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RESEARCH ARTICLE

Towards an Adaptive Routing Protocol for Low Power and Lossy Networks (RPL) for Reliable and Energy Efficient Communication in the Internet of Underwater Things (IoUT)

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Abstract – Internet of Underwater Things (IoUT) is emerging as a powerful technology to explore underwater things. Reliable communication between underwater things is a significant challenge compared to communication at the surface, notably the unique characteristics imposed by the underwater environment, such as water currents, noisy scenarios, and limited resources. Several routing protocols have been suggested to overcome the challenges in IoUT. The previous works mainly focus either on improving the reliability or energy efficiency of the routing process. Concentrating on both parameters makes the routing process too complex with substantial overhead. Routing techniques face challenges in solving the noise and water current issues in the IoUT environment. The proposed work utilizes the potential of the Routing Protocol for Low Power and Lossy Networks (RPL) on IoUT communication by enhancing its Objective Function (OF) to resolve the routing in the underwater environment. The proposed Underwater Adaptive RPL (UA-RPL) turns the inefficient DODAG construction into an efficient under noisy environment by extending DIO message features. Numerous neighboring nodes receive the extended DIO message, and the nodes that fit into the safety zone are decided according to the multiple routing metrics, such as hop count, ETX, and Energy factor. Entire network traffic is partitioned through multiple parent nodes with the best rank values and attains an energy-balancing routing over underwater things. It helps to improve the network lifetime without compromising communication reliability. The proposed work is evaluated to show its advantages over the underwater environment. The simulation results show that the UA-RPL delivers high performance when varying the underwater things from 15 to 60. Moreover, it outperforms the existing schemes under the IoUT environment.

Index Terms – Routing Protocol, Internet of Underwater Things, Noisy Environment, Water Current, Reliability, Energy Efficiency, RPL.

1. INTRODUCTION

The unprecedented growth of the Internet of Things (IoT) [1] has recently enabled many smart applications. Among them, smart underwater monitoring has many potential applications that enable interconnected underwater objects to explore the perspective of the underwater environment, mainly the inherent unexplored features of the ocean. The Internet of Underwater Things (IoUT) consists of interconnected underwater objects to explore deep water areas. The

RESEARCH ARTICLE

prominent IoUT applications are pollution control, climate recording, and prediction of natural disturbances. Most of the IoUT protocol design explores one-to-one communication. Due to the nature of acoustic communication, existing IoUT communication protocols need significant alteration [2][3][4]. Moreover, no work has been developed for IoUT by extending the Routing Protocol for Low Power and Lossy Networks (RPL) due to the need for topology structure construction and maintenance. For underwater environmental monitoring, such as sand, water, and so on, the topology structure constructed in RPL is highly suitable for data collection and forwarding. The RPL routing process has to build the Destination Oriented Directed Acyclic Graph (DODAG) to establish the connection between sensor nodes and the root [5]. The important functions used in RPL, such as Objective Functions (OFs) and a trickle algorithm, are explored in-depth to validate the suitability in an underwater environment. However, acoustic communication creates several challenges to routing under IoUT. The RPL routing under IoUT faces challenging constraints due to limited bandwidth and battery resources. Moreover, temperature, depth, noise, and salinity of the underwater environment are the factors that influence communication efficiency. Those factors produce variations in the RPL performance under IoUT compared to the RPL performance under the ground environment. Furthermore, underwater sensors cannot be completely static like surface-based Internet of Things (IoT) networks due to the sensor movement induced by water currents. Thus, it is essential to design the OFs, which are adaptive to the IoUT characteristics [6][7][8][9].

As per the OFs, the RPL selects greedy nodes for routing data packets to the sink node. Imbalanced energy consumption is possible when the sensor nodes nearer the sink node run out early due to frequent data transmission. Another OF used in the RPL is Minimum Hop with Hysteresis Objective Function (MRHOF) for active DODAG construction. The MRHOF considers the Expected Transmission Count (ETX), a strategic routing metric for DODAG construction. A single metric based OF in RPL may fail in energy-efficient DODAG construction under acoustic channel communication [10].

1.1. Motivation of the Work

IoUT, a novel extension of IoT, has enormous potential for interconnected underwater objects that enable a new breed of emerging applications [4][8]. Underwater exploration, environmental monitoring, and disaster prevention are some potential applications currently under development. The successful deployment of such applications must tackle the significant challenges present in the IoUT environment, such as long propagation delay, unreliability network environment, and narrow bandwidth. Notably, reliable routing is paramount for reliable communication for mission-critical IoUT applications. Unreliable IoUT network leads to poor data retransmission, large communication delay, higher bandwidth utilization, and higher energy consumption which significantly degrade the overall performance.

The motivation of this work is to investigate the challenges in designing IoUT routing that overcome the uniqueness of the network environment. To improve the utilization of the available resources without affecting the quality of routing service in the IoUT environment, it is paramount to consider multiple important factors in route construction. Thus, the proposed work plans to design an adaptive RPL routing for the IoUT environment and balance the energy consumption among nodes. The primary objective of the work is the preliminary investigation to explore the RPL routing for the IoUT environment. The aim of the proposed work is not only to highlight the issues of water characteristics on routing but also to present an effective solution to the issues of node movement due to water current, packet loss due to a noisy environment, and frequent DODAG changes due to variation in environmental factors.

1.2. Contributions of the Proposed Work

The primary contributions of the Underwater Adaptive RPL (UA-RPL) are listed as follows.

- To Design an IoUT adaptive routing by modifying the RPL functions such as DODAG Information Object (DIO) message features and objective functions.
- The UA-RPL improves the DODAG construction to mitigate the impact of a noisy underwater environment and mitigates unnecessary extension of the DODAG structure in depth.
- Instead of considering hop count or ETX alone, the UA-RPL considers the danger zone and arrival of angle along with hop count, ETX, and energy factor and reduces the negative impact of unexpected node movement due to water current and angle of arrival.
- To yield an energy-efficient RPL routing under acoustic communication, the UA-RPL tunes the Trickle parameter and avoids unnecessary DIO transmissions in the IoT network. It assists in constructing a complete DODAG construction and data forwarding.
- The superiority of the UA-RPL scheme is evaluated with the potential existing schemes under the IoUT environment using the Cooja simulator.

