Comprehensive Performance Analysis of RPL Objective Functions in IoT Networks.

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Abstract: As the movement for a vast implementation of IoT networks is rapidly accelerating, so many researchers are working to analyze the performance of RPL, the widely-used routing protocol for wireless sensor networks. The analysis usually involves a small number of metrics studied under a limited number of scenarios. In this paper however, we provide a comprehensive study for the performance of the two objective functions used in RPL; MRHOF and OF0, using the Cooja simulator in Contiki operating system. Using static-grid and mobile-random topologies with 25, 49, and 81 sender nodes including one sink node. Each topology was tested with three transmission ranges of 11, 20, and 50 meters to simulate sparse, moderate and dense networks. The selected metrics are convergence time, changes in DoDAG tree structures, average churn in the network, Average Power Consumption, Average Listen Duty Cycle, Average Transmit Duty Cycle, Average received packets, average lost packets, average duplicate packets, and average hop count. In fixed networks, the results show that OF0 usually perform better than MRHOF in terms of Energy Consumption, Convergence Time in the Static-Grid Topology, Listen Duty Cycle, and Transmit Duty Cycle.

Keywords: Internet of Things; RPL; Objective Function; OF0, MRHOF, Cooja, ConikiOS.

1. Introduction

Routing Protocol for Low power and Lossy Networks (RPL) [1], [2] is a dynamic routing protocol that works only with IPv6. Specified by Routing Over Low power and Lossy Networks (ROLL) Working Group as an internet routing protocol for Wireless Sensor Networks (WSN) and Internet of Things (IoT) applications. Its design is directly linked to the development of IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN) [3], [4] and based on Distance Vector Algorithms.

RPL constructs a Destination Oriented Directed Acyclic Graph (DoDAG) per sink node. In Contrast to a Directed Acyclic Graph (DAG), a DoDAG can only have one destination “root” node. Nodes select a preferred parent using DoDAG Information Object (DIO) messages of their neighbors. Each node informs its parent that it is its child using a Destination Advertisement Object (DAO) message. To save DIO broadcasting energy, a node can explicitly request a DIO with a DoDAG Information Solicitation (DIS).

RPL constructs one or more instances with unique instance IDs, each can have a different Objective Function (OF). Several DoDAGs can exist in a single instance with different DoDAG IDs. DoDAG is global with multiple DoDAGs, and local with just one root. Different DoDAG versions can be built by each root.

Objective Function (OF) determines the mechanism in which a parent is selected. It uses a rank calculated based on one or more metrics. This approximates the distance to the root and avoids loops, it is not a path cost. It is separated from the core of RPL specifications. That makes RPL adaptive to different applications just by changing OF in the DIO messages. An instance can use multiple OFs in the future.

RPL uses Objective Function Zero (OF0) [5], where a node adds a rank increase to the rank of its preferred parent. It chooses a preferred parent and a feasible backup in case the preferred parent is not accessible. OF0 uses ranks that approximates the hop count to the root. It prefers fewer “even if longer or poorer” hops. It estimates rank increase as follows:

$$R(N) = R(P) + Rank\_Increase.$$

Where, $R(N)$ is the Rank of node N, $R(P)$ is the Rank of the parent of node N, and,

$$Rank\_Increase = (Rf * Sp + Sr) * MinHopRankIncrease.$$

Where, Rf is the Rank factor to give a weight to a desired link, i.e., wired over wireless, Sp is the Step of rank based on the link properties with a certain neighbor, Sr is the Stretch of rank to select another feasible parent.

With multiple roots, OF0 selects the candidate with the smallest rank that connects to the preferred root. OF0 also supports triggered updates, such as; DoDAG repair calls.

RPL also uses Minimum Rank Objective Function with Hysteresis (MRHOF) [6]. It dynamically uses the Expected Transmission Count (ETX) as the default metric to calculate the rank. It selects the path that minimizes the metrics used, and uses hysteresis to reduce the churn “change of parent” caused by small metric changes over time, by avoiding selecting a new parent unless its rank is less than the current one by a given threshold. If the preferred parent is off, a node chooses from a set of feasible parents.

The metrics are advertised in DIO messages to calculate the rank. It can use the ETX metric to find the minimum ETX path to the root. Or use latency to find the minimum latency path.

Old class routing protocols like Open Shortest Path First (OSFP) [9], Intermediate System to Intermediate System (IS-IS) [10], Ad hoc On Demand Distance Vector (AODV) [11], and Optimized Link State Routing (OLSR) [12] did not satisfy the low power and lossy characteristics of WSN. That is why ROLL working group created RPL.

In this paper, we have discussed all the measure differences between the two objective functions of RPL. That will help people and researchers decide to choose one of them without the need to understand their internal mechanisms. It will also help in understanding the different behaviors of different network setups, and avoiding specific behaviors in the network.

We have tested each objective function on 18 different scenarios. That makes a total of 36 simulations. And We have collected our results on two times of interest “20 simulation minutes from start time, and convergence time”. Which means collecting a total of 72 result sets.

Each result set is a combination of 9 measured metrics along with the captured changes in DoDAG tree structures between the two times of interest. That makes a total of 720 comparison parameters that the authors believe will help in understanding the different behaviors of both objective functions and help in choosing among them.

The rest of this paper includes the following. Section two discusses related work to RPL. In section three we discuss our methodology used in order to assess the performance RPL and all different experimental sets used. Section four presets the results obtained with discussions to all cases where the objective function achieves better results. The last section presents summary and concluding remarks of this work along with suggested future work.

2. Related Work

Most of the recent work in the field of IoT and WSN has been introducing more power conservative routing protocols for wireless networks.

Long et al [7], compare between the performance of RPL and Collection Tree Protocol (CTP) [8]. It shows how RPL is better in terms of scalability. The results comparing RPL (ContikiRPL) with CTP (ContikiCollect) in terms of Packet Reception Ratio (PRR) and power, showed that CTP is better in small networks. While RPL dominates with larger networks with more data traffic.

In previous researches, RPL was simulated to investigate path quality, routing table size, control packet overhead, and loss of connectivity. RPL was not compared with similar routing protocols. Researches focused on RPL implementations, such as; ContikiRPL and TinyRPL in ContikiOS [13], [14] and TinyOS [15], [16]. They compared them in terms of either PRR or power consumption without linking the two.

CPT estimates the cost of the link between two nodes using the network, data-link, and physical layers' properties. This cost is called one-hop ETX. Accumulatively adding that up to the root is called global distance. The cost is distributed periodically using beacons to be used "the minimum" to select a parent.

