Enhancing Routing Protocol for Low Power and Lossy Networks

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***Abstract*— With the rise the of the Internet of Things (IoT) the Routing Protocol for Low Power and Lossy Networks (RPL) gained a lot of interest in the research community mainly for its flexibility to cope with different network topologies and its ability to offer features like Auto-Configuration, Self-Healing, Loop avoidance and detection, etc. Based on certain routing metrics, RPL's Objective Function (OF) assigns ranks to the nodes in the network then selects and optimizes the routes. This paper overviews the most used objective functions then proposes a modification on the Minimum Rank with Hysteresis Objective Function (MRHOF) which takes into consideration two metrics instead of one, to get more reliable and optimized routes.**

***Keywords*— RPL, Low-power and Lossy Networks, Objective Function, Routing, OF0, ETXOF, MRHOF.**

I. Introduction

Routing protocols are designed with the goal of enabling effective communication between different nodes. Therefore, the different characteristics and applications of the target network should be taken into consideration while designing the routing protocol [1]. RPL was designed for Low-power and Lossy Networks (LLNs); these networks use devices with scarce resources (limited energy power, limited computational power, limited memory, etc.) and are subject to high Packet Error Rates (PER). RPL is a Distance-Vector (DV) and a source routing protocol which operates at the IP level. Hence, RPL can operate over different types of link layers such as IEEE 802.15.4 PHY and MAC layers [2].

LLNs do not have a predefined topology. It is thus the job of RPL to find links and choose peers. To do so, RPL organizes the network as a Directed Acyclic Graph (DAG) with the sink located at the root and uses an Objective Function (OF) to minimize the cost of reaching the root from any node in this network. To cope with the different application requirements of the networks in LLNs or in the IoT in general, the Internet Engineering Task Force (IETF) assembled a group called Routing over Low Power and Lossy Networks (ROLL) group, to specify different link and node routing metrics and constraints [1]. Furthermore, the chosen metrics should be capable of combining different routing metrics together. However, no guidelines were provided [1]. RPL uses these metrics in its objective function in order to establish efficient routes between the nodes [3]. In RPL, one can freely choose the objective function, the routing metrics, the constraints and local policies to be used in the process of parent selection and route establishment, thus providing high flexibility [4]. As of now, only few objective functions have been developed properly. Hence, the area is still an open research field.

The objective function in RPL defines how to use the link metrics and constraints to assign ranks to the nodes in the network, thus creating the topology and selecting/optimizing the paths. But the RPL standard does not force the use of any specific objective function or any specific metrics keeping it open for implementations [4]. In [5], the IETF-ROLL group specified the Objective Function 0 (OF0). OF0 was designed to be used as the default OF and its goal is to find a good enough connectivity to the routing infrastructure. However, OF0 does not guarantee that the selected path will be optimized in accordance to a certain metric. The other objective functions have a similar shortcoming. In this paper, we first study the performance of the existing objective functions found in the literature. Then we propose an objective function that improves the performance of RPL by increasing the packet delivery ratio, without impacting the energy consumption.

The remainder of this paper is structured as follows. In Section II, we present the background and the basic concepts of RPL and survey the related work found in the literature. In section III we introduce our proposed objective function then in Section IV we evaluate its performance against its peers in literature, while measuring parameters such as packet delivery ratio, power consumption, and churn. Finally, conclusion and future work are presented in Section V.

II. Background and Related Work

In this section, we first present the basic concepts of RPL surveying some of the recent work found in the literature.

