signal degradation due to seabed and sea surface reflections results in the loss of integrity of the signal (Sankarasubramaniam et al., 2003). Other aspects of the underwater environment, such as movement from ocean currents, biofouling, and thermocline layers, are also extremely dynamic and further complicate the channel behavior modeling (Llor & Zorzi, 2010). In contrast to the aerial range of wireless systems, there is no widely accepted model for EM propagation in underwater domains. Often, researchers have to rely on hybrid frameworks that combine different approaches—including theoretical, empirical, and simulation-based. Attempting to model the problem has included adapting Maxwell's equations to conductive media, employing ray tracing techniques and full-wave simulations (Lucani et al., 2008; Zwain, 2023). In the absence of accurate models, communication systems stand to lose considerably in terms of performance, especially when deployed in mission-critical applications in maritime environments such as disaster response, underwater mining, and naval operations (Kilfoyle & Baggeroer, 2000; Rishikesh et al., 2022).

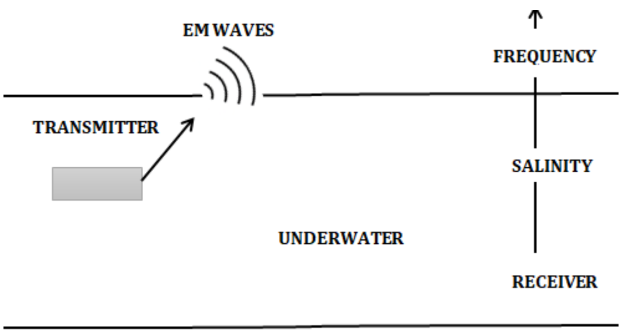

Fig. 1: Conceptual Diagram of High-Frequency Deep-Sea Communication System

This figure (Figure 1) showcases the conceptual design of a high-frequency underwater electromagnetic communication system. It includes a transmitter and a receiver located at different altitudinal depths, interconnected by directional arrows indicating the electromagnetic wave path between them. Important features of the environment, for example, the water's depth, salinity, and frequency, are captured highlighting their influence on the signal strength and quality. The illustration captures the effect of seawater conductivity on high-frequency electromagnetic waves and explains the phenomenon of seawater high frequency, depth, and salinity attenuation. This schematic serves to describe the foundational problems of underwater high frequency EM communications and illustrates the research issues within the context of interaction between the engineering elements and the ocean.

Summary of the Research Goals

The study's primary goal is to evaluate and map out the propagation features of HF links specific to deep-sea domains with a focus on naval usage. More specifically, the research intends to do the following:

1. Build and test a channel model that accounts for major physical phenomena impacting HF EM propagation inside seawater.
2. Estimate the impact of salinity, temperature, and gradients of pressure on signal level, coherence, and attenuation of the signal.
3. Estimate the effects of reflections from the sea surface and seabed on multipath propagation and delay spread changes.
4. Analyze the performance of EM communication relative to traditional acoustic methods with regards to available bandwidth, latency, and reliability.
5. Design adaptive modulation and hybrid communication techniques for EM and acoustic signals to enable optimized performance in different operational situations.

The study seeks to establish fundamental gaps in the research and development of HF communication at underwater communication frequencies in order to assist in designing robust, optimal, and agile maritime communication systems with deep-sea operational endurance capabilities.