1.3. Paper Organization

Section 2 reviews related previous work regarding RPL routing under underwater sensor networks. Section 3 provides the IoUT system model and problem formulation for the proposed UA-RPL. Section 4 discusses the proposed UA-RPL, improved DODAG construction, and objective function

RESEARCH ARTICLE

in detail. Section 5 explains the performance evaluation section with graphs. The final section 6 concludes the proposed work.

2. RELATED WORKS

Several works have been designed to enhance communication efficiency over IoUT applications [11][12][13]. The RPL defines OFs with routing rules in the network layer. There is a scope to use and extend the standardized OF for different IoT applications. Several works try to enhance the RPL by enhancing the OFs. Different OFs offers various routing performance by optimizing different routing parameters, e.g., hop count, ETX, delay, and energy consumption [14]. This section reviews RPL enhancements for IoT and routing protocols used in IoUT. It concludes that the basic RPL issues over IoUT and possibilities to improve the RPL for underwater environment monitoring.

2.1. RPL Enhancements for IoT

A flexible OF is suggested in [15] to offer reliable and energy-efficient communication, and it is named OF-Consumed energy and Forwarding delay (OF-ECF). A flexible OF is designed with different routing metrics, mainly ETX, consumed energy, and forwarding delay. However, it lacks in analyzing the impact of the noise environment on RPL. The efficiency of OF-ECF depends on the Control message broadcasting without loss. However, while using the OF-ECF in acoustic communication, a noisy environment and water current limit the advantages of OF-ECF compared to the ground environment. To provide the QoS, a new OPPortunistic fuzzy logic-based Objective Function (OOP-OF) is developed in [16]. The OOP-OF considers multiple metrics for selecting the parent node: hop count, ETX, and the number of children nodes. It improves the delay and packet delivery considerably. However, it consumes high energy. To design an optimized DODAG construction, energy-efficient routing paths via parent nodes should be selected. Using lexicographic and additive approaches, a new OFs scheme in [17] combines available energy, ETX, and hop count routing metrics. Using such metrics, the nodes estimate the rank value and decide on an optimal parent node DODAG construction. However, it lacks in considering other quality of services and its measurements in a noisy environment. Congestion-Aware Objective Function (CA-OF) is proposed in [18] to avoid network congestion due to the buffer node occupancy. It utilizes the advantages of the ETX metric to select less congested paths. However, it is not evaluated under large-scale networks and lacks in considering energy efficiency during multi-hop routing. In [19], a new objective function called IRH-OF is suggested. It attempts to decide the best parent among all the neighboring nodes using the defined metric cmIRH, which denotes a composite metric of Received Signal Strength Indicator (RSSI) inverse and hop count metrics. However, a single or two metrics are insufficient to offer efficient routing in most environments.

2.2. Routing Protocols for IoUT

IoUT environment makes several challenges for routing, such as noisy environment, water current issues, and so on. In previous, different protocols have been designed for IoUT, and this section provides a review of some of those schemes [20]. A new routing protocol, Power Control-based Opportunistic (PCR), is designed for IoUT [21]. It considers neighbor count, distance, link quality, and advancement of the packet to decide the optimal routing paths. Accordingly, an eligible neighbor node is considered a forwarder node for the next hop. However, the main challenges of underwater noise are not considered. Moreover, the specific issues provided by water current on node movement have yet to be addressed. In work [22], a Directional Selective Power Routing Protocol (DSPR) is suggested for IoUT to cope with most of these challenges. The DSPR considers the sender depth information and the angle of arrival information to solve the issues of water current and energy constraints. It explores selective power control to enhance network performance while reducing energy consumption. However, in a noisy environment, determining appropriate paths is challenging and is not handled in the previous work. Some previous works utilize the advantages of RPL, such as DODAG construction, for reliable and aggregated routing. To increase the downward path reliability of RPL, such storing and non-storing modes are selected optimally in [23]. The communication reliability of a node is improved by operating it in storing mode. However, it is inefficient due to memory constraints. Thus, hop interval is utilized to take Model Of oPeration (MOP) decisions for selecting the intermediate nodes. The nodes calculate the hop interval to decide their MOP. However, hop count alone cannot provide efficient communication, and it is essential to consider the hop length and routing issues due to the water current. Moreover, MOP does not handle the issues of DODAG construction and reliable communication. It focuses only on energy efficiency but not on the quality of communication. Enhanced Channel-Aware Routing Protocol (E-CARP) is designed to reduce energy consumption and expensive packet forwarding for data gathering and transmission in IoUT [24]. Thus, the proposed scheme aims at utilizing the advantages of RPL along with the improved features for handling noisy IoUT environment and water current issues. Moreover, sensor replacement due to energy loss is costly, and so it is prominent to develop an energy-efficient routing scheme for IoUT.

2.3. Problem Statement

Several challenges must be solved to design an adaptive routing protocol for the IoUT environment. The routing issues are listed as follows.

RESEARCH ARTICLE

- The underwater environment makes noise due to human activities, animals, and other factors, negatively impacting packet loss and routing efficiency.
- No work has been proposed to adapt the RPL under IoUT since such kind of network loss the RPL communication efficiency due to water current and other constraints.
- IoUT depth is the main factor that affects the efficiency of DODAG construction and the energy consumption of nodes during data forwarding. The design of such an energy-balanced and reliable routing topology for the underwater network is an open area for research.
- The IoUT environment makes inefficient communication results under the assumption of node mobility absence since the nodes can move by water current and other environmental factors.
- Hop count-based objective function is insufficient to offer reliable communication since the hop length and unexpected node movement affects the routing efficiency.

