

Development of an Improved Neighboring-Based Energy-Efficient Routing Protocol for Underwater Wireless Sensor Networks

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Abstract:

Underwater Wireless Sensor Networks (UWSNs) consist of sensor nodes deployed underwater to monitor and collect data on aquatic environments, essential for applications like military surveillance, oil & gas exploration and environmental monitoring. This research tackles the challenges of energy constraint and reliability of data transmission in UWSNs, which face issues such as variable channel conditions, significant signal attenuation, and limited bandwidth due to water currents and temperature variations. The Neighboring-Based Energy-Efficient Routing (NBEER) protocol is one of the techniques that was developed, which utilized a Neighbor Head Nodes (NHNs) selection strategy by considering nodes with high residual energy to collect data from other sensor nodes and sent it to the sink nodes on the water surface which aggregate the data and send it to the base station (BS) offshore, but the protocol do not consider the unpredictable conditions found in aquatic settings such as water currents and temperature variations during the selection of NHNs, resulted to inefficient energy utilization and diminishing network performance. To address this, a Dynamic Neighbor Adaptation (DNA) scheme was developed and integrated into NBEER, allowing the protocol to dynamically select Neighbor Head Nodes (NHNs) based on network conditions, energy level, water current, and temperature variation also, to re-cluster the displaced nodes to the nearest NHN after changes of water currents or temperature variation of the underwater environment. This adaptation improves load balancing and network stability. The proposed technique was simulated using MATLAB R2023b, the improved NBEER protocol achieved a reduced end-to-end delay of 47.55s, lower total energy consumption of 9.16J, a higher packet delivery ratio of 85.67% as performance metrics compared with 53.00s, 12.60J, and 78.80%, respectively as reported in literature. These results indicate improved network stability, more efficient energy utilization, reduced packet loss and prolonged network lifespan of the UWSNs.

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1. Introduction

Underwater wireless sensor networks (UWSNs) are networks used for monitoring tasks over specific underwater regions [1]. They are equipped with smart sensors and autonomous underwater vehicles that communicate cooperatively through wireless connections [2, 3]. UWSN have emerged as critical tools for various applications, including underwater imaging, marine data collection, military surveillance, Oil and Gas exploration, equipment monitoring [4, 5].

The components of UWSNs typically include underwater sensor nodes, autonomous underwater vehicles (AUVs), surface sinks, base stations, and communication systems [6, 7, 8]. These components work together to enable the monitoring and data collection tasks performed by UWSNs.

UWSNs use different communication mediums such as acoustic communication, optical communication, and radio frequency (RF) communication [9, 10]. Among these communication mediums acoustic communication is the most commonly used medium in UWSNs, due to its low attenuation in water and are less affected by changes in water temperature, salinity, and other environmental factors compared to other communication mediums [11]. Due to the attenuation of radio signals in an underwater environment, the global positioning system (GPS) cannot be used in UWSNs [12, 13]. Therefore, UWSNs use an acoustic method of communication to send and receive the data between the source and destination [14]. This analysis concludes that routing protocols designed for terrestrial wireless sensor networks (TWSNs) are inappropriate for underwater applications [15].

Routing protocols for UWSNs are crucial for establishing efficient communication paths in the challenging underwater environment [16]. These protocols address the unique characteristics of UWSNs, such as low bandwidth, large propagation latency, and limited battery power [17, 18]. Several routing protocols have been developed to tackle these challenges and optimize data transmission in UWSNs [19, 20, 21]. Some notable routing protocols include Energy-Efficient Clustering Multi-Hop Routing (EECMR) protocol, Neighboring-based Energy-Efficient Routing (NBEER) protocol, Cooperative-Relay NBEER (CR-NBEER) protocol, Balanced Energy Efficient Circular (BEEC) routing protocol, Energy-Efficient Depth-Based Routing (EEDBR) protocol, etc. [22, 23, 24].

The dynamic and harsh nature of underwater environments presents significant challenges for these networks [25, 26]. Existing routing protocols do not address the effect of environmental factors such as water currents and temperature variations during the selection of neighbor head nodes (NHNs), leading to inefficient energy usage and diminished network performance. This study focuses on addressing these factors by developing of an improved energy-efficient routing protocol that minimizes energy consumption, prolongs network lifespan, and ensures reliable data transmission in a dynamic underwater environment.

