



ORIGINAL RESEARCH ARTICLE

IMPROVED ENERGY-BASED EFFICIENT ROUTING PROTOCOL FOR UNDERWATER WIRELESS SENSOR NETWORKS

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ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) rely on small, energy-constrained sensors deployed at varying sea depths for applications such as surveillance, environmental monitoring, and data collection. However, high energy consumption and end-to-end delay, exacerbated by dynamic depth and turbidity variations, significantly impact communication efficiency. Existing protocols, such as the Neighboring-Based Energy-Efficient Routing Protocol (NBEER), attempt to optimize energy usage but fail to adapt to these environmental changes, leading to reduced network performance. To address this, an Improved Energy-Based Efficient Routing Protocol (IEBERP) was developed, integrating a Distributed Underwater Clustering Scheme (DUCS) for efficient cluster formation and a Strata Adaptation Scheme (SAS) to dynamically reassign displaced nodes to the nearest cluster head (CH) after depth or turbidity changes. The protocol was simulated in MATLAB (R2024b), and results showed significant performance improvements over NBEER, achieving 9.68 TEC, 81.45 PDR, 46.42 E2ED, 234 NAN, and 35,191 NPR, compared to NBEER's 12.60 TEC, 78.50 PDR, 53.00 E2ED, 198.30 NAN, and 22,500 NPR. These results highlight IEBERP's enhanced energy management and adaptive clustering, leading to improved routing efficiency, reduced latency, and higher packet delivery rates. This makes IEBERP a promising solution for reliable and energy-efficient communication in dynamic underwater environments.

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1.0 Introduction

Underwater wireless sensor network (UWSN) is a network of sensor nodes equipped with non-rechargeable and replaceable batteries, antenna, and processing unit deployed underwater for data collection and environmental monitoring (Luo et al, 2021; Chaurasiyya et al, 2022). UWSN is used in several applications including exploration, disaster risk prediction, and monitoring.

There are differences in the features and functions of UWSN compared to the terrestrial wireless sensor networks (TWSN). TWSN uses radio frequency (RF) for communication to send and receive data between the source and destination. Due to the attenuation of RF underwater, it is not used for communication in an underwater environment. UWSN uses acoustic signals as a communication medium. Acoustic signals travel five times slower than radio waves underwater, at around 1500 m/s. The turbidity and depth of the water affects the acoustic signals (Gite et al., 2023; Padmavathy et al, 2022). UWSN has several restrictions and difficulties such as high propagation latency, low bandwidth, dynamic network topology, high ocean interference, noise, and sensor nodes limited battery life. A routing protocol facilitates effective transfer of data from the source to the destination (Ismail et al, 2020; Hussain et al, 2023). In designing routing protocols for UWSNs, energy efficiency is a significant factor that requires consideration. Various researchers have examined some strategies to lower nodes energy consumption (Shah et al, 2023; Harb et al., 2024), among which includes cluster formation strategies. The clustering methods are often used to tackle the problems of

energy limitation of sensor nodes and deployment issues in both TWSN and UWSN (Abubakar et al, 2020; Kuang et al., 2024). In the clustering approach, sensor nodes are grouped into cluster and a leader node referred to as a Cluster Head (CH) is chosen in each cluster to aggregate and transfer data.

2. Materials and Method

This section is divided into two parts: it explains the materials and methods of the developed Improved Energy Based Efficient Routing Protocol (IEBERP) for UWSNs.

2.1 Materials

The materials used for the implementation of this research are:

1) Laptop computer with the following specifications

Processor:	Dual-core
Processor speed:	2.5GHz
RAM size:	8GB
Operating system:	64bit Windows operating system

2) MATLAB/SIMULINK (R2024b) software for the design and simulation.

2.2 Methods

This section is divided into two parts: the first explains the design of a strata underwater environment, the second covers the development of an improved energy-based efficient routing protocol for UWSN, use a distributed underwater clustering scheme (DUCS) for cluster formation, and a strata adaptation scheme for data transmission considering underwater depth and turbidity variations.

