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Analyzing the Impact of Mobile Nodes on the Performance of the Internet of Underwater Things (IoUT)

*Ibrahim Khider and Awab Abdelrahman and Boriy Mohammed Elyas Adam and Taqi-Eldin Abdalghni [1]
Sudan University of Science and Technology, Department of Electronics

Abstract
The Internet of Underwater Things (IoUT) is a novel class of the Internet of Things (IoT) and is defined as a network of smart, interconnected underwater objects. This paper focuses on analyzing and evaluating the performance of underwater wireless networks in the presence of mobile nodes. Key environmental factors, such as temperature, salinity, and depth—which play a major role in sound speed and communication quality—are taken into consideration. The study employs several key performance metrics, including Signal-to-Noise Ratio (SNR), Packet Loss Rate, Throughput, and Network Efficiency, to provide a comprehensive assessment of network performance.

Keywords: Mobile Nodes, Performance Metrics, Internet of Underwater Things (IoUT), AUVs, Simulation

تحليل تأثير العقد المتحركة على أداء إنترنت الأشياء تحت الماء

*إبراهيم خضر، أواب عبد الرحمن، بوري محمد إلياس آدم، تقي الدين عبد الغني
[1] قسم الإلكترونيات، جامعة السودان للعلوم والتكنولوجيا

الملخص
يُعدّ إنترنت الأشياء تحت الماء فئة حديثة من إنترنت الأشياء، ويُعرَّف بأنه شبكة من الكائنات الذكية المترابطة تحت سطح الماء. يركّز هذا البحث على تحليل وتقييم أداء الشبكات اللاسلكية تحت الماء في ظل وجود عقد متحركة، كما تم تضمين العوامل البيئية المؤثرة، مثل: درجة الحرارة والملوحة والعمق؛ نظرًا لدورها الرئيس في تحديد سرعة الصوت وجودة الاتصال. اعتمدت الدراسة على مجموعة من مؤشرات الأداء الرئيسة، من بينها: نسبة الإشارة إلى الضجيج، ومعدل فقدان الحزم، ومعدل الإنتاجية، وكفاءة الشبكة، وذلك بهدف تقديم تقييم شامل لأداء النظام.

الكلمات المفتاحية: العقد المتحركة، مؤشرات الأداء، إنترنت الأشياء تحت الماء، المركبات ذاتية التحكم تحت الماء، المحاكاة

1. Introduction

Underwater networks face multiple challenges, the most significant of which is signal attenuation caused by severe propagation losses and increased noise over long distances [1]. In addition, underwater communication suffers from substantial propagation delays due to the relatively slow speed of sound compared to electromagnetic waves, which negatively affects communication efficiency.

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Another critical challenge is power consumption, as significant energy is required for data transmission in underwater environments.

Environmental factors such as temperature and salinity also have a considerable impact on overall network performance. Temperature, in particular, plays a key role in increasing sound speed, which can reduce propagation delay and enhance network efficiency. These observations indicate that adapting communication strategies to environmental conditions can significantly improve system performance.

With respect to mobile nodes, previous studies have shown that they are effective in collecting data over large geographical areas. However, their effectiveness depends on carefully adjusting node mobility parameters, such as speed, to minimize signal loss and improve energy efficiency. Moreover, network efficiency and throughput can be enhanced by optimizing data transmission rates and reducing packet sizes, especially in scenarios where minimizing delay or packet loss is critical. Although mobile nodes provide an efficient solution for wide-area coverage, their movement must be carefully managed to mitigate adverse effects on communication quality.

In general, achieving optimal performance in underwater wireless sensor networks requires an integrated system design that considers environmental factors, node mobility, and operational conditions to enhance connectivity while minimizing data loss and energy consumption.

Recently, the rapid growth of interconnected physical objects has led to the emergence of the Internet of Things (IoT). The IoT has significantly transformed various domains, including healthcare, energy management, industrial processes, agriculture, livestock monitoring, infrastructure, and advanced technologies. This interconnected ecosystem enables objects to communicate globally, enhancing interaction with the surrounding environment and contributing to improved quality of life.

2. Related Work

Several studies have addressed the challenges and applications of the Internet of Underwater Things (IoUT). In [2], the authors present a comprehensive analysis of IoUT, focusing on applications such as environmental monitoring, underwater exploration, and disaster prevention. The study highlights the fundamental differences between Underwater Wireless Sensor Networks (UWSNs) and terrestrial networks, emphasizing challenges such as long propagation delays and low communication reliability. In addition, various underwater channel models essential for protocol design are evaluated.

