



Assessment and analysis of the performance of Multi-Hop Internet of Underwater Things Networks

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ABSTRACT

This study aims to evaluate the performance of multi-hop Internet of Underwater Things (IoUT) networks under varying environmental and network conditions. The Internet of Underwater Things (IoUT) is a technology that contributes to building smart cities, but it must overcome several challenges, including environmental concerns, connectivity barriers, and system architecture complexities. This paper presents a performance analysis of multi-hop Internet of Underwater Things Networks. We examine and assess the performance of multi-hop IoUT networks in terms of several key metrics, including throughput, network efficiency, packet loss rate, and signal-to-noise ratio (SNR). The analysis provides valuable insights into the capabilities and limitations of multi-hop IoUT networks.

1. INTRODUCTION

The Internet of Underwater Things (IoUT) has emerged as a technology for enhancing efficient and reliable communication in underwater environments [1]. To address IoUT networks consist of underwater sensors, actuators, and other devices that communicate with each other to collect, process, and transmit data. [2].

These networks have many applications in marine communication, underwater exploration, and other fields [3]. However, underwater communication presents significant challenges due to the harsh aquatic environment, which is characterized by limited bandwidth, high latency, and high error rates [4]. To address these challenges, multi-hop IoUT networks have been proposed as a viable solution for extending the coverage area and improving the reliability of underwater communication [5]. In a multi-hop IoUT network, data is transmitted from the source node to the destination node through multiple intermediate nodes [6].

Each intermediate node receives, processes, and forwards the data to the next node until the data reaches the destination node [7]. The performance of multi-hop IoUT networks is affected by different factors, including the number of hops, transmission power, modulation scheme, and packet size [8]. Figure 1 shows the block diagram of IoUT.

According to [9], underwater network simulation tools are categorized, and the integration of 5G in IoUT systems is explored. It examines the many tools accessible to researchers and

emphasizes the value of simulation in creating trustworthy underwater communication protocols. "With a primary focus on **IoUT** and a focus on underwater network modeling tools that students, in particular, may use in academic settings, this study is a useful resource. MatLab, GODUNOV, Riverbed Modeler, and COCO are notable examples of such open-source technologies that are easily accessible for educational purposes **due** to their comprehensive documentation and online tutorials[10].

Furthermore, in order to meet various requirements such as bit error rate and spectrum efficiency, IoUT in 5G-based systems focused on the real-world deployment and monitoring of CO underwater systems. [11].



Figure.1: block diagram of IoUT.

In [12] The authors introduced a new concept called Meandering Current Mobility (MC) to simulate ocean currents and evaluate the trajectory of sensor nodes.

In[13] researchers consider the Integrated sensing and communications ISAC design for UAV aided communications. They build the spatial model under the jittering effects and analyze the effect of the UAV movement and attitude variation to the channel estimation method by utilizing the ISAC technique, where the UAV sensing, the

communications, and the control are jointly considered to benefit the system performance.

In [14] Telnet and Superframe applications are considered in the proposed network, and the settings for Telnet and Superframe applications are then compared.

In [15] the multi-hop relay selection problem for unknown dynamic UASN topology scenarios is constructed as a CMAB learning model. It enables the proposed problem to be solved by exploring a dynamic low-dimensional relay-link sub-strategy space at a low cost without any complete prior CSI. Accordingly, a dynamic CMAB learning structure is proposed to efficiently achieve the superior strategy of dynamic high-dimensional multi-hop relay strategy space in [16] the authors present Underwater Multi-channel Medium Access Control with Cognitive Acoustics (UMMAC-CA) as a suitable channel access protocol for distributed UCANs. UMMAC-CA operates on a per-frame basis, similar to the Multi-channel Medium Access Control with Cognitive Radios (MMAC-CR) designed for distributed cognitive radio networks, but with notable differences. It employs a pre-determined data transmission matrix to allow all nodes to access the channel without contention, thus reducing the channel access overhead.

In [17] the researchers examine the use of Artificial Intelligence (AI), Machine Learning (ML), Reinforcement Learning (RL) and fuzzy logic to optimize routing protocols for underwater networks. They provide a comprehensive survey of existing AI-based approaches, emphasizing their novelties and constraints underwater. To assess the efficiency of these AI-based routing protocols, they carry out extensive simulations across various underwater environments where metrics such as packet delivery ratio, energy consumption, end-to-end delay, and computational efficiency are focused on.

