iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** I **Month of publication:** January 2026

DOI: https://doi.org/10.22214/ijraset.2026.76985

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue I Jan 2026- Available at www.ijraset.com

Analysis of Behaviour of EM Waves with Different Environmental Factor in Underwater Communication

Girish Kumar Tiwari[1], Pankhuri Vapta[2]
Dept. of Electronics & Communication Engineering, Ujjain Engineering College, Ujjain

Abstract: Electromagnetic (EM) wave–based underwater communication has emerged as a promising alternative for short-range and low-latency applications where acoustic and optical techniques face inherent limitations. However, the propagation behaviour of EM waves in seawater is strongly influenced by environmental factors such as frequency, salinity, depth, and medium stratification, which significantly constrain system performance. In this study, a comprehensive simulation-based analysis is carried out to investigate the behavior of electromagnetic waves in underwater environments under varying environmental conditions. A MATLAB-based numerical framework is developed to evaluate key propagation characteristics, including attenuation, path loss, penetration depth, phase delay, and the effects of layered seawater models, over a frequency range of 10 kHz to 100 MHz. Based on the obtained results, two practical design-oriented outcomes are derived: a frequency–distance feasibility map that delineates operational and non-operational regions for underwater EM communication, and a critical frequency threshold that defines the maximum usable frequency as a function of seawater salinity. The results reveal that attenuation increases sharply with frequency and salinity, layered seawater structures introduce additional propagation losses, and feasible communication ranges rapidly shrink at higher frequencies. The proposed analysis and derived feasibility metrics provide valuable insights and practical guidelines for the design and optimization of underwater electromagnetic communication systems under realistic environmental conditions.
Keywords: Underwater electromagnetic communication, seawater propagation modeling, frequency–distance feasibility analysis, critical frequency threshold, layered seawater effects.

I. INTRODUCTION

Underwater communication is a fundamental requirement for marine applications such as autonomous underwater vehicles, environmental monitoring, offshore inspection, and defense systems. Reliable data transmission in underwater environments remains challenging due to the complex electromagnetic and physical properties of seawater and the strong influence of environmental conditions on signal propagation. Acoustic and optical communication techniques dominate existing underwater systems but suffer from inherent limitations. Acoustic communication offers long-range capability at the expense of low data rates, high latency, and sensitivity to noise and multipath effects. Optical communication enables high data rates but is severely constrained by absorption, scattering, turbidity, and alignment requirements, limiting its applicability in realistic underwater environments. Electromagnetic (EM) wave–based communication has recently emerged as a promising alternative for short-range and shallow-water applications due to its low latency and robustness to turbidity. However, the high electrical conductivity of seawater causes severe attenuation of EM waves, making system performance highly sensitive to environmental factors such as frequency, salinity, depth, communication distance, and medium stratification.

Although prior studies have examined EM wave attenuation and penetration in seawater, most investigations consider isolated parameters or assume homogeneous media, offering limited guidance for practical system design. In particular, clear operational boundaries linking frequency and communication range under realistic environmental conditions remain insufficiently addressed.

To address this gap, this paper presents a simulation-based analysis of underwater EM wave propagation using a MATLAB framework that accounts for environmental variability and layered seawater structures. Key propagation metrics—including attenuation, path loss, penetration depth, and phase delay—are evaluated over a wide frequency range. Based on these results, two design-oriented outcomes are derived: a frequency–distance feasibility map that identifies operational limits and a salinity-dependent critical frequency threshold defining the upper usable frequency for underwater EM communication. These contributions provide practical insights for frequency selection and range planning in underwater electromagnetic communication systems.

II. PROBLEM STATEMENT AND OBJECTIVES

A. Problem Statement

Underwater electromagnetic (EM) wave–based communication has emerged as a potential alternative to acoustic and optical techniques for short-range and low-latency applications. However, the propagation of EM waves in seawater is severely constrained by the medium's high electrical conductivity and strong dependence on environmental conditions. Parameters such as operating frequency, salinity, water depth, communication distance, and vertical stratification significantly influence attenuation, penetration depth, phase distortion, and overall signal viability.