2. Methodology

This section comprises three parts: the first details of designing a dynamic underwater environment, the second is the development of a DNA scheme and integrate the scheme into NBEER to enable the selection of NHNs based on energy level, network conditions, water current and temperature variation, and the third outlines the approach for evaluating the improved NBEER performance.

2.1 Dynamic underwater environment design

This stage involves process of designing a dynamic underwater environment. Which described as follows: The special coverage was set to 550m x 450m x 350m with the transmission range between the sensor nodes of 250m, a channel frequency range of 2.412GHz to 2.472GHz, and a channel transmission frequency of 10KHz to 50KHz was used. The energy level of each sensor nodes was set to 22 joules, and packet size of 512bytes was used. The normal pressure of the ocean was set between the range of (40) – (44.1) psi, with the simulation randomly selecting pressures, any reading above this ranges the sensor nodes will detect high pressure. The normal temperature of the ocean was set between (-2°C) – (30°C), with the simulation randomly selecting temperatures, any reading above this ranges the sensor nodes will detect high temperature. The normal salinity of the ocean was set to 35 parts per thousand (ppt), with the simulation randomly selecting salinity levels, if the sensor nodes detect the salinity level is above the normal it will detect high salinity.

2.2 Improved NBEER Development

In this phase, the development of a DNA scheme and integrate it into the NBEER were discussed in detail: Two hundred and fifty (250) sensor nodes were randomly

deployed underwater each broadcasts a hello packet that contains its measured pressure level, salinity, temperature, and a unique ID to enable each node discover its neighbor enclosed by its transmission range. Based on the broadcast information, the sensor nodes were then divided into five clusters, in each cluster three neighbor head nodes (NHNs) will be elected based on network conditions, residual/renewable energy (R.E), water currents, and temperature variations also, to re-cluster the displaced nodes to the nearest NHN after changes of water currents or temperature variation of the underwater environment. The NHN selection process is computed using equation 1, which is based on the weighted gain w_g . Path loss between the communication node PL and signal to noise ratio SNR are computed using equation 2 and 3 respectively.

$$w_g = \frac{\min(PL_{s_i Ri}, PL_{s_i Di}) + \min(SNR_{s_i Ri}, SNR_{s_i Di})}{\max(R.E_{Ri}, R.E_{Di})} \quad (1)$$

$$PL = 20n \log_{10}(d) + c \quad (2)$$

$$SNR = \frac{P_{signal}}{P_{power}} \quad (3)$$

Where: s_i = Sender node, Ri = Relay node, Di = Destination node, d = Distance between transmitter and receiver, c = frequency, n = Signal strength power, P_{signal} = Power signal representing the strength of the transmitted signal, P_{power} = Power noise, representing the strength of the background noise, $R.E$ = Residual energy

Ten receivers (sinks) were positioned on the surface of the water, with one base station onshore, to collect data from NHNs. At every 50 seconds sink nodes broadcast hello packets containing energy levels, distance, network conditions, and environmental data. Based on this information, NHNs are grouped into A, B, and C to choose the best sink for data transmission. Group A NHNs prioritize sinks 1 and 2, transmitting data to the base station if available; otherwise, they check sinks 3 and 4. Group B NHNs prioritize sinks 5 and 6, with fallback options of sinks 3, 4, 7, and 8. Group C NHNs first check sinks 9 and 10, with fallback options of sinks 7 and 8. Data is aggregated and transmit to the base station after selecting the best sink. This process is on the basis of equation 4.

$$NN = \left[\frac{1 - W(X_{Max} - X(Q_a - Bs))}{X_{Max} - X_{Min}} - G \left(1 - \frac{I_{remaining}}{I_{Maximum}} \right) \right] NN^0 \quad (4)$$

Where: NN = Nearest neighbor, $X(Q_a - Bs)$ = Distance between the sensor node (Q_a) and the base station (Bs), W = Weight factor, G = Gain factor, X_{Max} = indicates the maximum distances between the base sink and the sensor nodes, X_{Min} = indicates the minimum distances between the base sink and the sensor nodes, $I_{remaining}$ = the remaining power of a node, $I_{Maximum}$ = the maximum energy of the main node, NN^0 = represents the maximum number of nearest neighbours.

2.3 Performance Evaluation

The performance evaluation of the developed scheme will be conducted using three performance metrics: End-to-end delay, total energy consumption, and packet delivery ratio. These metrics are crucial in assessing the efficiency and practicality of the INBEER in real-world applications.