2. SYSTEM MODEL

The system model consists of a multi-hop network architecture with underwater sensor nodes and sinks, where nodes communicate with each other through acoustic signals. The node characteristics include limited energy, processing, and storage capabilities. The underwater acoustic channel is modeled with attenuation, noise, and multipath effects. Various traffic patterns, including periodic and event-driven traffic, are considered. To address mobility and scalability, we developed an underwater wireless network, as illustrated in Figure 2, with a total of 25 sensor nodes set up in a mesh topology. The system uses the routing protocols VBF (Vector Based Forwarding) and DBR (Depth Based Routing) to contribute to a three-dimensional underwater network with AUV architecture.

The DBR uses sensor depth to find the best path, and the VBF uses directional forwarding to optimize energy usage by reducing the number of sensor nodes involved. Theoretically, sensors are placed at various depths to monitor and collect data about the surrounding marine environment, such as temperature, pressure, and oxygen levels, and store the information in a compressed storage unit. The sensors are connected to gateway nodes, which serve as a link between our

underwater network and the central control station on land.

The system also includes mobile nodes, which are AUVs that move around and gather data from the sensors before sending it to the gateway nodes. The gateway ensures secure, encrypted communication via acoustic signals and is integrated with solar-powered buoys to meet its energy requirements.

The initial distance between each sensor node in this network is roughly 20 meters. Our objective is to cover at least 500 square meters of the deployment area and distribute the sensors in a 3D polygonal shape. In addition, the system will experience scalability as the distance between nodes increases and the AUVs are involved.

The methodology involves simulating the Multi-Hop IoUT network using network simulation tools. Key performance metrics, including throughput, energy efficiency, packet loss rate, signal-to-noise ratio (SNR), and network efficiency, are evaluated under varying conditions. Parameters such as data rate, distance between nodes, number of hops, and node density are varied to analyze their impact on performance metrics. Statistical analysis and data visualization techniques are employed to analyze simulation results and identify trends. The system model and methodology provide a framework for assessing and analyzing the performance of Multi-Hop IoUT networks.

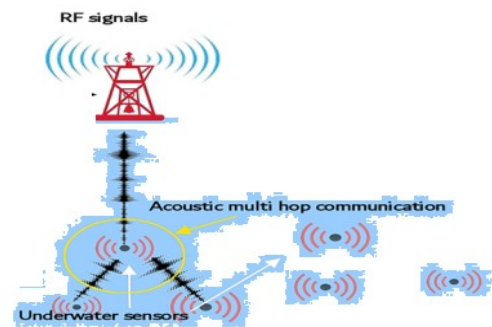


Figure.2: the block diagram of multi-hop network

Figure.2 shows fraction of the sensors network and resembles how sensors communicate via multi-hop acoustic links and depicts the type of media used underwater communication

3.PERFORMANCE METRICS

The system underwent performance analysis to evaluate its optimal operating conditions and to reduce flaws, add new features and reach the stable operating condition. The metrics used to analyze the system are throughput, energy consumption, energy efficiency, latency and packet loss. Throughput is the Total data transmission rate (Dr_{Total}), it has a reverse relation with data access time (T_{access}), therefore, higher throughput means a more efficient network the throughput can be calculated via formula:

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

Energy efficiency reflects how efficiently energy is used for data transmission. It presents the relationship between the total consumed energy per certain amount of data. Higher values indicate better performance.

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

Latency Indicates the average time required for packets to reach their destination. Lower latency indicates a faster network.

$$L = \frac{\sum T_{ps} - T_{pr}}{PR_{total}} \quad (3)$$

Packet loss rate (PLR) represents the percentage of packets lost during transmission. It is used to analyze connectivity issues, packet loss depends significantly on the water environment factors like temperature and pressure, the packet loss rate calculation formula is:

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

Additional key metrics for evaluating underwater communication efficiency include the signal-to-noise ratio (SNR) and network efficiency (NE), Signal-to-Noise ratio (SNR) Indicates the quality of the signal received. Higher SNR values indicate better signal quality.

$$SNR = 10 \times \log \left(\frac{S_{power}}{N_{power}} \right) \quad (5)$$

While Network Efficiency (NE) evaluates how well the network utilizes the available bandwidth to transfer data successfully considering the throughput value :

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

All these performance metrics change according to network conditions we modified the network specifications in terms of multi hop communications and then tested some of these metrics under different environmental conditions.