Although several studies have analyzed individual propagation characteristics of EM waves in seawater, most existing works focus on isolated parameters or assume homogeneous environmental conditions. Such simplified approaches provide limited insight into the practical feasibility of underwater EM communication systems, particularly when realistic operating conditions involve varying salinity, depth-dependent conductivity, and finite communication ranges. Moreover, there is a lack of systematic analysis that translates fundamental propagation behavior into clear operational limits, such as usable frequency bands for a given distance or environment-dependent frequency thresholds.

Therefore, there is a need for a comprehensive study that not only evaluates classical propagation metrics but also derives design-oriented indicators that can guide frequency selection, range planning, and system feasibility assessment for underwater electromagnetic communication.

B. Objectives

The primary objective of this study is to analyze the behavior of electromagnetic waves in underwater environments under the influence of key environmental factors and to derive practical insights for communication system design. The specific objectives are:

1) To investigate the variation of electromagnetic wave attenuation with operating frequency in seawater.\
2) To compare electromagnetic wave propagation characteristics in homogeneous and layered seawater models.
3) To derive a frequency–distance feasibility map that identifies operational and non-operational regions for underwater EM communication.
4) To identify a critical frequency threshold from penetration depth characteristics under varying salinity conditions.

III.SYSTEM MODEL AND METHODOLOGY

A. System Model

The underwater environment is modeled as a lossy conductive medium characterized by permeability μ, permittivity ε, and electrical conductivity σ. Seawater permeability is assumed equal to free-space permeability μ0, while conductivity is treated as a function of salinity and depth.

Under plane-wave propagation assumptions, the complex propagation constant in seawater is given by:

$$\gamma = \alpha + j\beta = \sqrt{\{j\omega\mu\,(\sigma + j\omega\varepsilon)\}}$$

where α is the attenuation constant, β is the phase constant, and ω=2πf is the angular frequency.

The attenuation constant is expressed as:

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^{2}}-1\right]}$$

To represent realistic ocean conditions, two seawater models are considered:

- Homogeneous model, assuming constant conductivity throughout the water column.
- Layered model, where the medium is divided into multiple horizontal layers with depth-dependent conductivity values.

B. Methodology

A MATLAB-based numerical simulation framework is developed to analyze underwater electromagnetic wave propagation in the frequency domain. Simulations are performed over a frequency range of 10 kHz–100 MHz for varying salinity levels, communication distances, and seawater stratifications.

Key propagation metrics—including attenuation, penetration depth, and path loss—are computed from the attenuation constant. Penetration depth δ is defined as:

$$\delta = 1/\alpha$$

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue I Jan 2026- Available at www.ijraset.com

Based on the simulated propagation characteristics, two higher-level design metrics are derived:

1) A frequency–distance feasibility map, constructed from attenuation and path loss constraints.
2) A critical frequency threshold, identified from penetration depth behavior under varying salinity conditions.

This methodology ensures that feasibility limits are derived directly from electromagnetic propagation theory rather than empirical assumptions.

.

IV. RESULTS AND DISCUSSION

A. *Attenuation versus Frequency*

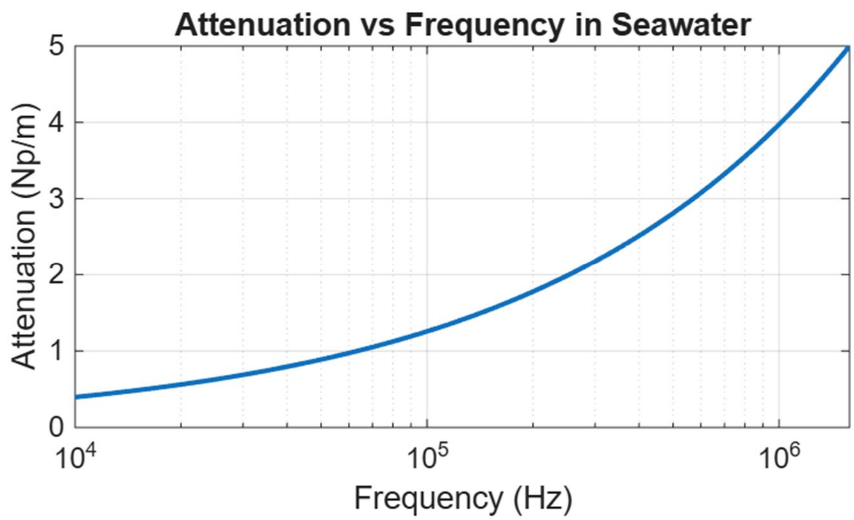


Fig. 1 Attenuation vs Frequency in Seawater

Fig. 1 shows the variation of electromagnetic wave attenuation with frequency in seawater. Attenuation increases rapidly with frequency due to the high electrical conductivity of seawater, which causes enhanced ohmic losses at higher frequencies.