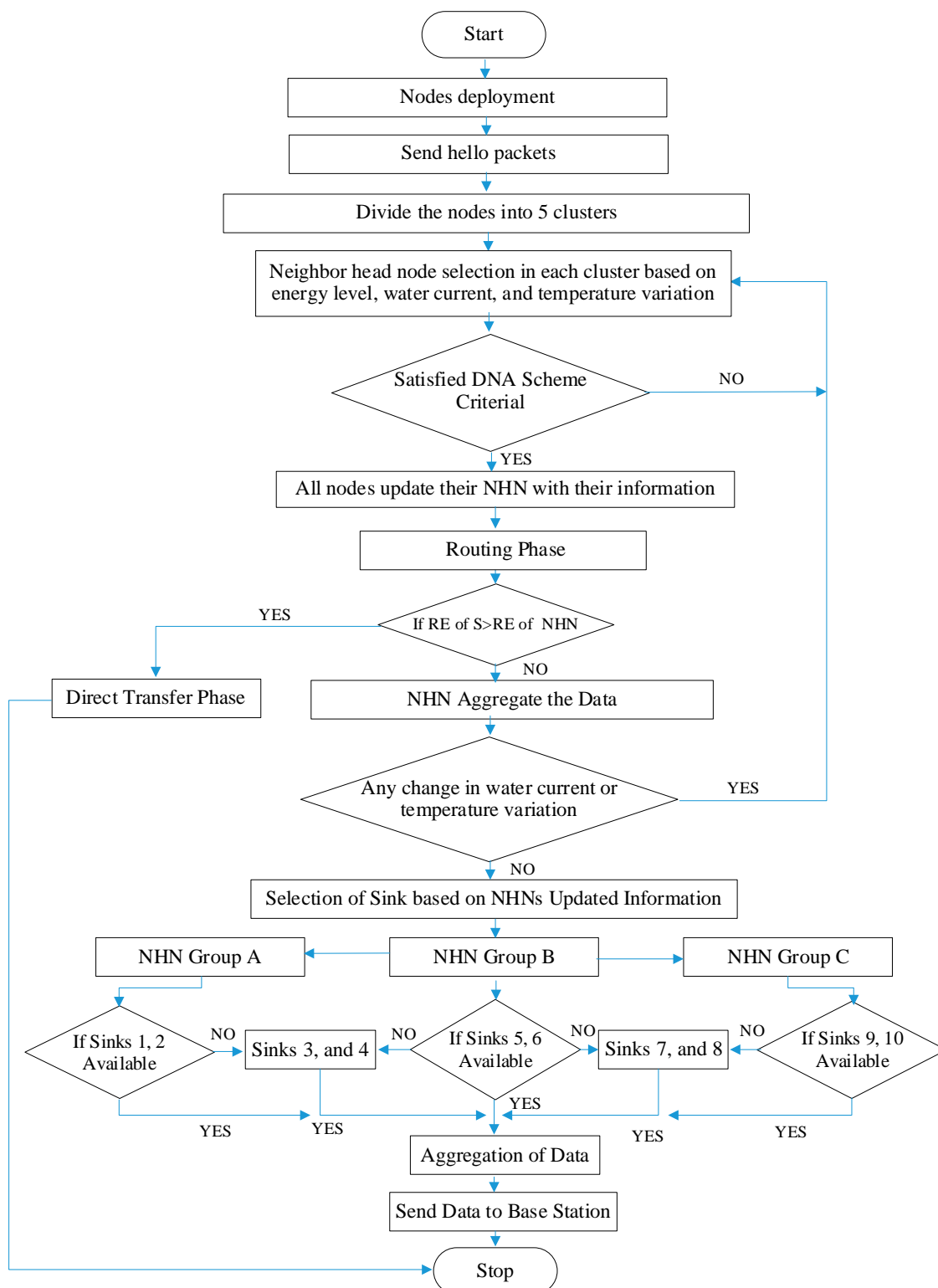


Figure 1: Improved Neighboring-Based Energy-Efficient Routing Protocol for UWSNs Flowchart

3 Results And Discussion

This section presents the simulation results of the proposed INBEER, with detailed analysis and discussion. Each metric is discussed in detail, with reference to tabular, graphical, and chart representations. The performance evaluation of INBEER in contrast to the existing protocol NBEER. The main objective of this research was to evaluate the performance of INBEER and NBEER by utilizing

essential performance metrics including end-to-end delay (E2ED), total energy consumption (TEC), and packet delivery ratio (PDR).