A. Network architecture of RPL

RPL organizes the network as a Directed Acyclic Graph (DAG) with the sink located at the root and uses an Objective Function to minimize the cost of reaching the root from any node in this network. Hence, "A DAG rooted at a single destination" (DAG root) will create the Destination Oriented DAG or in short, the DODAG [6]. The roots for the DODAG are chosen from the most popular destination nodes (the sinks) and the nodes providing access to the internet (the getaway nodes) [2]. Thus, the network can consist of one or more DODAGs as shown in Figure 1. These DODAGs can form together an RPL network Instance. Each DODAG in the RPL Instance is identified by a DODAGID which is unique in the RPL Instance it belongs to [6]. Multiple RPL Instances can run concurrently on the network. Each Instance is identified by an RPLInstanceID. Nevertheless, each RPL Instance is logically independent from the other Instances [6]. Consequently, each RPL Instance can include one or more DODAGs. Each node can be a member of multiple RPL Instances but one DODAG within each Instance as it is the case of nodes 18 and 22 in Figure 1 where both nodes are members of DODAGs 2 and 3. However, DODAG 2 belong to RPL Instance 1 and DODAG 3 belongs to RPL Instance 2. In DODAG 2, node 22 is the child of node 18 and in DODAG 3, node 22 is the parent of node 18. There are three types of nodes in RPL: A Host node is a node that generates data and sends it to other nodes, a Router node receives and forwards data, and a Border Router (also referred to as Low-Power and Lossy Border Router (LBR)) is the root of the DODAG and acts as an edge router [2]. In Figure 1, Node 7 in DODAG 1 can be a Host Node that generates data and sends it to node 4, and node 2 can be a Router Node which receives and forwards data. Node 1, which is the root of DODAG 1, is a Border Router. The rank of each node represents the position of the node in the DODAG with respect to the root and other nodes. As the figure shows, the root has the lowest rank and the rank increases in the downstream direction.

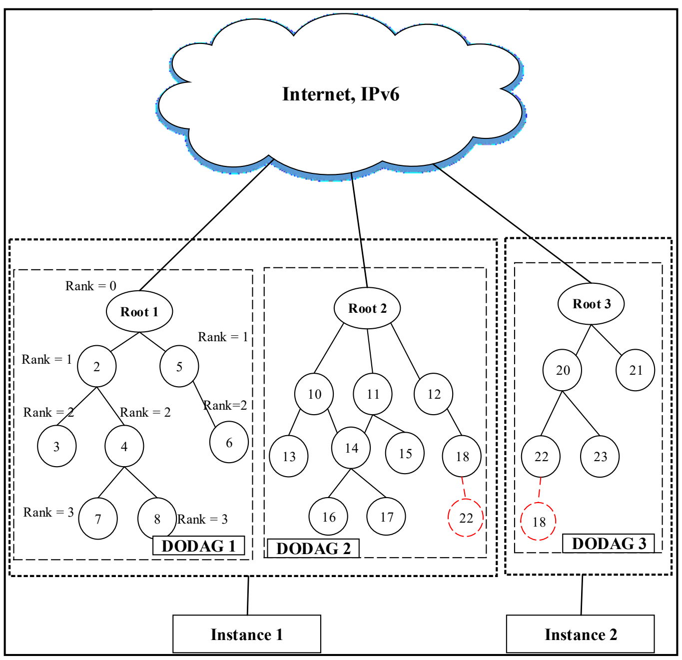

Figure 1. RPL Network.

B. *RPL control messages*

RPL control messages are new ICMPv6 (Internet Control Message Protocol version 6) control messages. They start with an ICMPv6 header followed by a message body and possibly followed by some options [6]. The header contains a type field, a code field and checksum. The type field should have a value of 155 to point that it is an RPL ICMPv6 control message. The code field is to distinguish the type of the message. Indeed, there are 9 types of RPL control messages as shown in Figure 2 and can briefly be described as follows:

- DIS (DODAG Information Solicitation) control message: it is sent from a requesting node to other nodes to solicit them to send to the requesting node a DIO (DODAG Information Object) message, so the requesting node can explore its neighborhood for nearby DODAGs.
- DIO (DODAG Information Object) message: it plays an important role by helping nodes in discovering different RPL Instances with their configuration parameters and in constructing a DODAG. It can be sent as a reply to DIS or triggered by the root when constructing a DODAG. It contains information about the RPLInstanceID, DODAGID, DODAG Version Number, the Rank, and the objective code point (OCP) which identifies the objective function the DODAG is using and so on.
- DAO (Destination Advertisement Object) message: it is used to propagate destination information to trace visited nodes upward along the DODAG to the root.
- DAO-ACK (Destination Advertisement Object Acknowledgment) message.
- Secure DIS (DODAG Information Solicitation control) message.
- Secure DIO (DODAG Information Object) message.
- Secure DAO (Destination Advertisement Object) message.
- Secure DAO-ACK (Destination Advertisement Object Acknowledgment message).
- Consistency Check (CC): It must be sent as a secured RPL message and is used to check the counter of the secure message and to issue challenge-responses.