This result establishes a fundamental limitation of underwater EM communication: while lower frequencies experience reduced attenuation and support longer ranges, higher frequencies become impractical due to severe signal loss. This frequency-dependent behavior forms the basis for subsequent feasibility analysis.

B. *Penetration Depth versus Frequency for Different Salinity Levels*

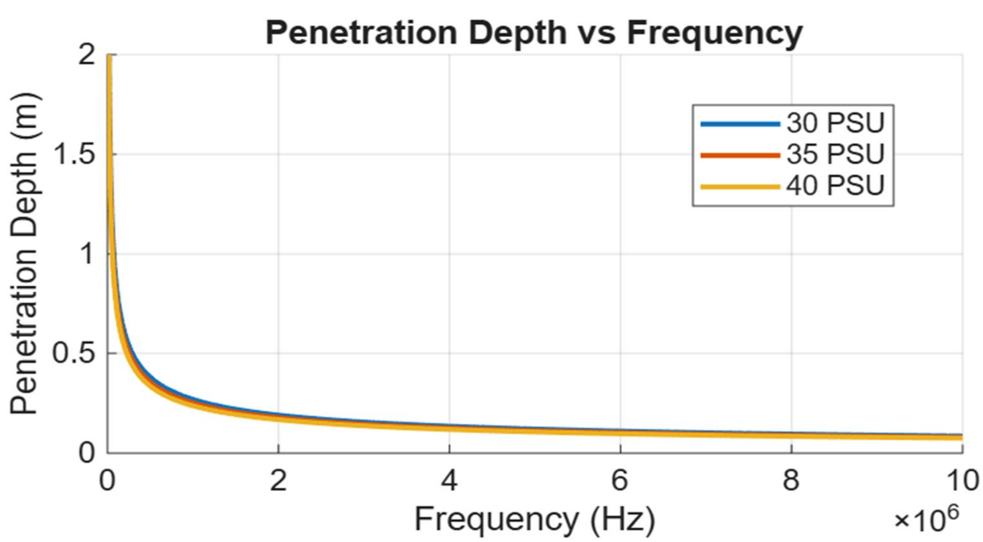


Fig. 2 Penetration Depth vs Frequency

Fig. 2 depicts the variation of penetration depth with frequency for salinity levels of 30 PSU, 35 PSU, and 40 PSU. The results demonstrate a sharp decrease in penetration depth with increasing frequency for all salinity values. Additionally, higher salinity levels result in consistently lower penetration depths across the entire frequency range.

This behavior is explained by the increased ionic concentration associated with higher salinity, which leads to higher electrical conductivity and greater electromagnetic energy loss. These results indicate that environmental salinity plays a critical role in determining the usable frequency range for underwater EM communication.

From the penetration depth characteristics, a critical frequency threshold is identified for each salinity level. This threshold represents a transition point beyond which electromagnetic wave penetration becomes insufficient for practical underwater communication, regardless of transmit power. The observed shift of this threshold toward lower frequencies with increasing salinity highlights the dominant role of ionic conductivity in constraining EM-based underwater systems