3.1 End-to-end delay

Table 1 and Figure 2 shows the E2ED results in a tabular and graphical representation, respectively. If a data packet takes longer than expected, it is marked as delayed

occurred indicating latency as it moves between sensor nodes. The E2ED simulations ran for 10000s, split into ten slices, 1000s each. The analysis focused on each simulation cycle. At 1000s the E2ED of the developed INBEER was higher with a value of 83.52s due to the wider distances between the sensor nodes, as compared to NBEER with a value 78.00s. Network stability is achieved at 2000s with a value of 72.48s as compared to NBEER with 74.00s, as the network sparsity steadily grows, it results in data being transmitted over the minimum distance. At 10000s the developed INBEER achieved lower E2ED of 19.03s

compared to NBEER with 25.00s, INBEER demonstrates lower E2ED compared to competing protocol namely NBEER. The reason for this superiority lies in the shorter distance among sensor nodes in both dense and sparse conditions. The Figure 2 shows the results of comparison between INBEER, and NBEER in graphical representation.

The average E2ED values are shown in Figure 3, revealing that the INBEER protocol outperformed the NBEER protocol. INBEER shows an average E2ED of 47.55 s, outperformed NBEER 53.00s.

Table 1: End-to-End Delay Evaluation of INBEER and NBEER

Protocol	E2ED At 0s	E2ED At 1000s	E2ED At 2000s	E2ED At 3000s	E2ED At 4000s	E2ED At 5000s	E2ED At 6000s	E2ED At 7000s	E2ED At 8000s	E2ED At 9000s	E2ED At 10000s	Avg E2ED
NBEER	0	78.00	74.00	68.00	60.00	50.00	51.00	42.00	40.00	42.00	25.00	53.00
INBEER	0	83.52	72.48	57.25	47.24	45.55	43.58	45.44	32.13	29.27	19.03	47.55

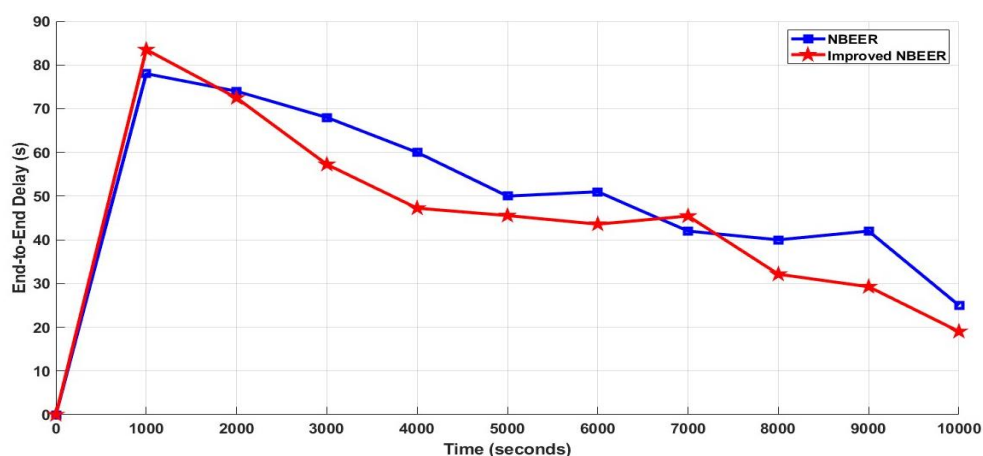


Figure 2: End-to-End Delay of the Developed INBEER and NBEER

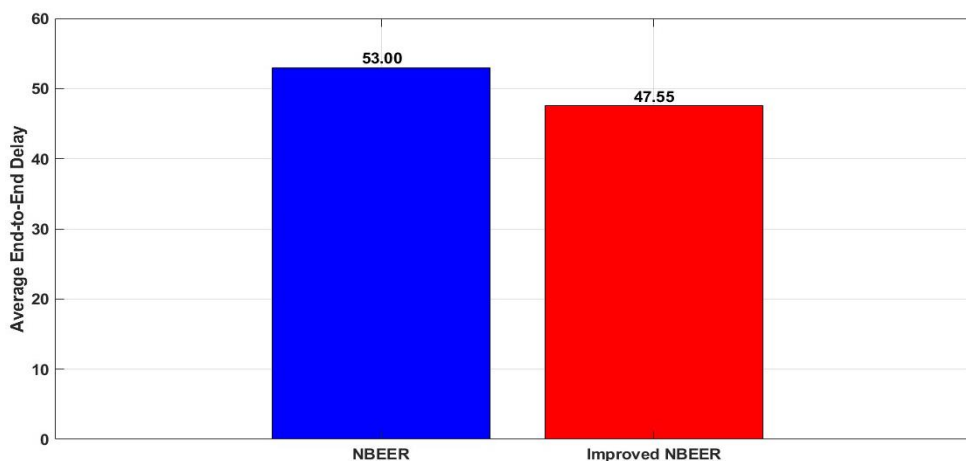


Figure 3: Average End-to-End Delay of INBEER and NBEER

3.2 Total energy consumption

Table 2 and Figure 4 shows the total energy consumed by all protocols namely Improved NBEER and NBEER. These protocols underwent testing every 1000 seconds during simulation, a total of 10000 seconds. At 1000s the TEC of the developed INBEER is higher with a value of 18.51j as compared to NBEER with a value of 16.00j, due to the additional environmental sensing nodes

strategically placed within the underwater network. Network stability is achieved at 2000s with a value of 15.20j as compared with NBEER with a value of 16.20j, as the distance between the sensor nodes to the sink nodes decreases. The results depicted in the table and figure shows that the INBEER demonstrated outstanding performance by minimizing the total energy consumption when compared to existing protocols. The primary and

critical factor contributing to the superior performance of the INBEER protocol is the development of DNA scheme that selects neighbor head nodes (NHNs) based on energy level, network condition, water current, and temperature variation also, to re-cluster the displaced nodes to the nearest NHN after changes of water currents or temperature variation of the underwater environment. These play a crucial role in enhancing network performance and minimizing energy consumption.

Figure 4 shows the graphical representation of results of all protocols such as INBEER, and NBEER with respect to simulation time.

The average energy consumption determined for these protocols are shown in Figure 5, which clearly INBEER demonstrates the superior performance. INBEER exhibiting an average TEC of 9.16J, outperformed NBEER which is 12.60J.

Table 2: Evaluation of Total Energy Consumption of INBEER and NBEER

Protocol	TEC At 0s	TEC At 1000s	TEC At 2000s	TEC At 3000s	TEC At 4000s	TEC At 5000s	TEC At 6000s	TEC At 7000s	TEC At 8000s	TEC At 9000s	TEC At 10000s	Avg TEC
NBEER	0	16.00	16.20	16.30	13.80	12.79	12.39	11.50	10.87	8.15	8.01	12.60
INBEER	0	18.51	15.20	13.67	10.42	8.04	6.71	7.01	4.61	4.20	3.23	9.16