We have dispersed the sensor nodes so that there is a consistent distance between each pair of sensor nodes. In this situation, the data is transferred from the source node to the gateway node via at least one intermediate node. Through routing protocols, the network finds the best route between source nodes and the gateway node. We implemented the DBR protocol, which means that the routing process is dependent on node depth and that each hop has a unique transmission and propagation delay based on its location and specifications. We used the following formula to determine the signal's overall delay:

$$D_t = \frac{P_s}{D_r} + \frac{D}{S_s} \times n \quad (7)$$

Where:

P_s is the packet size, D_r is the data rate. D is the distance between the sensor node and the gateway node, S_s is the signal speed, n is the number of hops

And the total energy consumption formula is:

$$\text{Total energy consumption} = (T_{power} + R_{power}) \times n \quad (8)$$

Impact of an environmental condition (water condition)

In these scenario we've analyzed the impact of the environmental condition of the water like depth, salinity and temperature, those factors effect the signal speed, energy consumption and packet loss. The acoustic signal speed is the most vulnerable property against those factors the speed of the signal is calculated by the following formula:

$$C = 1449.2 + 4.6T - 0.05T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016D \quad (9)$$

Where:

- C is the speed of sound in m/s.
- T is the temperature in degrees.
- S is the salinity in psu.
- D is the depth in meters.
- 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 we've done so far were under optimal water conditions assuming that there's no noise or attenuation, but in reality water condition impact significantly on the signal causing what known as the packet loss which is the amount of packets dropped and couldn't be delivered to the destination node, the packet loss is calculated through the formula:

$$\text{Packet loss rate} = 1 - e^{-\alpha d} \quad (10)$$

Where: α is the attenuation coefficient which is measuring by using the packet loss model, d is the distance in meters.

The energy consumption scenario is calculated through:

$$\text{Energy consumption} = P_t \times D_t \quad (11)$$

Where: P_t is the transmission power in watts, D_t is the total delay in seconds.

4. SIMULATION ENVIRONMENT

Using Matlab as the simulation software, we measured the network performance of throughput, energy, packet loss, latency, signals attenuation and loss, and network efficiency. Simulations were conducted under varying water depths, temperature levels, and communication scenarios.. Finally, we placed the sensor nodes at varying distances from the gateway node and each other. The calculations were based on the formulas mentioned in the previous section. Table 1's values served as the inputs for our computations.

Table.1,simulation parameters

Parameter	Value
Noise Model	AWGN
BER	10^{-3}
Packet size	5 KB
Modulation scheme	BPSK
Propagation speed	1500 m/s
Transmission power	0.1 W
Reception power	0.05 W
Salinity	35 psu
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 packet
Temperature	5 to 25°

5. RESULTS AND DISCUSSION

We started by simulating the network's throughput under various settings, including multi hop communications. In the multi-hop communication scenario, the total distance is divided into a number of hops, so it is necessary to know the productivity of this scenario and its effectiveness, depending on the change in the number of jumps, the total distance and the data transfer rate, and here we will use a set of values according to the table of coefficients and to calculate productivity, we calculated the distance for each jump by dividing the total distance by the number of jumps, and we calculated the transmission, spread time and total time , we found that as the total distance increases, throughput decreases due to propagation time and also increasing the number of jumps reduces productivity due to the increased delay resulting from each jump as shown in Figure 3.

As distance increases, signal strength decreases due to attenuation, leading to a decrease in throughput. For short distance (e.g., 100m): Throughput approaches the maximum data rate, with minimal packet loss. For medium distance (e.g., 500m): Throughput decreases due to increased packet loss and retransmissions. For long distance (e.g., 1000m): Throughput significantly decreases, with high packet loss and potential network disconnection.

Figure 4 shows the relationship between throughput and distance using different numbers of fixed distance hops the graph depicts a constant levels of throughput in every different set of hops although there's a decrease in throughput as the number of hops increase, it's worth noting that throughput have a stable value as the total distance to gateway increase, it can be an advantage if the design of the network only concerns the total distance to the gateway node.

Throughput is affected by the number of hops. As shown in Figure 4. Throughput decreases as the distance increases for

all hop counts. Increasing the number of hops further reduces throughput due to additional delay and packet loss. While multi-hop networks support reliable long-distance communication, their throughput may be constrained.

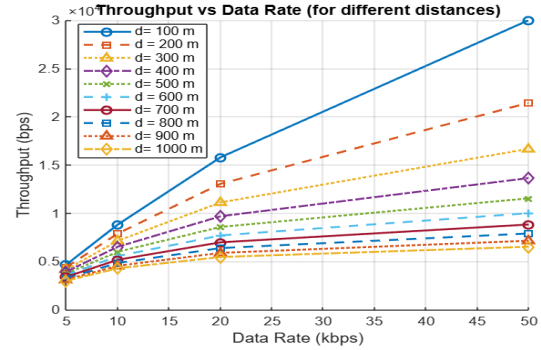
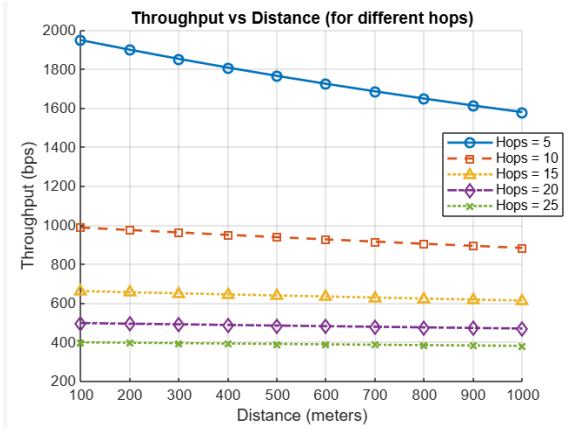
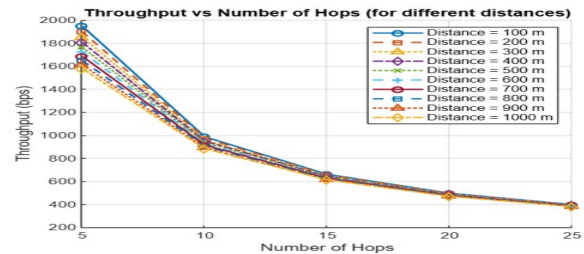
**Figure 3:** Throughput Vs Data Rate**Figure 4:** Throughput Vs Distance for Different Hops

Figure 5 shows that the throughput which have a high value in a small number of hops but as distance increase it shows some total degradation, The stable values of throughput can be used with regard to other performance metric to determine which number of hops at certain distance will be beneficial. Throughput decreases as the number of hops increases for all distances. The rate of throughput degradation is more pronounced over longer distances, although multi-hop networks can still provide reliable communication.

**Figure 5:** Throughput Vs Number of Hops

In order to determine and simulate how much energy our system uses. we measured the energy efficiency where the amount of transmitted data for each simulation was 500 KB.

The energy efficiency is inversely proportional to the energy consumption. Figure 6 shows the relationship between energy efficiency and distance to the gateway node using multi hop communication with various number of hops, the consumption for single hop communication showed the highest level of efficiency but the is going downward sharply as the distance increase, on the other hand multi hop communication showed a high consumption levels compared to single hop.

Energy efficiency is significantly impacted by distance and number of hops. At short distances (e.g., 100m), energy efficiency is high with minimal consumption. However, as distance increases to medium (e.g., 500m) and long (e.g., 1000m) ranges, energy efficiency decreases due to higher transmission power and packet loss, leading to network disconnection.

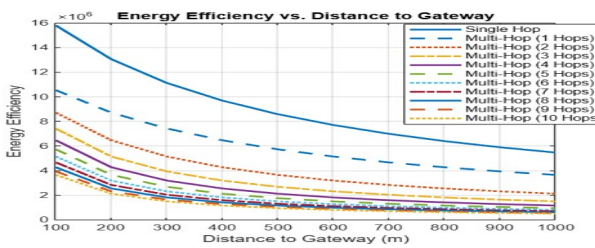


Figure 6: Energy efficiency Vs Distance

Figure 7 shows a relationship between distance per hop and total distance from source node to gateway and their impact on energy efficiency, as the distance between the hops increases consume high power but the curve becomes more stable as the distance to the gateway increase. All that indicates the leverage of multi-hop communication over single hop communication for large scale networks.

Energy efficiency is influenced by hop distance, with shorter distances yielding better efficiency. Specifically, short hops (100m) result in high efficiency and minimal consumption, while medium hops (500m) see decreased efficiency due to increased transmission power and packet loss. Long hops (1000m) significantly compromise efficiency, leading to high consumption and potential disconnection.

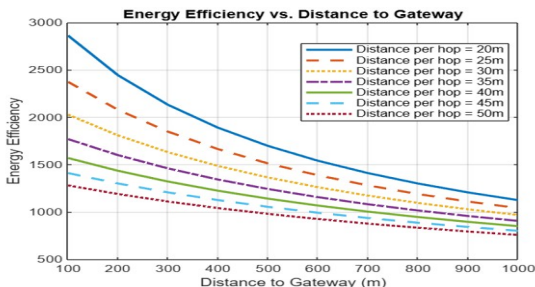


Figure7: Energy efficiency Vs Distance

Figure 8 shows the relationship between packet loss rate and the number of hops in multi hop communication it is also shows how different degrees of temperature and and Multihop

and their effect in packet loss. Packet loss rate is affected by the distance between nodes and the number of hops. For a fixed distance of 300m, the packet loss rate will vary depending on the number of hops and temperature.

Temperature changes can affect the performance of underwater communication systems, leading to increased packet loss rates.

The results show that the packet loss rate increases with increasing distance or number of hops due to the cumulative accumulation of loss probabilities for each hop.

In addition, environmental conditions such as high temperature positively affect packet loss reduction by increasing the speed of sound and reducing the propagation time

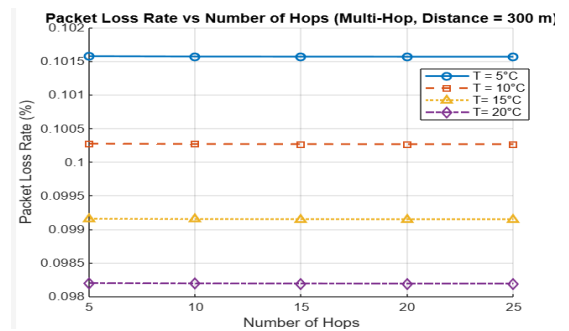


Figure 8: Packet Loss Rate Vs Number of Hops

Figure 9 shows the relationship between packet loss rate and distance at a fixed number of hops (10 hops) in multi hop communication considering different degrees of temperature.

Packet loss rate is affected by the distance between nodes and the number of hops. With 10 hops, the packet loss rate will vary depending on the distance and temperature. Temperature changes can affect the performance of underwater communication systems, leading to increased packet loss rates

Packet loss rate increases as distance increases for all temperatures, due to increased signal attenuation and noise. Multihop networks with 10 hops can provide reliable communication over long distances, but packet loss rate may be significant.

Figure 10, demonstrates how SNR and distance relate to one another in a multi-hop communication scenario with a fixed number of hops (5 hops) and varying temperatures. The findings show that the buildup of noise over several hops causes SNR to drop more precipitously.

Higher temperatures, on the other hand, greatly increase SNR by speeding up sound, which lowers noise for every hop. SNR is a critical metric in underwater communication systems, determining the reliability and efficiency of data transmission. SNR decreases as distance increases due to signal attenuation and noise.

Temperature changes can affect the noise level in underwater communication systems, impacting SNR. High temperatures can increase the noise level, reducing SNR. SNR decreases as the number of hops increases, due to accumulated

noise and signal attenuation. it was expected for Shorter hop distances can improve SNR by reducing signal attenuation

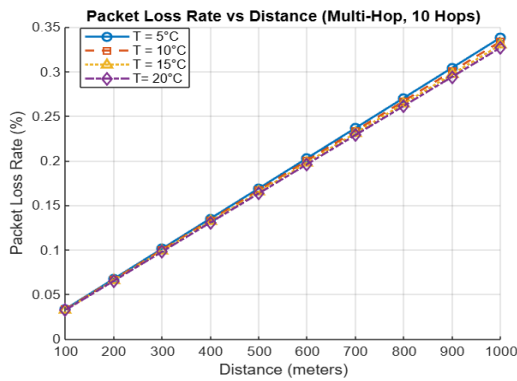


Figure 9: Packet Loss Rate Vs Distance (Multi-Hop, 10 Hops)

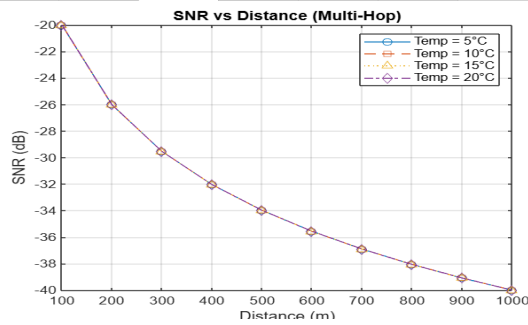


Figure10: SNR Vs Distance (Multi-Hop)

Figure 11, shows depicts the relationship between SNR and the number of hops in a Multi-Hop communication scenario for a fixed distance (1000 meters) under different temperatures. SNR significantly decreases with increasing hops due to the cumulative noise introduced by each additional hop. Higher temperatures slightly improve SNR by increasing the speed of sound, reducing noise at each hop.