C. Homogeneous versus Layered Seawater Model

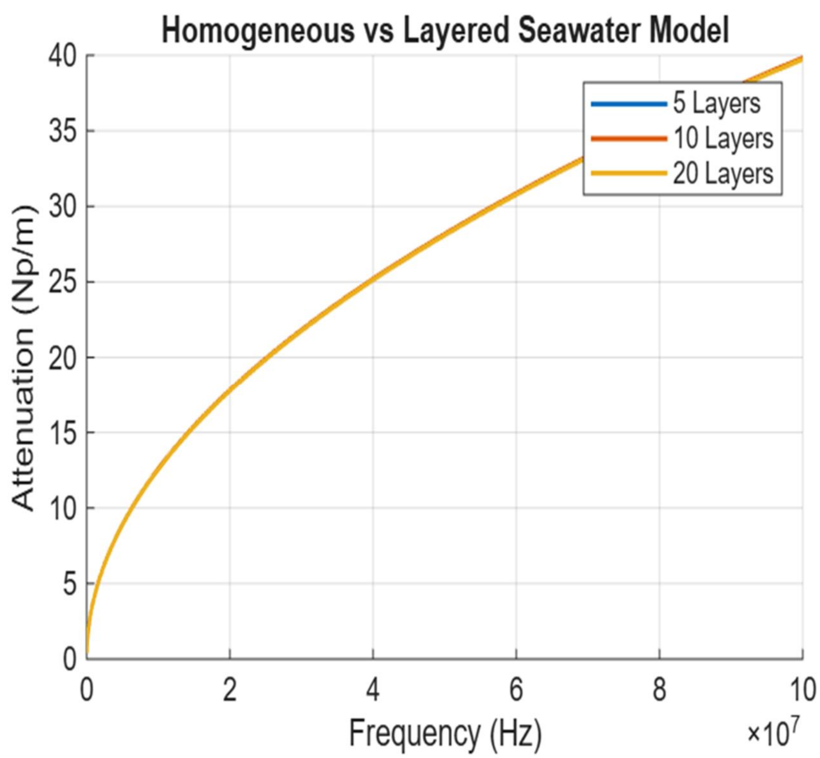


Fig. 3 Homogenous vs Layered Seawater Model

Fig. 3 compares electromagnetic wave propagation characteristics obtained using homogeneous and layered seawater models under identical environmental and operating conditions. In the homogeneous model, seawater conductivity is assumed constant throughout the water column, whereas the layered model accounts for depth-dependent variations in conductivity to represent realistic ocean stratification.

The results show that the layered seawater model consistently predicts higher attenuation and reduced penetration depth compared to the homogeneous assumption. This deviation arises from cumulative losses introduced by conductivity variations across layers, which are not captured in simplified homogeneous models.

These findings indicate that homogeneous seawater assumptions tend to underestimate propagation losses and may overestimate achievable communication range in realistic underwater environments. The observed differences become more pronounced at higher frequencies, where electromagnetic waves are more sensitive to conductivity variations.

This comparison highlights the necessity of incorporating layered seawater modeling when evaluating underwater electromagnetic communication performance, particularly for shallow-water and coastal environments where stratification effects are significant.

D. Frequency–Distance Feasibility Analysis

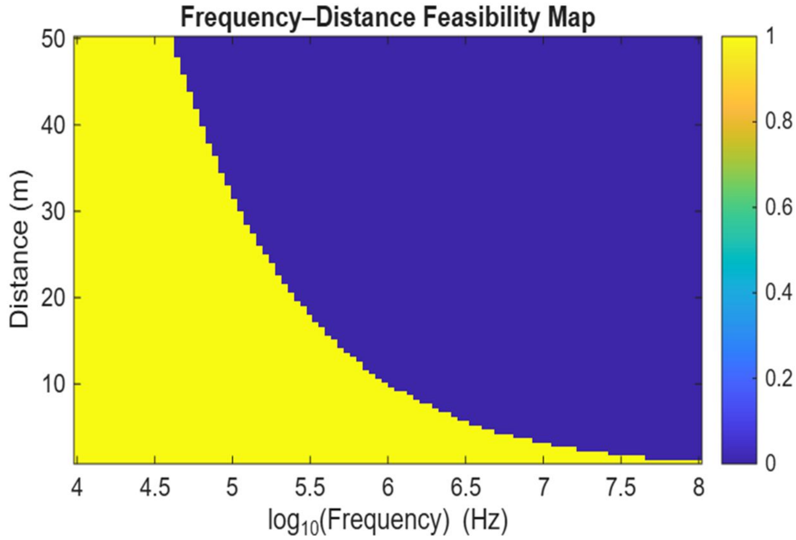


Fig.4 Frequency vs Distance Feasibility

Fig. 4 illustrates the derived frequency–distance feasibility map for underwater electromagnetic communication. The map explicitly delineates operational and non-operational regions based on acceptable attenuation limits.

The results demonstrate that low-frequency signals remain feasible over relatively larger distances, whereas higher frequencies rapidly become non-operational even at short ranges. Environmental factors such as salinity significantly shift the feasibility boundary, underscoring the importance of realistic environmental modeling.