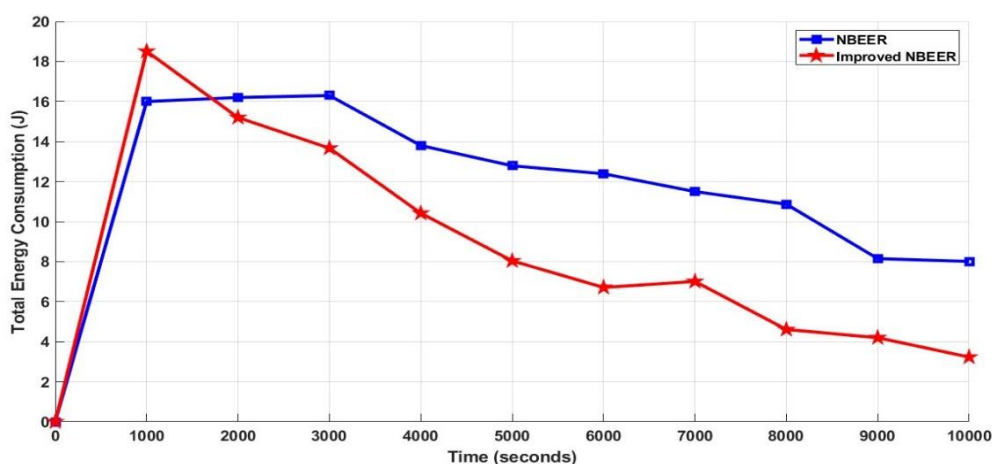


Figure 4: Total Energy Consumption of Developed INBEER and NBEER

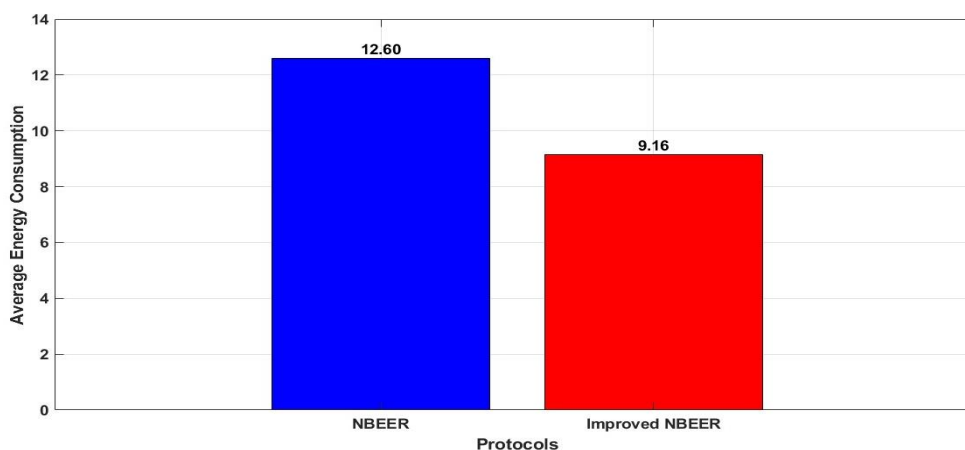


Figure 5: Average Energy Consumption of INBEER and NBEER

3.3 Packet delivery ratio

In sensor networks, the ratio of an entity can be measured as a percentage. Packet Delivery Ratio (PDR) indicates the percentage of packets that were successfully delivered to their intended destination compared to the total number of packets involved in the delivery process. Notably, an increase in the distance between sensor nodes leads to a decrease in the PDR, as these two parameters share a direct relationship, when one parameter increases the other decreases. This relationship ultimately influences the

distance factor. The PDR simulations were conducted over 10,000s, divide into ten, with analysis focused on each 1000s. At 1000s the PDR of the developed INBEER is lower with a value of 98.99% compared to NBEER with a value of 100%, this is due to the higher energy consumed at initialization stage, however, the system stability achieved at 4000s with a value of 95.65% compared to NBEER with 93%. The INBEER approach incorporates a cooperation and dynamic neighbor adaptation strategy for the selection of NHNs, which is the key factor contributing to the superior

performance of the INBEER with respect to PDR, as demonstrated in Table 3 and Figure 6. The INBEER outperforms NBEER, demonstrating remarkably higher PDR values. This superiority can be ascribed to the cooperation of neighboring nodes and the neighbor head node (NHN) selection strategy. Through the utilization of NHNs, INBEER successfully reduces packet loss and attains an impressive PDR.

Figure 6 shows the graphical representation of results of all protocols such as INBEER, and NBEER with respect to simulation time.

However, Figure 7 shows the overall average PDR achieved by the developed INBEER method with existing method like NBEER. INBEER shows an average PDR of 85.67%, outperformed NBEER which have 78.80%.

Table 3: Packet Delivery Ratio Evaluation of INBEER and NBEER

Protocol	PDR At 0s	PDR At 1000s	PDR At 2000s	PDR At 3000s	PDR At 4000s	PDR At 5000s	PDR At 6000s	PDR At 7000s	PDR At 8000s	PDR At 9000s	PDR At 10000s	Avg PDR
NBEER	0	100	100	100	93	91	82	72	58	56	36	78.80
DNA-EERP	0	98.99	98.57	97.87	95.65	92.10	85.73	86.03	77.49	65.67	58.56	85.67