C. *DODAG construction*

To construct a DODAG, the root broadcasts a destination information object (DIO) control message to the other nodes in the downward direction. The information contained in the broadcasted DIO message will allow the receiving node to identify the objective function and use it to calculate its rank (position with respect to the DODAG root) based on the rank of the sender node. Hence, a node that receives a DIO message can join the DODAG by 1) adding the address of the sender of DIO message to its parent list, 2) calculating its rank, and then 3) advertising the same DIO message but with an updated rank information [2]. Furthermore, to ensure conversion and a loop free network, each node will select as parent the node which advertises a DIO message with the minimum rank [1].

After constructing the DODAG, each node will have a default upward path (which is produced by choosing the node which advertised a DIO message with the minimum rank) to reach the DODAG root. The downward routes from the root to the nodes are to be supported and maintained if the mode of operation field in the DIO control message is different from zero. In this case, each node joining the DODAG sends a unicast Destination Advertisement Object (DAO) control message to determine the reverse route information [2].

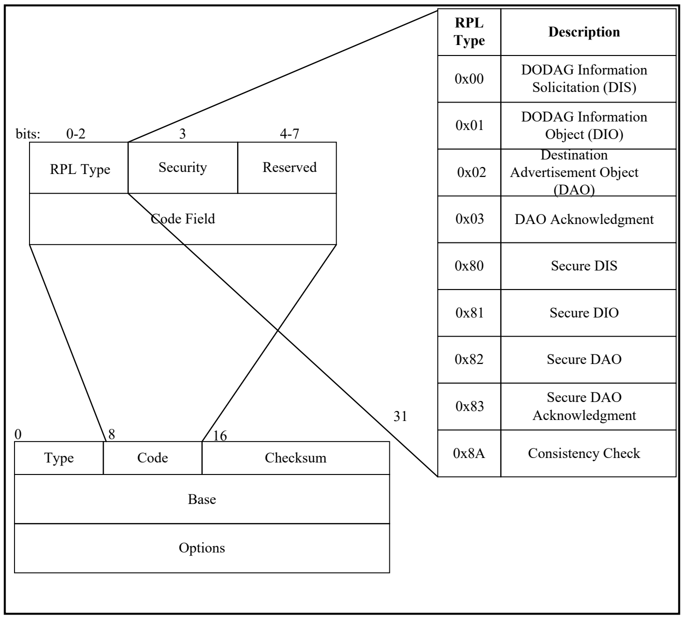

Figure 2. RPL Control Messages.

As mentioned earlier, the IETF-ROLL group specified different link and node routing metrics and constraints to cope with the different application requirements in LLNs. RPL uses these metrics in its objective function to establish routes by selecting the parents of each nodes [3] and assigning ranks to the nodes in the network, thus creating the topology and selecting and optimizing paths in the DODAG. Furthermore, all the DODAGs in the same RPL instance share the same routing metrics, constraints and the OF. Hence, multiple RPL Instances with different OFs can be formed in the same network and are operationally independent from one another. A node that is a member of multiple RPL Instances can differentiate between them using the RPLInstanceID included in the DIO message.

D. Related work

RPL standard does not force the use of any specific objective function or any specific metrics keeping it open for implementations. Several approaches were proposed in the literature attempting to develop objective functions for RPL [4, 5, 7-10].

In [5], the IETF-ROLL group specified the objective function 0 (OF0). OF0 was designed to be used as the default OF and its goal is to find a good enough connectivity to the routing infrastructure. Thus, OF0 will find the nearest DODAG root that provides connectivity. However, OF0 does not guarantee that the selected path will be optimized according to a certain metric.

The expected number of transmission objective function (ETXOF) was proposed in [7]. Unlike OF0, ETXOF's goal is not only to find a path to the DODAG root, but also to find an optimized path using the expected number of transmissions (ETX) metric. These are the expected number of transmissions required to transmit a packet and receive the acknowledgment successfully. Therefore, ETXOF minimizes the sum of ETX from the node to the root. It is worth mentioning here that Cisco uses the ETXOF in its CG-Mesh System [4].

