

New RPL Protocol for IoT Applications

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Abstract—The Objective Function (OF) can be used by the Routing protocol for low power lossy networks (RPL) to construct a Destination Oriented Directed Acyclic Graph (DODAG) based on routing metrics. The standard OFs suffer from long hops when selecting the route, which may cause consume the node's energy faster. In this paper, we suggest an improvement of RPL OF that considers three metrics. The results show that the proposed protocol increases network lifetime by reducing energy consumption, increasing efficiency, increasing Packet Delivery Ratio (PDR), and decreasing packet loss ratio. In terms of PDR, packet loss ratio, and average power consumption, the best performance of the proposed protocol is shown in the network with 70 nodes and when the transmission range is 50m. Compared with the MRHOF, the proposed protocol increased the PDR by 58.425%, decreased the packet loss ratio by 0.21765, and decreased the total power consumption by 181.815mW. In terms of the average Expected Transmission Count (ETX) the best performance of the proposed protocol is shown in the network with 60 nodes and the transmission range is 40m. The proposed protocol reduced the average ETX by 49 compared to the MRHOF.

Index Terms—RPL, Low-power and Lossy Networks, Objective Function (OF), MRHOF, IoT, Routing Protocol.

I. INTRODUCTION

THE RPL is Low Power Lossy Networks (LLNs networks) routing protocol was created to handle resource-constrained equipment, routing in smart cities, manufacturing, smart homes, and many applications [1]. When the resources in these devices are limited, poor quality paths can quickly deplete the limited resources. The routing protocols like Open Shortest Path First (OSPF), Ad Hoc on Demand Vector(AODV), Optimized Link State Routing(OLSR), and Dynamic Source Routing (DSR) can't overcome the LLNS networking's constraints like low data lost, low data rates, low power consumption, and network stability [2].

The RPL protocol is built on the IEEE 802.15.4 MAC layer and the physical layer. There are two types of nodes in the RPL network. The sink node, gathers data from all network nodes. The source nodes, on the other hand, collect data from various sensors. After the RPL node routing topology is created, all the common nodes in the network will periodically send their data to the sink node. A Destination Centered Directed Acyclic Graph (DODAG) is the basis of the creation of RPL networks. The standard Objective Function (OF), on the other hand, has

several problems that can be traced back to the use of only one metric such as selecting inefficient routes like paths containing nodes with small residual energy, which may consume the node's energy faster than other nodes. The other problem of RPL is unbalanced chosen by parents that make bottleneck nodes that cause more network delay and high packet loss ratio because of the high congestion nodes, especially the nodes that locate near to the sink node. We attempted to address these issues in this research by proposing an enhanced RPL objective function that takes into account three metrics (Load, Residual Energy, and ETX metrics) rather than only one. The tool used in this paper is the Cooja simulator.

The remainder of this paper is organized as follows. First, in Section II, the DODAG Creation is explained. In section III we explained the problem statement. Section IV reviews the related work that attempts to improve the RPL objective function. Section V defines the proposed objective function model to enhance the RPL protocol. In section VI, the simulation results are evaluated with three network scenarios (50, 60, and 70 nodes) and show the results of the proposed protocol and compare it with the RPL MRHOF with different transmission ranges (40m, 50m, and 60m), in terms of the PDR, average packet loss ratio, total power consumption, and average ETX. Finally, section VII concludes the paper.

II. THE DODAG CREATION

A Destination Oriented Directed Acyclic Graph (DODAG) is the basis of the creation of RPL networks. To build and optimize the path, the OFs choose the best parent nodes. The DODAG relation produces a series of specific edges, as demonstrated in Figure 1. The RPL DODAG is constructed by linking the leaf node to the sink (root) node via a sequence of pathways. The topology's structure lacks a defined loop. Each node in a network has a rank value that reflects its position in comparison to the sink node. The rank value is usually an integer number, and the DODAG sink node holds the minimum rank value for the whole network. The rank value raises the path relation from the root (sink) node to the leaf node downwards, while it decreased from the leaf node to the root node upwards. The root node in the DODAG network collects all of the data. The network's nodes will communicate with not only their own parents, but also their neighbors. The node ranking is the scalar expression within a DODAG of the position of that node. The OF will be in charge of determining the exact rank measurement. During the development of the DODAG network, each router node can choose several potential parent nodes based on its OF. The OF defines how RPL nodes choose and improve routes within an RPL instance [3] [4].