3. PROBLEM FORMULATION

There are several applications for IoUT; underwater environmental monitoring helps to analyze the water level, sand, and other factors. Thus, the proposed work improves and applies the RPL for underwater environmental monitoring. Assume that the underwater environment consists of N number of sensors deployed on a 3D sea surface area. For simplicity, the proposed scheme considers a non-mobile scenario for IoUT, even though the proposed design considers a movement of sensors due to water current. Let the set N = {n1, . . . , $n_{|N|}$} of sensor nodes deployed in an underwater environment and the network topology with a directed graph G = (V, E), where V represents a set of sensor nodes, and E denotes the communication links. An edge $e_{ij} \in E$ exists if a communication link is present between the nodes n_i and n_j. All nodes are assumed to be provided with antenna arrays to determine the arrival angle of the received control message. Before improving the RPL, the problems associated with the RPL under IoUT need to be described. To modify the RPL protocol based on IoUT characteristics, the UA-RPL (y) output can be formulated as follows.

$$y = \big(\mathrm{UA} - \mathrm{RPL(Rl)}\big) - (\mathrm{UA} - \mathrm{RPL(Oh)}) \quad (1)$$

In equation (1), y represents the quality of RPL under IoUT in terms of reliability (Rl) and overhead (Oh). Basic RPL performs a DODAG construction via DIO message broadcasting. The notation SPD denotes the probability of Successful DIO Packet Delivery (SPD), and E-DODAG denotes the efficiency of the DODAG structure.

$$\mathrm{E - DODAG} \propto \mathrm{SPD} \quad (2)$$

From the above equation (2), the E-DODAG is directly proportional to the SPD, which depends on several factors. The DIO message loss is increased with the network traffic. It may change the DODAG structure efficiency. Moreover, noise under the acoustic channel in IoUT may corrupt and lose DIO messages. It is the main factor behind the decrease in SPD and E-DODAG. Because of a noisy underwater environment, there is a high possibility of building a DODAG structure with short life routes, and it tends to be an inefficient RPL for IoUT. Another vital factor that needs to be considered while extending the RPL to IoUT is unavoidable node mobility. Underwater sensor network nodes are not static like ground-based sensor network nodes. Instead, the sensors experience movement due to different activities and currents of the underwater environment. The selected parent nodes, which can move from the safety zone to the danger zone, immediately affect the SPD as in equation (3).

$$\mathrm{SPD} \propto \theta_C \quad (3)$$

Whenever a neighboring node starts from safety to danger zone with an angle θ equal to or higher than the critical angle θ_C. It should be rejected in the creation of the DODAG structure. The issues above in RPL over the IoUT environment must be solved properly to make it suitable for an acoustic environment.

4. PROPOSED ROUTING METHODOLOGY FOR IOUT

Due to the salient features of the IoUT, it is paramount to design an underwater adaptive RPL protocol. The IoUT is responsible for collecting, aggregating, and transmitting data to control centers deployed above the surface. Apart from effective underwater communication management, the IoUT assists in identifying shipwrecks, early signs of tsunamis, the health of animals, and so on. However, IoUT is prone to challenging issues, such as resource constraints of the nodes with limited processing capacity, routing protocol execution consuming high energy in a noisy environment, and difficulty in replacing the node. Thus, improving IoUT lifetime by minimizing energy consumption and attaining communication reliability in a minimum number of transmissions is vital. The proposed work integrates several features into RPL regarding underwater sensor networks. The components integrated with the RPL are divided into underwater-Adaptive RPL, UA-RPL with Improved DODAG Discovery, and Multi Parent DODAG structure. Figure 1 illustrates the UA-RPL block diagram.

4.1. Improved DODAG Discovery

Underwater noise is the main factor influencing acoustic channel performance. In such DODAG construction processes, the data noise in the underwater environment can be divided into ambient noise and noises by human beings. Both the noise affects the communication channel capacity.

RESEARCH ARTICLE

The noisy environment tends to have a high packet loss rate of RPL control and data packets during DODAG construction and data forwarding. The nodes cannot sense the packets effectively due to noise. The ineffective and extended DODAG structure may tend to depth and unnecessarily consume more energy. Thus, the proposed UA-RPL plans to integrate DIO's parent list and neighbor list and utilize them to avoid differences in DODAG structure in both noisy and normal environments. An effective DODAG structure is the first successful step to leading the RPL as effective in the underwater environment.

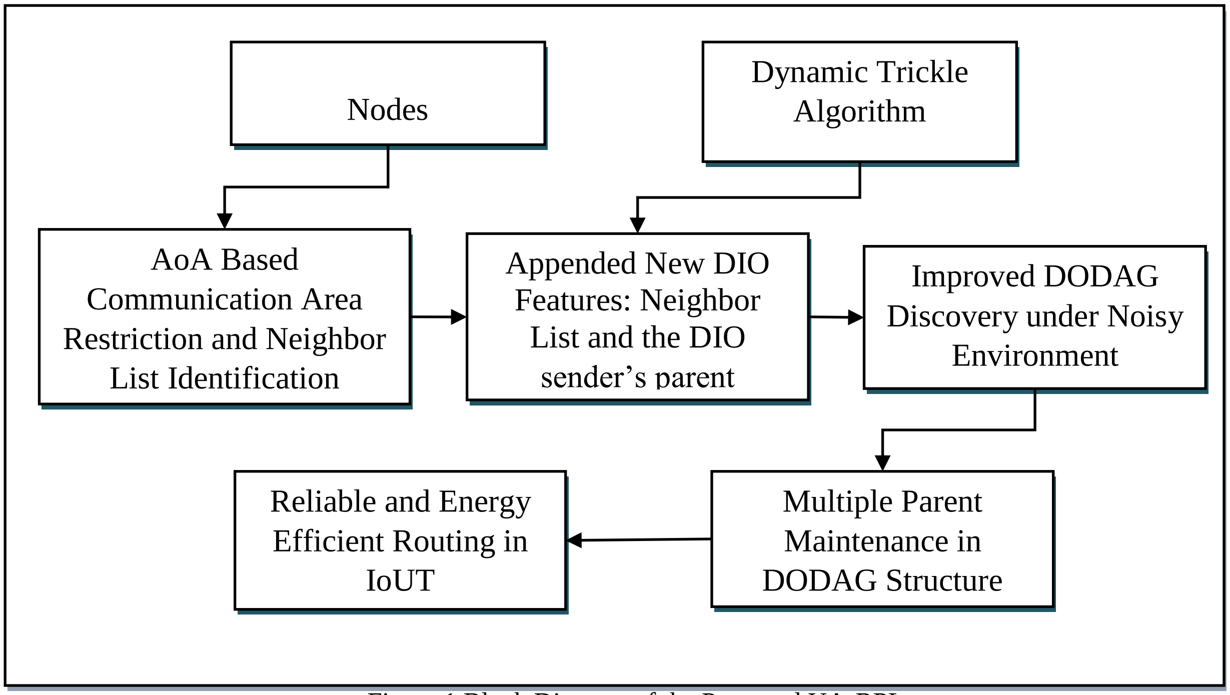

Figure 1 Block Diagram of the Proposed UA-RPL

4.2. Multi Parent Route Selection and Energy Efficient Data Forwarding

Imbalanced energy consumption is another major issue affecting IoUT networks. As per the available objective functions, some nodes may have to forward many packets, leading to entire energy loss. Therefore it degrades the lifetime of the whole network. The proposed work plans to equalize the energy consumption among sensor nodes in IoUT by allowing the multi-parent DODAG structure for data forwarding. The data is forwarded towards the sink node through different parent nodes at a certain probability, improving the energy balancing and effectively reducing the communication delay. The proposed scheme assumes no movement in underwater sensor nodes. However, they may move due to the water current. To avoid the impact of such movement, the UA-RPL takes into account the danger zone and arrival of angle in rank estimation. Figure 2 shows the flow diagram for the proposed work.