To avoid loops, CTP uses data path validation by checking the rank of the sender. If it is less "parent" or equal "sibling" than the receiver, it assumes it is a loop packet. In that case, the receiver sends the sender a correcting beacon to correct the packet. The frequency of beaconing is carefully set using trickle algorithm. Small intervals adapt quickly to changing networks at a cost of bandwidth and power. While large intervals save bandwidth and power at a cost of inconsistent network.

Beside PRR and power consumption per packet, the paper tested the number of loop packets, switching parents, and convergence time. Convergence is the time between the first DIO message and the formation of DoDAG. PRR is the total received data packets by the total sent. Power per packet is LPM, processing, listening, and transmitting powers during the transmission of each two packets.

Sky motes in Contiki 2.6 used with transmission and interference range of 35 meters. Transmission (Tx) and Reception (Rx) success rates were set to 100%. ContikiMAC was used, it outperforms X-MAC by lower power Radio Duty Cycle (RDC). X-MAC sends preambles until receiving an acknowledgment to further send the data. However, ContikiMAC sends the data until receiving an acknowledgment, the transmission time is then saved to learn the RDC of the receiver. At the beginning ContikiMAC consumes more power than X-MAC. But later, ContikiMAC saves power 10 times lower than X-MAC.

The tests were made with 10 X 10 grid topologies having the sink at the center and the edge each time. Placing the sink at the center produces better PRR and power consumption than at the edge. That is due to smaller average hops in case of center sink, and because the parents' routing tables "except the sink" are reduced. The average of 30 repeated tests was used at 20 minutes with different random seeds using 9, 25, and 49. Data packets only sent after convergence at rates from 1 to 4 packets/minute.

Abuein et al, [18], focused on the Packet Delivery Ratio (PDR) and Energy Consumption (EC) in non-mobile network. These two metrics were tested under two different topologies "fixed and random". Their results show that PDR is more efficient with OF0 in lower density networks. While MRHOF has better EC with higher density networks.

Pradeska et al, [17], used Contiki 2.7 to proof reliability and quality of MRHOF vs. low power, mobility adaption, and quick formation of the network in OF0. Latency and Packet Delivery Ratio (PDR) used as metrics in mobility tests. And for fixed tests, PDR, hop count, ETX, power consumption, and convergence time were used. RPL has proved a good performance in high dense networks. It efficiently handles control and data messages.

Researches showed that nodes' positions directly affect the convergence time. Power consumption increases as the distance/hops to the root increases. Those factors are also affected by the topology "grid or random" and the position of the root "Center or Edge". PDR "PRR in the previous paper" is inversely related to ETX. Latency is the difference in time between the packet transmission and reception. The average end to end latency is calculated between the node and the root.

The paper used 25, 49, and 81 nodes in each test with both grid and random topologies. Transmission and interference ranges were 20 and 50 m respectively. Tx and Rx were 100%. Average ETX and hop counts gathered at convergence and at five minutes of simulation time.

ETX and hop count collected using Cooja Collect View Tool. PDR was tested with only 25 nodes in a random topology. Tx was 100%, while Rx was 25%, 50%, 75%, and 100%. The data rates used were 10, 30, 50, and 70 packets/minute. Both transmission and interference ranges were 50 m. Latency tests had the same configuration as PDR tests except for Rx set to 100%. The results were taken at five minutes of the simulation time.

Mobility was used just to test PDR at five minutes of simulation time. First with a static sink and a sender that linearly moves away from the sink at speed of 1 meter/second. Transmission range was set to 60 and 70 m, and interference range was 100 m.

The second test with 10 nodes, two of them moving along a track. Transmission and interference ranges were 20 m. UDP sink and sender codes from Contiki examples were used for convergence, ETX, hop, and power measurements.

While server and client codes were used for PDR and latency tests. OF0 convergence time was smaller in general than MRHOF in both grid and random topologies. MRHOF rank complex calculations caused that, compared to OF0 hop count. MRHOF average power consumption is always more than OF0 because the CPU power.

No changes in average ETX during the whole 5 minutes of the simulation with OF0. But with MRHOF, ETX decreased with 13.9% and 16.5% in the random and grid networks respectively due to the update metric mechanism, while OF0 only resets its calculations. For the same reason, average hop count did not change with OF0.

While with MRHOF in the random topology, it increased to 0.03125, and decreased to 0.0125 with 25 and 81 nodes respectively. That is because MRHOF choses the path with minimum ETX, despite the number of hops required to reach the root.

PDR values in the static topology were higher “better/reliable” for MRHOF than OF0, specially with higher data rates. PDR decreases for both OFs as the data rates increases, but the PDR difference of the two OFs increases for higher data rates.

But, strange results were noticed regarding the relationship between the PDR and Rx values. As Rx increases, PDR should increase as well. But that was not always the case. With Rx = 100%, PDR was worse than lower Rx. That was reported to Contiki developers.

There was no difference in PDR with mobile topology of 2 nodes for both OFs with no alternative parents. But with 10 nodes, there are changes that increase as data rate increases. However, there is no domination by any OF during all the tests. The most significant difference was recorded for MRHOF with 70 packets/minutes. That shows that MRHOF is affected more by mobility.

MRHOF latency was lower “better” than OF0. The significant difference was 0.763 second with 30 packets/minute. They want to try higher data rates in the future because there is no systematic pattern with these results.

There are many other works that focused on routing and optimizing the power consumed in such process. For example, the work done in Kamruzzaman et al, [20] focused on designing an energy aware routing protocol for Cognitive Radio Ad Hoc networks. The work presented in Cherif et al, [21], also focused on a predictive preemptive routing protocol for optimizing the energy consumption in Ad Hoc networks.

3. Methodology

3.1 Test environment

The main goal of this paper is to intensively study the performance of the two objective functions in the RPL protocol used in different IoT operating systems including the Contiki OS. Those objective functions are MRHOF and OF0.

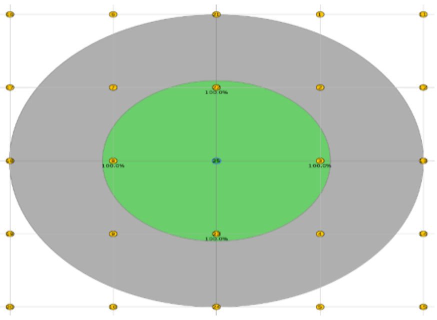

Figure 1. Fixed Grid Topology 25 Nodes, TX=11.