Figure 12 shows the relationship between network efficiency and multi hop communication in different degrees of temperature and fixed distance, there's a significant degradation of network efficiency as the number of hops goes larger.

It was noted that Network efficiency is affected by the number of hops, with each hop introducing additional delay, packet loss, and energy consumption. in addition to that temperature changes affect the performance of underwater communication systems, impacting network efficiency, result in lower network efficiency due to increased noise levels and reduced reliability.

6.CONCLUSION

As the performance of underwater wireless sensor networks (UWSNs) was examined in this study in a variety of

situations, including Multi-Hop communication, while taking into account the effects of environmental variables including depth, temperature, salinity, and latency at each hop.

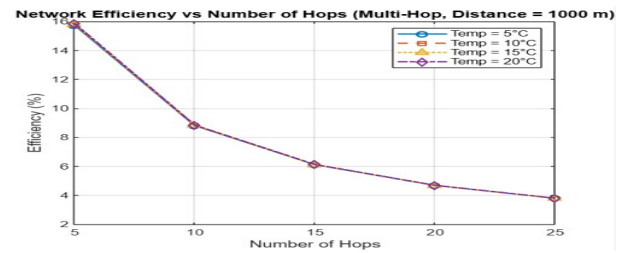


Figure 11: SNR Vs Number of Hops (Multi-Hop, Distance = 1000m)

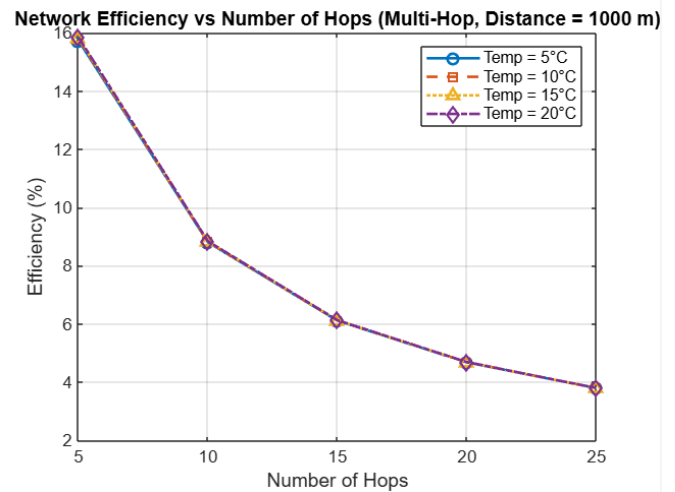


Figure 12: Network Efficiency Vs Number of Hops (Multi-Hop, Distance = 1000m)

In conclusion, this comprehensive assessment and analysis of Multi-Hop Internet of Underwater Things (IoUT) networks reveals that optimizing network performance requires careful consideration of various factors, including data rate, hop count, energy efficiency, packet loss rate, signal-to-noise ratio (SNR), and network efficiency. The study highlights the complex trade-offs among these metrics. It demonstrates that while throughput increases with data rate, it decreases with both distance and hop count, while energy efficiency significantly decreases with increasing distance and hop count.

Furthermore, packet loss rate increases with distance and hop count, SNR degrades with distance and hop count, and network efficiency decreases with increasing hop count. These findings provide valuable insights for designing and optimizing Multi-Hop IoUT networks, emphasizing the need for adaptive routing protocols, advanced signal processing techniques, and novel network architectures that balance energy efficiency, throughput, and reliability. This ultimately supports the broader adoption of IoUT networks across a wide range of applications.

Future research directions for Multi-Hop Internet of Underwater Things (IoUT) networks include applying

machine learning techniques to optimize network performance and predict behavior, investigating cooperative communication techniques for enhanced reliability and efficiency, developing accurate underwater channel models for improved simulation and prediction, and exploring network coding techniques to boost throughput and reliability.

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