4.3. Dynamic Trickle Algorithm

The trickle timer in RPL assists in mitigating the control traffic overhead. The trickle algorithm increases the sending rate of the DIO if an inconsistency is detected to resolve it quickly. Otherwise, increasing the window size reduces the DIO packet sending rate exponentially. Moreover, the randomly chosen factors in the Trickle algorithm may reduce the RPL efficiency in terms of throughput or control overhead. To yield an effective result under the IoUT environment, the UA-RPL tunes the Trickle parameter and avoids unnecessary DIO transmissions. It ensures complete DODAG construction and data forwarding.

4.4. Scope for Improving the DODAG Discovery Process in IoUT

The basic RPL functions are designed as per the ground-IoT scenarios, i.e., without considering the impact of a noisy environment and with no particular attention to node mobility. However, the acoustic channel communication using RPL under IoUT faces some the routing challenges, such as packet loss due to noise under IoUT and unexpected node movement due to water current, and the proposed scheme needs to improve those RPL functions, making them suitable for IoUT. The RPL protocol defines different functions for routing path discovery and data forwarding. To construct the routing paths between the root and sensor nodes, the RPL executes the concept of the DODAG using various control messages. Those control messages are discussed as follows.

(i) DODAG Information Object (DIO): The process of the DIO message is to construct a DODAG rooted at the root node. Moreover, the DIO message provides the rank value for supporting efficient DODAG construction.

(ii) DODAG Information Solicitation (DIS): A node that sends the DIO messages solicits the DIS message when it joins a stable network.

(iii) Destination Advertisement Object (DAO): The DAO message helps build routes from root nodes to sensors.

Using the DIO message broadcasting, the UA-RPL announces its rank value to its neighboring nodes, and it should decide on a node with a high-rank value as its parent. This process is continued until an entire DODAG is constructed. The DIO message broadcasting and rank estimation need to be modified as per the IoUT characteristics to facilitate an energy-efficient DODAG discovery process at the network layer.

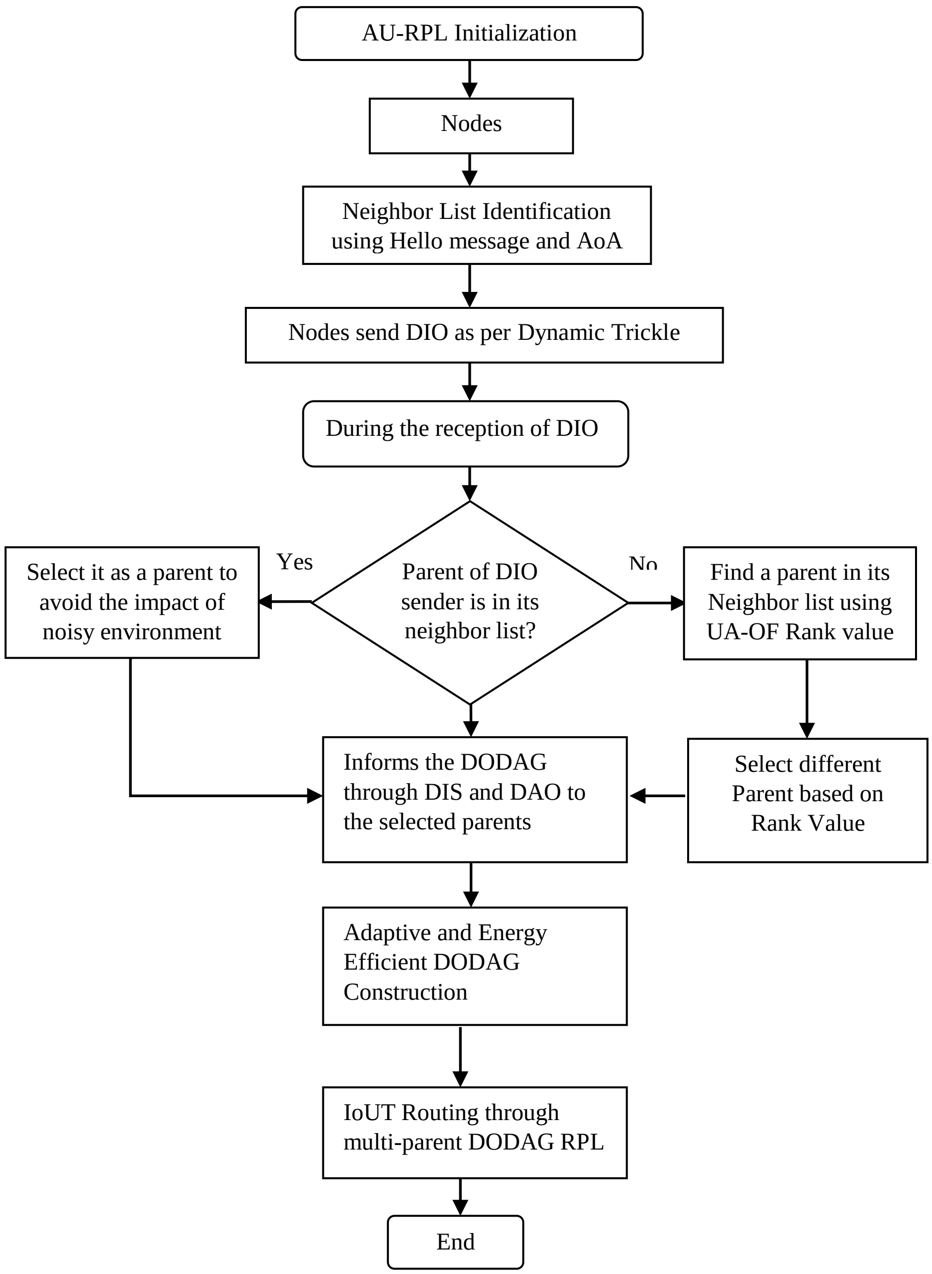

Figure 2 Flow Diagram of the Proposed Work

RESEARCH ARTICLE

4.4.1. DODAG Construction under Noisy Environment

The underwater environment is noisy, which may lead to DIO message loss while executing the RPL. The DIO message loss changes the DODAG structure and reduces its efficiency. The loss of a DIO communication from its designated parent mitigates its link connection and leads to joining with the least preferred parent. Thus, it tends to increase transmission delay and node energy consumption.