The feasibility map provides an intuitive and practical design tool for frequency selection and range planning in underwater EM communication systems.

V. CONCLUSIONS

This paper presented a comprehensive simulation-based investigation of electromagnetic wave propagation in underwater environments under the influence of key environmental factors, including frequency, salinity, water depth, communication distance, and medium stratification. Using a MATLAB-based numerical framework, fundamental propagation characteristics such as attenuation, path loss, penetration depth, phase delay, and the effects of homogeneous and layered seawater models were systematically analyzed over a wide frequency range.

The results confirm that electromagnetic wave attenuation increases sharply with frequency and salinity, leading to rapid degradation of communication range at higher frequencies. Phase delay was observed to increase cumulatively with depth, indicating potential challenges for phase-sensitive underwater communication schemes. Furthermore, layered seawater models exhibited higher attenuation compared to homogeneous assumptions, demonstrating that simplified models may underestimate propagation losses in realistic stratified underwater environments.

Beyond conventional propagation analysis, this study derived two design-oriented outcomes from the simulation results. First, a **frequency–distance feasibility map** was obtained, explicitly identifying operational and non-operational regions for underwater electromagnetic communication. This representation provides a practical visualization of communication limits and directly links operating frequency with achievable range under given environmental conditions. Second, a **critical frequency threshold** was identified from penetration depth characteristics, defining an environment-dependent upper bound on usable frequency as a function of seawater salinity. Together, these derived metrics translate fundamental electromagnetic behavior into actionable design guidelines.

Overall, the findings demonstrate that underwater EM communication is best suited for short-range applications at low frequencies and that environmental variability plays a decisive role in determining system feasibility. The proposed feasibility-based analysis framework extends existing studies and provides a more practical foundation for the design and optimization of underwater electromagnetic communication systems.

REFERENCES

[1] A. Sommerfeld, Electromagnetic Theory. New York, NY, USA: Academic Press, 1949.

[2] A. J. F. Hales, “The effect of salinity and temperature on electromagnetic wave attenuation in seawater,” Ocean Engineering, vol. 102, pp. 230–239, 2015.

[3] X. Wang et al., “Electromagnetic wave propagation in layered seawater,” Nature Communications, vol. 15, no. 1, 2024.

[4] Z. Ge et al., “Impact of variable seawater conductivity on ocean-induced electromagnetic fields,” Frontiers in Marine Science, 2023.

[5] J. R. Wait, Electromagnetic Waves in Stratified Media. New York, NY, USA: Pergamon Press, 1970.

[6] J. A. Kong, Electromagnetic Wave Theory. Cambridge, MA, USA: EMW Publishing, 2008.

[7] S. Somaraju and J. R. Trumpf, “Frequency, temperature and salinity variation of the permittivity of seawater,” IEEE Trans. Antennas Propag., vol. 54, no. 11, pp. 3441–3448, 2006.

[8] M. Stojanovic and J. Preisig, “Underwater acoustic communication channels: Propagation models and statistical characterization,” IEEE Commun. Mag., vol. 47, no. 1, pp. 84–89, 2009.

[9]] A. Akyildiz, D. Pompili, and T. Melodia, “Underwater acoustic sensor networks: Research challenges,” Ad Hoc Networks, vol. 3, no. 3, pp. 257–279, 2005..

[10] A. Shaw and A. I. Al-Shamma’a, “Underwater electromagnetic communication: Theoretical analysis and experimental results,” Progress In Electromagnetics Research, vol. 134, pp. 453–475, 2013.