In [3], the authors propose a flexible IoUT network framework capable of supporting heterogeneous system components. The study discusses operational challenges in dynamic and unpredictable ocean environments and suggests deployment strategies for effective IoUT implementation. Furthermore, it outlines emerging IoUT applications in environmental monitoring, oil and gas operations, and maritime security, while proposing solutions for reliable underwater communication.

The authors in [4] and [5] review recent advancements in IoUT research, identifying major challenges related to communication reliability, energy storage, and latency. These studies describe the architectural layers of IoUT systems, including perception, network, and application layers, and examine enabling technologies that support IoUT-based applications.

Simulation tools for underwater networks are surveyed in [6] and [7], where the authors categorize existing simulators and discuss the potential integration of 5G technologies into IoUT systems. These studies emphasize the importance of simulation in the development and validation of reliable underwater communication protocols.

Mobility management in underwater acoustic sensor networks (UASNs) has been investigated as a means to overcome challenges such as limited bandwidth, high latency, and shadow zones, thereby enhancing data collection efficiency and overall network performance [8]. Similarly, mobility management strategies in UWSNs aim to handle the movement of sensor nodes and sinks to improve coverage, connectivity, and energy efficiency. While mobility can introduce instability into the network, it also offers advantages such as dynamic node repositioning and improved resource utilization [9].

Depth-based routing protocols have been proposed to address continuous node movement in aquatic environments. The performance of these protocols is highly dependent on accurate depth information obtained from sensor nodes. Although depth information is not always prioritized in all acoustic channel models, several notable models incorporate depth parameters to better estimate channel conditions [10].

In [11], the authors analyze two widely used acoustic propagation models, namely Thorp and the Monterey-Miami Parabolic Equation (MMPE), in predicting transmission losses for several depth-based routing protocols, including Depth-Based Routing (DBR), Energy-Efficient Depth-Based Routing (EEDBR), Adaptive Mobility of Courier Nodes in Threshold-Optimized DBR (AMCTD), and Improved Adaptive Mobility of Courier Nodes in Threshold-Optimized DBR (IAMCTD).

Furthermore, the authors in [12] propose a routing scheme for underwater wireless networks based on a trust model and a void-avoidance algorithm. The proposed approach evaluates node behavior using direct, indirect, and environmental trust metrics while considering channel conditions. It prioritizes minimal cabling distance and introduces a two-hop availability checking mechanism to avoid void regions, thereby identifying transmission paths that minimize energy consumption and latency.

3. Network Model

We constructed an underwater wireless network consisting of 25 sensor nodes deployed in a mesh topology, integrated with Autonomous Underwater Vehicles (AUVs) to enhance mobility and scalability. The network employs Vector-Based Forwarding (VBF) and Depth-Based Routing (DBR) protocols to optimize energy consumption and determine optimal communication routes. Sensor nodes are deployed at varying depths to monitor marine environments, collecting data on parameters such as pressure, temperature, and oxygen levels.

The sensor nodes are connected to gateway nodes, which act as a bridge between the underwater network and a terrestrial central control station, providing secure and encrypted communication via acoustic signals. The gateway nodes are powered by solar panels and are integrated with buoys for stability. Mobile AUVs collect data from the sensors and transmit it to the gateway nodes.

The block diagram illustrates the sensor network, showing both single-hop and multi-hop communication between sensor nodes, as well as the types of media used underwater and on the surface.