The work proposed in [8] introduced the minimum rank with hysteresis objective function (MRHOF) and defined it as an objective function that selects routes that minimize a metric, while using hysteresis to reduce churn in response to small metric changes. Consequently, ETXOF can be regarded as a MRHOF using the ETX metric. MRHOF aims to find the path with the minimum cost. Therefore, it will change its current path with this new path only if the cost is less than the current used path by at least a given threshold. This is called "hysteresis" and is useful in reducing the churn or in other words to reduce the number of parent changes to maintain the stability of the network. The term *Path Cost* is defined as quantifying a property of an end-to-end path. Also, the term *Selected Metric* is defined as the metric chosen for path selection by the network operator. By default, MRHOF uses the Expected Transmission Count (ETX) as a metric to compute path cost. Thus, the path cost of a neighbor represents the cost of the path, in terms of the selected metric, from a node to the root of the Destination-Oriented DAG through that neighbor. To calculate the path cost, two components are used. In the first component, the selected metric for the link to the candidate neighbor is chosen (for example ETX if a link metric), or the selected metric for the node is chosen (for example Energy if a node metric). In the second component, the value of the selected metric in the metric container in the DIO sent by the candidate neighbor. These two components are added together to get the path cost to a candidate neighbor. After computing the path cost of all the reachable neighbors the node selects a parent and computes its rank.

The performance of OF0 and MRHOF with respect to Power Consumption and Packet Delivery Ration (PDR) were evaluated in [3]. The simulation environment consisted of a light density network comprised of 20 to 40 nodes in a random topology as well as in grid topology using the COOJA simulator. The TX range is set to 100m and the TX% to 100%. The RX% was set to 20%, 40%, 60%, 80%, and 100%. They observed that for both objective functions having the RX value set to 60% will have an almost similar outcome with regards to PDR as to setting the RX value to 100%. However, the power consumption will decrease as the RX% increases. Also, the results showed that MRHOF consumed less energy than OF0 but OF0 had a slightly better PDR than MRHOF.

In [9], also the COOJA simulator was used to evaluate the performance of RPL for both OF0 and ETXOF using PDR, power consumption, network ETX, and control overhead as parameters. The results of the evaluation showed that ETXOF consumed less power than OF0 and had a better PDR, better network ETX and a better control overhead.

In [10] a new energy aware objective function is developed and implemented in a real-life scenario using Zolertia Z1 nodes. This energy efficient objective function allows nodes to change their parent based on the actual remaining energy of the neighbor nodes. It also considers a threshold of 5% to avoid frequent hop changes, which helps maintain stability. The conducted evaluation showed the performance of RPL in two situations, 1) when all nodes are able to see the sink and 2) when some nodes are completely isolated without multi-hop. In both situations OF0, ETXOF, and Energy efficient OF were compared. In both situations, the network lifetime was longer when the energy efficient OF was used compared to OF0 and ETXOF. However, the packet loss percentage and topology changes/hour were lower while using ETXOF and not the energy efficient objective function. Furthermore, packet loss percentage of OF0 was the highest reaching to almost 25% in the extended network.

III. Proposed Work

As mentioned in section II, in RPL one can freely choose the objective function, the routing metrics, the constraints, and the local policies to be used in the process of parent selection and route establishment for the purpose of providing high flexibility. Since OF0 does not take link quality into consideration while selecting parents and only tries to find a good enough path, new objective functions were developed taking into consideration a combination of metrics such as node energy, hop-count, ETX, throughput, and latency. ETXOF [7] takes the ETX metric into consideration ignoring the energy consumption which affects the lifetime of the network. Similarly, the energy efficient objective function [10] takes the energy consumption into consideration ignoring other metrics which resulted in more packet loss and topology changes/hour. Similarly, MRHOF [8] can be programmed to minimize any metric. Therefore, studying these approaches implies that it is not enough to have one metric-based objective function such as "energy efficient only" OF, or an "ETX minimizer only" OF because of the tradeoff that exists among some of the metrics. Indeed, improving performance considering one metric does not guarantee to have a good performance when considering other metrics, but it might negatively impact them.

We are motivated by the lack of a comprehensive objective function that can take into consideration the minimization of more than one metric. Thus, we propose an adaptive approach that might use more than one metric to minimize, using the Minimum Rank with Hysteresis Objective Function (MRHOF) as shown in Table I. This approach is expandable but in this paper we limit the discussion to two metrics: energy and the Expected Transmission Count (ETX). The MRHOF RFC [8] explains that, if the chosen metric is energy, then the path cost is computed by adding the energy metric and the value of this metric as advertised in the metric container in the DIO message of the candidate. Unlike MRHOF in which the two components that are needed for the path cost calculation are: (1) the energy metric and (2) its value which is advertised by the candidate neighbor in the DIO message, in our approach we chose the energy metric which is a node metric, and for the second component, instead of only getting the energy metric value from the DIO message, we also get the ETX metric. We give equal weights to each of these metrics, and add them to compute the new path cost.

TABLE I

Metrics Used by Different Objective Functions			
	Hop-count	ETX	Energy
OF0	X		
MRHOF with ETX		X	
MRHOF with Energy			X
MRHOF with ETX + Energy		X	X

IV. Evaluation and Preliminary Results

To implement and test our proposition for path cost calculation and compare its performance with that of (1) MRHOF using the ETX metric and (2) MRHOF using Energy metric, we used the Contiki 2.7/Cooja simulator [11].

A. Simulation and Network Setup

Contiki is an open source, lightweight, and portable operating system dedicated for WSNs and extensively used for IoT. Cooja is the network simulator in Contiki, which provides developers with a powerful simulation environment allowing them to make use of fully emulated hardware devices to run their applications on large scale networks [11].

For our experiment, we have first designed light density networks of 25 nodes and used in some experiments random topology to distribute the nodes, and afterwards we repeated the same experiments using a grid topology. We also studied the performance with a smaller network of 15 nodes and a larger network of 35 nodes. We set the transmitting range to 50 meters, the interference range to 100 meters, the Transmission Success Ratio (TX) to 75% and varied the Reception Success Ratio (RX) to 20%, 40% and 80%. Also, mote start up delays were set to 1ms and simulation results were collected after 1800 seconds. Furthermore, for our simulations we used the ETX metric with MRHOF, the Energy metric with MRHOF, and the modified MRHOF path cost calculation method as explained in section III with Energy and ETX metrics.

To determine the number of simulation runs we used the central limit theorem as described in [1]. We set the normal variate to 90% confidence interval and set the precision level to +/- 5.

In the experiments we run, we have measured several metrics such as 1) Packet Delivery Ratio which is defined as the ratio of the packets delivered to total packets sent, 2) Average Power Consumption which is defined as the average rate of energy consumption by the nodes in the network, 3) churn which is defined as the number of parent switches, and 4) ETX to next hop which is defined as the expected number of transmissions to successfully transmit and acknowledge a packet.

B. Simulation Results:

In Figure 3, we measure the PDR while varying the RX%. Figure 3 (a) shows the obtained PDR results for 25 nodes deployed randomly while Figure 3(b) shows the obtained results in a grid topology with same number of nodes. We observe that PDR in the random deployment was lower, and in both deployments when the RX% set to 20% the PDR is the lowest but remained above 90% and reached to almost 100% when RX% was set to 80%. Furthermore, it is apparent that the proposed approach (using ETX + Energy) as metrics for MRHOF gave the highest Packet Delivery Ratio in most of the test cases especially when the RX% was low. This was expected since the OF took into consideration not only the ETX, but also the energy of the nodes while optimizing the paths. Thus, changing the path structure in compliance to nodes with more energy and thus with more reliance.