2.2.1 Design of a strata underwater environment

In this stage, a strata underwater environment is designed with the following parameters: the network area was set to 550m × 450m × 350m; the transmission range was set to 250 m, water turbidity was set to less than 10 nephelometric turbidity unit (NTU), and normal water depth was set to 450m as used in the work of Shah et al, (2023). The turbidity variation range was set between 1 and 15 NTU and depth variation range was set between 1m to 450m, a channel frequency of 2.412GHz to 2.472GHz, and a transmission frequency of 10KHz to 50KHz to simulate a dynamic underwater environment. The simulation parameters were executed to form a strata underwater environment suitable for the simulation of the proposed IEBERP.

2.2.2 Development of an improved energy-based efficient routing protocol (IEBERP) for UWSNs

In this network, 250 sensor nodes were deployed at various depths within a layered underwater environment. Additionally, 10 sink nodes were deployed at the water's surface in a random distribution. These sink nodes are gateways for data transmission to an offshore base station. To efficiently manage data collection and transmission, the network organized itself into 10 clusters using distributed underwater clustering scheme. Each cluster is led by a Cluster Head Node (CHN), which was selected based on the energy levels of nodes within that. Nodes with higher residual energy are prioritized as potential CHNs since they have more power available for the intensive task of data aggregation and forwarding. The CHN of each cluster continuously monitored its member nodes for key metrics: energy level, depth, and water turbidity. The inclusion of depth and turbidity as dynamic parameters allowed the CHN to respond to environmental changes. If a node's depth or turbidity changes, the CHN can adjust the cluster structure, either by reassigning nodes to neighboring clusters or by reorganizing nodes within its cluster. This adaptability ensured stable connections and data transmission across the network despite environmental fluctuations. Also, the CHN reduce energy use within its cluster. It temporarily deactivates nodes with energy levels below the 15J threshold, The IEBERP place sensor nodes with 15J threshold on hold mode, when the high residual energy is equal to threshold plus 2, the threshold will now be threshold minus 5 that is (10), this will keep on repeating itself to produce a dynamic threshold. Placing them on "hold" status to conserve power. Only nodes with higher energy levels are permitted to transmit data to the CHN. This energy-aware strategy helps extend the overall lifespan of the network. Once the CHN gathered data from active, high-energy nodes, it performed redundancy checks to remove duplicate information, thus minimizing unnecessary data transmission. After filtering the data, the CHN forwarded the information in two possible directions: (1) to the nearest CHN located at a shallower depth, thereby leveraging hierarchical forwarding, or (2) directly to the nearest available sink node at the surface, if it is the most efficient path. Finally, the surface-level sink nodes received data packets and relayed

them to an offshore base station for processing and analysis. This multi-layered, energy-efficient design ensured reliable data transmission across the underwater network, even in challenging and dynamic environmental conditions.

The CHNs is computed using equation 1 (Domingo & Prior, 2007).

$$CH_{prob} = \frac{C_i}{C_{MAX}} \times C_{prob} \tag{1}$$

Where C_{MAX} denotes the maximum battery capacity and C_i denotes the node's battery level, or residual energy. The number of initial cluster-head announcements is limited by a small constant fraction called C_{prob} , which is used to set the initial proportion of CH. In order to ensure that the routing protocol will continue to function even in the event that sensor battery levels throughout the network are low, it is required to improve the likelihood that certain nodes will elect themselves as CHs by preventing CH_{prob} from falling below a small probability, p_{min} (Domingo & Prior, 2007). Figure 1 shows the flowchart of the developed IEBERP.

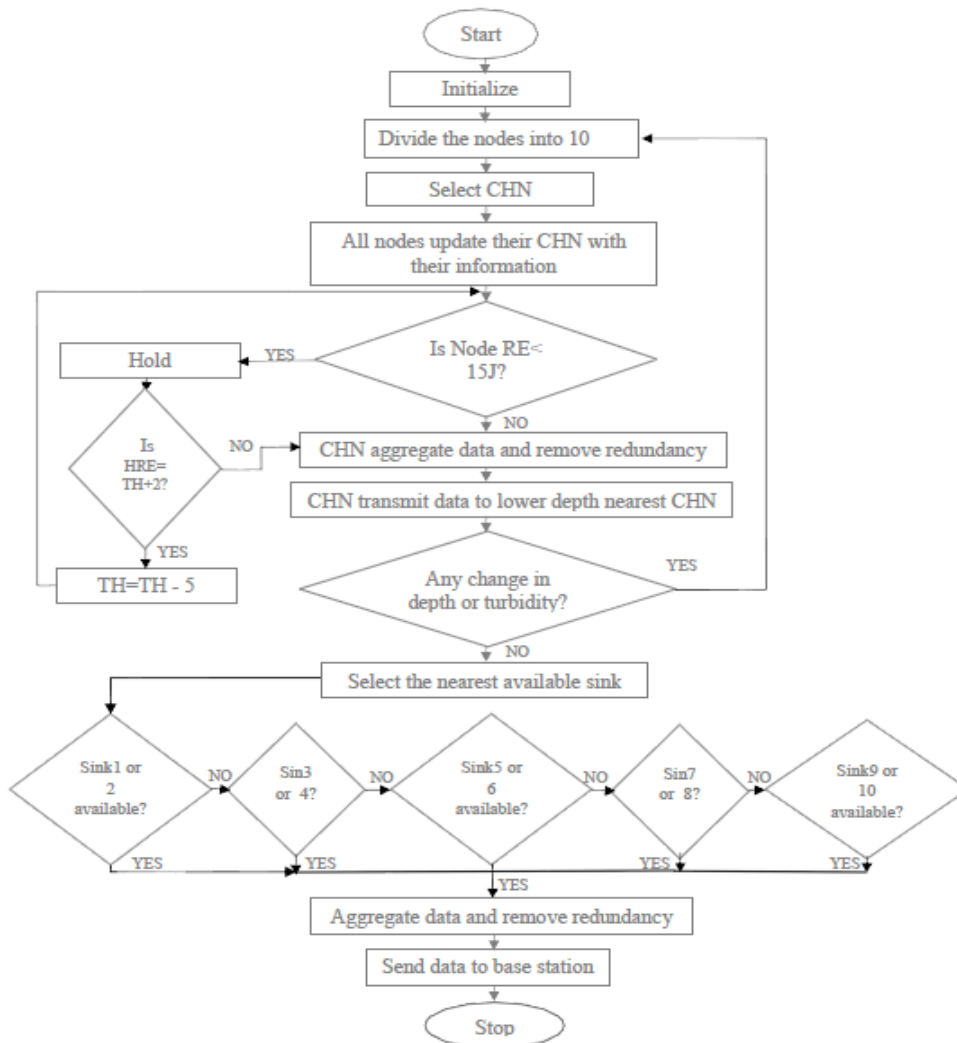


Figure 1: flowchart of the developed IEBERP

3. Results and Discussion

This section presents the simulation results of the proposed IEBERP, with discussion. Each metric is examined using graph representations, comparing the performance of IEBERP protocol with existing protocols like CEER, Co-UWSN and NBEER. The primary focus is on evaluating these protocols using key metrics such as TEC, E2ED, PDR, NPR and NAN.

3.1 Total Energy Consumption

The simulation was conducted for 10000 seconds at 1000-second intervals as used in the work of (Shah *et al.*, 2023). The IEBERP protocol was executed over multiple rounds of simulation time (10,000 seconds at a 1000-second interval). The Total Energy Consumption (TEC) was computed the results indicated that between 1000 and 2000 seconds of simulation time before the integration of strata adaptation scheme, the Co-UWSN, CEER, and NBEER protocols initially outperformed the developed IEBERP protocol. However, with the integration of a strata adaptation scheme, IEBERP effectively stabilized at 4000 seconds with 11.94 TEC, where the Co-UWSN, CEER, and NBEER protocols had 13.98, 15.54, and 13.80 TEC respectively. Table I shows the simulation summary of TEC obtained for IEBERP and existing Co-UWSN.

Table I: Total Energy Consumption of IEBERP, Co-UWSN, CEER and NBEER

Protocol	TEC	TEC	TEC	TEC	TEC	TEC	TEC	TEC	TEC	TEC	TEC	Avg TEC
	At	At	At	At	At	At	At	At	At	At	At	
	0s	1000s	2000s	3000s	4000s	5000s	6000s	7000s	8000s	9000s	10000s	
CO-UWSN	0	17.35	15.00	14.19	13.98	13.68	13.50	12.48	11.95	11.01	9.79	13.29
CEER	0	16.93	16.37	15.82	14.54	14.47	13.41	13.91	12.57	8.57	4.93	13.15
NBEER	0	16.00	16.20	16.30	13.80	12.79	12.39	11.50	10.87	8.15	8.01	12.60
IEBERP	0	18.49	15.79	13.64	11.94	10.35	8.91	7.03	5.74	4.33	2.46	9.86

Figure 2 shows the graph comparison of the developed IEBERP, and existing Co-UWSN, CEER and NBEER protocols.

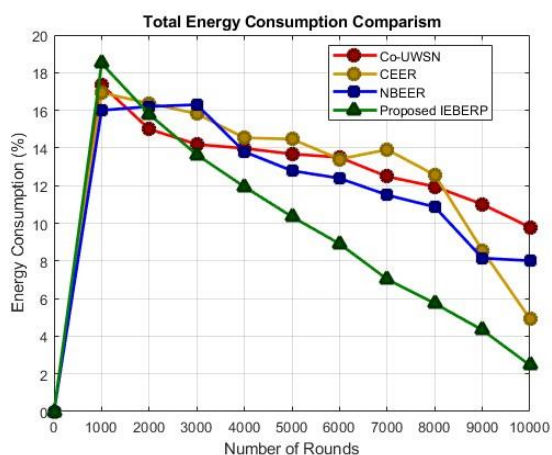


Figure 2: Graph Illustration Comparison of the Total Energy Consumption

This demonstrated superior energy conservation. By selectively placing nodes in hold mode and adapting to dynamic changes. The acoustic sensor nodes in sleep mode utilized only 1-100µA compared to 1-100A in active mode per cycle (Sanchez *et al.*, 2012), enabling substantial energy savings. This strategy of putting lower-energy nodes into sleep mode significantly extends the network’s lifetime and enhances its overall efficiency. The TEC obtained from the developed IEBERP showed a significant improvement by achieving an average of 9.8 TEC. This shows a significant improvement over the existing Co-UWSN, CEER and NBEER protocols with 13.29 TEC, 13.15 TEC, and 12.60 TEC. This led to improvement in the routing efficiency of the developed IEBERP.

3.2 Number of Alive node

The IEBERP protocol simulation conducted for 10,000 seconds with intervals of 1,000 seconds. The number of Alive Nodes was calculated. The simulation results conducted showed that between 1000 to 9000 seconds, the IEBERP demonstrated a significant improvement in Number of Alive Nodes (NAN) compared to existing Co-UWSN, CEER, and NBEER protocols. This improvement is primarily attributed to IEBERP’s strategic approach to energy management. Unlike the compared protocols, IEBERP optimized energy usage by shifting the data transmission load away from nodes with lower energy to those with higher energy reserves. This approach prevented the lower-energy nodes from prematurely depleting their power, reducing the strain or overhead cost on those weaker nodes. Table 2 shows the summary of NAN for the developed IEBERP, NBEER, CEER and Co-UWSN protocols.

Table 2: Number of Alive Nodes for IEBERP, Co-UWSN, CEER and NBEER

Protocol	AN	AN	AN	AN	AN	AN	AN	AN	AN	AN	AN	Avg
	At	At	At	At	At	At	At	At	At	At	At	AN
	0s	1000s	2000s	3000s	4000s	5000s	6000s	7000s	8000s	9000s	10000s	
CO-UWSN	0	225	217	207	191	170	168	160	150	139	135	176.20
CEER	0	215	209	204	198	182	180	178	172	168	167	187.30
NBEER	0	220	218	212	203	198	195	192	184	181	180	198.30
IEBERP	0	248	249	248	246	247	247	236	233	225	167	234.6

Figure 3 shows the graph illustration of NAN comparison of the developed IEBERP and existing Co-UWSN, CEER, and NBEER.

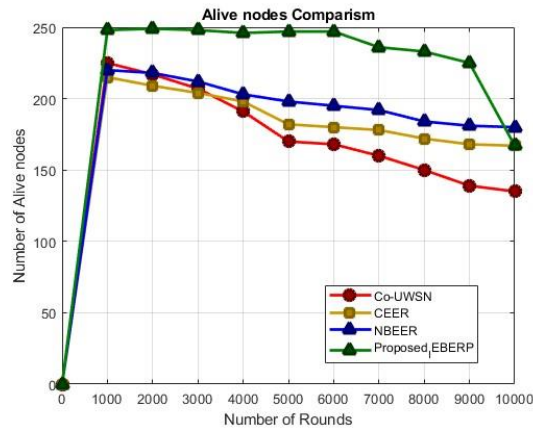


Figure 3: Graph Illustration Comparison of the Total Number of Alive Nodes

By alleviating the workload on nodes with low energy, IEBERP extended their operational lifespan, allowing them to remain active in the network longer. This effectively delays the point at which nodes start to fail due to energy exhaustion, thereby maintaining a higher count of alive nodes over time. However, once the simulation reached 9000 seconds, the rate of node depletion increased as more lower-energy nodes began to exhaust their energy. The developed IEBERP achieved the average of 234.6 NAN outperforming the existing Co-UWSN, CEER and NBEER protocols with 176.20, 187.30 and 198.30 NAN respectively.

3.3 Packet Delivery Ratio

The IEBERP protocol simulation was executed for 10,000 seconds with intervals of 1,000 seconds. The Packet Delivery Ratio (PDR) was computed. The results showed that the IEBERP achieved high packet delivery ratio (PDR) between 6000 and 10000 seconds. At 6000 seconds, the IEBERP achieved 85.51 PDR, whereas the Co-UWSN, CEER and NBEER protocols achieved 77, 40.88, and 81 PDR. The developed IEBERP protocol maintained a stable PDR due to its adaptive mechanisms, which enabled it to efficiently respond to the changing underwater environment, specifically dynamic variations in depth and turbidity. Thus, outperforming the existing Co-UWSN, CEER, and NBEER protocols. These environmental changes can affect signal strength and node connectivity, thereby affecting network stability. Table 3 presents the summary of the PDR of the developed IEBERP, NBEER, CEER and Co-UWSN protocols.

Table 3: Packet Delivery Ratio for IEBERP, NBEER, CEER and Co-UWSN

Protocol	PDR	PDR	PDR	PDR	PDR	PDR	PDR	PDR	PDR	PDR	PDR	Avg
	At	At	At	At	At	At	At	At	At	At	At	PDR
	0s	1000s	2000s	3000s	4000s	5000s	6000s	7000s	8000s	9000s	10000s	
CO-UWSN	0	100	100	98	90	81	77	65	61	57	42	77.10
CEER	0	99.51	99.51	78.95	64.22	42.60	40.88	38.94	24.35	24.21	22.34	53.55
NBEER	0	100	100	100	91	83	81	68	62	58	45	78.80
IEBERP	0	79.22	80.15	76.44	74.98	78.86	85.51	87.54	83.34	88.58	79.91	81.45

Figure 4 shows the graph illustration comparison of the developed IEBERP and existing Co-UWSN, CEER, and NBEER.

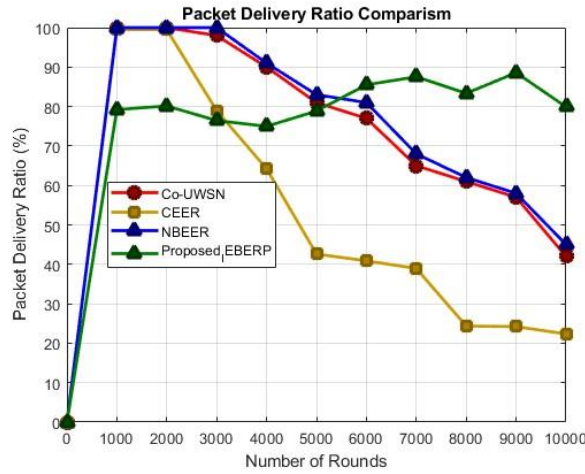


Figure 4: Graph Illustration Comparison of the Packet Delivery Ratio

The primary reason for this improvement in PDR is IEERP's enhanced capability to maintain a higher number of alive nodes throughout the simulation. A greater number of active nodes helped in sustaining connectivity and allowed more consistent data packet forwarding paths, which in turn improved the overall delivery success rate. This resulting in improved routing efficiency.

The PDR of the developed IEERP achieved an average of 81.45% PDR outperforming the Co-UWSN, CEER and NBEER protocols with 11.10%, 53.55% and 78.80% respectively.

3.4 Number of Packets received

The Number of Packets Received (NPR) showed that the IEERP achieved a high NPR at the destination throughout the simulation period. This is due to its efficient management of both intra-cluster and inter-cluster communication. By carefully coordinating data transmission within and between clusters. Table 4 shows the summary of NPR of the developed IEERP, NBEER, CEER, and Co-UWSN protocols.

Table 4: Number of Packets Received for IEERP, NBEER, CEER and Co-UWSN

Protocol	NPR	NPR	NPR	NPR	NPR	NPR	NPR	NPR	NPR	NPR	NPR
	At	At	At	At	At	At	At	At	At	At	At
	0s	1000s	2000s	3000s	4000s	5000s	6000s	7000s	8000s	9000s	10000s
CO-UWSN	0	5000	10000	14700	18000	20250	23100	22750	24400	25650	21000
CEER	0	4975.5	9951	118142.5	12844	10650	12264	13629	9740	10894	11170
NBEER	0	5000	10000	15000	18200	20750	24300	23800	24800	26100	22500
IEERP	0	7102	14135	17661	20514	24405	27959	30340	31536	33813	35191

Figure 5 illustrates NPR graph comparison of the developed IEERP, NBEER, CEER, and Co-UWSN protocols.

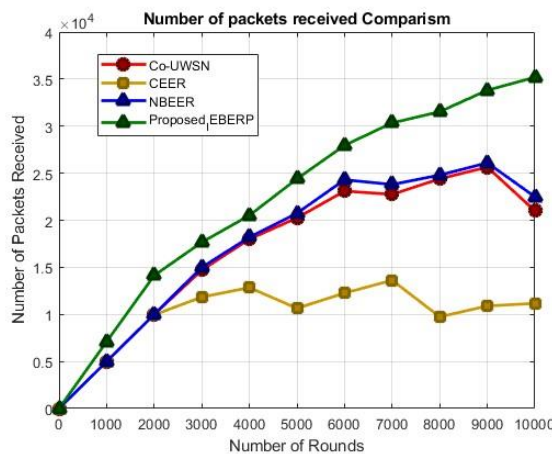


Figure 5: Graph Illustration Comparison of the Number of Packets Received

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The IEBERP reduced the chances of packet collisions across the network. This reduction in collisions allows for smoother and more reliable data flow, enabling a greater number of packets to successfully reach their destination. The IEBERP achieved 35191 NPR at 10,000 seconds outperforming NBEER, CEER, and Co-UWSN with 22500, 11170, and 21000 packets respectively. The NPR increased over time, indicating that IEBERP improved transmission efficiency by reducing redundant data and minimizing packet retransmissions.

3.5 End to end Delay

The IEBERP protocol simulation results for 10000 seconds at a 1000 interval were captured. The E2ED was computed and the results shows that the developed IEBERP maintain between 39s to 49s end-to-end delay (E2ED) after 10000 simulation time at 1000 interval. IEBERP achieved a reduced E2ED due to its adaptability to the dynamic underwater environment, specifically changes in depth and turbidity. As depth increases, the distance between the source and destination nodes can vary, impacting transmission time. Table 5 presents the summary of E2ED of the developed IEBERP, NBEER, CEER and Co-UWSN protocols.

Table 5: End to End Delay for IEBERP, NBEER, CEER and Co-UWSN Protocols

Protocol	E2ED	E2ED	E2ED	E2ED	E2ED	E2ED	E2ED	E2ED	E2ED	E2ED	E2ED	Avg E2ED
	At	At	At	At	At	At	At	At	At	At		
	0s	1000s	2000s	3000s	4000s	5000s	6000s	7000s	8000s	9000s	10000s	
CO-UWSN	0	84.03	80.01	72.02	60.01	51.03	50.03	42.71	43.29	34.80	34.01	55.19
CEER	0	86.00	82.00	79.00	76.00	75.00	72.00	68.00	70.00	62.00	68.00	73.80
NBEER	0	78.00	74.00	68.00	60.00	50.00	51.00	42.00	40.00	42.00	25.00	53.00
IEBERP	0	49.19	44.34	47.58	46.99	48.58	48.58	45	49.27	44.97	39.76	46.42

Figure 6 shows the graph illustration of E2ED of the developed IEBERP, NBEER, CEER, and Co-UWSN protocols.

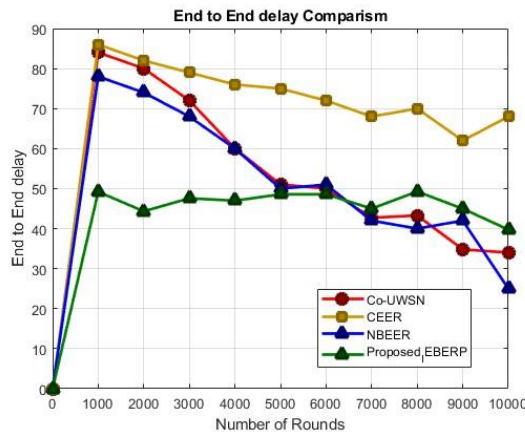


Figure 6: Graph Illustration comparison of the End-to-End Delay

The IEBERP responds to these changes by adjusting its routing strategy, allowing it to maintain efficient data transmission and minimize delay. The average E2ED showed that IEBERP achieved optimal delay of 46.42, outperforming Co-UWSN, CEER, and NBEER with 55.19, 73.80, and 53.00 delay respectively. The developed IEBERP maintained optimal E2ED, due to the strata adaptation scheme's ability to dynamically reassign displaced nodes to nearby clusters after losing their initial connection, which led to improved routing efficiency.

4. Conclusion

This work developed an improved energy based efficient routing protocol (IEBERP) for UWSN that adapt to dynamic turbidity and depth changes in the underwater environment to enhance routing performance. The developed protocol utilized a distributed underwater clustering scheme, and strata adaptation scheme to improve the routing efficiency of the UWSN. The developed IEBERP protocol achieved 9.86J TEC, 81.45% PDR, 46.42 E2ED, 234 NAN and 35191.00 NPR outperforming the NBEER with 12.60J TEC, 78.50% PDR, 53.00s E2ED, 198.30 NAN and 22500 NPR. The IEBERP achieved 21% TEC improvement over the existing NBEER that improved the IEBERP energy efficiency. The future work can integrate machine learning algorithms to enable IEBERP to predict environmental changes and adjust routing paths proactively, enhancing the

protocol's ability to minimize energy consumption and transmission delay before the issues arises. This could improve overall network efficiency, especially in highly dynamic environments.

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