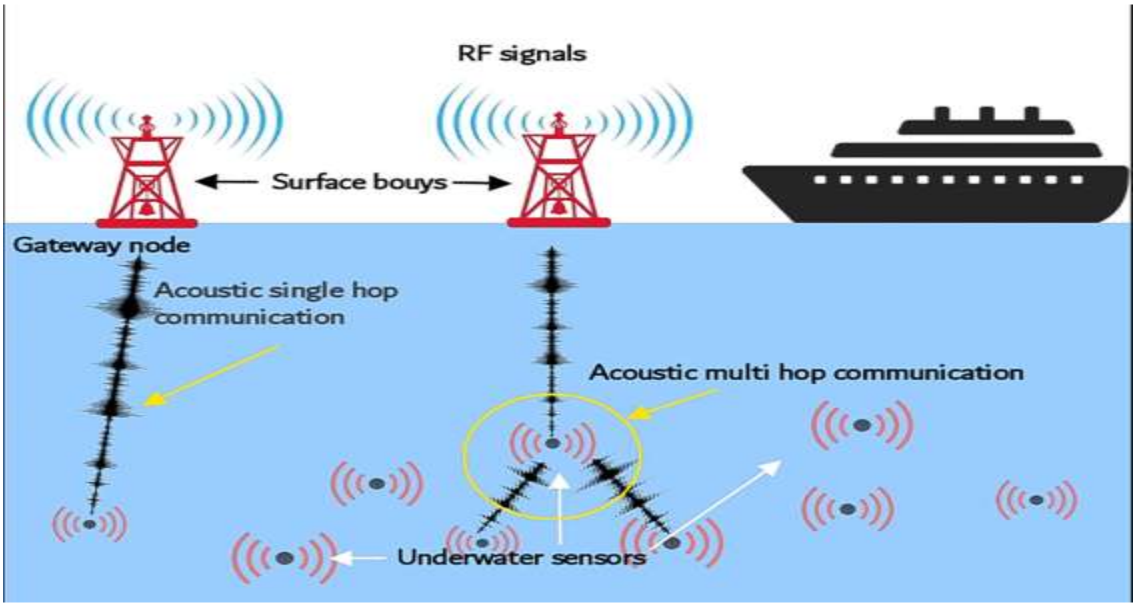

Figure.1: depiction of the block diagram of the network

4.Performance Metrics

Our system underwent performance analysis to optimize its operation, reduce flaws, and achieve stable conditions. The key metrics used to evaluate the system include throughput, energy consumption, energy efficiency, latency, and packet loss.

- Throughput (Th): The rate of data transmission, inversely related to data access time. Higher throughput indicates a more efficient network. It can be calculated as:

$$Th=\frac{Dr_{total}}{T_{access}} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

- Energy Efficiency (EE): Reflects how efficiently energy is utilized for data transmission. It represents the ratio of total transmitted data to total energy consumed. Higher values indicate better performance:

$$EE=\frac{DT_{total}}{EC_{total}} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

- Latency (L): The average time required for packets to reach their destination. Lower latency indicates a faster network:

$$L=\frac{\Sigma(T_{ps}-T_{Pr})}{PR_{total}} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

- Packet Loss Rate (PLR): Represents the percentage of packets lost during transmission, significantly influenced by environmental factors such as temperature and pressure:

$$PLR=\frac{PS_{total}-PR_{total}}{PS_{total}} *100 \ldots\ldots\ldots \quad (4)$$

- Signal-to-Noise Ratio (SNR): Indicates the quality of the received signal. Higher SNR values denote better signal quality:

$$SNR=10*log_{10}\left(\frac{S_{power}}{N_{power}}\right) \ldots\ldots\ldots\ldots \quad (5)$$

- Network Efficiency (NE): Evaluates how effectively the network utilizes available bandwidth considering throughput:

$$NE=\frac{Th}{BW} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where:

- Th = Throughput
- Dr_{total} = Total data received
- T_{access} = Data access time

- EE = Energy efficiency
- DT_{total} = Total data transmitted
- EC_{total} = Total energy consumed
- L = Latency
- T_{ps} = Time Packet sent
- T_{pr} = Time Packet received
- PR_{total} = Total packets received
- PS_{total} = Total packets sent
- SNR = Signal-to-noise ratio
- S_{power} = Signal power
- N_{power} = Noise power
- NE= Network efficiency
- BW= Bandwidth

In the mobile node scenario, mobile nodes (small AUVs or robots) collect data from static sensor nodes and deliver it to the gateway node. Mobile nodes follow specific routes to gather data wirelessly and then move to the gateway for transmission.

- **Collection Time:**

$$T_{coll}=T_{datacollnod}*N_{staticnode} \text{ ………. } (7)$$

- **Transmission Delay:**

$$transmission\ delay=\frac{P_s}{D_r} \text{………… } (8)$$

- **Total Delay:**

$$total\ delay=T_{coll}+transmission\ delay+T_{travel} \text{ ……………. } (9)$$

- **Total Energy Consumption:**

$$E_{total}=E_{movement}+E_{transs} \text{ ………………………………………..} (10)$$

Where:

$$E_{movement}=T_{travel}*P_{movement}$$

$$E_{transs}=total\ delay*P_{transs}$$

Environmental factors such as depth, salinity, and temperature affect signal speed, energy consumption, and packet loss. The speed of acoustic signals is calculated as:

$$C=1449.2+4.6T-0.055T^2+0.00029T^3+(1.34-0.01T)(S-35)+0.016D \text{…… } (11)$$

Where: C is the speed of sound (m/s). T is temperature (°C). S is salinity (psu). D is the depth (m). Propagation delay = $\frac{D}{S_s}$. D is the distance between the sensor node and the gateway node. S_s is the signal speed. All of the calculations performed so far were conducted under optimal water conditions, assuming the absence of noise and attenuation. However, in reality, water conditions significantly affect signal propagation, causing packet loss, which represents the number of packets that are dropped and cannot be delivered to the destination node. The packet loss is calculated as follows:

$$\text{Packet loss rate} = 1-e^{-\alpha d} \text{ ………………………………… } (12)$$

Where α is the attenuation coefficient, d is the distance (m). The energy consumption is scenario is calculated through:

Energy consumption:

$$\text{Energy consumption} = P_t * D_t \text{ ……………………………… } (13)$$

Where **Pt** is transmission power (**W**). **Dt** is the total delay (s).