Using the Cooja simulator of Contiki 3.0 to build three grid topologies with 25, 49, and 81 nodes of 10-meter distance between each two nodes horizontally and vertically. Each topology consists sender nodes and one sink node in the middle of the grid as seen in Figures 1, 2 and 3.

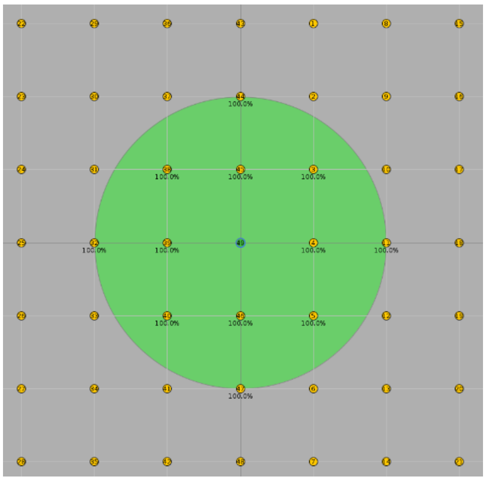

Figure 2. Fixed Grid Topology 49 Nodes, TX=20.

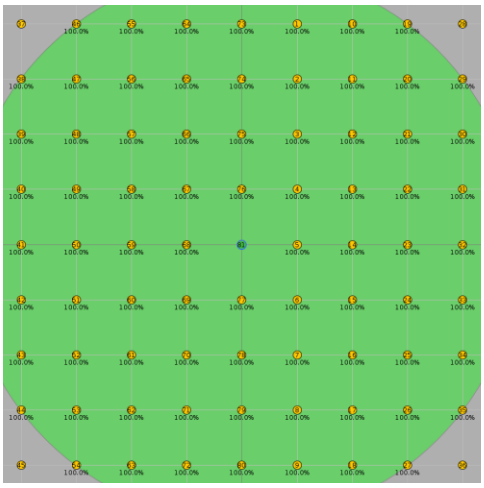

Figure 3. Fixed Grid Topology 81 Nodes, TX=50.

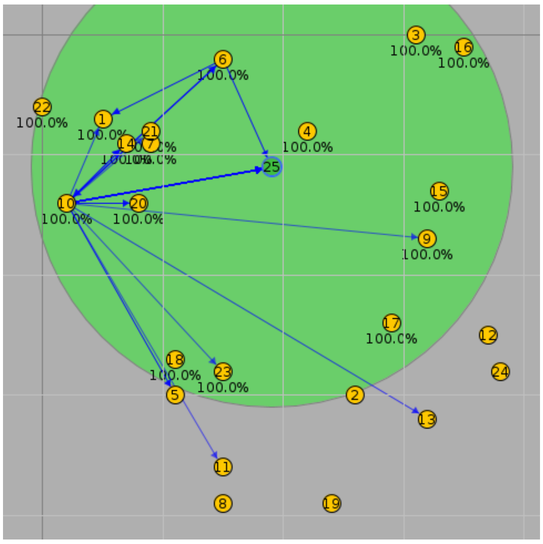

Figure 4. Random Waypoint 25 nodes, TX=20.

The second topology used BonnMotion tool to create a mobility model for each topology; 25, 49, and 81 nodes. also, the Random Waypoint model was set to pause at 20 minutes. The Cooja simulation timeout was set to 1 hour, so the movements are repeated 3 times.

The boundaries of the movements are 40X40, 60X60, and 80X80 meters for 25, 49, and 81 nodes respectively. Minimum, Maximum speeds are set to 1 and 2 meters respectively. While, the maximum pause time for a node is set to 1 minute. The topologies are shown in Figures 4, 5 and 6.

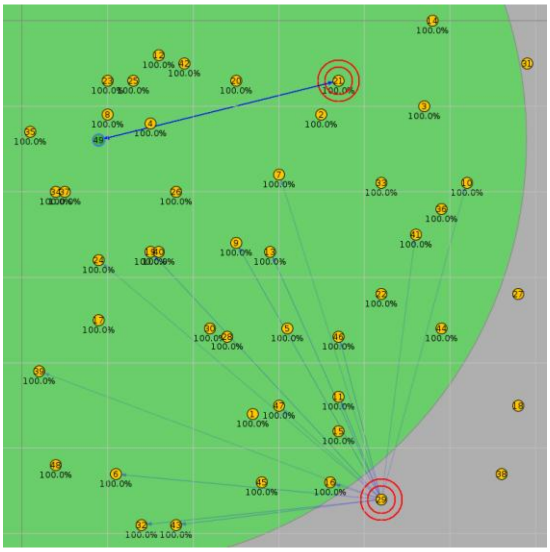

Figure 5. Random Waypoint 49 nodes, TX=50.

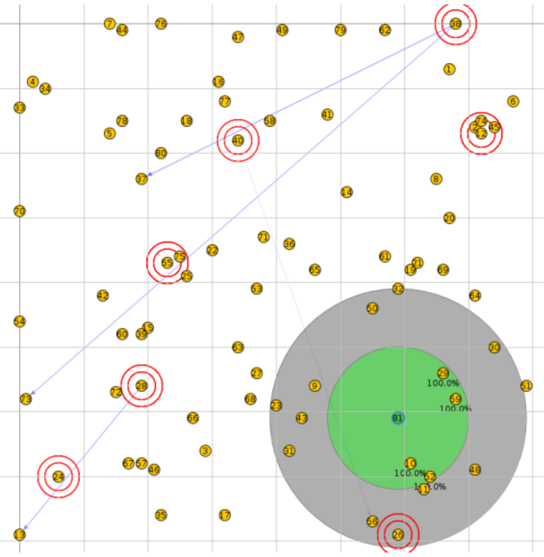

Figure 6. Random Waypoint 81 nodes, TX=11.

Each topology was tested with three different transmission ranges; 11, 20, and 50 meters. Transmission range 11 was selected to reach the minimum number of nodes, the overall experiment topological hierarchy is shown in Figure 7.

3.2 Metrics

The main compared metric was the convergence time of the network. checking if each of the objective functions used will differently affect the time needed to fully build the network under those different scenarios. Also, capturing the structure of the DoDAG tree at the convergence time, and at 20 minutes of the simulation time.

Then using other metrics to compare their results of the two objective functions two times, one time was at the convergence of the network, and the other time was at 20 minutes from the starting time of the simulation.

