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Routing Protocol for Low-Power and Lossy Network Performance Comparison for Objective Functions

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ABSTRACT

IPv6 Routing Protocol for Low-Power and Lossy Network (RPL) is the de-facto routing standard for Wireless Sensor Network (WSN). Minimum Rank with Hysteresis Objective Function (MRHOF) and Objective Function Zero (OF0) are two Objective Functions (OFs) that drives RPL. The challenge to Application Developers is validating the Quality of Service (QoS) of RPL through its OFs, to enable them to build an appreciable confidence level. RPL Simulations was carried out on a total of one hundred (100) nodes, starting with 10 nodes and incremented by 10 until the 100th node, for a duration of twenty (20) minutes. The OFs were validated with various QoS metrics, which are Packet Delivery Ratio (PDR), Churn Rate (CR), Convergence Time (CT) and Power Consumption (PC). From the results, PDR; MRHOF had a steady value of 100% while OF0 had 78% at their minimum, MRHOF outperformed OF0. For CR, MRHOF, and OF0; 35% and 11% respectively. The network is more stable with less CR, OF0 outperformed MRHOF. For CT; MRHOF and OF0; 134224 ms and 59571 ms respectively. Delay increases with increasing CT, OF0 outperformed MRHOF. PC was measured with reference to Microcontroller Unit (MCU) power, Listen power, Transmit power and Low Power Mode (LPM) operations. From the results, MRHOF consumes more power than OF0. The validity of these results is at 98% confidence level as each simulation was performed five times. It is expected that these results will guide developers and researchers on their choice of OF in their projects.

Key words : Wireless Sensor Networks, wireless Routing Protocol, Objectives Function, MRHOF, OF0

1. INTRODUCTION

Wireless Sensor Network (WSN), a subset of the Internet of Things (IoT) is the network of sensor nodes [1]–[3], [22]-[23]. This emerging network paradigm is rapidly gaining ground as it finds its ways into our everyday lives; it has found its use in agriculture (smart farming), logistics and haulages (smart logistics), homes (smart homes) academic (smart campus), marketplaces (smart markets) and in the industries. In WSN, the transmission of data packets in a network is in most cases handled by very small resource constrained sensor nodes that form the building block of the IoT [4]. The constrained resources of these autonomous devices are; power, processing capacity, and memory and this are exactly why the network formed is sometimes referred to as Low-power and Lossy Network (LLN).

In 2012, the Internet regulatory body; the Internet Engineering Task Force (IETF) came up with the IPv6 Routing Over Low-power and Lossy Network (RPL), documented as Request for Comment draft (RFC 6550) [5]; RPL became the de-facto routing standard for WSN [6]. Routing of data packets between nodes from a source to destination can be effectively performed by RPL. RPL uses the Direct Acyclic Graph (DAG) to build a non-cyclic routing path topology which has no closed loop with each node having a single path pointing towards a single destination node called the Root Node or Sink [7]. With the combination of other DAGs, RPL forms what is known as the Destination Oriented Directed Acyclic Graph (DODAG) which is identified by a unique DODAG-ID [6].

Alongside DODAG, RPL is further driven by two Objective Functions (OFs) namely the Minimum Rank with Hysteresis Objective Function (MRHOF) and Objective Function Zero (OF0). Using the designated node or link metrics/constraints, nodes uses either of these OFs to decide their preferred parent node, rank and routing path to the Root Node. MRHOF and OF0 provides different features while building the DODAG routing map. The intent of this paper is to examine the QoS of RPL with respect to these OFs in order to ascertain their uniqueness, behaviours and features [8]. The outcome is intended to help researchers and developers understand RPL as well as guide them in the implementation of RPL in their projects.

This paper is divided into seven sections. Section I introduces the paper. Section II talks about RPL overview, while section III discusses OFs and their types. Section IV discusses related works, while section V focuses on RPL QoS Performance Metrics. Section VII discusses the simulation environment settings, simulation, and discussions on the results. The paper comes to an end with conclusion and future work in section VII.

2. RPL OVERVIEW

In RPL, DAG establishes a well-connected loop-free tree-like routing path between all nodes in the LLN making it even possible for a node to have one preferred parents and other alternate parents to route its data through to the Sink [9]. More interestingly, RPL creates what is called

Destination Oriented DAG (mostly called DODAG), this tree-like graph creates a multipoint to single point connected graph where all the nodes in the sensor network point to the Sink which is also referred to as the Root of the tree. Fig 1 shows a typical multihop WSN topological architecture.

1.1 RPL DODAG Terminologies (Control Messages)

DIS: DODAG Information Solicitation

DIS packet is the first set of control messages that is sent across the network upon powering the nodes on [10]. It is a probe packet that solicites for information needed by nodes to joint the sensor network.

DIO: DODAG Information Object

Upon request by the DIS probe packet, the Sink node is the first to reply by broadcasting the first set of DIO packets across the network [6]. DIO packets carry information that allows a node to discover an RPL Instance, learn its configuration parameters, select a DODAG parent set, and maintain the DODAG.

DAO: Destination Advertisement Object.

A DAO packet is a destination advertisement packet sent by unicast mode towards the Sink through neighboring nodes. It is used to advertise and acknowledge the reception of DIO packets and to build and maintain the upward routing path along the DODAG as well as advertise nodes addresses and prefixes across all hops visited.