5. Simulation Environment

Simulations were conducted under varying water depths, temperatures, and mobile node scenarios. Sensor nodes were deployed at different distances from each other and from the gateway node. Calculations were performed using the formulas presented in the previous section. MATLAB was employed to measure network performance metrics, including throughput, energy consumption, packet loss, latency, signal attenuation, and overall network efficiency. Simulation input parameters are summarized in Table 1.

The simulation model for evaluating the impact of mobile nodes on IoUT performance includes several assumptions and limitations:

- Simplified underwater communication channels, which are affected by multipath fading, Doppler spread, and noise.
- Fixed transmission range and data rate, which may not reflect real-world scenarios accurately.
- Limited consideration of underwater node mobility, including ocean currents and water pressure.

These assumptions may affect the accuracy and reliability of the simulation results. Future work should refine the model to better capture the complexities of IoUT networks.

It is important to note that simulations were conducted under ideal conditions and specific parameter ranges. Real-world factors such as water currents, marine life, and equipment failures may significantly affect mobile node performance. Future studies could incorporate realistic simulation scenarios, experimental validation, or field trials to improve the understanding of underwater environments and mobile node performance.

Table 1: Simulation parameters

Parameter	Value
Routing protocols	Vector-Based Forwarding (VBF) and Depth-Based Routing (DBR) protocols
Packet size	5 KB
Propagation speed	1500 m/s
Transmission power	0.1 W
Reception power	0.05 W
Salinity	35 Gram/Km
Movement power of the mobile node	0.5 W
Distance to gateway node	100 to 1000m
Distance between hops	10 to 100m
Data rate	5 to 30 KB/s
Number of sent packets	100 packets
Temperature	5 to 25°

6. Results and Discussion

Simulations were conducted to evaluate the throughput of the network in the mobile node deployment scenario and to assess the impact of environmental conditions. The performance of a mobile node collecting data from 25 fixed nodes distributed across the network and transmitting it to a gateway node was analyzed. Throughput analysis was based on two main variables: mobile speed and distance to the gateway. DBR and VBF routing protocols, which are designed for specific environments such as underwater networks, were selected. Mobility and environmental factors interact by affecting link quality. These protocols use depth-, distance-, or location-based metrics to determine the optimal path, and their performance is influenced by how effectively they handle changes in mobility and network physical conditions.

The results indicate that as the mobile node speed increases, travel time decreases, leading to improved throughput. Conversely, as the distance between the mobile node and the gateway increases, travel time increases, resulting in reduced throughput. The graphs show that throughput is higher at higher speeds and shorter distances. A 3D plot clearly illustrates the relationship between throughput, node speed, and distance to the gateway, showing gradual changes in throughput across the surface.

Figure 2 presents a 3D representation of mobile node throughput, accounting for the distance to the gateway and mobile node speed. The graph demonstrates that throughput in this scenario is more strongly affected by distance than by mobile speed, as the peak-level region is relatively small compared with the low throughput levels.