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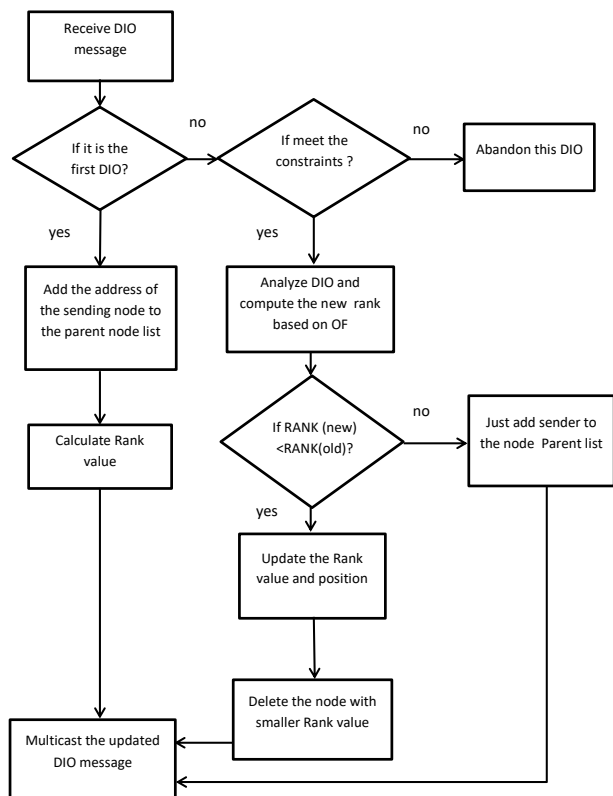


Fig. 1. The process to build DODAG

RPL uses objective function (OF) operations to choose a preferred parent for traffic forwarding. The OF considers a variety of parameters and constraints of nodes and networks to choose the best route. The Internet Engineering Task Force (IETF) Routing Over Low power and Lossy networks (ROLL) working group has two standard OFs, named OF zero (OF0), and Minimum Rank with Hysteresis Objective Function (MRHOF) [5] [6]. In the RPL when constructing the DODAG and select parents, the RPL may suffer from select inefficient routes like paths contain nodes with small residual energy, which may cause consume the nod's energy faster than other nodes. The other issue with RPL is that it is unbalanced by parents, resulting in bottleneck nodes that create increased network delay and a high packet loss ratio due to high congestion nodes, particularly those located near the sink node. To improve network performance, many articles have been presented to improve RPL efficiency.

III. THE PROBLEM STATEMENT

In RPL, the OFs that are used to select the forwarding node (parent node), may suffer from the problem of long hops, when the network becomes heavy because of the large number of nodes when the size of the network increases. This is due to the single metric RPL objective function, such as hop count, or ETX. In addition, a flocking effect can be a result of the parent selection scheme in RPL, which refers to the incidence of attracting nodes and continuous switching from one parent to another. As a consequence, this flocking phenomenon would have a major effect on QoS provisioning

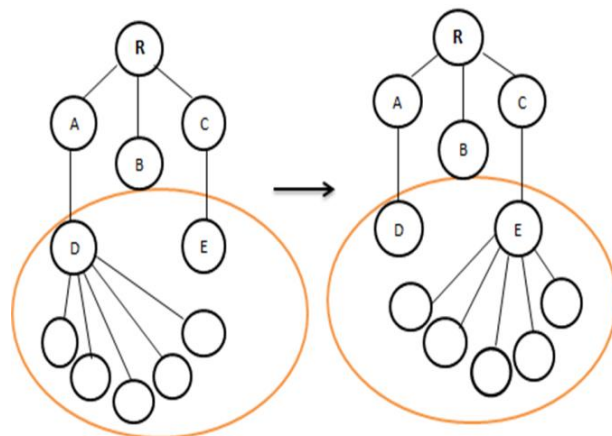


Fig. 2. The Flocking Phenomena

that essentially restricts the services of the IoT application. Since selecting parents in the OF0 does not consider link quality and only tries to find a path with minimum hop count, this metric is not efficient enough because it does not take into consideration the long hop that negatively affects energy consumption and QoS. While MRHOF only takes the ETX metric without consideration of other metrics, this harms the network performance. According to the RPL MRHOF objective function, each node chooses their preferred parent based on the lower rank which is based on a lower ETX value. This parent selection process may result in the flocking effect, which attracts nodes quickly and disrupts network balancing [6].

Consider the network in Figure 2 to have a better understanding of the situation. Nodes D and E, which have rank values of 10 and 11, respectively, are candidate parents of multiple nodes in this topology. The shared transmission range area of the nodes is shown in the orange circle. As the preferred parent, since node D has a lower rank than node E, all the relevant nodes in their area will choose D as their preferred parent because it broadcasts the lowest route cost. After a time, when the parent E broadcasts a lower rank than parent D and all of the nodes in the coverage area satisfy the rank policy, all of the relevant nodes switch to node E as their preferred parent. Nodes will switch their preferred parent again if a new node enters the network and broadcasts the better rank value. As a result of this scenario, flocking occurs, with repeated parents quickly moving (switching) from one to the other parent. In large-scale IoT networks, the flocking effect causes frequent parent changes, which leads to network instability. Consequently, the network will not run smoothly, and it will have a substantial influence on QoS needs.

RPL has many strong specifications, including a quick initialization, self-healing, and loop-free topology. The load imbalance, on the other hand, is regarded as a major weakness in RPL protocol. In addition to universal delivery, RPL specifically defines a non-uniform implementation of large-scale LLNs, resulting in unequal data traffic. As a result, the energy of overburdened nodes will deplete even more quickly

than other nodes in the network. However, if the overloaded node is a bottleneck node (the nodes that lie near the root, the first hop), the problem is even more serious. The nodes near the sink node suffer from depleted energy faster than other nodes, because the MRHOF protocol depends on the ETX only to build DODAG and select the parent. We proposed the Load metric as a solution for the problem of the bottleneck nodes because it makes a load balance that extends the network lifetime, while the RE metric is a solution for both flocking phenomena and bottleneck problems.

IV. RELATED WORK

The authors in [7] attempted to optimize the lifetime of the network, by choosing the next hops to the DODAG sink node according to the residual energy of the node. Nodes are added time period spend in each state from node energy (idle, receive, sense, transmit, compute). The cost of the calculated path would then equate to the residual energy of the path's node. Nodes would then pick a neighbor which path to the sink node holds the best maximum value of a lifetime and according to the new proposed OF. The major downside of this approach is an observed deterioration of the efficiency of the transmission inefficient routes with poor radio links that may be used.

The authors in [8] proposed a new approach for increasing network reliability while maintaining a balanced energy usage across network nodes. The authors created the Estimated Lifetime (ELT) metric to determine how long a node will last before it runs out of energy. The proposed OF ensured that topology nodes had balanced power consumption independent of their distances from the DODAG sink, based on simulation performance. However, there is an extra delay.

In [9], the authors mentioned their suggested Bounded Degree RPL solution (BD-RPL). Instead of using the children count as a measure, they used it to set a limit for DODAG by limiting the children count a favored parent can have. The research scheme's strength is that it has no additional overhead when compared to RPL. It is also unaffected by the radio link quality metric. According to the researchers, BD-RPL improved PDR by 10%, reduced power consumption by 50%, and reduced delay by 60% when compared to standard RPL.

In [10], the paper proposes a new RPL metric based on the approximate node Queue Backlog to increase overall throughput efficiency, maintaining regular delay, and being compatible with multiple network equipment. In [11], the authors proposed a new OF called (LB-OF), which attempts to balance the distribution of loads across all nodes in LLNs, particularly bottleneck nodes. The authors achieved this by substituting the ETX metric, which took into account the children count in the rank calculation and thus favored parent selection. The proposed technique allowed the children count for overstretched nodes to be balanced in relation to MRHOF, ensuring node lifetime optimization. Despite this, the authors did not investigate the proposed OF effect on the PDR and latency.

The authors in [12] proposed an OF dependent on a composite metric using the OF-EC fuzzy logic framework. As

input fuzzy method, they chose HC, ETX, and power metrics, but computed power consumption differently. Therefore, both transmitter and receiver consumed energy, processing energy, and both maximum and low energy usage modes were used to assess the energy consumption. The authors say that, with comparison to other RPLs, the proposed OF-EC efficient performance in calculating PDR, delay, the lifetime of the network, energy consumption, and convergence time. The authors in [13] proposed the Composite Metric OF (CMOF), which mixes latency and ETX route metrics that are supposed to increase both latency and PDR by choosing better communication and fewer traffic routes. In reality, while ETX will guarantee the use of secure connections, by summing the time packets spend in the transmitted queue and the time is taken to reach the link, latency will quantify both traffic and contention at any node. The paper adjusts transmission power to assist establish the network topology and reducing congestion to improve latency and PDR, but in the simulation, they test only the network with 12 nodes, many network scales should be taken to accurately determine the protocol efficiency.

The authors in [14], presented an objective function called (OFER) depending on a hybrid routing metric to get an optimal parent choice. A collection of weighted metrics, including packet loss, connection consistency ETX due to queue occupancy, the node's remaining duration to live, and latency, are combined with the CER metric. In comparison to standard RPL, EN-RPL reduces packet loss by up to 37 percent and reduces power consumption by up to 46.5 percent, according to simulation data. In terms of network stability, the evaluation findings of OF-ER exceed state-of-the-art load balancing based OF. The paper argues that not only could OF-ER minimize queue loss and power consumption, but also extend the planned lifetime of the node. But, the authors failed to mention the metric impact on traffic or its ability to support different network sizes.

V. THE PROPOSED OBJECTIVE FUNCTION

In RPL, the OFs that used to select the forwarding node (parent) may suffer from the problem of long hops, when the network becomes heavy because of the large number of nodes when the size of the network increases [15], this due to the single metric RPL objective function, such as hop count or Expected Transmission Count (ETX). In addition, a flocking effect can be a result of the parent selection scheme in RPL, which referred to the incidence of attracting nodes and continuously switching from one parent to another, as a consequence, this flocking phenomenon would have a major effect on QoS provisioning, which essentially restricts the services of the IoT application. Since selecting parents in the objective function zero (OF0), does not take link quality into consideration and only tries to find a path with minimum hop count, this metric is not efficient enough because it does not take into consideration the long hop that is effect negatively in energy consumption and QoS, while MRHOF is only taking the ETX metric without consideration of other metrics, this affects negatively on the network performance. Since the objective function, routing parameters, constraints,

and local policies to be used in the parent selection and route establishment process can be freely chosen in the RPL, in order to provide high flexibility, therefore, we designed a new objective function that combines three metrics: node residual energy, load metric, and ETX, the residual energy metric solve the problem of the selecting the nodes with low energy, so it prevents the network drop early. The load metric prevents selecting the bottleneck nodes therefore the proposed protocol solved the problem of the flocking phenomena and the bottleneck problem. Every node when it selects parent and constructs the DODAG from the candidate parent nodes, should select the node that has minimum ETX, minimum load metric, and maximum node residual energy.

A. Calculate Residual Energy

As a representation of the network lifetime, we used the residual energy metric (RE). Therefore, when construct DODAG and select a parent every node should not select a parent that has low residual energy to prevent choosing nodes that have low energy. Based on its various operating modes, the energy consumption of each node is calculated. These modes are usually listening mode which includes (listen + receive (RX) + idle modes), transmission mode (TX mode), processing mode (CPU mode), and low power mode (sleep mode). The current energy consumption can be calculated as Eq.(1) [3].

$$EC(x) = P_{sleep}(x) \times T_{sleep}(x) + P_{tx}(x) \times T_{tx}(x) + P_{cpu}(x) \times T_{cpu}(x) + P_{les}(x) \times T_{les}(x)$$

where $EC(x)$ is the energy consumed by node (x). P_{mode} is the power consumption modes (P_{les} , P_{Tx} , P_{cpu} , P_{sleep}). T_{mode} is the duration of time in each mode (T_{les} , T_{Tx} , T_{cpu} , T_{sleep}). Equation 2 can be used to calculate residual energy.

$$RE(x) = EMax(x) - EC(x) \quad (1)$$

where $RE(x)$ is the residual energy of the node (x), $EMax(x)$ is the maximum energy of the node (x).

B. Calculate Load Metric

The network data traffic is a quantity of data transmission at a specific amount of time across the network. A load balancing method was proposed by the authors in [11]. The load metric can be used to make balance of the data traffic in the network. Depending on the number of children present throughout the parent node, the load is calculated. The DODAG nodes broadcast all participant nodes with DIO message. The participant node or sender node computes for each preferred parent the number of children. Finally, based on the cumulative children number present in the link, the DODAG generate the rank. The participant node selects the parent from the candidate parent list, based on the load metric. The load metric can be calculated as Eqs. (3) and (4).

$$NT = \sum_{i=1}^n CN(i) \quad (2)$$

where N is the node traffic, CN is the children number.

$$L(Px) = \sum_{N=1}^n NT(N) \quad (3)$$

where $L(Px)$ is the load on parent (x).

The number of children that connect with this node is used to determine node traffic.

C. Calculate the Proposed Objective Function

The Objective Function (OF) determines how to construct the DODAG and selects the parents, in the RPL network to optimize the path. The proposed objective function composite three metrics to increase energy efficiency. This objective function focuses on issues like data traffic in multi-point to point communications. The bottle-neck occurs nearby sink node. Becoming a chosen parent, for more children means unbalanced load, high congestion, more loss packet, and more overhead, thereby wasting its own energy even faster than other preferred parents did. A load metric has been proposed to solve this problem, providing each chosen parent with how many children they have. On the basis of that, in the rank measurement, we take into consideration the number of children. Every node when it selects parent and construct the DODAG from the candidate parent nodes, should select the node that has minimum ETX, minimum load metric, and maximum node residual energy (max RE + min ETX + min Load).

VI. NETWORK SETUP AND SIMULATION RESULT ANALYSIS

In this paper, the Cooja /Contiki3 simulator has been used for the simulations. In the Contiki area, this simulator is integrated and can run the very same executable as those for real-life nodes. The 'Unit Disk Graph Model (UDGM)' was used. The smart home is the case study of our proposed, the transmission range (maximum distance where a packet can still be received) is taken (40m, 50m, and 60m), and interference distance is designed for this model (the maximal distance of the collision domain) is 100m. For the MAC protocol, the CSMA protocol was used. The simulation area is 100m × 100m, the type of the nodes is sky motes, with three network topologies (50, 60 and 70 nodes). In each network we used three transmission ranges (40m, 50m, and 60m), with random distribution of nodes. Table 1 shows the network parameters that used in this simulation. The time of simulation for each network is 1200 sec. We applied the MRHOF OF and the proposed protocol on each network and several metrics are calculated such as, Total Power Consumption, Packet Delivery Ratio (PDR), Packet Loss Ratio, and ETX.

A. Packet Delivery Ratio

PDR is "defined as the number of data packets received by the sink (root) node to the number of data packets sent to the sink (root) node". Figure 3 shows the packet delivery ratio (PDR) with the number of nodes (50, 60, 70 nodes), each node implemented with various transmission ranges (40m, 50m, and

TABLE I
SIMULATION NETWORK PARAMETERS

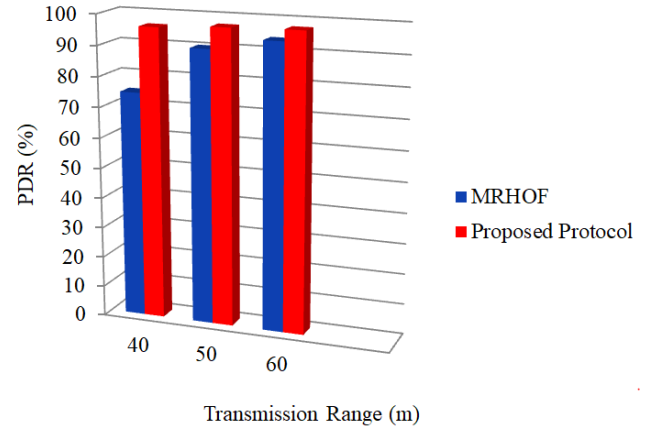
Parameter	Value
Operating System	Ubuntu 14.04, Instant Contiki 3
Simulator	Cooja simulator
Simulation area	100m × 100m
Transmission range	40m, 50m, 60m
Interference range	100m
Radio model	Unit Disk Graph Medium (UDGM)
Packet format	IPv6
Number of nodes	50, 60, 70 nodes
Type of nodes	1 sink node, and 49, 59, 69 sender nodes
Packet size	127-byte payload
microcontroller	MSP430
Transport layer protocol	UDP/IPv6
MAC layer reliability	Enabled
Node type	Tmote (Sky mote)
Data Link layer	CSMA/CA
MAC	Standard IEEE 802.15.4 MAC
Physical	Standard IEEE 802.15.4 PHY

60m), each node is sending 20 packets in each MRHOF and the proposed protocol.

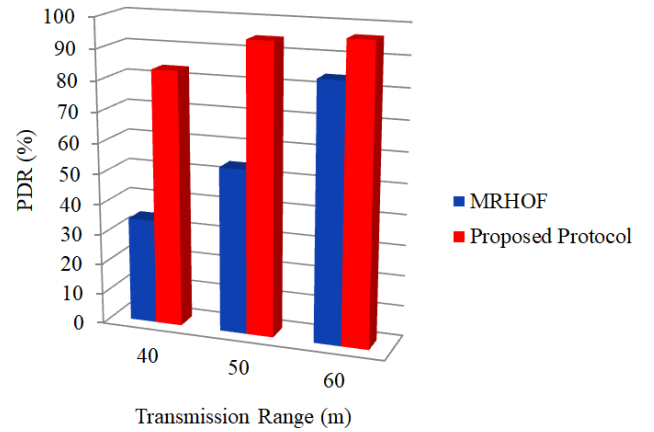
The network with 50 nodes in the first topology, as seen in Figure (3a), has a transmission range of 40m. The packet delivery ratio in the MRHOF is around 74.695, while it is 96.02 in the proposed protocol. The packet delivery ratio in the MRHOF is around 90.1, and in the suggested protocol is 97.145 while the transmission range of 50m. The packet delivery ratio in the MRHOF is around 93.88 while the transmission range of 60m, but it is 97.55 in the proposed protocol. The second topology, as seen in Figure (3b), has 60 nodes and a transmission range of 40m. The packet delivery ratio in the MRHOF is approximately 34.31, although it is 83.475 in the proposed protocol. The packet delivery ratio in the MRHOF is around 53.985 for a transmission range of 50m, and 94.575 in the proposed protocol. The packet delivery ratio in the MRHOF is around 83.985 for a transmission range of 60m, and 96.525 in the proposed protocol. The network with 70 nodes, with a transmission range of 40m, is seen in the third topology, as seen in Figure (3c). The results show that in the MRHOF, the packet delivery ratio is about 31.2, while in the suggested protocol, it is 85.505. The packet delivery ratio in the MRHOF is around 34.69 for a transmission range of 50m, and it is 93.115 in the proposed protocol. In case the transmission range is 60m, we found that the packet delivery ratio in the MRHOF is about 94.35, and in the proposed protocol is 97.1. Figures 3a, 3b, 3c show that the efficiency of the proposed protocol increased when the number of nodes increased especially with the low transmission ranges (40,50). In the standard protocol and proposed protocol, the PDR increased when the transmission range increased because the network hop count to the sink node decreased. In the case of the transmission range is 60m, most of the nodes reach the sink in one hop, and the rest of the nodes need two hops, so the effect of the proposed protocol is not visible.

B. Total Lost Packet

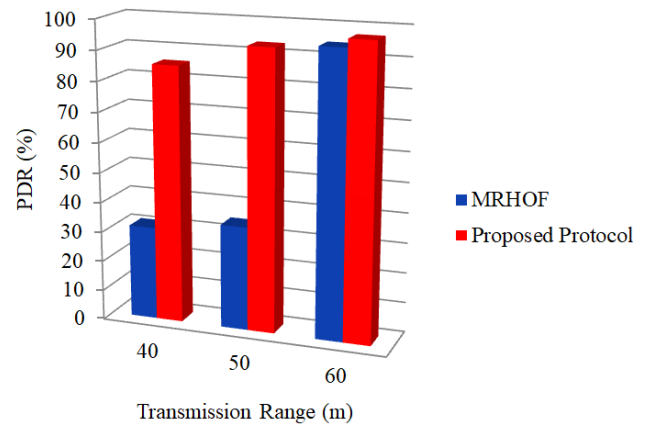
Figure 4 (a, b, c) shows the total lost packet for three network topologies (50, 60, and 70 nodes), each network implemented with various transmission ranges (40m, 50m, and



(a) 50 node



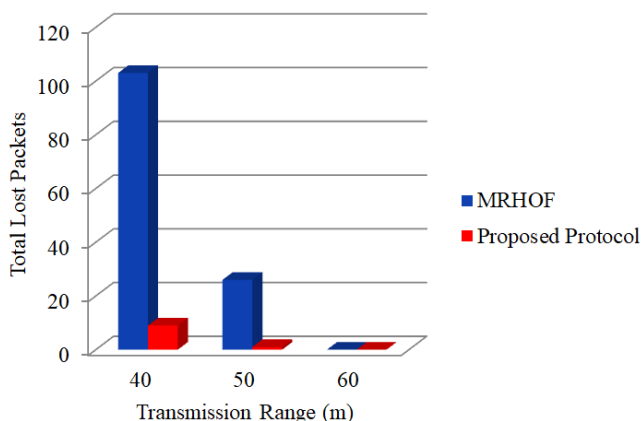
(b) 60 node



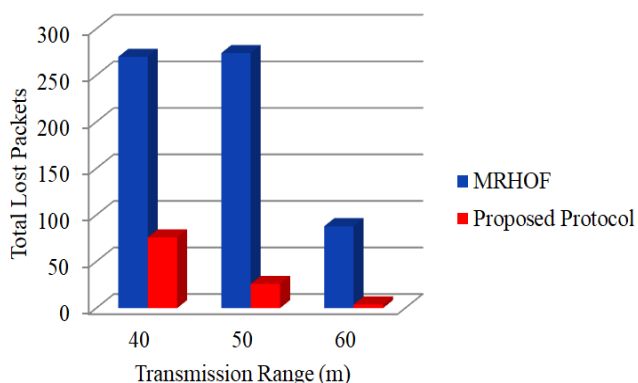
(c) 70 node

Fig. 3. (a, b, c) The packet delivery ratio with various transmission ranges for three network topologies (50,60,70 nodes).

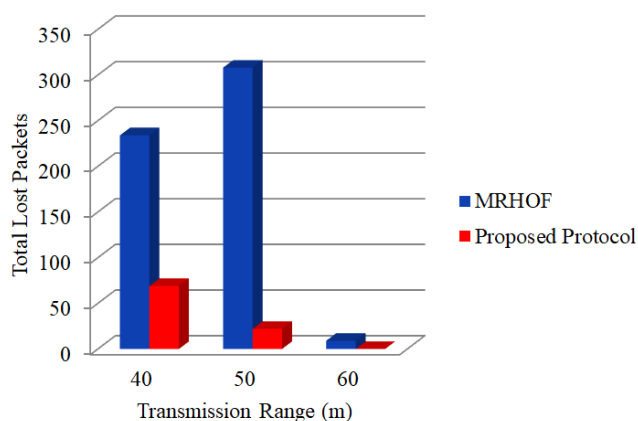
60m), and each node is sends 20 packets for each MRHOF and a newly proposed protocol. When the PDR increased the total lost packet decreases it can reach zero in some cases(transmission range of 60m) because the network has a good efficiency with the fewer hop count routes.



(a) 50 node



(b) 60 node



(c) 70 node

Fig. 4. (a, b, c) The total lost packet with various transmission range for three topologies(50, 60, 70 nodes)

C. Total Power Consumption

Because the sensor nodes are battery-powered, the total consumption is an important parameter for an efficient sensor network operation, therefore we measured this parameter in order to extrapolate their effect on network efficiency. The table 2 shows the summary of the total power consumption for MRHOF and proposed protocol.

TABLE II
THE TOTAL POWER CONSUMPTION OF THE MRHOF AND PROPOSED PROTOCOL

Number of Nodes	Transmission Range (m)	MRHOF Total Power Consumption (mw)	Proposed Protocol Total Power Consumption (mw)
50	40	135.534	98.147
	50	116.914	92.659
	60	102.165	86.191
60	40	253.523	152.043
	50	264.969	132.809
	60	168.15	115.581
70	40	313.605	169.602
	50	330.924	149.109
	60	145.659	132.135

TABLE III
THE AVERAGE ETX FOR THE MRHOF AND PROPOSED PROTOCOL

Number of Nodes	Transmission Range (m)	MRHOF Average ETX	Proposed Protocol Average ETX
50	40	52	23
	50	35	23
	60	37	26
60	40	78	29
	50	54	27
	60	32	21
70	40	71	29
	50	54	25
	60	27	21

Figure 5(a, b, c) shows that the Proposed protocol consume less energy than MRHOF protocol, for various transmission ranges for three network topologies (50, 60, 70) nodes, the MRHOF protocol is still performing poorly in terms of energy consumption. In the proposed protocol the power consumption decreased when the transmission range increased because the proposed protocol makes load balancing and consumes less energy, due to estimates the best parent among preferred nodes and considering a load metric when selecting the route to the sink node.

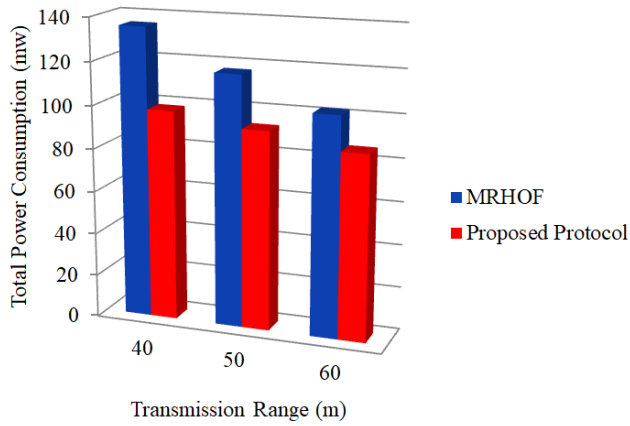
D. Average Expected Transmission Count (ETX)

Figure 6(a, b, c) shows the Average ETX for various Transmission ranges, for three network topologies (50, 60, 70 nodes). The average ETX was the lowest in the proposed protocol and increased with MRHOF. A smaller ETX means a lower energy consumption, which indicates a better quality of the routes to the sink node. The table 3 shows the summery of the average ETX for both MRHOF and proposed protocol.

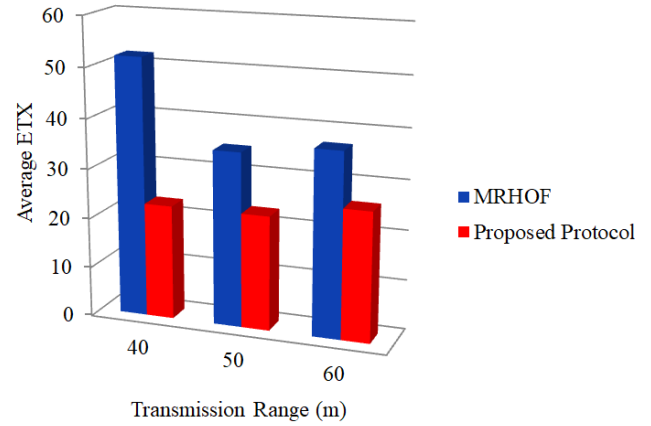
This indicates that the MRHOF protocol performance in large scale networks with transmission range less than 60m is so bad, but the proposed protocol keeps the high performance in different transmission ranges (has high PDR, Low Packet loss ratio, Low power consumption, and Low ETX in all topologies).

VII. CONCLUSION

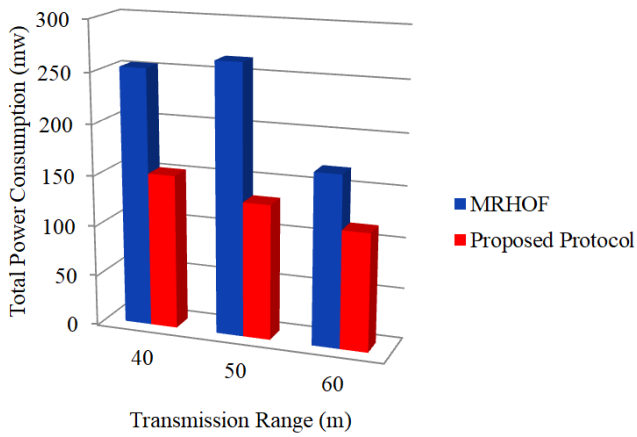
A brief overview of the RPL routing protocol is presented in this paper and an improvement of the MRHOF in the existing



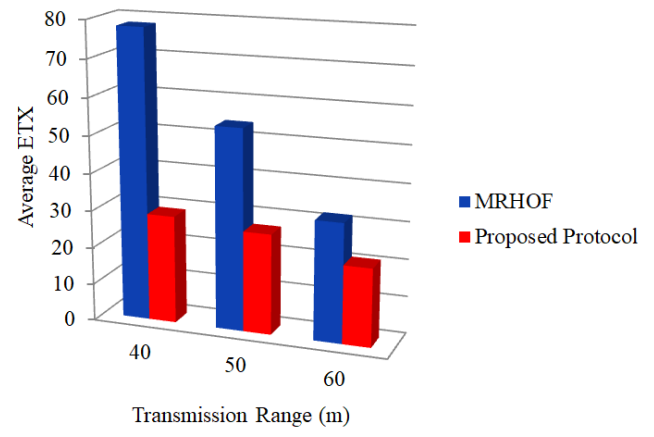
(a) 50 node



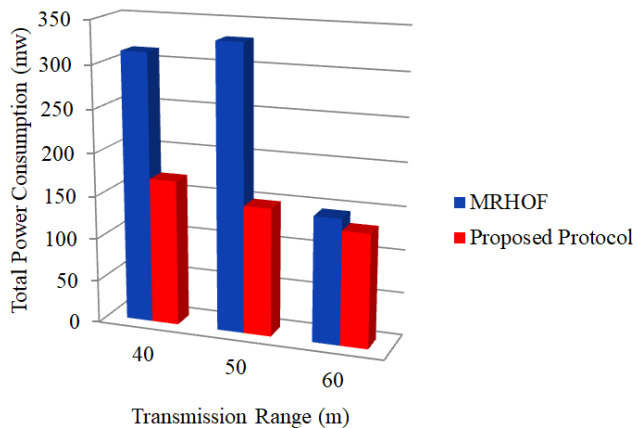
(a) 50 node



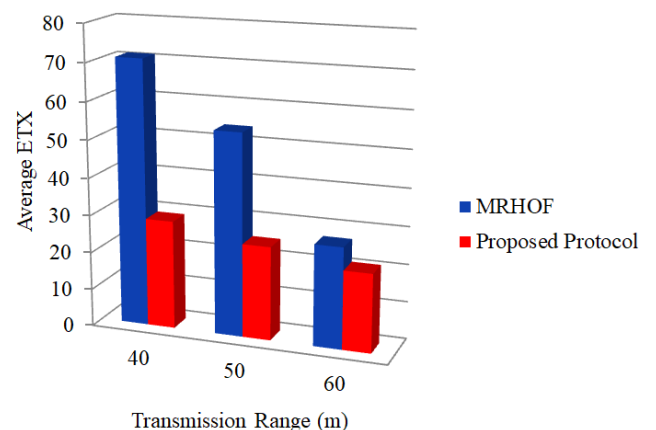
(b) 60 node



(b) 60 node



(c) 70 node



(c) 70 node

Fig. 5. (a, b, c) The total power consumption for various transmission ranges for three topologies(50, 60, 70 nodes.)

Fig. 6. (a, b, c) The average ETX with various transmission range for three topologies(50, 60, 70 nodes)

RPL protocol is proposed. In addition, a configuration based on a combination of three metrics (load, residual energy, ETX) is carried out and simulations are carried out in Instant Contiki 3/ Cooja, the results indicate that in all network scenarios (50,60,70 nodes), with various transmission ranges (40m,50m,

and 60m), the proposed protocol will effectively select a better routing path and achieve the goal of lower packet loss ratios, higher packet delivery ratios, lower average ETX and lower power consumption than the original RPL protocol. The results show that the efficiency of the proposed protocol increased

when the number of nodes increased especially with the low transmission ranges (40,50), the PDR increased when the transmission range increased while the power consumption and packet loss ratio decreased because the network hop count to the sink node decreased. In the case of the transmission range is 60m, most of the nodes reach the sink in one hop, and the rest of the nodes need two hops, so the effect of the proposed protocol is not clearly visible in the case of packet delivery ratio calculation. Other approaches may be used to get high protocol efficiency and conserve more energy, for future work the following points are suggested: Proposing an efficient trickle time algorithm that provides trickle DIO time to increase efficiency more, and it would be fascinating to research the RPL behavior with mobility models.

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