Those metrics are the average churn “change of parent” in the network, the Average Power Consumption (APC), Average Listen Duty Cycle (ALDC), Average Transmit Duty Cycle (ATDC), average received packets “metrics updates”, average lost packets, average duplicate packets, and average hop count

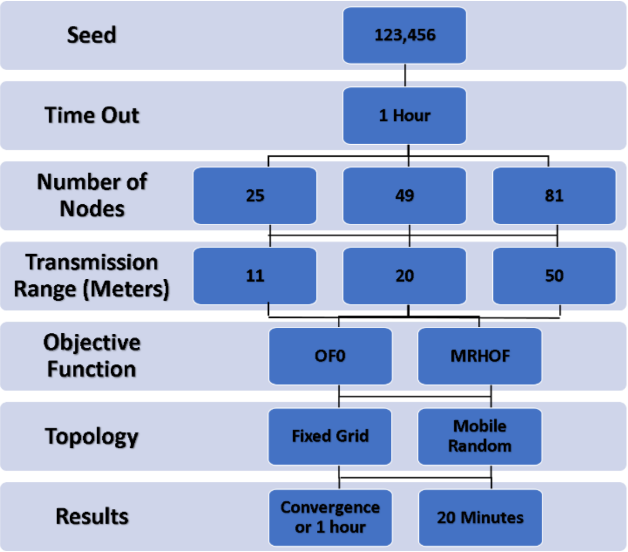

Figure 7. The Experiment Hierarchy.

4. Results

4.1 DoDAG Tree structures

From Table 1, the nodes with OF0 with a fixed grid topology never change their preferred parent, while MRHOF rarely retains the tree structures. However, with random mobile nodes, it is obvious to notice that most of the experiments tended to change the tree structures between convergence/1 hour and 20 minutes of the simulation time.

Table 1. Changes of tree structures between 20 minutes and convergence/1 hour

Changes of Tree Structures				
	Fixed Grid		Random Mobile	
	MRHOF	OF0	MRHOF	OF0
25 nodes TR= 11	Same	Same	Changed	Changed
25 nodes TR= 20	Changed	Same	Changed	Same
25 nodes TR= 50	Same	Same	Same	Same
49nodes TR= 11	Changed	Same	Changed	Changed
49 nodes TR= 20	Changed	Same	Changed	Changed
49 nodes TR= 50	Changed	Same	Changed	Same
81 nodes TR= 11	Changed	Same	Changed	Changed

That is basically a good habit because the nodes allow frequently changing parents in correspondence with their positions.

4.2 Fixed-Grid Topology Results

4.2.1 Convergence Time and Network Churn

Figure 8 shows that the convergence time increases as the number of nodes in the network increase. Another factor is the number of neighbors for each node, more neighbors means more calculations.

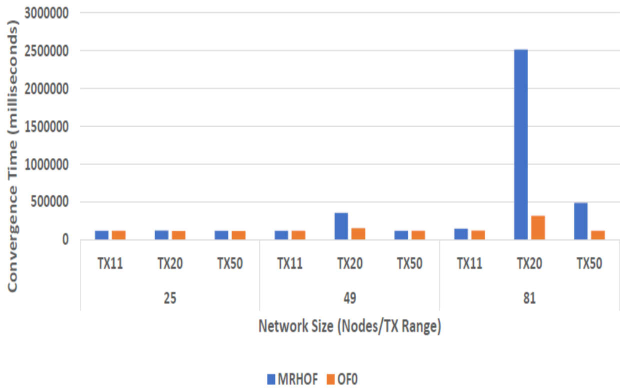

Figure 8. Convergence Time of Fixed Grid Topologies.

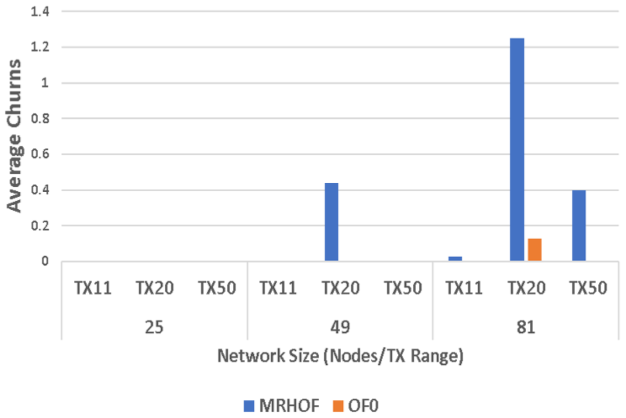

Figure 9. Fixed Grid Average Churn at Convergence.

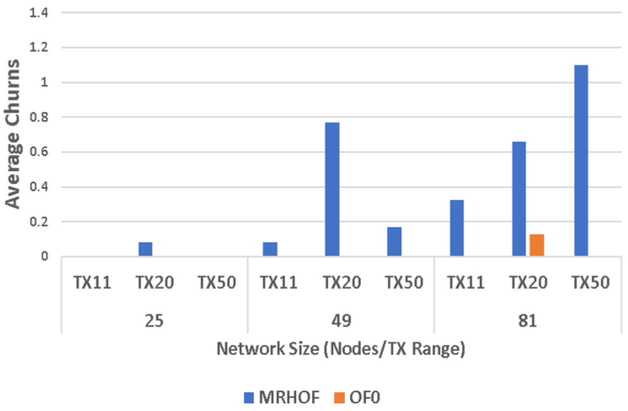

Figure 10. Fixed Grid Average Churn at 20 Minutes.

Those calculations are updated overtime leading to change of parents that causes recalculations for the metrics. That can be seen by the average of churn “change of parent” in the network as in Figures 9, 10.

4.2.2 Power and Duty Cycle

In terms of power, Figures 11, 12 shows that the Average Power Consumption (APC) in the network was higher for MRHOF at convergence time in most of the tests. But, at 20 minutes, the difference between MRHOF and OF0 starts to decrease.

That is mainly because MRHOF consumes more power at the beginning due to the churn that causes the nodes to recalculate their metrics.

However, as the time passes, the nodes have the best selection for their preferred parents and the number of churns and metric updates is going to decrease.

Figures 13, 14 and 15, 16 shows the average radio duty cycle for both listen and transmit operations respectively

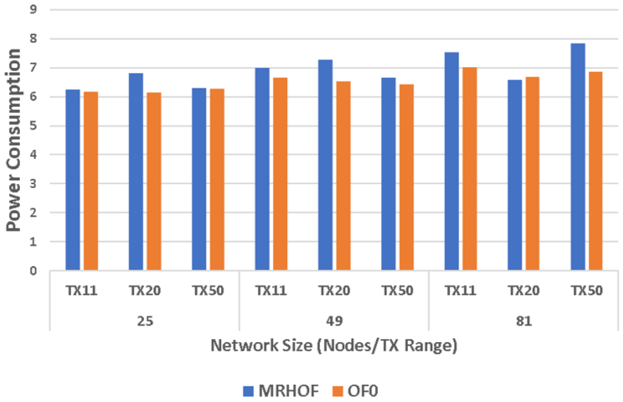

Figure 11. Fixed Grid Average Power Consumption at Convergence.

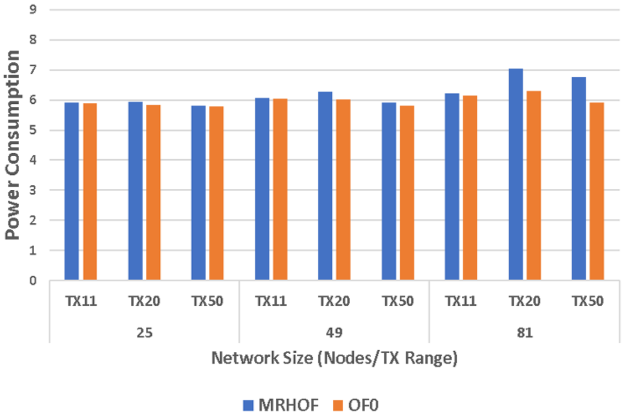

Figure 12. Fixed Grid Average Power Consumption at 20 Minutes.

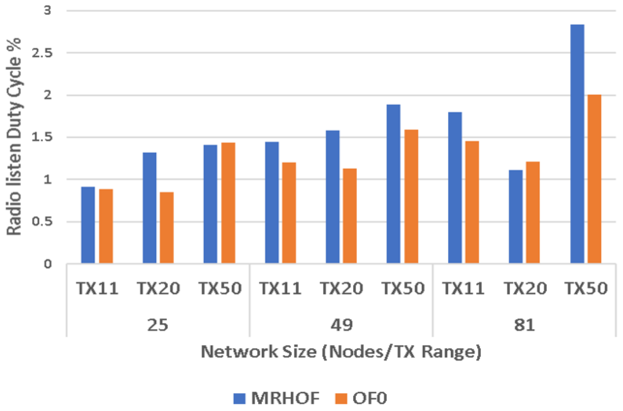

Figure 13. Fixed Grid Average Listen Duty Cycle at Convergence.

From there, seeing that MRHOF always produces the highest duty cycles. Like the power consumption, the difference between OF0 and MRHOF increases with more nodes, and with more neighbors around the node “if not reaching the sink node”, with the notice that ALDC “listening” decreases at 20 minutes. But, ATDC “transmission” dramatically decreases at 20 minutes. Which again means that the network has started to settle down by having less churn and metric updates.

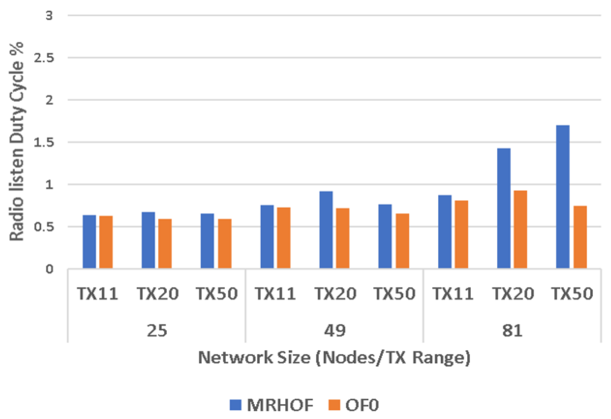

Figure 14. Fixed Grid Average Listen Duty Cycle at 20 Minutes.

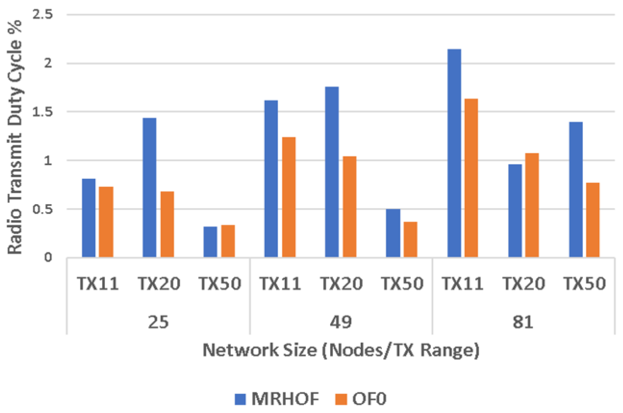

Figure 15. Fixed Grid Average Transmit Duty Cycle at Convergence.

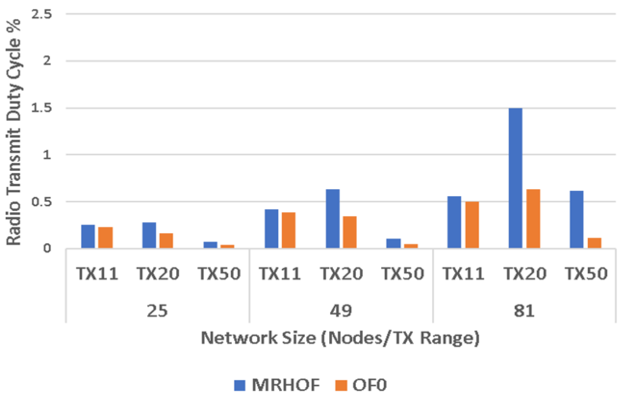

Figure 16. Fixed Grid Average Transmit Duty Cycle at 20 Minutes.

4.2.3 Metrics Updates "Received Packets

Because most of the topologies have a fast conversion times "around 5 minutes", as shown in Figures 17, 18 there is a huge difference between the received packets at convergence and at 20 minutes. That is mainly because the nodes keep updating their metrics and churn even after the last node in the network has joined the tree.

The only weird value is for 81 nodes at 20 meter of transmission range, that is because it converged after those 20 minutes "at around 41 minutes". Hence, the average number of packets received at convergence for that network topology is a lot more than the average number of packets at 20 minutes.

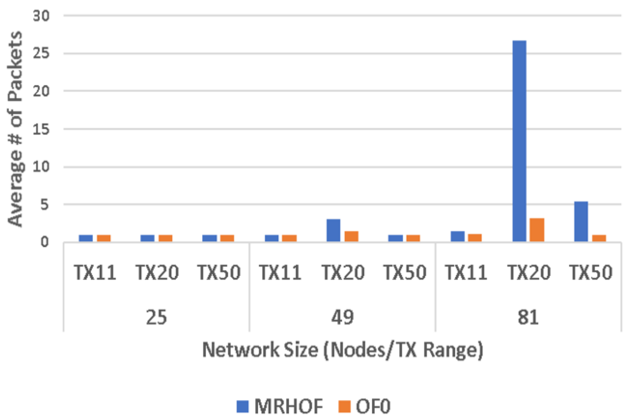

Figure 17. Fixed Grid Average Received Packets at Convergence.

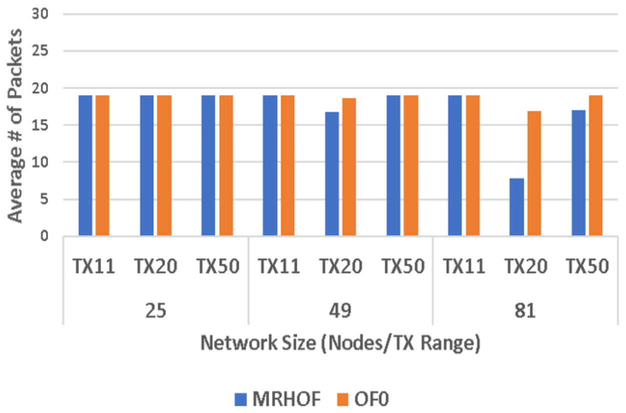

Figure 18. Fixed Grid Average Received Packets at 20 Minutes.

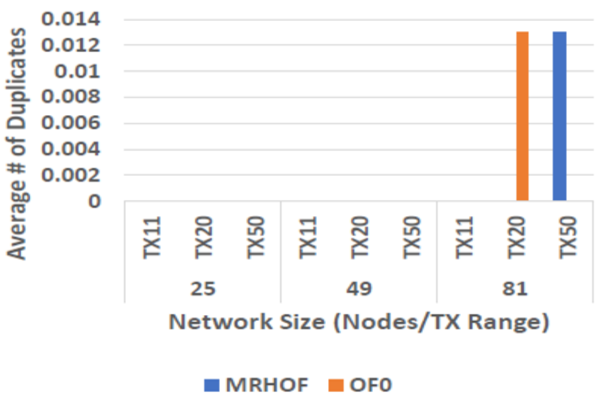

Figure 19. Fixed Grid Average Number of Duplicate Packets at Convergence.

4.2.4 Lost and Duplicate Packets

As shown in Figures 19, 20, only one duplicate packet was created at convergence "remains the same at 20 minutes" with 81 nodes topology. With transmission range of 20 meters, the duplicate was created by OF0. And with transmission range of 50 meters, it was caused by MRHOF. While, Figures 21, 22 shows the average lost packets. It is obvious that MRHOF causes more lost packets than OF0. It is also obvious that lost packets are also caused by increasing the number of nodes in the network.

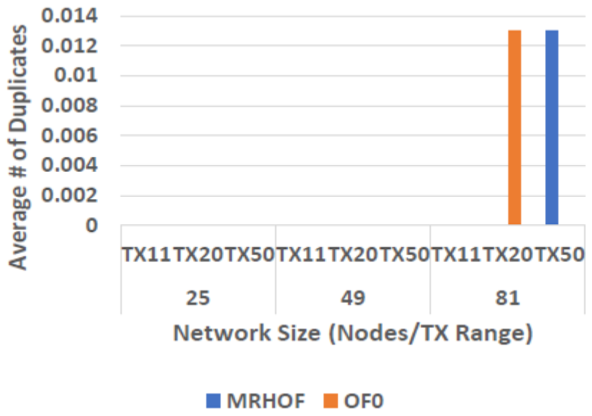

Figure 20. Fixed Grid Average Number of Duplicate Packets at 20 Minutes.

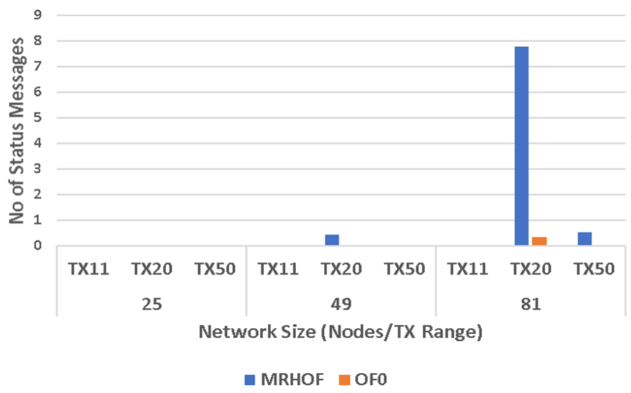

Figure 21. Fixed Grid Average Number of Lost Packets at Convergence.

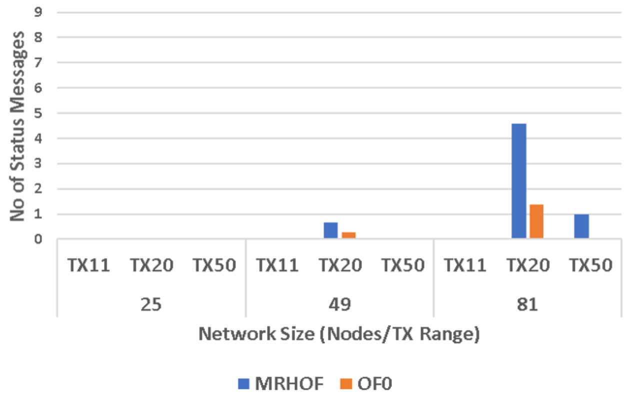

Figure 22. Fixed Grid Average Number of Lost Packets at 20 Minutes.

4.2.5 Average Hop Count

It is obvious from Figures 23, 24 that the average hop count for both OF0 and MRHOF is so close to each other.

MRHOF is a little higher than OF0 specially at convergence. That is because MRHOF always seeks to find the optimal path for each node. So, the path calculations are getting better and better overtime.

For 25 and 49 nodes, the average hop count, for both objective functions, is almost "exactly, for 25 nodes" the same with transmission range of 11 and 50.

The difference increases as the number of nodes increase, and as there are more options to select from for a preferred parent. That means, less hops to the sink node does not mean a better path.

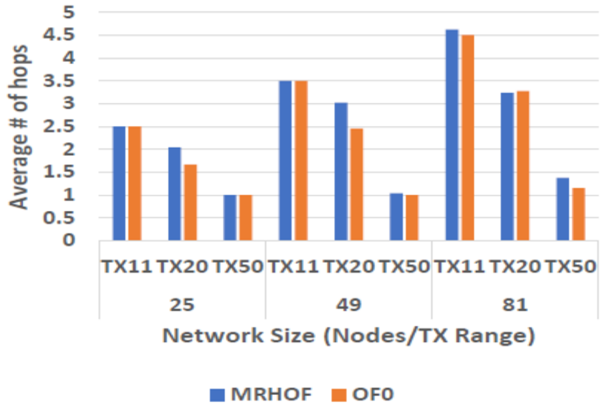

Figure 23. Fixed Grid Average Hop Count at Convergence.