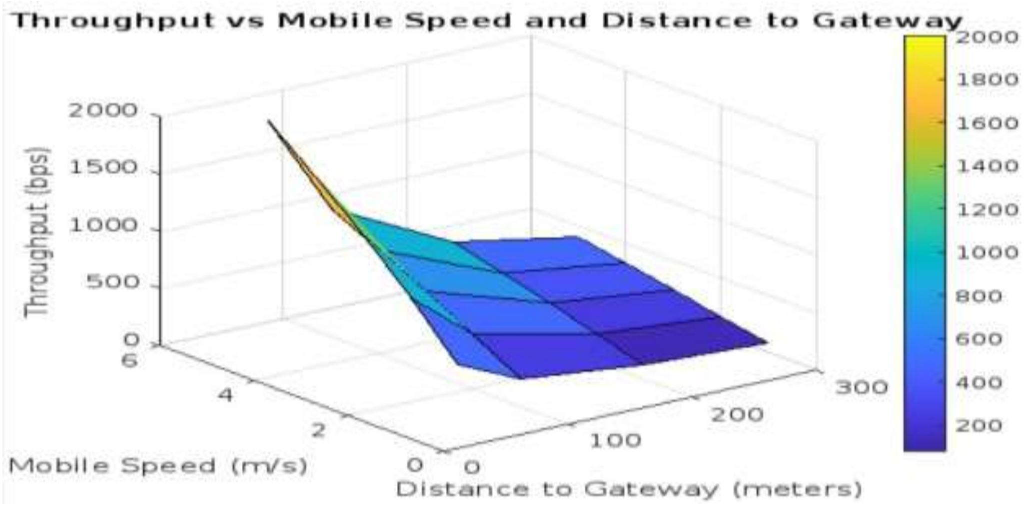

Figure.2, Throughput Vs Mobile Speed and Distance to Gateway

Figure 3 illustrates the relationship between mobile node throughput, distance to the gateway, and mobile node speed. The peak regions of throughput are more evident here, highlighting the impact of distance even at high speeds. In this scenario, the effects of environmental conditions, such as temperature, depth, and salinity, on underwater network performance in terms of throughput are analyzed. These factors primarily influence the speed of sound in water, which is calculated using the Mackenzie equation, taking into account the cumulative effect of temperature, salinity, and depth.

The speed of sound directly affects propagation delay, defined as the time required for the signal to travel from the sending node to the receiving node. Throughput is calculated by dividing the transmitted data (packet size) by the total time, which includes both transmission delay and propagation time. Results show that increasing temperature improves the speed of sound, reducing propagation time and increasing throughput.

Increasing depth has a dual effect: sound speed improves at intermediate depths due to increased pressure, but at very great depths, the effect is less pronounced. Graphs show that throughput is higher at high temperatures and shallow depths, indicating that environmental conditions play a pivotal role in enhancing underwater network performance. A 3D surface plot depicts the relationship between temperature, depth, and throughput, while the contour plot highlights areas where throughput is optimal.

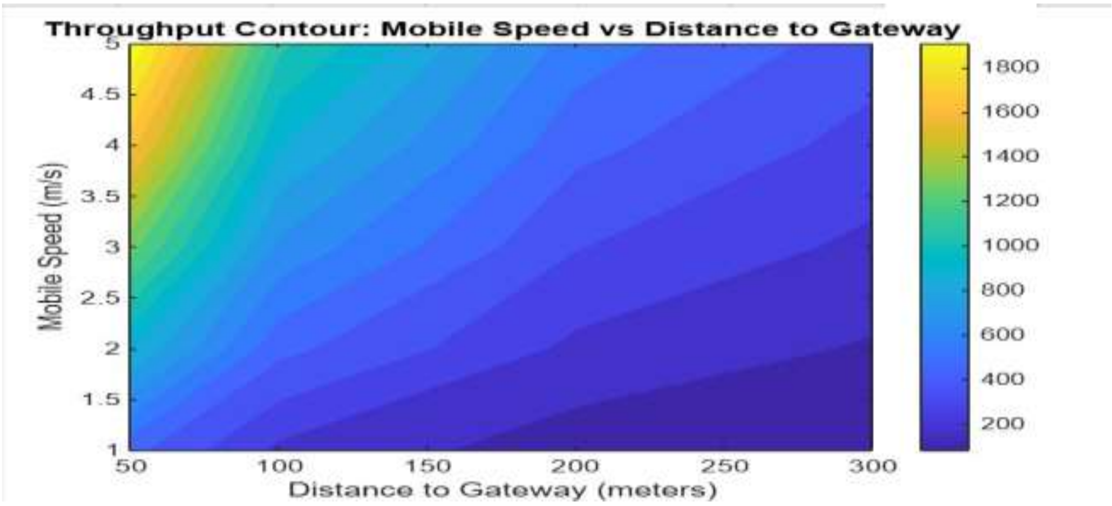

Figure 3, Throughput Contour

Figure4 clearly illustrates that higher temperatures significantly improve throughput. Depth has an upward effect on throughput, but it is minor compared to temperature.