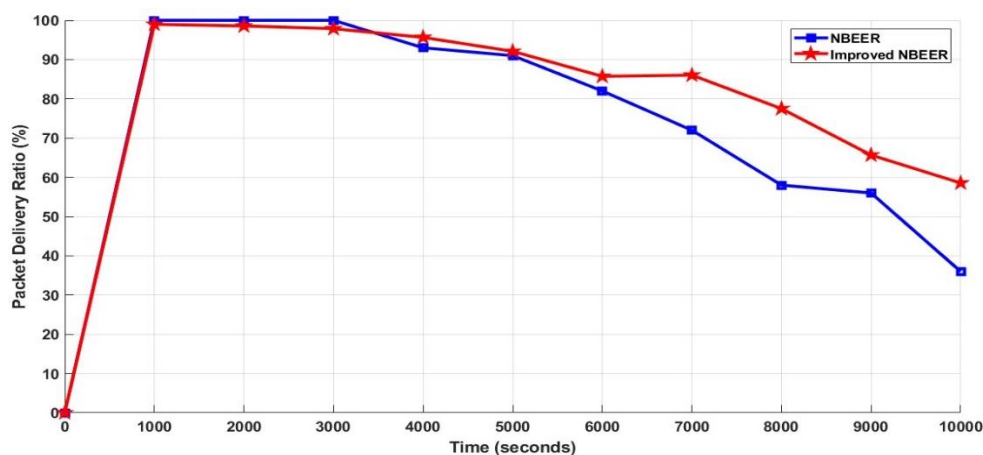


Figure 6: Packet Delivery Ratio of Developed INBEER and NBEER

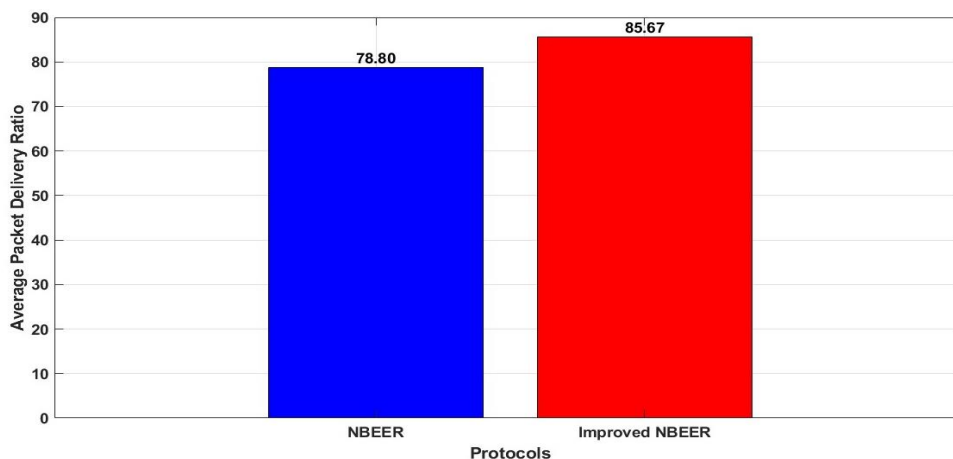


Figure 7: Average Packet Delivery Ratio of INBEER and NBEER

The findings, as depicted in Figure 7, reveal that the INBEER was able to achieve the highest PDR. These findings confirm the improved effectiveness and reliability of INBEER, showing its capacity to sustain high PDR in underwater wireless sensor networks.

4 Conclusion

In this research, an Improved Neighboring-Based Energy-Efficient Routing Protocol (INBEER) was developed for UWSN. UWSNs are specialized networks that consist of autonomous sensor nodes deployed in underwater

environments for diverse applications, including oceanic exploration, environmental monitoring, underwater surveillance, and resource management. The existing routing protocols for UWSNs often encounter challenges in balancing energy efficiency and reliable data transmission, which results in inefficient energy utilization and diminishing network performance. To address this, an INBEER was developed to facilitate the selection of neighbor head nodes (NHNs) according to network's condition, energy level, water current, and temperature variation. The developed INBEER was simulated using MATLAB R2023b. The

performance of the developed technique was evaluated using end-to-end delay, total energy consumption, and packet delivery ratio as performance metrics with a recorded performance of average end-to-end delay of 47.55 s, total energy consumption of 9.16 Joules, and packet delivery ratio of 85.67% as compared with 53.00s, 12.60J, 78.80% respectively as reported in literature. These results highlight the INBEER's effectiveness in enhancing network stability, energy efficiency, and overall performance, outperforming other similar existing protocols.

Recommendations for Further Work

Enhance the INBEER methodology by incorporating additional sensor nodes that will also consider the depth and turbidity of the ocean/sea during the selection of cluster heads (CHs). By exploring these avenues for improvement, the INBEER can continue to evolve as a robust and secure solution for energy-efficient routing protocol for UWSNs, providing valuable contributions to the field of UWSNs.

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