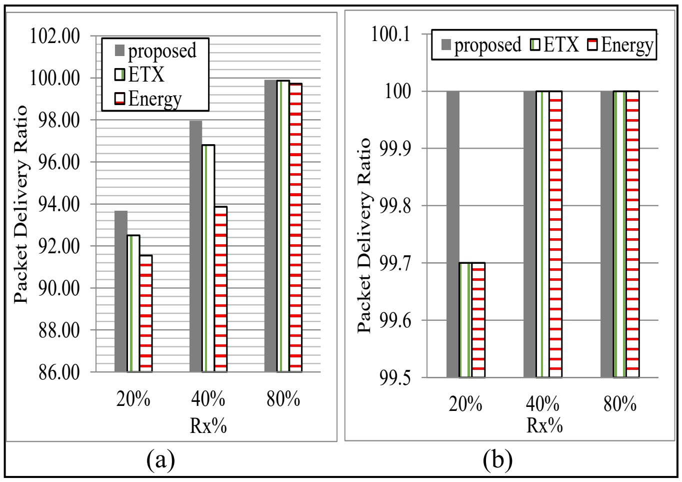

Figure 3. PDR for 25 nodes (a) random deployment, (b) grid delpoyment

Figure 4 presents a general overview of the simulation results obtained when measuring the average power consumption of the network while varying the RX%. The figure shows that when the RX% is high the nodes were consuming less energy in both deployments. It is obvious that the energy consumption increased as the RX% decreased. We can easily observe that using two metrics does not have a severe impact on the power consumption but in many cases a power saving was obtained such as when the RX% is set to 40% and 80% in the random deployment environment (Figure 4(a)) and when RX is set to 80% in the grid deployment (Figure 4(b)).

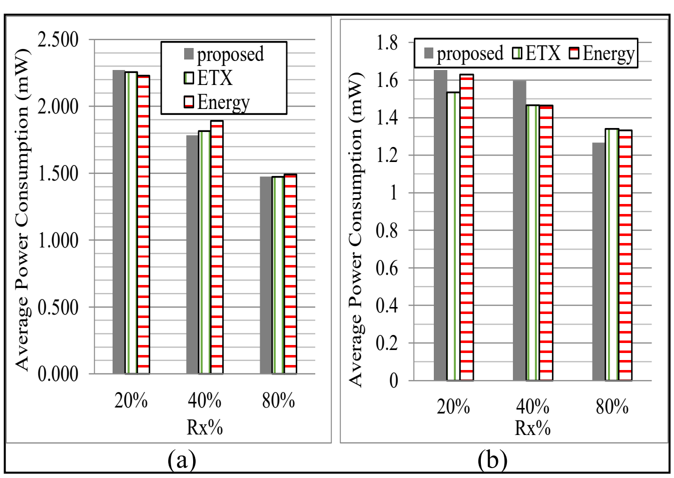

Figure 4. Average Power Consumption for 25 nodes (a) random deployment, (b) grid deployment

Figure 5 shows the behavior of churn while varying the values of RX% using random (Figure 5(a)) and grid (Figure 5 (b)) topologies of 25 nodes. We observe that the churn increases as the RX% values decrease and that churn in the random deployment was higher than the grid deployment. We notice that in most cases the proposed approach that is based on using MRHOF with ETX + Energy yielded better results compared to MRHOF with Energy metric and MRHOF with ETX metric.

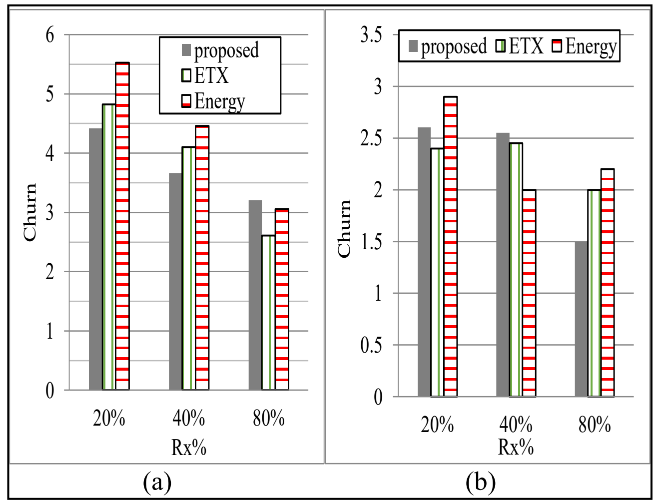

Figure 5. Churn for 25 nodes: (a) random deployment, (b) grid deployment

Figure 6 shows the ETX to next hop while varying the values of RX% using random and grid topologies of 25 nodes. The ETX was lowest when RX% was set to 80%. The ETX increased as the value of RX% decreased. We notice that MRHOF with ETX + Energy performed best with RX% set to 20% and 40% in the random deployment and 80% in the grid deployment.