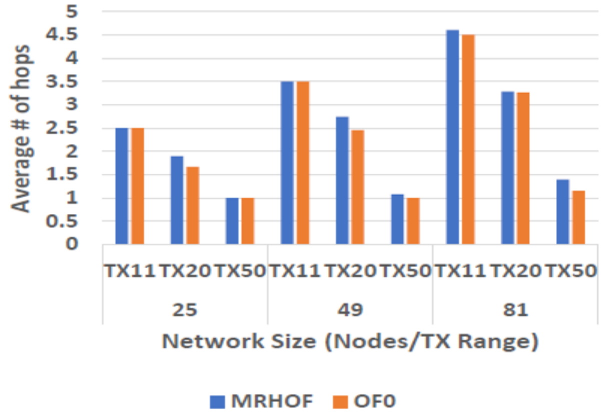

Figure 24. Fixed Grid Average Hop Count at 20 Minutes.

And that is clearly differentiate between the mechanisms of both objective functions, where OF0 chooses the shortest path in terms of hop count, while MRHOF chooses the shortest path in terms of other metrics.

4.3 Mobile Random Topology Results

4.3.1 Motes without parents

With mobility, a new observation has raised in some experiments, some nodes have never selected a parent "within 1 hour" as shown in Table 2.

Table 2. The number of nodes without a parent during 1 hour of simulation time (Mobile Random Topology).

Motes Without a Parent During 1 Hour		
	MRHOF	OF0
25 nodes TR= 11	0	8
25 nodes TR= 20	0	0
25 nodes TR= 50	0	0
49nodes TR= 11	9	22
49 nodes TR= 20	3	1
49 nodes TR= 50	0	0
81 nodes TR= 11	41	57
81 nodes TR= 20	46	21
81 nodes TR= 50	3	0

That happened in around half of the experiments. The strange thing is that these nodes usually pass by the sink node and stay near it for a sufficient time to contact with it. But it does not contact it.

4.3.2 Convergence Time

From Figure 25, more than half of the experiments failed to converge within 1 hour. And that is the main reason why for the rest of the metrics, only comparing them at 20 minutes of the simulation time.

The results show that sparse networks extremely delay the convergence of the network.

4.3.3 Average Churn in the network

As shown in Figure 26, during the first 20 minutes of simulation time, churn only takes place with MRHOF. Seeing that during the first 20 minutes, nodes with OF0 did not change their preferred parent. However, some did after that.

4.3.4 Power and Duty Cycle

When it comes to the power, MRHOF always consumes more power due to the intensive calculations that also needs more and longer wake up duration it does as discussed earlier with the fixed topologies.

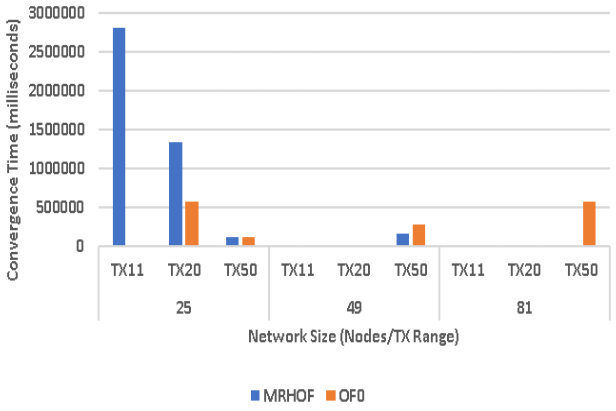

Figure 25. Mobile Random Convergence Time (Within 1 Hour).

That is clearly shown in Figure 27. And because the nodes keep updating their new metrics, listen and transmit duty cycles of the nodes are also going to be higher for MRHOF as shown in Figures 28, 29.

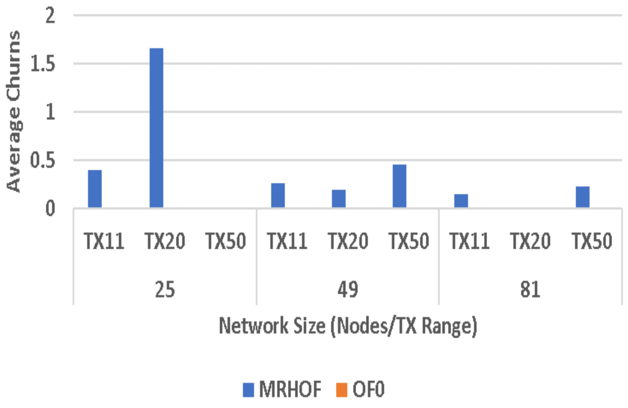

Figure 26. Mobile Random Average Churn at 20 Minutes.

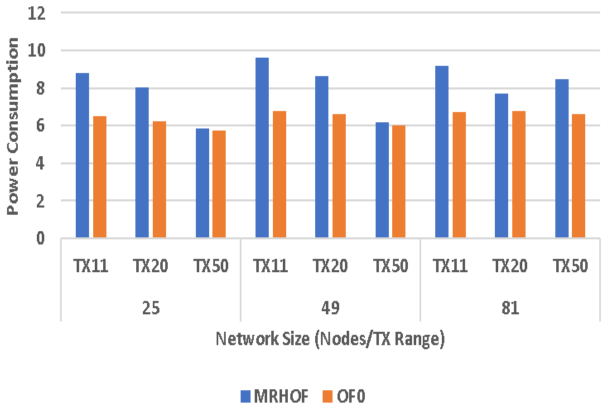

Figure 27. Mobile Random Average Power Consumption at 20 Minutes.

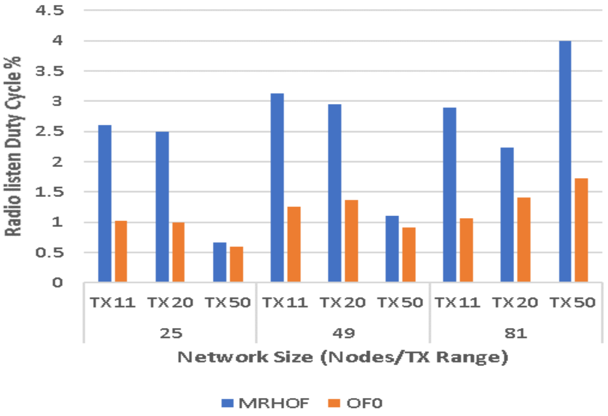

Figure 28. Mobile Random Average Listen Duty Cycle.