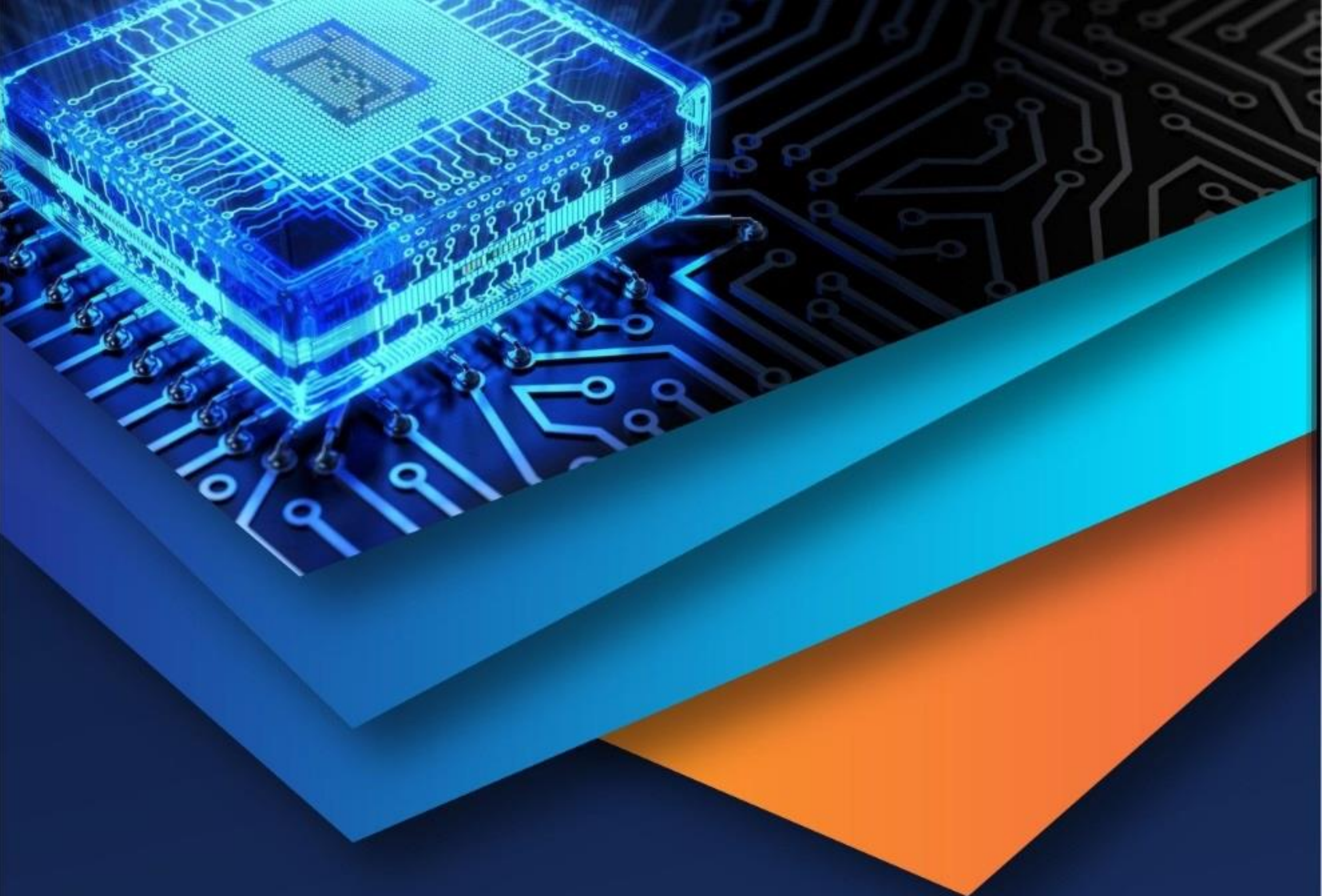
[11] I. F. Akyildiz, P. Wang, and Z. Sun, “Realizing underwater communication through magnetic induction,” IEEE Commun. Mag., vol. 53, no. 11, pp. 42–48, 2015.

[12] A. R. Forster and R. W. P. King, “Electromagnetic fields in sea water,” IEEE Trans. Antennas Propag., vol. 20, no. 2, pp. 183–191, 1972.

[13] A. R. Forster and R. W. P. King, “Electromagnetic fields in sea water,” IEEE Trans. Antennas Propag., vol. 20, no. 2, pp. 183–191, 1972.

[14] L. Li and J. Wang, “Analysis of EM wave attenuation in conductive underwater environments,” IEEE Access, vol. 8, pp. 189234–189244, 2020.

[15] H. Kaushal and G. Kaddoum, “Underwater optical wireless communication,” IEEE Access, vol. 4, pp. 1518–1547, 2016.



10.22214/IJRASET

INDEX COPERNICUS 45.98

ISRA JIF IMPACT FACTOR: 7.129

SJIFactor IMPACT FACTOR: 7.429

TOGETHER WE REACH THE GOAL

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY