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Performance Evaluation of Routing Protocols for Underwater Wireless Sensor Networks

Taj Rahman [1], Irfan Ahmad [1], Asim Zeb [2], Inayat Khan [3], Gauhar Ali [4,*] and Mohammed ElAffendi [4]

1 Department of Physical & Numerical Science, Qurtuba University of Science & Information Technology, Peshawar 25000, Pakistan
2 Department of Computer Science, Abbottabad University of Science and Technology, Abbottabad 22500, Pakistan
3 Department of Computer Science, University of Engineering & Technology, Mardan 23200, Pakistan
4 EIAS Data Science and Blockchain Lab, College of Computer and Information Sciences, Prince Sultan University, Riyadh 11586, Saudi Arabia
* Correspondence: gali@psu.edu.sa

Abstract: Underwater Wireless Sensor Networks (UWSNs) are emerging technology for disclosing multiple applications, such as oil, earth quick, and marine environments. All sensor nodes deployed in UWSNs operate through limited power batteries. Prolonging the network's lifetime in such environments is an essential task and a hot topic among researchers. Multiple routing protocols have been designed to overcome the limited power issue and reduce energy consumption. Each routing protocol evaluated different parameters, but the issue is still unclear as to which one is better. In this study, we evaluated multiple routing protocols to investigate which is better in terms of parameters, such as packet delivery ratio (PDR), energy consumption, end-to-end delay, and the number of alive nodes. The simulation results indicate that Reliability and Adaptive Cooperation for Efficient UWSNs Using Sink Mobility (RACE-SM) performs better in all performance metrics than other routing schemes.

Keywords: UWSNs; underwater; comparative analysis; routing protocols

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1. Introduction

UWSNs are currently the most considerable research field. A 3/4 portion of the world is enclosed by water. It contains multiple applications, such as oil, gas, mines, and other minerals [1]. Therefore, the UWSNs are taking the consideration of scientists to explore these things with modern UWSN technology. UWSNs differ from Terrestrial Wireless Sensor Networks (TWSNs) and IoT-based WSNs in many aspects, such as node mobility and communication techniques. TWSNs use radio signals to transmit data from source to destination [2].

In contrast, UWSNs mostly use acoustic communications to transfer data from the sensor node to the base station or sink node. Figure 1 shows the basic structure of the UWSNs. UWSNs and Under-water Acoustic Networks (UWANs) have several unique properties, such as localization, flexibility, and scalability [3–5].

UWSNs mainly contain multiple sensor nodes, autonomous vehicles, sink nodes, and a satellite base station [6]. All of these communications are done through routing protocols. Still, compared to TWSNs, UWSN routing protocols have many limitations, such as low bandwidth, transmission power, network topology, energy consumption, and high propagation delay [7,8]. It is important to understand the minimum energy consumption of sensor devices, packet delivery ratio, battery, and transmission loss [9,10].

One of the fundamental issues in UWSNs is the design of routing protocols. Most researchers are working nowadays to overcome these challenges. They are developing energy-efficient routing protocols to increase the network lifetime in UWSN environments [11]. The main issue in these routing protocols is focused on the physical layer instead of the network layer, as routing techniques are the most important era.

There are three types of UWSN routing protocols: Localization based, localization-free, and cooperative routing protocols. Those protocols in which the sensor nodes already know the sink node's location and itself are called Localization based. Moreover, due to the mobility nature of UWSNs, localization-based routing protocols are not better. Localization-free routing strategies mean GPS signals, which are also not better because, due to the nature of UWSNs, electromagnetic signals do not propagate in these environments. Another disadvantage of these routing protocols is the waste of node resources to obtain information about the sensor node location [12].

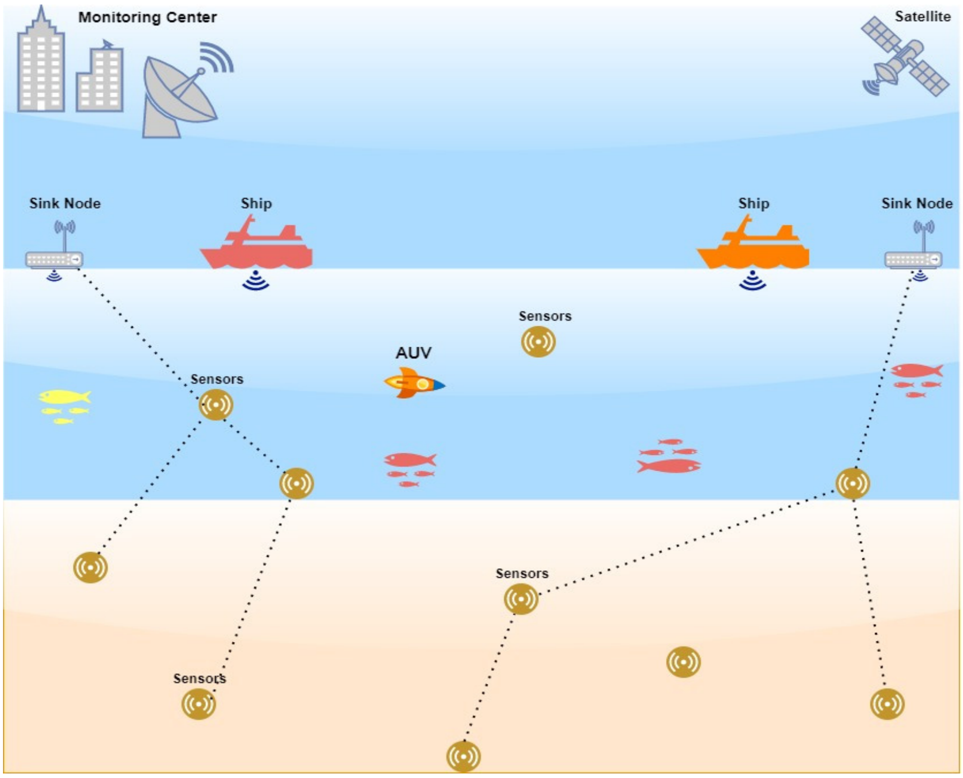

Figure 1. The basic structure of UWSNs.

Cooperative routing is the technique of using the other sensor node resource to transfer from source to destination. The cooperative method normally transfers data between the sink and sensor node through multiple hops. However, cooperative routing (C.R.) takes the underwater channel advantage for transmitting packets through relay nodes in every hop.

Initial C.R. ideas were proposed by Van der Meulen [13], who characterized C.R. as a routing method at the physical layer using cooperative transmission. To improve energy efficiency, link reliability, network performance, and throughput, nodes with a single antenna and a limited amount of available energy can use the resources of other nodes to transmit data through the cooperative method. Data are transferred through multiple relay nodes instead of direct communication.

The main cooperative routing methods for UWSNs considered in this paper are RACE-SM, Energy-efficient regional-based cooperative routing protocol for underwater sensor networks with sink mobility (EERBCR), an energy-efficient data gathering scheme in underwater wireless sensor networks (EEDG), Improved Cooperative Routing Scheme for UWSNs Using Energy Harvesting (EH-UWSN), Multilayer Sinks and Cooperation-Based Data Routing Techniques for Underwater Acoustic Wireless Sensor Networks (MuLSi-Co), and Geographic and Cooperative Opportunistic Routing Protocol for Underwater Sensor Networks (GCORP).

RACE-SM improved the end-to-end delay, PDR, and energy consumption of the UWSNs by using the sink mobility technique instead of the single relay node. The paper also uses the cooperative method to transmit data between the sender and the receiver. In RACE-SM, data are forwarded both directly and through multiple hops. EERBCR is another state-of-the-art routing protocol that uses sink mobility and cooperative methods for data transfers from source to destination. EERBCR divided the whole area into four regions and assigned a sink node in each area, which moved around the region and sensed the packets from the sensor node.

The EH-UWSN is an improved cooperative routing scheme designed to solve energy-consumption issues in the harvesting environment. In EH-UWSN, data are transferred through relay nodes from source to destination. MuLsi-Co is an improved version of the MuLsi routing protocol. MuLsi is a non-cooperative routing algorithm that transfers data through a single relay node. However, MuLsi-Co uses a cooperative routing scheme for data transmission from sender to receiver.

This study analyses the performance metrics of recently designed routing protocols for UWSNs, such as RACE-SM, EERBCR, EH-UWSN, MuLSi-CO, MuLSI, GCORP, and EEDG. Different parameters of the mentioned routing protocols were examined and evaluated. The contributions of this paper are concise, as follows:

- A brief overview of RACE-SM, EERBCR, EH-UWSN, MuLSi-Co, MuLSi, GCORP, and EEDG are introduced.
- Simulation analysis of seven currently designed routing protocols. This analysis examines the impact of the mentioned routing protocols on end-to-end delay, energy consumption, number of live nodes, and PDR.

The remaining paper is arranged as follows. Section 2 discusses the literature review, and in Section 3, the simulation results are presented. Finally, the conclusion is explained in Section 4.

2. Literature Review

In this section, we will discuss the energy-efficient cooperative routing protocols that we will evaluate. In addition, some other cooperative schemes will also be presented.

2.1. Cooperative Energy-Efficient Protocol for Underwater WSNs (Co-UWSN)

Co-UWSN is a cooperative routing (C.R.) protocol introduced in [14]. The source sensor node transmits data through multiple hops. Each sensor node is designed with only one antenna. As one antenna is insufficient to cover all the areas and provide signals for data communication from source to destination, the relay node concept is used. The relay node works as a repeater, receives the data packets, and retransmits them to the other hop and then to the destination. Multiple factors help in network reliability. One of these is the network topology, and in this scheme, the authors divide the network into different parts. Data transmission between the sender and receiver nodes is done through the cooperation method using the relay route.

Co-UWSN routing protocol operation is divided into initialization, cooperation, and routing. In the first stage, it will perform three tasks: (1) the location of the sink node is defined, (2) all the sensor nodes identify their neighbors, and (3) all possible paths to the sink node are estimated. In the second stage, (1) the source node shares its details with the destination and relay nodes, and (2) the forwarder nodes will transfer the received information to the destination node. The receiver node uses the FRC (Fixed Ratio Combining) method to combine these two signals. During the routing and relay selection stage, relay nodes obtain data from the source nodes based on the immediate channel condition, which relies on the weight factor. The weight factor is based on the SNR from the source to each neighboring node, as well as the depth and residual energy (RE). The neighbor whose weight function value is the highest will act as a relay. This protocol's advantages are (i) Better energy consumption, (ii) improved network lifetime, and (iii) reduced end-to-end delay.

2.2. Reliability Adaptive Cooperation for Energy-Efficient Routing Protocol Using Sink Mobility (RACE-SM)

The RACE-SM was introduced in [15]. It is an updated version of the cooperative routing protocol for UWSNs called Reliability and Adaptive Cooperation for Efficient (RACE). The RACE-SMs of the sink mobility scheme fixed the problems with a single relay node. All sensor nodes transfer the data directly to the sink if the sink node is within the communication range. The cooperative method transfers packets between the source and the destination when the sink is not in the communication range. GPS-equipped mobile sinks are put in place on the water's surface. The arrival time and speed of the acoustic waves are used to determine how far away these mobile sinks are. The sensor nodes obtain the coordinates by measuring how close the sink is to the surface.

The sink nodes are set up in a certain place on the surface or top of the water and then move a pre-defined path. All sink nodes move in the same area, and their memory stores the coordinates of that area so that they can change the direction in which they move. These are the network's mid-boundary, center, and corner. Then, it compares the stored and current coordinates when moving forward. Before exchanging data, a sink node and a sensor node set up a link. Each sink node broadcasts the information packets within a 150 m range. The proposed routing protocol improved the number of live nodes, energy consumption, PDR, and end-to-end delays.

2.3. Energy-Efficient Regional-Based Cooperative Routing Protocol for Underwater Sensor Networks with Sink Mobility (EERBCR)

The authors proposed an EERBCR protocol with sink mobility for UWSNs [16] to enhance the network lifetime. In EERBCR, the network area was distributed into 12 zones, three-by-four horizontally and vertically. Four mobile sinks are placed at equal distances from one another, while 100 sensor devices are distributed at random. Each mobile sink traverses a predetermined straight route and services three zones. All sensor nodes are in sleep mode until the sink node arrives in their zone, at which point the sink node broadcasts a hello packet. Each node inside the region receives the message and activates itself. When the sink is ready to move to another region and leave the specific zone, it broadcasts another message to warn the sensor nodes of leaving, allowing them to return to sleep mode.

During the phase of initialization, sensor and sink nodes are deployed. Random sensor nodes are placed in aquatic environments. The nodes have restricted energy, while the sink nodes have no such restrictions. Initially, depth and position information are shared among regionally based neighbors. Each sink traverses three vertical and one horizontal region; more specifically, each sink traverses three square zones out of 12. There are two types of data transmission in the data transmission stage: (1) Direct transmission, a sensor node usually scans its transmission range for a mobile sink. After a predetermined amount of time, the transmission range of each sensor is computed for this purpose. The time interval for calculating the transmission range is set to 100 s.

(2) Because EERBCR is also a cooperative routing protocol, the forwarder node will route the packets if the mobile sink is not within the communication range of a sensor node. Essentially, the relay node is selected from the sensor node's neighbors. The criteria for relay node selection are as follows. (I) The relay node must originate in the same region as the sensor node. (II) The relay node has the shortest distance to sink and the highest remaining energy.

2.4. Improved Cooperative Routing Scheme for UWSNs Using Energy Harvesting (EH-UWSN)

The authors proposed the Improved Cooperative Routing Scheme EH-UWSN in [17]. EH-UWSN is a routing protocol that saves energy and has high throughput. The authors show how energy can be gained by coordinating the transfer of data packets using next-hop. Using Energy Harvesting, the nodes can charge their batteries from the outside. The goal is to extend the network's life and move data by working together while limiting energy. At the sink node, the combination method is determined by the ratio of signal to noise (SNRC).

2.5. Multilayer Sinks and Cooperation-Based Data Routing Techniques (MuLSi-Co) for Underwater Acoustic Wireless Sensor Networks (UA-WSNs)

The authors in [18] introduced two routing schemes: the multilayer sink and Multilayer Sinks and Cooperation-Based Data Routing strategies. The first routing protocol suggests a network structure with multiple layers instead of a single solid structure. It also suggests putting sinks in the best place, which reduces the number of communication hops. Additionally, it is a good idea to pick the best forwarder from the nodes based on how close they are to the sink. Because of this, the network performs well. Unlike traditional algorithms, the one proposed does not need to know where the nodes are. However, because there is only one link, the MuLSi algorithm does not meet the requirement that it works reliably.

Thus, the MuLSi-Co algorithm uses how the nodes work together to obtain reliable communication. In cooperation, the destination node receives more than one copy of the same information. Then, it puts these packets together to ensure that the data is received correctly. The synchronization problem is solved by the fact that the relay sends data without delay. Additionally, the fact that the data is overheard eliminates any redundant communications.

After the sink and other sensor nodes are installed, information about the sinks and nodes is shared. Information is gathered in parts to reduce the amount of data that needs to be handled, the amount of traffic, and the amount of energy needed. The goal of gathering information or knowledge is to find out how far away nodes are from the sink and their neighbors so that the best ones can be selected to forward data. Using the fact that nodes can broadcast, the proposed algorithms try to stop packets from being sent more than once. When both nodes hear the same data packet, they remove it from their memory. They think that the data has been sent to another place. In the proposed algorithm, acknowledgement is not considered. This is done to reduce traffic, data overhead, and energy costs.

The selection of the relay is the most important part of cooperation. The best relay choice from nearby ones tends to improve performance. The cooperation method works well, but it takes more time and energy. Therefore, the suggested MuLSi-Co chooses the relay closest to the destination to reduce the amount of time it takes and the effects of the channel. The data are moved forward in the proposed cooperative algorithm in three steps. The sender sends its data to the relay and forwarder in the first step. In the second step, the forwarder keeps the data for a while. It waits for the relay data. The relay sends data to the forwarder as it receives it. In the third stage, two copies of the same data are combined to make one reliable data packet.

2.6. Geographic and Cooperative Opportunistic Routing Protocol for Underwater Sensor Networks (GCORP)

The authors of [19] introduced the GCORP. In GCORP, the data packets are transmitted from the sender node to the sinks with the help of intermediary relay nodes. First, the GCORP protocol sets up a network architecture based on sinks. Then, the source node decides on a relay forwarding set based on the depth factor. With the help of relay nodes, the multi-sink architecture is used by the GCORP protocol to collect data packets from the nodes that made them.

GCORP picks the best relay to send the packets to the surface sinks at each hop. Every surface sink on the sea has a Global Positioning System (GPS) to send periodic beacons to tell the underwater nodes where it is. First, the source node chooses a group of relay nodes that will speed up the packets and increase the chance that they will be delivered (PDP) in the direction of surface sinks. The authors developed an algorithm based on the depth fitness factor to determine how close a packet is to the sink to the surface.

2.7. An Energy-Efficient Data Gathering Scheme in Underwater Wireless Sensor Networks Using a Mobile Sink (EEDG)

The authors in [20] suggested EEDG routing protocols. The mentioned routing protocol aims to fix the low bandwidth, packet loss, and energy consumption issues in UWSNS in three steps. In the first step, the energy consumption load is achieved by grouping the sensor nodes into smaller groups to select as temporary forwarder nodes. In the second step, the proposed MAC protocol reduces collision rates and packet loss by requiring ordinary nodes to deliver data to their forwarder nodes only during specified time frames. Finally, the suggested graph structure reduces the delay in data collection over the entire network by allowing the mobile sink to connect forwarder nodes to the degree set for them in the graph.

3. Performance Evaluation and Simulation Results

This section defines the compared routing protocols' performance evaluation and simulation results. We have recently analyzed and developed seven routing protocols: RACE-SM, EH-UWSN, MuLSi-Co, EERBCR, MuLSi, GCORP, and EEDG. For the simulation, we used MATLAB. We have randomly deployed the 200 sensor nodes in a 1000×1000 simulation area. The simulation parameters are listed in Table 1. Initially, we have considered three main performance metrics: energy consumption, PDR, and end–to–end delay.

Table 1. Parameters Used in Simulation.

Parameters	Value
Width	1000 m
Breadth	1000 m
Depth	1000 m
Deployed Sensor Nodes	200
Sink Nodes	10
Transmission Range	220 m
Total number of rounds	8000
Data rate	150,000
Packet Size	1000 bits

3.1. Performance Metrics

The performance metrics for all compared protocols are defined as follows:

- **Residual Energy:** It describes the distinction between the startup nodes' power and the nodes utilized during the operation.
- **Network Lifetime:** The overall time spent running the network is referred to as the network lifetime.
- **Packet Data Ratio:** The packet delivery ratio (PDR) can be measured as the number of packets delivered in total to the total number of packets sent from the source node to the destination node in the network.

3.2. Results

This section describes the results of all analyzed routing protocols. This work has been designed with a height of 1000 m $\times$ 1000 m $\times$ 1000 m with 200 sensor nodes moving randomly in a 3D environment.

3.2.1. Energy Consumption

Figure 2 shows the energy consumption of all evaluated routing protocols. Compared to other routing strategies, the RACE-SM scheme applies the least energy. The RACE-SM uses the sink movement method to obtain data from the sensor nodes and send them directly to the source and the sink node. Additionally, direct data transmission between the source and sink nodes uses the least energy because only one sensor node is involved.

Multi performs better than EERBCR, Mulsi-Co, GCORP, EH-UWSN, and EEDG cooperative routing protocols because of the placement of the sink node in the optimal position, which decreases the route length and forwarding nodes to transmit the data from the sender to receiver. The EH-UWSN uses less energy than the EERBCR, Mulsi-Co, GCORP, and EEDG. The EH-UWSN recharges the sensor node batteries from the surrounding objectives to improve the network lifetime by decreasing energy consumption. All other routing schemes, such as MuLSi-Co, EERBCR, and GCORP, have the same energy consumption due to their cooperative nature. To increase the reliability of the network, cooperative methods have been utilized. In the cooperation process, data are transferred through multiple nodes; hence, it uses more energy than direct data transfer. Table 2 addresses the energy consumption of all evaluated routing schemes.

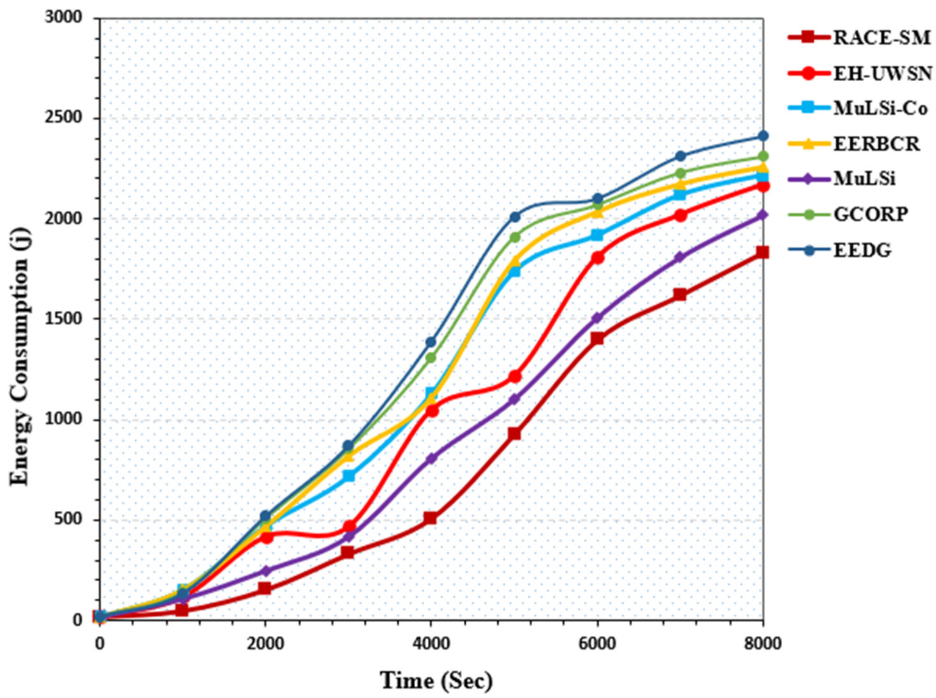

Figure 2. Energy consumption.

Table 2. The energy consumption of all routing protocols.

Rounds	RACE-SM	EH-UWSN	MulSi-Co	EERBCR	MulSi	GCORP	EEDG
0	20	20	20	20	20	20	20
1000	50	120	155	155	110	142	135
2000	155	420	472	470	250	510	521
3000	333	470	718	820	420	855	870
4000	510	1050	1130	1110	810	1310	1390
5000	929	1220	1740	1790	1105	1910	2010
6000	1399	1810	1920	2033	1510	2070	2100
7000	1620	2020	2120	2170	1810	2230	2310
8000	1833	2170	2219	2255	2020	2310	2410

3.2.2. End–to–End Delay

Figure 3 shows the end-to-end delay results for all tested routing schemes. The graph shows that RACE-SM has the lowest latency among all routing protocols. This is because of how easy it is to move the sink. The source and the destination are the only two places where data transfer occurs. Using the sink-moving method by RACE-SM, sensor nodes send data directly to the sink node when the sink is in the communication range. This reduces the number of nodes between the source and the destination.

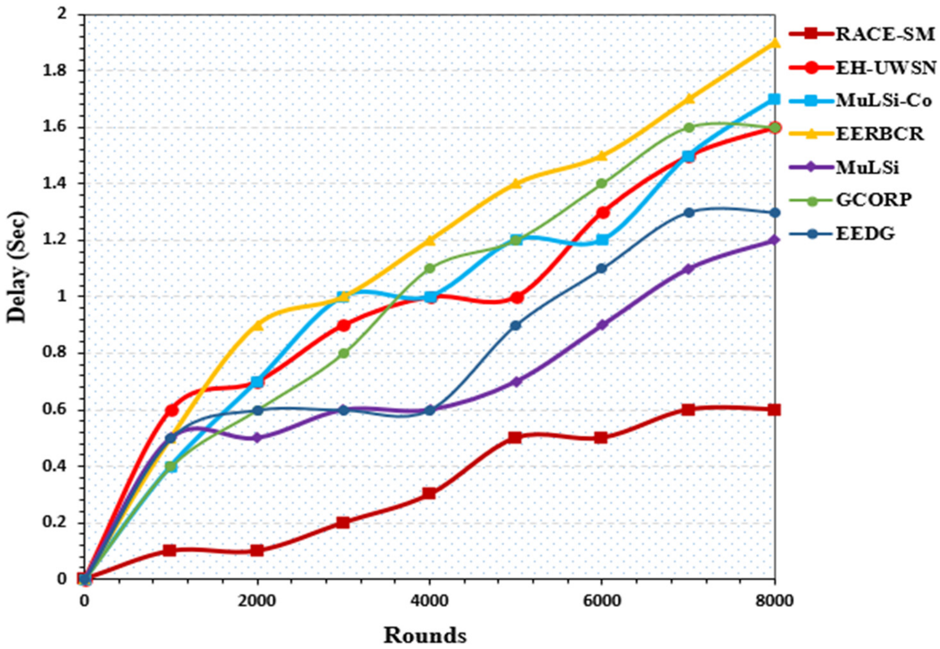

Figure 3. End-to-End Delay.

The latency of the MuLSi and EEDG is less than that of the EERBCR, Mulsi-Co, GCORP, and EH-UWSN cooperative routing protocols. This is because one hop and a maximum of two hops are used instead of a multi-hop for data transmission between the source and destination. Latency is the same for EERBCR, Mulsi-Co, GCORP, and EH-UWSN because they all use multi-hops to send data between the source and the destination. Table 3 addresses the end-to-end delays of all evaluated routing schemes.

Table 3. The end-to-end delay of all evaluated routing protocols.

Rounds	RACE-SM	EH-UWSN	MulSi-Co	EERBCR	MulSi	GCORP	EEDG
0	0	0	0	0	0	0	0
1000	0.1	0.6	0.4	0.5	0.5	0.4	0.5
2000	0.1	0.7	0.7	0.9	0.5	0.6	0.6
3000	0.2	0.9	1	1	0.6	0.8	0.6
4000	0.3	1	1	1.2	0.6	1.1	0.6
5000	0.5	1	1.2	1.4	0.7	1.2	0.9
6000	0.5	1.3	1.2	1.5	0.9	1.4	1.1
7000	0.6	1.5	1.5	1.7	1.1	1.6	1.3
8000	0.6	1.6	1.7	1.9	1.2	1.6	1.3

3.2.3. Packet Delivery Ratio

Figure 4 shows the PDR for all tested routing schemes. The graph shows that the RACE-SM has a much higher PDR than any other method. The reason for obtaining a higher PDR is that BER has decreased. The other reason is that the function's parameters, such as the shortest distance and energy consumption, are used to choose the relay node that will carry the signal from sender to receiver.

EH-UWSN and MuLSi-Co have approximately the same packet delivery ratio at the start of simulation but slowly reduced when crossed the 4000 rounds. MuLSi-Co uses two methods: transferring data directly to the mobile sink node when the mobile sink is in the communication range and through multiple relay nodes. MuLSi is a non-cooperative routing strategy that searches for the best forwarder node while it does not have the location information of the forwarder and the sink node. It also uses multiple hops for data transmission from source to destination, consuming more energy, and the nodes decrease the energy quickly. Therefore, PDR is significantly smaller than other routing strategies. RACE-SM has a greater PDR from the beginning to the completion of the simulation than existing routing systems. The PDR of all protocols mentioned here is for the same data rate. However, it will affect if the data rate has changed. Table 4 addresses the PDR of all evaluated routing schemes.

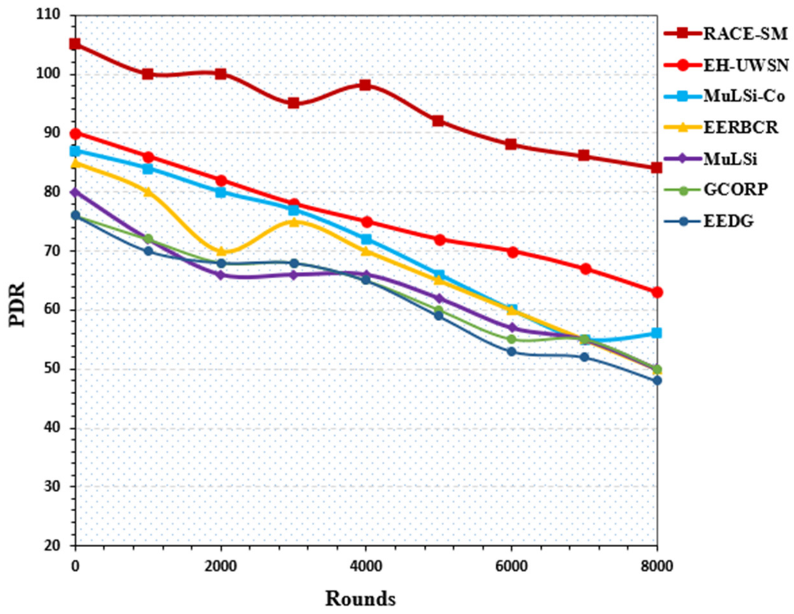

Figure 4. Shows Packet Delivery Ratio.

Table 4. Addressing PDR.

Rounds	RACE-SM	EH-UWSN	MulSi-Co	EERBCR	MulSi	GCORP	EEDG
0	105	90	87	85	80	76	76
1000	100	86	84	80	72	72	70
2000	100	82	80	70	66	68	68
3000	95	78	77	75	66	68	68
4000	98	75	72	70	66	65	65
5000	92	72	66	65	62	60	59
6000	88	70	60	60	57	55	53
7000	86	67	55	55	55	55	52
8000	84	63	56	50	50	50	48

3.2.4. Number of Alive Nodes

Figure 5 represents the total number of active nodes across all examined routing protocols. Based on the simulation findings, the RACE-SM has more live nodes than the other routing strategies. The primary reason for this is to reduce energy consumption. Furthermore, selecting the optimal forwarder node for data transmission is impacted since it will consume the least energy and transport the data at the lowest cost. Consequently, the number of active sensor nodes will be significant. The EH-UWSN is the other routing protocol with the maximum number of live nodes because it uses the maximum of two forwarder nodes and charges the sensor node batteries from surrounding objects; therefore, the nodes are alive for a maximum time.

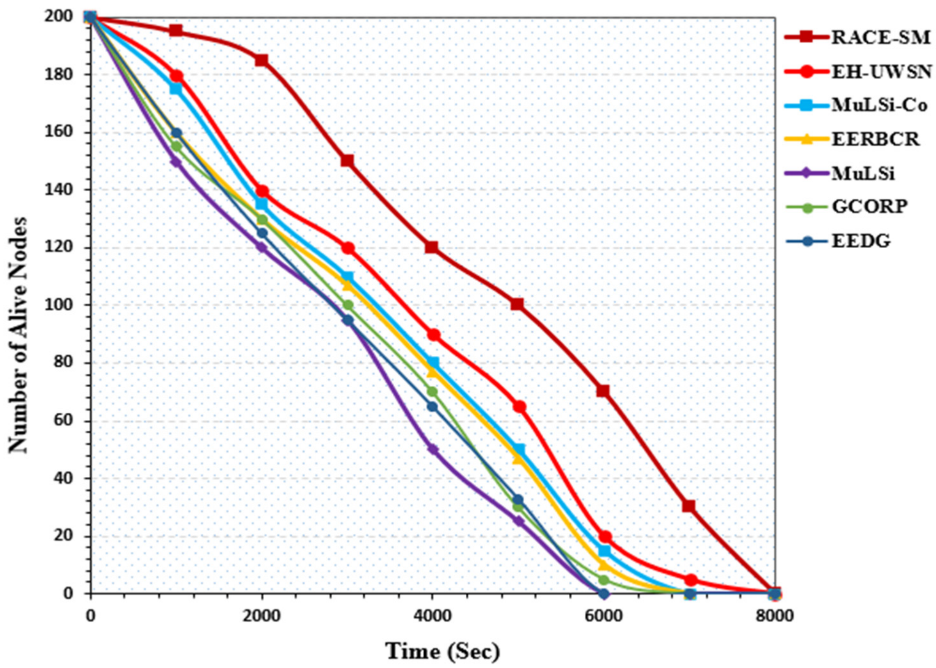

Figure 5. The Number of Alive Nodes.

The number of live nodes in RACE-SM at around 5000 is 100, EH-UWSN has 65, MuLSi-Co has 40, and others have approximately 20 active nodes. After 5000 rounds, all routing schemes' active nodes drain energy quickly and die much quicker than the RACE-SM. RACE-SM uses two methods to transmit the data between the source and destination: direct transfer when the sink node is in the communication range and the cooperative method, which means transferring data through multiple hops, which also helps to increase the network reliability. Table 5 addresses the number of alive nodes of all evaluated routing schemes.

Table 5. Addressing the Number of Alive Nodes.

Rounds	RACE-SM	EH-UWSN	MulSi-Co	EERBCR	MulSi	GCORP	EEDG
0	200	200	200	200	200	200	200
1000	195	180	175	160	150	155	160
2000	185	140	135	130	120	130	125
3000	150	120	110	107	95	100	95
4000	120	90	80	77	50	70	65
5000	100	65	50	47	25	30	33
6000	70	20	15	10	0	5	0
7000	30	5	0	0	0	0	0
8000	0	0	0	0	0	0	0

4. Conclusions

This research evaluated seven cooperative energy consumption routing protocols through a simulation study. The performance metrics used in this study are energy consumption, end-to-end delay, PDR, and the number of alive nodes. Based on the simulation results, RACE-SM outperforms all performance metrics from all other evaluated routing protocols. MuLSi performs better than other routing protocols in terms of end-to-end delay because it uses a single forwarder node for data transfer, which reduces latency and decreases end-to-end delay. EH-UWSN performs better after RACE-SM in terms of energy consumption, PDR, and the number of alive nodes. EERBCR, GCORP, and EEDG are approximately the same in all performance metrics. In the future, we will test these and other recently designed routing protocols with other performance metrics within different types of network structures, such as dense networks, to understand which protocol is better for different types of network structures.

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Data Availability Statement: The materials supporting this study are available upon request from the first author.

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