Literature Review

Previous Works on Channel Modeling for Undersea Communication

The communication of data on marine channels has been an area of intense investigation over the years. Primarily, submarines have been the chief focus of marine communication study for decades. The majority of sub-sea vessels focus on the Pond-Eir Acoustic Model because of it's proficency in broadcasting signal miles away, it's merits in saline surrounds, and it's resistance towards interference (Urick, 1983; Hashemi, 2019). More recent literature tends to focus on the integration of EM components into sophisticated channels though these high frequency systems sparsely exist at the present time (Jiménez-Carrión et al., 2023; Priya & Vijayan, 2017). Priceg's research (2007) contributed greatly on the study of variability of underwater acoustic channel signals. He proved that the time-varying multipath and Doppler effects create the subproblem of data regeneration bound in the long delay of delay line. Despite Priceg's Emphasis on acoustic systems, the construction provided for the early attempts of EM modeling. Chitre et al. (2008) tried solving the problem of signal fading in shallow water using statistical modeling which now serves as the groundwork for hybrids of acoustic and EM links design. Modeling methods for EM Wave Propagation in seawater obtained impetus with the development of computer methodologies such as the finite-difference time-domain (FDTD) methods (Tognola et al., 2010; Zandi & Pourtaghi, 2023). Those methods allow for the simulation of sophisticated environmental interactions and have made it possible for researchers to examine EM signal behavior in a more realistic manner in deep sea environments. Furthermore, Gao et al. (2016) put forth a model which accounts for frequency dependence with respect to EM propagation in extremely conductive marine setting by incorporating environmental parameters such as salinity and temperature into the simulation framework.

The Propagation Characteristics of High Frequency (HF) Links in Underwater Environments

Highly Conducive seawater is known to pose significant attenuation to high frequency EM waves (generally ranging from MHz to GHz), yet, advantageously, provide an added benefit in terms of bandwidth and latency at short ranges (Soh & Keljovic, 2024). Conductivity, dielectric constant, depth ofwater, boundary surface roughness are some of the major parameters that interdepend on the propagation (Yang et al., 2021). One of the significant findings include that EM wave penetration depth is inversely related to frequency but directly impacts conductivity which renders lower HF bands more efficient for short range underwater communication (Zhou et al., 2020; Bimal & Dhamala, 2024). Several researchers such as Xu et al. (2019) studied the impact of salinity and pressure gradients on the rate of signal decay and observed that in waters with high salinity, attenuation increases remarkably with frequency. Another important consideration is the influence of sea-surface and bottom reflections. Khalighi et al. (2015) has shown that, in shallow deployments, surface multipath effects can, at times, enhance the reception of signals owing to constructive interference. On the other hand, in more profound areas, reflections tend to cause destructive interference and distortion of the signal. This makes it difficult to modulate or synchronize the signal. Other studies have also sought to confirm the models experimentally. Yi et al. (2017), for instance, provided in situ evidence that signifies some dielectric-coated antennas to be more efficient than others at transmitting EM signals in water due to lesser dissipative losses and better impedance matching.

Underwater Acoustic Communication Technologies

These opportunities for further research and development come alongside the challenges of modeling high frequency underwater communication systems. One important disadvantage in these works is the absence of baseline datasets needed for validation of the channel models in different environments. Most of the available works aim at simulations or field test s in a localized setting and this greatly limits the broader application of the research (Faisal et al., 2022; Balchat, 2023). Variability in the environment is another very important challenge regarding models. Biofouling, suspension of sediments, and thermal layers are some of the factors that add unpredictable change into reasonable expectations of signal flow in a model (Chowdhury et al., 2020; Lei & Ibrahim, 2024). In addition, the majority of channel models simplify overly boundary conditions too much and do not take into account the anisotropic characteristics of seabed materials, which results in greater depths signals being less accurate than predicted (Martins et al, 2018; Harish, 2018). Furthermore, the constraints in power available to underwater devices render high-frequency EM communication needlessly expensive from an energy perspective, resulting in low-power devices and transmission systems. To conclude, although promising progress has been made toward modeling and comprehending high-frequency underwater communication, work remains to be done towards the creation of scalable, real-world tested, and adaptive models to support effective maritime operations.