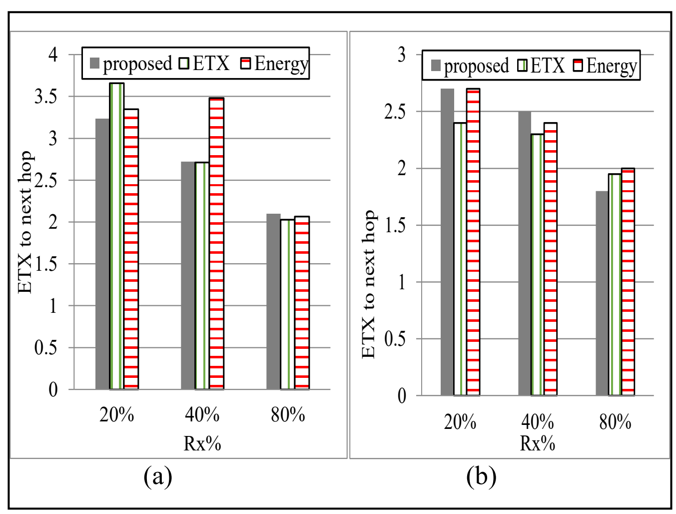

Figure 6. ETX to next hop for 25 nodes: a) random deployment, (b) grid deployment

In general, we observe that when in the random deployment and with low RX% the network performance is the poorest concerning PDR, energy consumption, churn and ETX. In these disadvantaged conditions we notice that the proposed modification of MRHOF using ETX and Energy outperformed MRHOF using one metric since it is taking two metrics into consideration while trying to cope with the different condition of the network.

To study the performance of these approaches with different network settings and environment, we have run several experiments using a smaller or larger number of nodes. Tables II, III, and IV show the obtained results while measuring packet delivery ratio, average power consumption, and the churn respectively while varying the values of RX% (20% and 80%) using random topologies of 15 and 35 nodes. We notice that, in general, PDR decreases as the number of the nodes in the network increases reaching as low as 87% with 35 nodes while using the MRHOF with the Energy metric. Moreover, we note that PDR increases as the values of RX increases. We also note that, while the number of nodes was 15, and even when the RX% is set to 20%, which is considered very low, the PDR remained higher than 99.5% for all cases and reached 100% when RX was set to 40% and higher. Also, the power consumption of the network in general increases as we increase the number of nodes. We note that in many of the test cases, the network was consuming less energy while the MRHOF was taking into consideration not only the Energy metric, but a combination of Energy and ETX metrics. Furthermore, we notice that MRHOF with ETX was consuming less energy than MRHOF with Energy and MRHOF with Energy + ETX when the RX% was high (80%).

TABLE II

Packet Delivery Ratio				
	RX	**ETX + Energy**	**ETX**	**Energy**
15 Nodes	20%	***99.66***	99.42	99.63
	80%	***100.00***	99.76	***100.00***
35 Nodes	20%	***88.42***	87.37	87.16
	80%	***99.83***	99.52	99.64

TABLE III

Average Power Consumption (mW)				
	RX	**ETX + Energy**	**ETX**	**Energy**
15 Nodes	20%	***1.681***	1.767	1.721
	80%	1.233	***1.209***	1.277
35 Nodes	20%	***2.350***	2.387	2.402
	80%	***1.424***	1.429	1.461

TABLE IV

Churn				
	RX	**ETX + Energy**	**ETX**	**Energy**
15 Nodes	20%	1.167	1.357	***0.858***
	80%	***0.595***	0.750	0.750
35 Nodes	20%	***6.359***	6.588	6.478
	80%	***2.961***	3.442	3.981

V. Conclusion

In this paper, we proposed a modification to the Minimum Rank with Hysteresis Objective Function by altering the method of calculating the value of the path cost. Thus, instead of using one metric in the method, we presented a way of taking two metrics into consideration. We designed medium to light density network and we implemented our work using the Contiki Cooja simulator. We noticed that the performance of the network was enhanced in terms of Packet Delivery Ratio while using MRHOF with ETX + Energy, without affecting the power consumption, and the churn of the network. Hence, we conclude that an Objective Function that minimizes one metric only is not sufficient and an Objective Function that takes into consideration more than one metric will be more efficient and effective. Furthermore, research can be done to test the behavior of the network while using other combinations of metrics.

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