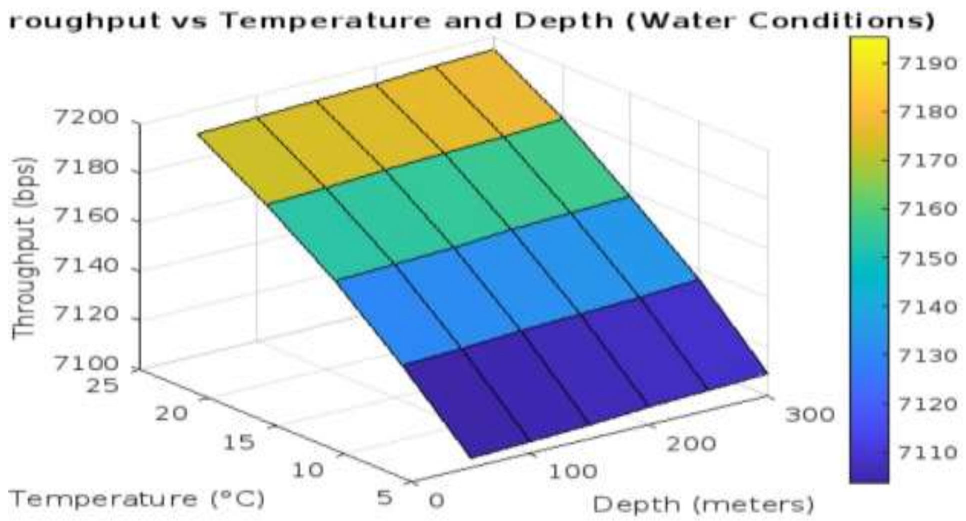

Figure.4,Throughput Vs Temperature and Depth(Water conditions)

Figure 5 depicts the peak levels of throughput, with the yellow region indicating the dominant role of temperature in improving network performance.

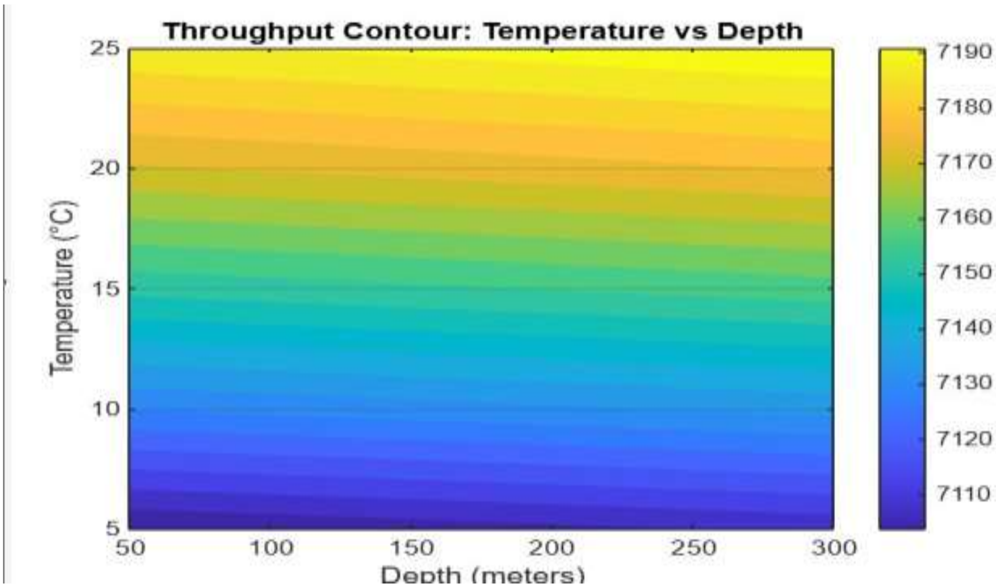

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Figure.5, Throughput Contour (Temp. Vs Depth)

Figure6 demonstrates that packet loss rate increases with increasing distance between the mobile node and the gateway or with decreasing mobile node speed due to longer total transmission time. Environmental effects also show that higher temperatures improve the speed of sound, reducing propagation delay and packet loss rate. Results are presented using two graphs: the first shows the relationship between packet loss rate and distance at a constant mobile node speed, and the second shows the relationship between packet loss rate and mobile node speed at a constant temperature, highlighting the combined effect of environmental conditions and mobility on network performance. Packet loss rate increases as distance increases, suggesting that higher mobile node speed could help mitigate this effect.

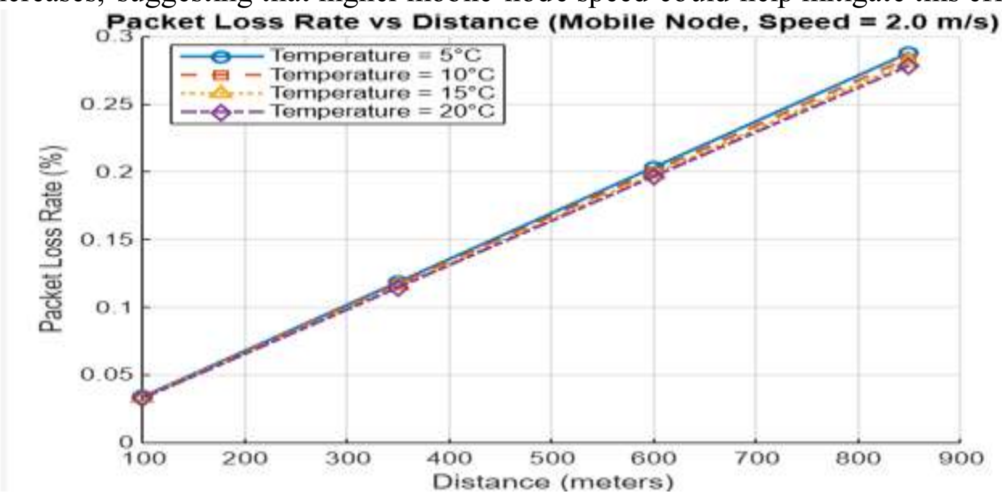

Figure.6, Packet Loss Rate Vs Distance (Mobile Node, Speed = 2.0 m/s)

Figure 7 illustrates the relationship between packet loss rate and mobile node speed at different distances. This graph confirms the proposal, as the constant levels of packet loss at varying speeds indicate that distance is the primary factor influencing packet loss rate.

Figure.7, Packet Loss Rate Vs Mobile Speed (Mobile Node, Temp. = 15°C)

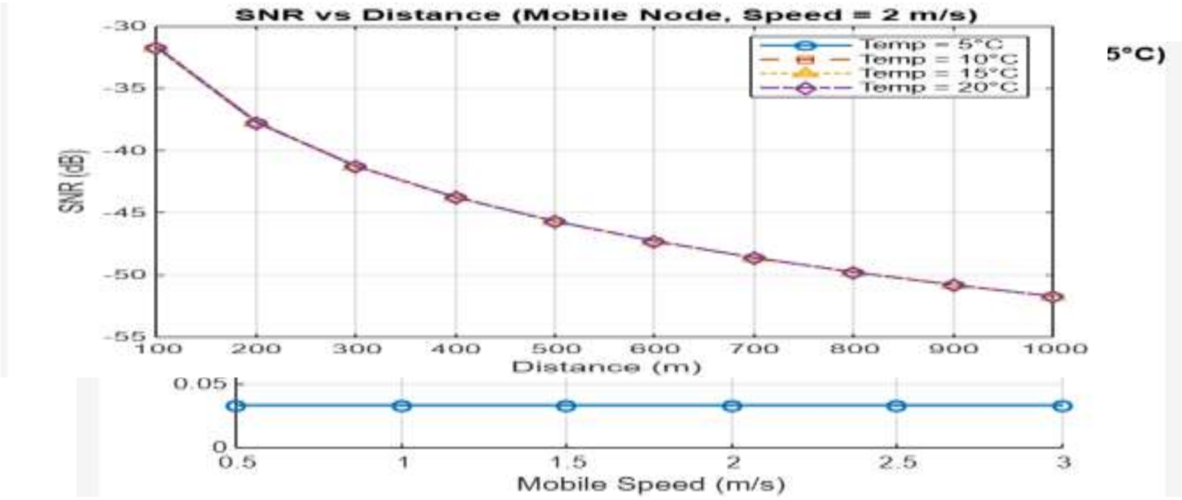

Figure.8 SNR Vs Distance (Mobile Node, Speed = 2 m/s)

Figure 8 depicts the relationship between SNR and distance in a mobile node scenario at a fixed node speed of 2 m/s under different temperatures. The plot demonstrates that SNR decreases with increasing distance due to rising noise power caused by longer distances. Additionally, node mobility weakens signal strength due to dynamic effects. However, higher temperatures improve SNR by mitigating the impact of noise.

Figure 9 shows the relationship between SNR and mobile node speed at a fixed distance of 1000 meters under different temperatures. SNR decreases as mobile node speed increases due to weaker signal strength caused by mobility. Nevertheless, higher temperatures slightly enhance SNR by increasing the speed of sound, thereby mitigating the effects of mobility.