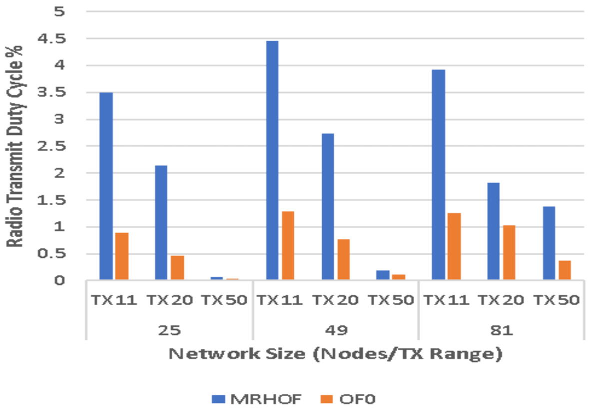

Figure 29. Mobile Random Average Transmit Duty Cycle.

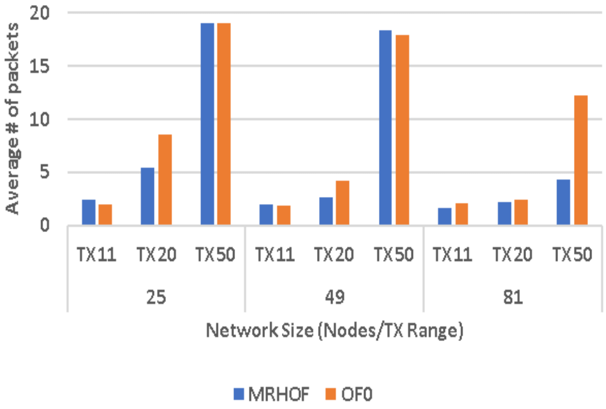

Figure 30. Mobile Random Average Received Packets at 20 Minutes.

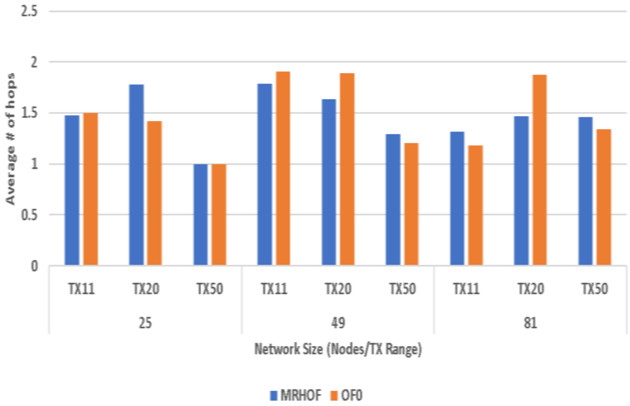

Figure 31. Mobile Random Average Hop Count at 20 Minutes.

4.3.5 Metric Updates (Received Packets)

Average received packets is generally higher for OF0 in most of the cases as shown in Figure 30.

That is mainly because the beacon interval for OF0 is shorter, causing more packets to be sent.

However, most of the sent packets are lost as shown in Figure 32.

4.3.6 Average Hop Count

The hop count variation of all the experimented topologies is shown in Figure 31.

There is generally no domination of either objective functions in terms of hop count.

4.3.7 Lost and Duplicate Packets

As seen in Figure 32, MRHOF causes less lost packets than OF0. That shows the level of reliability in MRHOF compared to OF0.

However, during the first 20 minutes, Duplicate packets took place only one time with MRHOF only as shown in Figure 33.

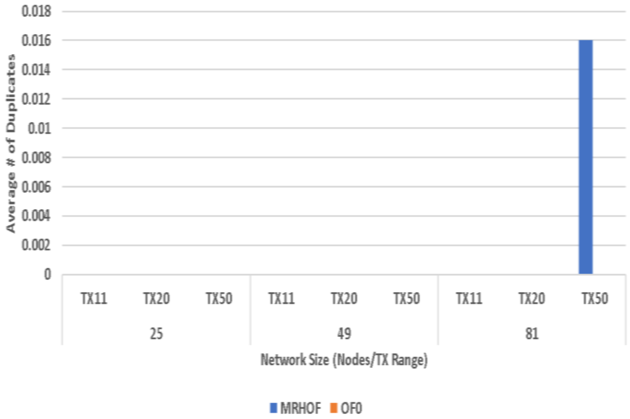

Figure 32. Mobile Random Average Number of Duplicate Packets at 20 Minutes.

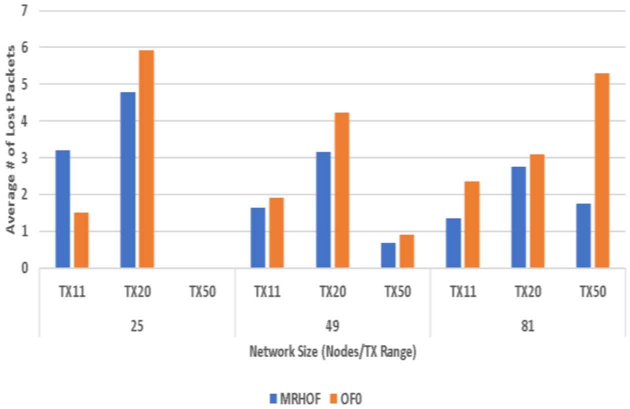

Figure 33. Mobile Random Average Number of Lost Packets at 20 Minutes.

5. Conclusion and future work

The simulation experiments done in this paper concludes that:

- OF0 is better than MRHOF in terms of Energy Consumption, Convergence Time in the Static-Grid Topology, Listen Duty Cycle, and Transmit Duty Cycle.
- There is no big difference of both Objective Functions in Mobile-Random Topology except that OF0 is better than MRHOF in Power Consumption.
- The RPL Routing Protocol and Its Objective Functions need more enhancements to deal with Mobile-Random Based Networks.

As a future work, we aim to study the effect of the Success Rate of transmission or reception in the network, in addition to modifying the internal parent selection methods of the Objective Functions that may enhance the Convergence Time of the Mobile-Random Based Networks.

We also aim to study the security effects of implementing multiple objective functions in the same network. That is important because heterogeneous networks tend to be more vulnerable to security attacks [19]. That is because it is difficult to implement unified security rules and procedures to differently structured networks.

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