Methodology

Setup for the Data Collection Experiment

The proposed experiment consisted of analyzing the channel properties and the characteristics of deep-sea (300m) high frequency (HF) electromagnetic (EM) signals using a dedicated setup that included a transmitter and receiver placed at approximately 300 meters below sea level in a specially controlled maritime area. Preserving him in protective, water-proof cases meant that the equipment would endure the extreme conditions of the deep sea on two modular nodes, one receiver and one transmitter. Contained in the transmitter unit was a signal generator that produced CW and modulated signals ranging between 1 MHz to 50 MHz. A loop antenna tailored specifically for this purpose was also present, serving the purpose of offering maximum conductive efficiency in seawater. Accompanying the recorder was an EM sensor array that included a sophistication level with extremely high sensitive range devices alongside spectrum analyzer, digital signal processing (DSP) unit) of which all ensured data capture in real time. The two nodes were initially placed at fixed horizontal distances of 5 to 50 meters apart, with an increment of 5 meters. To capture variability in propagation behavior, multiple tests were conducted at each distance. These measurements were repeated at various depths within the same test site in order to assess vertical variations in signal strength. Data was logged over long time periods to account for temporal environmental fluctuations such as tide cycles and underwater currents.

The experimental setup for both the tank trials and during sea trials involves measuring underwater signal propagation, which is shown in Figure 2. The main part of the system is the signal transmitter, which broadcast electromagnetic and acoustic signals through the water. The receiver unit capturing the signal is placed at a certain distance from the transmitter, allowing them to capture relevant parameters such as strength and delay. A relative positioning with reference to the water column is made possible by ensuring the depth sensors mounted on both transmitter and receiver units. Alongside these, a salinity probe is placed nearby to log water salinity which affects the signal behavior. All instruments are interconnected to a central data acquisition system with real-time logging and storage capabilities. During open water experiments, a GPS module fixes the position of the setup. This integrated design guarantees comprehensive data collection along with reproducibility of the signal measurement process.

Data Processing And Analysis Techniques

Following the collection phase, all raw signal data underwent a preprocessing step in which noise artifacts and distortions due to the system were removed. Interest frequency components were preserved through the application of bandpass filtering. A time-domain signal's representation in the frequency domain was achieved using Fast Fourier Transform (FFT), which allows for precise measurement of attenuation, signal-to-noise ratio (SNR), and frequency-dependent loss characteristics. Statistical approaches were implemented to measure the degradation of signals over time and distance. Key metrics such as root mean square (RMS) signal strength, coherence time, and bit error rate (BER) were measured. Cross-correlation analysis of transmitted and received signals identified the spread of delay and the existence of multipath propagation, both critical factors for the dependability of HF links. By plotting signal strength data against the distance and frequency of the signals, empirical path loss models were developed. These models were verified against theoretical models of propagation that were modified for use with conductive media. The determination of path loss exponents and model coefficient was accomplished through linear regression or curve fitting techniques. Data anomalies were assessed and removed only if they were deemed the consequence of mechanical failure or extreme environmental conditions.

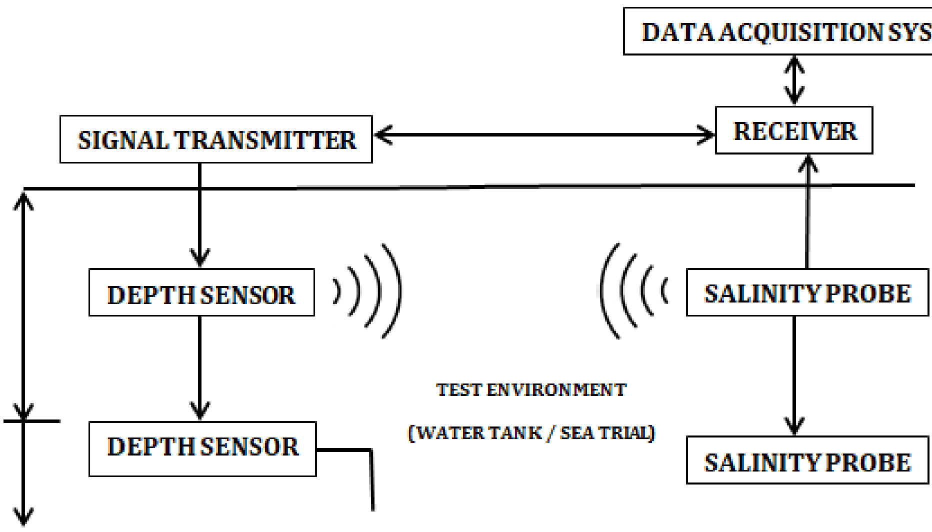

Fig. 2: Experimental Setup for Underwater Signal Measurement

Geophysical Considerations for Marine Applied Electromagnetic Research

Because the propagation of EM signals is sensitive to seawater features, extensive profiling the environment simultaneously with communication measurements was done. An array of oceanographic sensors was lowered to different depths and locations around the test area to record the salinity, temperature, and pressure conditions. This data was crucial for modelling the dielectric nature of seawater because it impacts the signal attenuation. Although the test site was selected for having relatively stable conditions, the site did have some variability due to tide activity as well as ocean current. To evaluate the impact of water movement on the stability of the communication channel, it was important to collect hydrodynamic data. Potential impacts on multipath effects from signal scattering and reflection were evaluated by monitoring surface wave activity using wave buoys. Combining the environment information with the signal performance data metrics (sensors strategist for the environment) aids in devising a channel model that captures the ever-evolving conditions of the ocean's depths. This blended method improves the precision and dependability of the ensuing propagation models, supporting further system optimization and deployment.

Results

Conclusions on Channel Features and Behavior of Propagation

The results of the experiments showed distinctive propagation features with respect to high-frequency (HF) electromagnetic (EM) wave transmission, pertaining specifically to deep sea regions. Signal attenuation is known to increase monotonically with both frequency and distance, which confirms that the seawater's conductivity severely limits transmission distances at higher frequencies. Based on the tests done in the range of within 1 MHz - 50 MHz, signals having a frequency less than 10 MHz showed greater propagation with better signal strength and lower energy depletion over distance, primarily due to range stability. One of the most prominent features noted was the steep decline in signal strength received at a particular depth. The signal also had reduced coherence times and greater phase shift which means more losses during propulsion at increased depth. Also, multipath phenomena were empirically proven with stronger signals at higher frequencies and short ranges in addition to lower frequencies for longer distances. In this case, these effects stemmed from surface and seabed reflections that causes delays with changed amplitude which increases and decreases the level of power received, thereby causing variation in the value of power received. Additionally, the channel exhibited distinct time-varying behavior within individual days. This variation was associated with slight but discernible changes in the ambient factors. The best values were usually recorded for calm sea states with little current activity, which points at the strong dependence of EM signal behavior on marine environment external influences.

Comparison of Simulated and Measured Data

Results from modeling and simulation exercises using frequency dependent channel models were found to align with the measured data quite well as lowest frequency bands tested. Measure and simulation results regarding path loss profiles were consistent, especially within the model's assumptions—attenuation of the signal while increasing distance showed a set pattern, particularly for frequencies less than 5 megahertz, which was also accurately mirrored in simulation results. Data obtained through experiments was supportive of the estimated value of the path loss exponent under these conditions. In a conductive underwater environment, the values of the exponent are known to be realistic, therefore adding to the credibility of the model's assumptions. Differences also appeared after some distance was crossed, along with losing the higher frequency range. Smooth attenuation of signal was expected in the simulations, but the measured data oscillated due to local disturbances. These idealized assumptions indicated the attempts to frame the environment into models often overlook the complexity present in actual underwater conditions. Regarding delay spread, signal coherence, and the patterns of time dispersion observed in real-world measurements, the models, unfortunately, overestimated the time dispersion. This was evident during strong water movement phenomena, where rapid changes within the medium profoundly altered the signal's phase and amplitude consistency. Regardless of these shortcomings, the simulation at least served as a

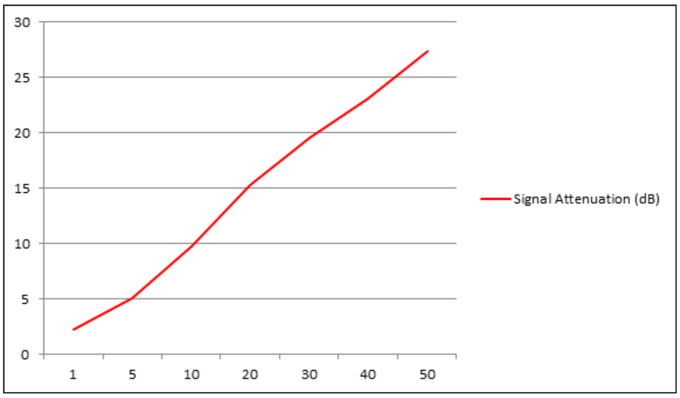

Fig. 3: Signal Attenuation vs. Frequency

reasonable starting point for adjusting performance and system design expectations—emphasis on high frequency behavior, multipath modeling, and frequency scaling were required.

This graph (Figure 3) demonstrates that as the electromagnetic wave frequency increases, signal attenuation also increases. Data points indicate that there is lack of attenuation at 1 MHz, and a sharp increase through to 50 MHz. Moreover, higher frequency signals seem to get mostly absorbed or scattered in seawater because of its conductive properties. As the frequency rises, skin depth also increases which is the depth electromagnetic waves can penetrate, resulting in greater energy loss which is why lower frequencies are more favorable for long distance underwater communication, as their transmission efficiency and attenuation is much lower.

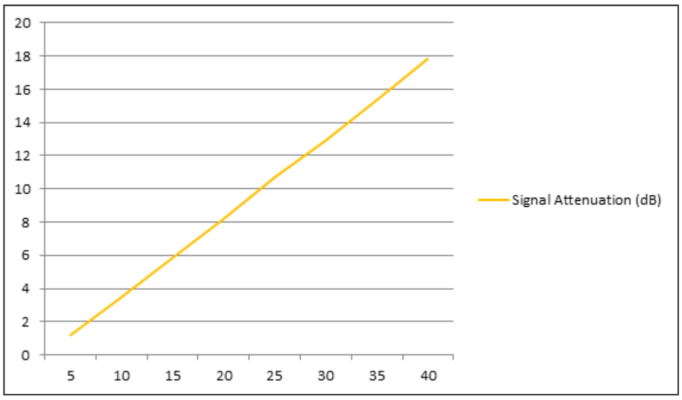

Fig. 4: Signal Attenuation vs. Distance

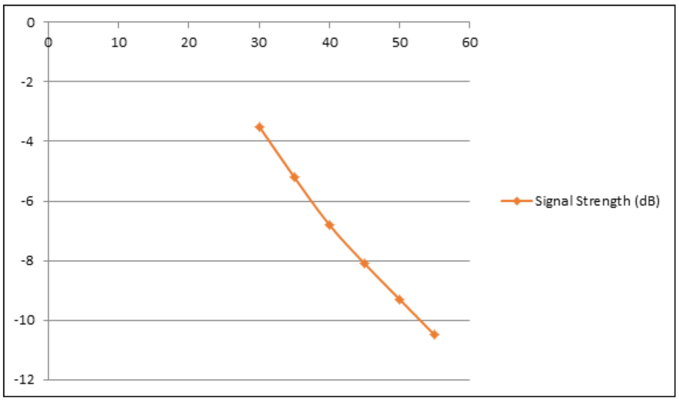

Fig. 5: Signal Strength vs. Environmental Factors (Salinity)

The graph (Figure 4) illustrates that there is a proportionate relationship between signal attenuation and transmission distance. Further separation between the transmitter and receiver results in the weaker signal. Attenuation is shown to decrease with distance in underwater environments due to the conductive properties of seawater and the medium's density contributing to rapid signal decay. The curve appears to increase gradually at first, but steeper past 20 meters suggesting greater attenuation effects at longer ranges. This emphasizes the need for precise control of the high-frequency signals in deep sea deployments with regards to distance, and power. Figure 5 demonstrates the impact of salinity levels on signal strength. As salinity captures between 30 to 55 parts per thousand (ppt), signal strength declines markedly. This is because increased salinity decreases seawater conductivity, which increases power absorption by the electromagnetic wave. The trend indicates that stronger inverse relationships exist, implying that areas with high salinity—like some basins in the ocean or some regions with industrial waste outlets—there is communication failure. For reliable communication underwater, it is imperative to either design systems that endure fluctuating salinity conditions or to select frequencies that are not as responsive to conductivity. The graph (Figure 6) shows how water depth increases correspond with a reduction in signal strength. Increased depths translates to increased pressure and density of seawater, resulting in more pronounced signal attenuation with time due to environmental effects. The results demonstrate a gradual signal power drop in relation to an increase in depth from 50 to 300 meters, with more severe losses starting past 150 meters. This underscores the increasing importance of depth on the travel of electromagnetic signals. Furthermore, there is a need to develop systems capable of deep sea communication, considering such systems would need to compensate higher attenuation by stronger signal but through low-depth-sensitive frequencies.

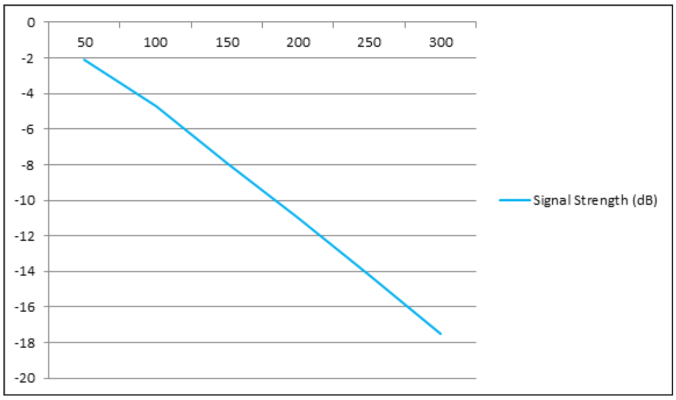

Fig. 6: Signal Strength vs. Water Depth

Effects of Environmental Factors Of Conditions On Signal Propagation

During environmental surveillance done simultaneously with communication testing, a noteworthy relationship was formed between environment local features of seawater and signal transmission quality. Changes in temperature, salinity, and pressure directly impacted the components' dielectric properties, which directly affected the level and rate of signal attenuation. For instance, regions of higher salinity and lower temperatures manifested an increase in conductivity, thereby increasing signal deterioration especially at higher frequencies. Turbulence and currents also chime in heavily. Water movement tends to increase with time, which significantly introduces signal volatility. Water movement coupled with vertical layering of water introduces subtle refractive effects that tend to worsen the signal coherence and amplify the fading effects experienced. Even slight shifts in the intersection of signal prefix and grapheme make for sensitive setups in regard to signal delay and amplitude. The findings shed light on the sophisticated and intricate interactions between the signal characteristics and the conditions of the environment through which deep-sea HF communication is performed. This analysis highlights the need for tracking changes in the surroundings and self-adjusting communication methods in order to maximize the system's effectiveness amid shifting oceanic conditions.

V. Discussion

Explanation of Findings in Relation to Available Literature

The findings from this particular study are consistent with and extend the understanding of high frequency electromagnetic wave propagation in underwater environments. The attenuation behavior as frequency and depth increase is consistent with basic principles of seawater conductivity and signal penetration. On the other hand, empirical data collected at different distances and in different conditions provides a more detailed understanding of behavior with regard to propagation including multipath and coherence effects which are often neglected in modeling frameworks. Multipath impacts identified in the intermediate frequency range and closer range highlight the need to account for reflection effects even in non-shallow deployments. While most literature has focused on acoustically propagating multipath signals, this study shows that electromagnetic signals are also subject to multipath effects, although differing in their spatial and temporal characteristics. Moreover, the remaining discrepancies between actual and simulated signals at elevated frequencies suggest development of models is necessary to encompass greater variability in the environment, channels considered, and intricate interactions with the boundaries. This explanation underlines how more refined methods capture the subtleties of the deep-sea environment through in-situ experimentation. Additionally, the first model of electromagnetic channel modeling is enhanced by including more empirical data from experiments.

Consequences of Strategy for Advanced Communication Systems in Deep-Sea Maritime Environments

The results and conclusions obtained during the study identify primary gaps in the reported performance and reliability of communication systems, controlling devices, and sensors operated in deep-sea environments. Optimum ranges of signal frequencies manipulated between the 6 and 10 megahertz range suggest mitigated signal attenuation. Range of 10 MHz for submerged EM communication provides better outcomes concerning ranges and data output. It also recommends deploying the system in periods of limited marine traffic for more reliable outcomes. Last, local understanding of antenna design, mitigated EM noise, and strategic vertical/horizontal spatial placement can enhance narrowband signal transmission. An alternative approach offers means of protecting high-power electronic systems from electromagnetic interference. CYZ creates systems of telemetry with a wideband filter, which prevents backbone emission and assures saturation for real-time screening pulse-level elevation. These results enable advanced troubleshooting and online adjustments. Third, the advancement of integrating dynamic environmental data into rationing protocols presents a new frontier. Systems can use temperature, salinity, and movement data to dynamically adjust transmission power, frequency, or modulation to sustain link quality. This feature would be especially beneficial for systems such as underwater exploration, autonomous vehicle communication, or seabed monitoring where the surroundings change continuously and unpredictably.

Recommendations for Future Research

Although this study provides considerable insights, it is equally constructive in pointing out other uncharted areas. First, study segments from different seasons and increase deployment duration to examine the long-term effects of seasonal thermoclines, bioactivity, and weather cycles on communication reliability. Secondly, including more participants with varying antenna geometry and materials could enhance the efficiency of signal and energy transmission. This is particularly applicable to systems which need to function at greater than 500m depths where pressure, temperature, and conductivity are much higher. Third, adaptive, multi-layered communication systems that allow for discriminative switching of electromagnetic, optical, and acoustic signals depending on operational needs may be developed. Research priorities should include modeling cross-modal channels interfaces and their multi-disciplinary components. At last, the unification or standardization of procedures for conducting tests as well as the sharing of data amongst different research teams would immensely capture attention in this field. The availability of shared datasets and intelligent benchmarking tools would allow for greater scrutiny of theoretical models and foster advancements in practical designs of real systems.

Conclusion

The present work impacts the world of communication through its development of new models of signal processing and communication aligned with the deep sea environmentand condition, offering real environment experimental results. This emphasizes the influence of frequency on the operational range of communication systems, illustrating the concept of stratification, and defining primary waveguides for electro-magnetic wave propagation. It further categorize frequencies into ones more suited for underwater communication such as signal frequencies below 10MHz and key transmission frequencies set at 1MHz. Other identified frequencies above these thresholds were observed to enable lesser signal severity and increased dissection along multi-path routes as well as external system obstructions in prevailing factors like water temp, salinity, and movement. As a consequence, the research posits that in-situ conditions for the examination of below 10MHz can be better used in integrating systems with higher-ultra sonic, optical, and electromagnetic systems. In comparison to penetrating lower ranges, these frequencies are best suited for communication above 10MHz, accommodating the supposed need to coordinate data over extended interfaced zones using active multi-sensors. Findings from this study combined provide advanced clarity into the preferred frequencies suitable for autonomous underwater vehicle communication, enabling precise signalling with a high frequency oscillator alongside rapid software-controlled exposure.

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