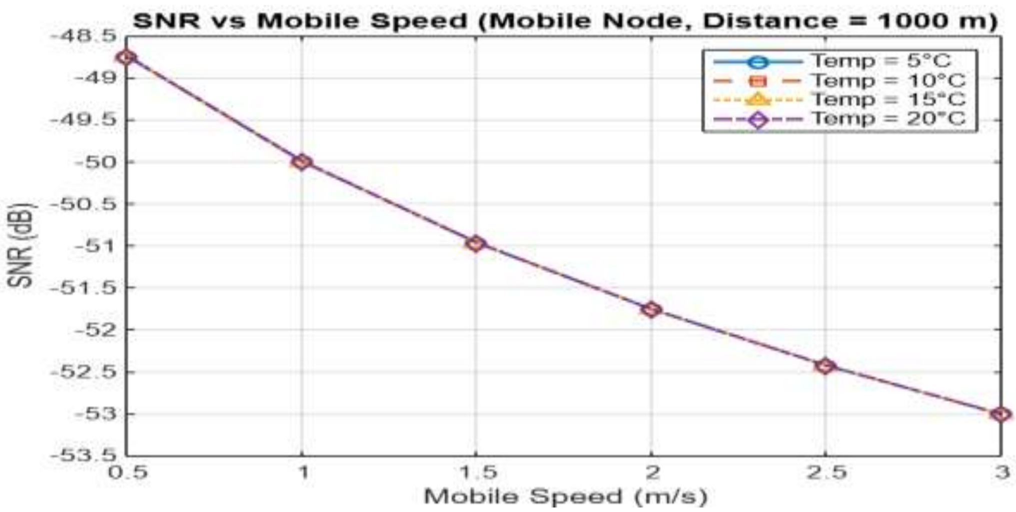

Figure.9 SNR Vs Mobile Speed (Mobile Node, Distance = 1000 m)

Figure 10 illustrates the relationship between network efficiency and distance in a mobile node scenario at a moving speed of 2 m/s. A significant degradation in network efficiency is observed as distance increases. This indicates that network efficiency levels drop considerably in long-range networks, emphasizing the need to minimize other factors that could exacerbate network performance issues.

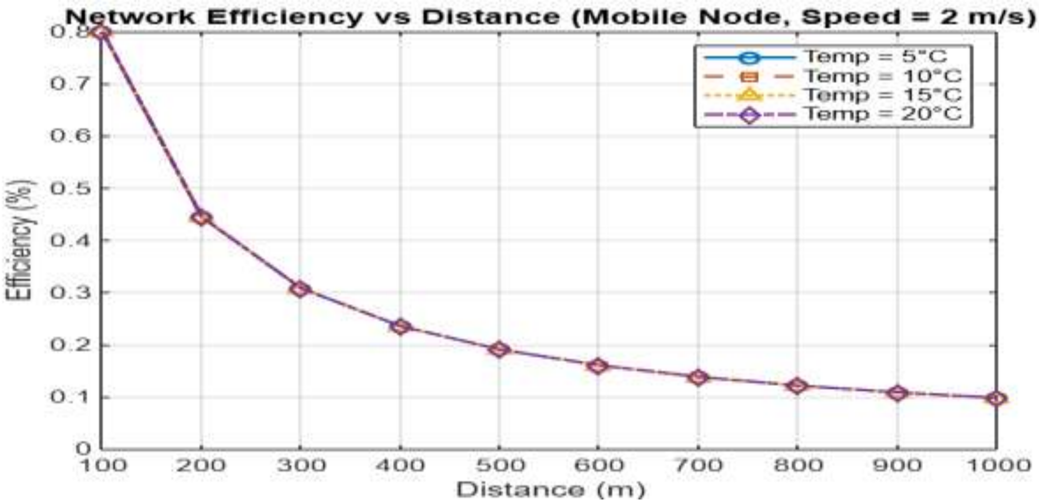

Figure.10, Network Efficiency Vs Distance (Mobile Node, Speed = 2m/s)

7. Conclusion

In this study, the performance of underwater wireless networks under mobile node communication was analyzed while incorporating the effects of environmental factors such as temperature, salinity, and depth. Several performance metrics, including packet loss rate, throughput, and network efficiency, were evaluated to identify the challenges and limitations of underwater communication systems.

The results consistently highlighted the significant impact of distance on all performance metrics. As the distance between nodes increased, higher noise levels and signal attenuation were observed, leading to reduced throughput and network efficiency. Furthermore, environmental conditions, particularly temperature, played a critical role in network performance. Higher temperatures improved the speed of sound in water, reducing propagation delay and consequently enhancing overall network performance. In contrast, adverse conditions such as lower temperatures increased packet loss and reduced efficiency.

Mobile node communication proved effective for dynamic data collection over wide underwater areas. However, increasing the speed of the mobile node negatively affected network efficiency due to signal degradation caused by mobility. The results also indicated that environmental conditions significantly influenced mobile node performance, with higher temperatures improving performance across all evaluated metrics.

Across all scenarios, network efficiency was found to be highly sensitive to the combined effects of distance, data rate, and environmental factors. While mobile nodes provided flexibility and improved coverage, they required careful tuning of speed and distance parameters to maintain acceptable levels of network efficiency.

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