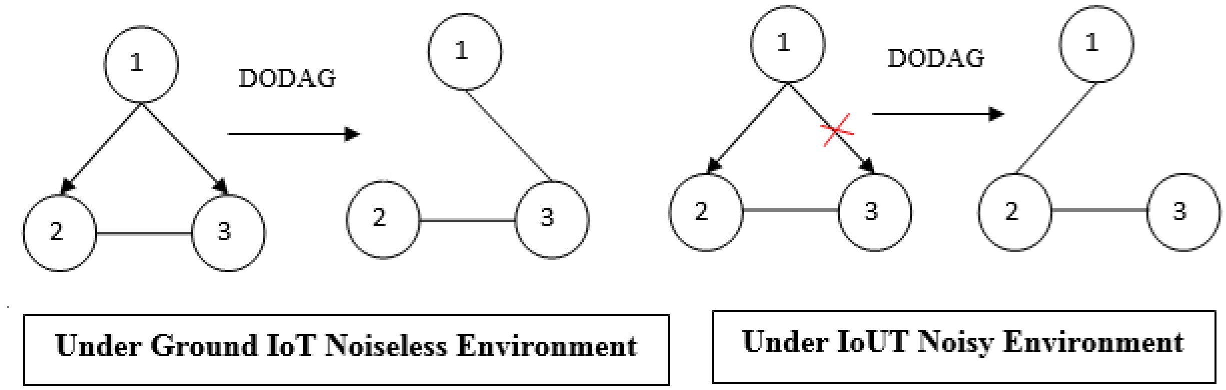

Figure 3 Difference in DODAG Structure under Ground and IoUT Environment

As is shown in Figure 3, considering that nodes 1, 2, and 3 are neighbors. Here, node 1 is the preferred parent for both Node 2 and Node 3. The DODAG construction process has to consider two essential situations: the noisy and noiseless environment. It is assumed that the Ground IoT application is noiseless. The DIO message can be transmitted to all neighbors in the noiseless environment successfully. When a root node starts DODAG construction, it joins the DODAG after broadcasting the DIS message to identify a node that joined the DODAG around it. The first two parts of Figure 3 illustrate the process of DODAG construction in the noiseless environment. When node 1 sends a DIO message, neighbor node 2 and node 3 receive it. Nodes 2 and 3 select node 1 as its parent and construct the DODAG topology. However, when node 1 broadcasts a DIO message in a noisy environment, only node 2 receives the DIO message and joins the DODAG, and node 3 fails to join. After that, node 2 starts DIO broadcasting, and node 3 joins DODAG with node 2 as a parent after receiving the DIO message from node 2. This scenario illustrates the construction of the DODAG topology under different situations. Thus, inefficient DODAG construction and data transmission increase transmission latency and power consumption.

4.4.2. New DIO Message Features

The phenomena mentioned above are induced due to the loss of DIO messages. The UA-RPL designs a repair method to solve the issues of DIO message loss. The method employs the restricted neighbor list and determines the appropriate parent by checking the identity of a parent node that sends the current DIO message. As per the design of RPL, each node starts to send a DIS message to know about the DODAG structure. Each node in the structure receives DIS messages from the neighboring nodes. Nodes can identify and generate the neighbor list as per the node id using such received DIS messages. However, in UA-RPL, the neighbor zone is divided into safe and danger zones and is explained in the following section. To mitigate the impact of node movement out of the communication range of its connected parent node due to water current, the nodes in the danger zone are rejected from the DODAG construction. As per the proposed scheme, the DIO sender's parent node ID information and restricted neighbors in the safe zone are appended to the DIO message. For instance, the DIO message receiver node has the parent of the DIO's sender in its restricted neighbor list; the neighbor list of the DIO receiver has both the DIO sender and the DIO sender's parent. In figure 2, if node 3 receives a DIO message from node 2 along with the parent identity as node 1, then node 3 can check the availability of the parent node 1. If it is available, the DIO receiver, node 3 takes the DIO sender's parent (node 1) as its parent instead of the DIO sender node 2. It can repair the network topology even after DIO message loss. This process is carried out as follows:

(1) Every node maintains its restricted neighbor list.

(2) A node that sends a DIO message should append the node ID of its preferred parent. In the case of the root node, the ID of its parent node is null in the DIO message.

(3) A node receiving DIO verifies the DIO sender's parent ID in the restricted neighbor list. If it is in a restricted neighbor list, the receiver transmits a DIS message only to the DIO sender's parent and selects it as a preferred parent if available.

(4) After deciding the preferred parent, the DIO receiver informs its DODAG by informing with a DAO message to the

RESEARCH ARTICLE

selected parent. All the nodes above execute these processes until an entire network topology is constructed.

4.5. Routing Metrics and Multi-Parent DODAG Construction

The proposed work takes into multiple metrics to estimate the rank value of a node and to construct an efficient multi-parent DODAG construction. Most of the important metrics that have to be used in the DODAG construction are Hop Count, ETX, Energy factor, and SinkAoA. However, hop count/ETX/Energy factor-based DODAG or distant links may be broken easily due to the node movement induced by the water current. Thus, the nodes are selected only from the safety zone for DODAG construction. Considering that ¾ of the communication range is a safety zone, the remaining area around the node is the danger zone. Figure 4 illustrates the safe and danger zone of a node. The proposed scheme appends a metric to determine the quality of the neighboring nodes as per its link strength, the estimated Arrival of Angle (AoA).

- Whenever a neighboring node sends the DIO packet at an arrival angle θ lower than the critical angle θc, it is considered the neighboring node in the safest zone.
- Whenever a neighboring node sends the DIO packet in an arrival angle θ equal to or greater than the critical angle θc, it is considered the neighboring node in the danger zone.

Finally, the neighbors located in the safest zone are involved in the rank estimation and DODAG construction. The rank is estimated using the following metrics;

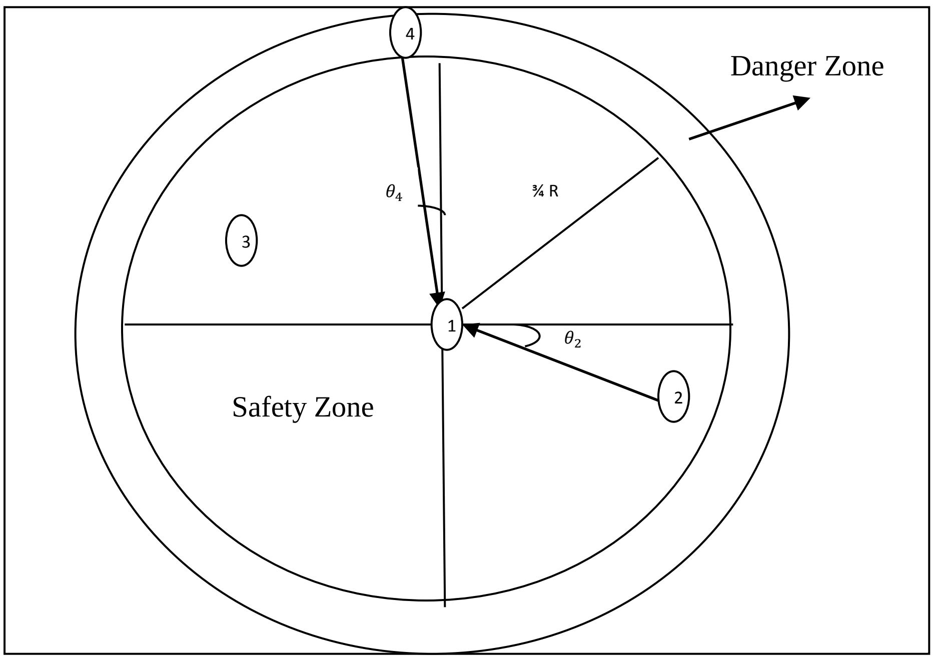

Figure 4 Safe and Danger Zone of a Node

Hop count denotes the number of hops between the root node and a node. The ETX and Energy Factor (EF) are explained in equations (4) and (5) as follows.

$$\mathrm{ETX}_k = 1 \,/\, (\mathrm{Df} \ast \mathrm{Dr})_k \qquad (4)$$

$$\mathrm{EF}_i = \sum_{\mathrm{i=1}}^{|\mathrm{Nh}|} \mathrm{TE}_{\mathrm{i\ over\ t\ time}} \Big/ \mathrm{RE_i} \qquad (5)$$

The Df in equation (4) represents the probability of a received packet by node i, and Dr represents the probability measure of the successfully received acknowledgment packet. The EF denotes the energy factor, measured as the division between Total Energy (TE) needed to be consumed by node i over time t and the Remaining Energy (RE) of node i. The Rank is the multiplication of the factors above. Once the DIO message and the rank value are received, a node selects two different parent nodes and receives a DAO message from such parent nodes. Moreover, the network traffic is sent via two different parents alternatively. It improves the balanced energy consumption and network lifetime.

4.6. Dynamic Trickle Parameter in UA-RPL

The Trickle algorithm restricts the DIO message propagation without impacting the DODAG efficiency. Each node executes the Trickle algorithm for deciding the transmitting interval I of the DIO message. During initialization, the DIO message transmission is scheduled by each node at a random time t in the transmitting interval. The node estimates the

RESEARCH ARTICLE

number of received messages during the interval t and stores it in a variable redundancy counter c. The nodes increment the counter c each time after receiving a new DIO message. After t time, the c value of a node is compared with the redundancy threshold k. If the value retained by c is smaller than the k value, the node transmits the DIO message; otherwise, a node suppresses the DIO message propagation. It is the basic concept of the Trickle algorithm. However, the basic trickle timer model only considers the number of nodes that involve consistent DIO message transmissions but lacks consideration of the DIO message loss rate due to the noisy environment. Also, the nodes randomly decide the value of t interval Imin and Imax. Initially, it is assigned as equal to the Imin. The minimum value of I in a noisy environment tends to lose the DIO message sent from multiple nodes over a small interval, inefficient DODAG construction, and unnecessary DIO transmissions. To maintain the advantages of UA-RPL without increasing the control overhead, the dynamic trickle algorithm assigns the initial I value as 2*Imin, which should be less than Imax. It helps to facilitate the nodes to send DIO messages at different times, mitigates the impact of a noisy environment, and energy-efficient routing in the network layer.

The proposed UA-RPL algorithm dynamically adjusts the k value to support DIO message transmission adaptively. The variation in k depends on the DIO loss rate due to the noisy IoUT environment. Setting the larger k value decreases the convergence efficiency and increases the DIO message sending rate, resulting in high energy consumption. Therefore, it is crucial to maintain consistent DIO message transmission over efficient k value without increasing the number of DIO transmissions in the IoUT environment. To maintain the advantages of UA-RPL without increasing the control overhead, the dynamic trickle algorithm in AU-RPL assigns the initial I value as 2*Imin, which should be less than Imax. To accomplish better DODAG construction, the proposed AU-RPL comprises the DIO loss rate based on equation (5) to adjust the k value dynamically.

$$\mathrm{L_{DIO}} = \frac{\text{DIO Received Neighbors}}{\text{Total Neighbors}} \,..(6)$$

$$\mathrm{K} = 2 * \mathrm{I_{min}} * \mathrm{L_{DIO}} \,.....(7)$$

In equation (6), the term $\mathrm{L_{DIO}}$ refers to the DIO loss rate. According to equation (7), the UA-RPL adjusts the k value based on $\mathrm{L_{DIO}}$ at specific time interval t. Thus, the k value in UA-RPL is adaptively adjusted without increasing the DIO transmission overhead. The k value is a little too much in a noisy environment and low in a noiseless environment. It helps to facilitate the nodes to send DIO messages at different times, mitigates the impact of a noisy environment, and energy-efficient routing in the network layer. Moreover, the entire design process of UA-RPL is explained in algorithm 1.

//UA-RPL Design Algorithm//

Input: Underwater RPL Nodes and OF parameters

Process: Multi-parent IoUT-RPL DODAG Construction

Output: Energy Efficient Reliable IoUT Routing with Minimum Overhead

Nodes **do {**

IoUT-RPL Network Initialization;

Broadcast Hello and AoA messages;

Construct the neighbor list based on danger and safe zone;

Sending the DIO messages to the neighbors according to dynamic trickle timer;

DIO Receiver Nodes **Do {**

Check its neighbor list for parent selection;

If (DIO sender is in neighbor list) {

Selects the DIO sender as parent node;

Else {

Estimates the UA-OF rank value to the nodes in neighbor list;

Select different parent node based on rank value;

}}

Informs the DODAG to the selected parent nodes via DIS and DAO;

Energy efficient DODAG Construction;

Starts the routing process through constructed multi-parent DODAG;

Accomplishing energy efficient reliable routing;

}};

Algorithm 1 Design Process of UA-RPL

5. PERFORMANCE EVALUATION AND RESULTS DISCUSSION

Simulation models are designed for the IoUT environment using NS2 [25] and NS3[26] simulators. Considering the reliability of Cooja for the IoT environment, the proposed UA-RPLis assessed using the Cooja simulator executed on the Contiki Operating System. The Cooja simulator is an open-source tool that assists in simulating the IoUT applications. The nodes are deployed based on the assumption that they are uniformly distributed within a 200m × 200m × 200m three-dimensional topology. Moreover, it is assumed that the proposed scheme adopts antenna array settings for AoA measurement. Assume that there is natural and human-made

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noise in the acoustic channel model. The proposed work is compared with the basic RPL [5], MOP-RPL [23], and OF-ECF [15]. Moreover, the proposed scheme adopts the settings used in the acoustic channel. The performance metrics such as packet delivery ratio, throughput, control overhead, delay, and energy consumption are evaluated under various network densities such as 15, 30, 45, and 60. Table 1 describes the considered parameters and their corresponding values for performance evaluation.

Table 1 Simulation Parameters

PARAMETER	VALUES
Simulator	Contiki Cooja Simulator
Number of Nodes	15, 30, 45, and 60
Traffic Type	Constant Bit Rate
Initial Energy of Nodes	1000 J
Area	200m x 200m x200m
Communication Range	50m
MAC Type	CSAM/CA-based MAC, IPv6
Propagation Type	Unit Disk Graph Model
Routing Protocol	RPL
Transport Agent	UDP
Data Transmission Interval	3 seconds
Simulation Time	10 minutes

5.1. Simulation Results

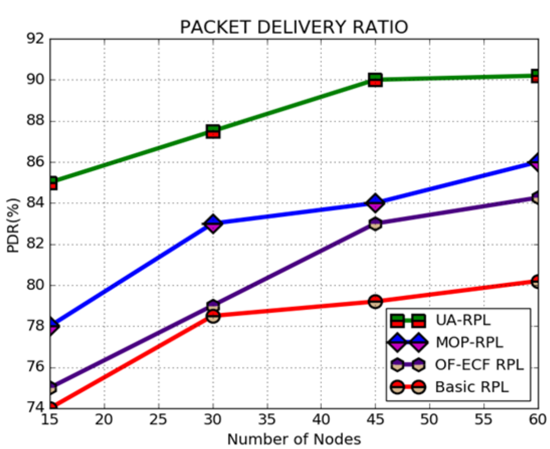

Figure 5 Number of Nodes Vs. Packet Delivery Ratio

To analyze the performance of UA-RPL, MOP-RPL, OF-ECF RPL, and Basic RPL routing, the number of nodes varies from 15 to 60. Figure 5 illustrates that the packet delivery ratio of all the works escalates the packet delivery ratio by increasing the number of nodes from low to high over the underwater network area. After reaching 45 and 60 nodes, the network is saturated, so all the works do not show a huge difference in their results. For instance, the packet delivery ratio difference in UA-RPL is 3% when the number of nodes varies from 15 to 30 under IoUT. However, under the same scenario, the packet delivery difference is 0.2 when the nodes are increased from 45 to 60. Compared to others, the proposed work outperforms all the existing schemes. After that, the MOP RPL attains high PDR than others. Because it dynamically decides on the storing mode of nodes in the DODAG structure and reduces the impact of the water current on routing performance. Even though the OF-ECF RPL makes composite metric-based topology creation, the impact of water current and underwater noise tends to create inefficient topology structure and frequent topology change. For instance, with 45 node scenario, the packet delivery ratio of UA-RPL, MOP-RPL, OF-ECF RPL, and Basic RPL attain 90, 86, 84, and 80%, respectively.

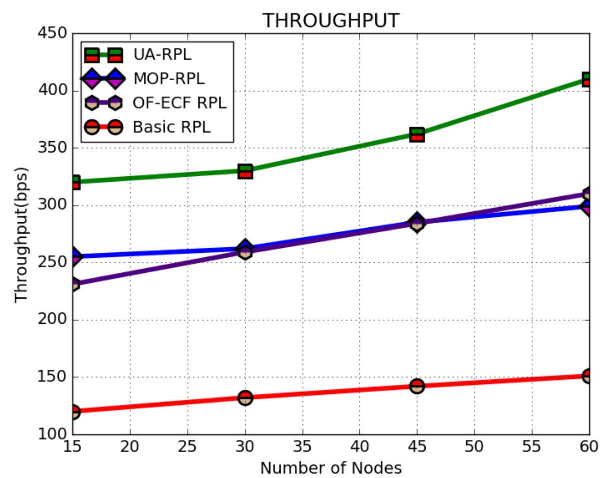

Figure 6 Number of Nodes Vs. Throughput

Figure 6 shows the throughput results of UA-RPL, MOP-RPL, OF-ECF RPL, and Basic RPL routing by varying the number of nodes from 15 to 60. The UA-RPL increases the throughput by varying the number of nodes from low to high. When a node has a sufficient number of neighbors, the impact of water current is less, and the possibility of creating an efficient DODAG structure is high, resulting in better throughput. For instance, the UA-RPL accomplishes 320 and 415 bits/second throughput for 15 and 60 number of nodes scenarios, respectively. The Throughput of UA-RPL is high under all node density scenarios compared with other MOP-RPL, OF-ECF RPL, and Basic RPL routing protocols. The reason is that the UA-RPL forwards the packets through

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efficient routes due to its new OF design and trickle timer model.

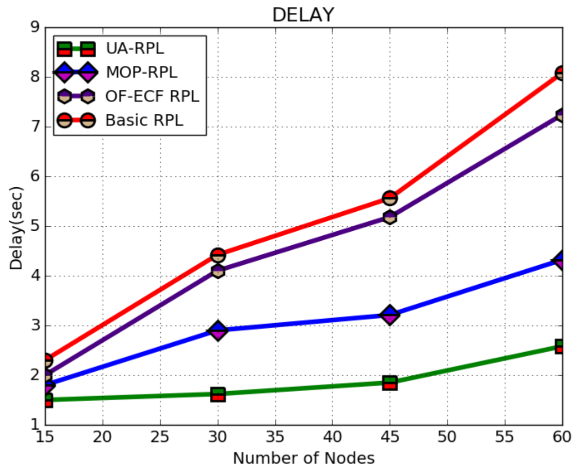

Figure 7 Number of Nodes Vs. Delay

Figures 7 demonstrate the comparative results of delay of UA-RPL, MOP-RPL, OF-ECF RPL, and Basic RPL routing protocols over the IoUT environment. It is observed that the difference in delay between all the protocols is small in the case of sparse network topology. The communication delay is increased at the point of 45 and above node topology. The UA-RPL follows a dynamic trickle algorithm and decides the initial trickle interval for mitigating packet collision and loss in the network. It helps in reducing the delay of communication than all other works. For instance, the UA-RPL reduces the delay by 1.36, 3.53, and 4.13 seconds compared with the MOP-RPL, OF-ECF RPL, and Basic RPL, respectively, when 45 numbers of nodes are presented in the underwater IoT network.

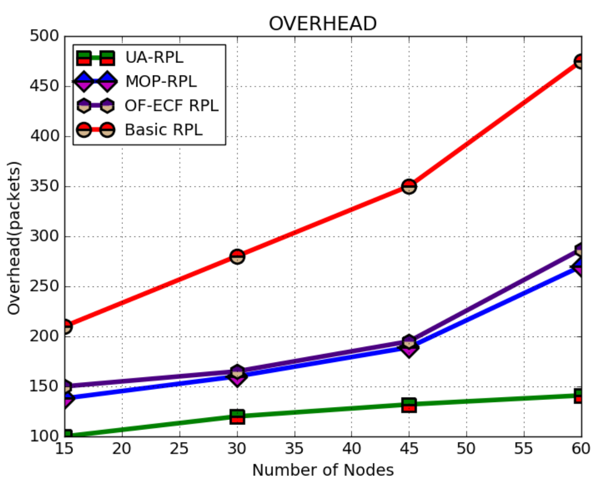

Figure 8 Number of Nodes Vs. Overhead

Figure 8 depicts the overhead results of UA-RPL, MOP-RPL, OF-ECF RPL, and Basic RPL routing protocols obtained by varying the number of nodes from 15 to 60. All the works experience increased routing overhead with the increase in the number of nodes. Unnecessary packet loss and retransmissions due to water current and noisy environment can be avoided mostly using improved DODAG discovery and multi-parent communication topology. It increases the stability of DODAG construction in UA-RPL and reduces the overhead in the network. The MOP-RPL takes a dynamic decision on DODAG construction and handles the network topology, even when the connected nodes are moved due to water current. Thus, the MOP-RPL reduces the delay by nearly 4 seconds compared to Basic RPL under 60 nodes topology. However, the UA-RPL accomplishes less overhead under all node density scenarios than other existing works.

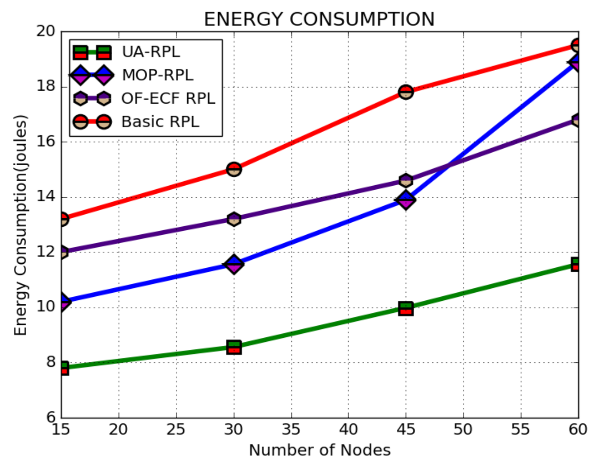

Figure 9 Number of Nodes Vs. Energy Consumption

To analyze the performance of UA-RPL routing, the number of nodes varies from 15 to 60. Figure 9 illustrates the performance of UA-RPL, MOP-RPL, OF-ECF RPL, and Basic RPL by varying the number of nodes over an underwater scenario. The figure shows that the energy consumption of all the works increases with the increase in the number of nodes over the same underwater scenario. The dynamic trickle and neighbor list attached DIO messages improve the DODAG construction efficiency and attempt to save the battery resources of nodes. Moreover, multi-parent-based data forwarding creates an energy-balanced network scenario. Even though MOP takes dynamic decisions to reduce energy consumption, the impact of environmental noise affects the communication quality and tends to unnecessary control message broadcasting for the DODAG reconstruction process. Thus, the MOP-RPL tends to have high energy consumption compared to OF-ECF and Basic RPL. For instance, the UA-RPL increases the energy consumption from 7.8 to 11.56 Joules when increasing the

RESEARCH ARTICLE

node density from 15 to 60 under the IoUT environment. However, the UA-RPL reduces the energy consumption by nearly 1.7, 4.5, and 6.3 Joules when compared with MOP-RPL, OF-ECF RPL, and Basic RPL when 60 nodes are present in the network.

6. CONCLUSION

The proposed work addressed the challenges of underwater environment characteristics in the design of an efficient routing technique. The standardized OFs of RPL lack in dealing with noisy environment and water current issues on routing reliability. The proposed work integrates neighboring and parent nodes to send the DIO control message with RPL to select optimal parent nodes to overcome the noisy environment issue. The proposed work has evaluated the rank value for the restricted neighboring nodes using Hop count, ETX, and energy factor. The proposed UA-RPL selects multiple parent nodes for splitting the network traffic instead of a single parent and improves the energy efficiency of routing. Moreover, this work tunes the trickle parameter and mitigates the routing overhead further. The proposed UA-RPL is estimated using the Contiki Cooja simulator and compared with the Basic RPL, MOP-RPL, and OF-ECF RPL under IoUT scenarios. The proposed LA-RPL delivers 80.2% of data packets in 8.08 seconds by spending 475 control packets and consuming 19.5 Joules under 60 nodes topology.

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