Destination Advertisement Object – Acknowledgement (DAO-ACK):

DAO-ACK is sent as a unicast packet by receiving node. As an acknowledgment to earlier DAO sent, Root Node or Parent Nodes are requested to send to sender/leaf nodes acknowledgement in the form of DAO-ACK [11]. DAO-ACK carries information such as RPLInstanceID, DAOSequence, and status of the node.

3. OBJECTIVE FUNCTIONS (OF)

In the IETF Request For Comments – RFC 6550 document [5], RPL defines two (2) distinct Objective Functions used by nodes to select their preferred parents, find path to the Root Node as well as obtain their rank(s) [12].

Objective Function Zero (OF0)

OF0 uses the Hop Count (HC) metric for parent selection, node path to sink selection and node ranking. Hop Count metrics is estimated by the number of hops traversed in order to successfully deliver data packet from source to destination node [13]. Hop Count can be used as a metrics or a constraint. If used as metric, it is incremented by each visited node where the first node bears the value of one hop count. If used as a constraint, the DIO message broadcasted by the DODAG root indicates the maximum number of hop that a path may be traversed, by these conditions a node rank, parent and path to Root Node is computed [5].

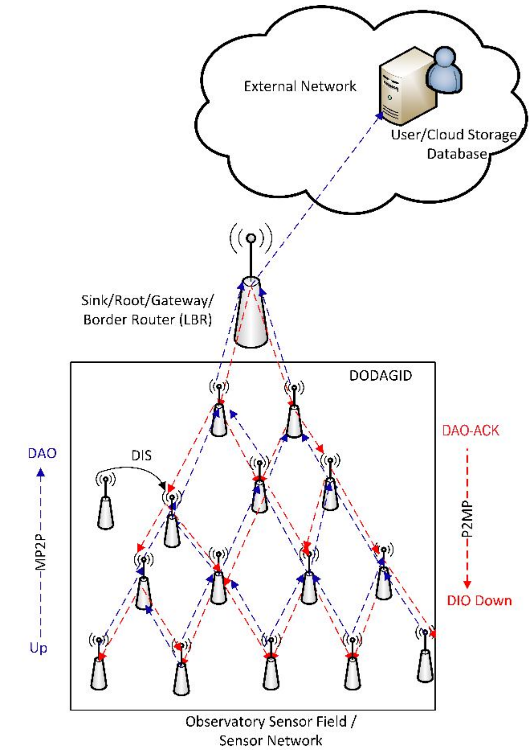

Figure 1: WSN RPL DODAG Topology

Minimum Rank with Hysteresis Objective Function (MRHOF)

Commonly pronounced as "MR"-"HOF", Minimum Rank with Hysteresis Objective Function is the second OF defined by IETF and uses the node and link metrics/constraints as its measures. MRHOF uses the Expected Transmission Cost (ETX); which is a scalar value of what it costs to successfully transmit data from source to destination node while using hysteresis to reduce path instability due to minor metrics changes [14]. These metrics could be node metric (residual node energy, hop count) or link metrics (link latency, packet delivery ratio, and throughput). A link with a low ETX signifies a high-quality communication link hence high Packet Delivery Ratio (PDR) and low delay or latency, while the reverse signifies low-quality link and low PDR hence high delay [7]. In order words, ETX is inversely proportional to PDR and directly proportional to Latency (L) [11].

$$ETX = \propto L \propto \frac{1}{PDR} \quad (1)$$

4. RELATED WORKS

This section focuses of some of the recent works on RPL in the last few years. Uneven load distribution and congestions problems were pointed as a major concern in the IETF RPL. In [15], the authors raised this concern as a major reason for packet loss especially under heavy traffic where queueing and congestion is likely to occur, hence this phenomenon affects node ranking, parent selection, and route selection. An improved RPL called QU-RPL was proposed to mitigate this pressing concern. QU-RPL is a queuing utilization based RPL that achieves load balancing and significantly improve the end-to-end packet delivery rate while also reducing latency. QU-RPL uses the queue utilization and hop distance to Root Node information of neighbouring nodes to estimate nodes preferred parent node, rank, and route to sink. According to the authors, the proposed RPL is said to out-perform the IETF RPL with respect to their experimental results.In a mobile node environment, mRPL was proposed by [16]. In mRPL smart algorithm is used to lessen the hands-off delays of data using data discovery and data transmission mechanism. In the data transmission phase, the parent nodes estimate the average radio signal strength (ARSSI) amongst the mobile nodes, mobile nodes chooses node with highest value of ARSSI. In this mechanism, using the mRPL timer, the Sink node sends acknowledgment packets at a faster rate which improves reliability and reduces packet loss as compared to RPL [16]. In LBR RPL two distinct OFs was proposed by [17]. The multicast of DIO messages is sent to the entire neighbor nodes using the two objective function the rank of nodes is calculated by the depth values of the objective function. When the time expired, nodes re-estimates the new routes and packets are routed through the updated routes.

5. QUALITY OF SERVICE (QoS) PERFORMANCE METRICS

The Quality of Service (QoS) performance metrics used in this study are as follow;

1.2 Packet Delivery Ratio (PDR)

PDR is a measure of how reliable the network is. It is simply defined as the percentage measure of the ratio between the total packets received at the destination node to the total packets sent by the source [14]. This is represented by the equation below:

$$PDR = \frac{Total\,Number\,of\,Packets\,received\,at\,Destination\,Node}{Total\,Number\,of\,Packet\,sent\,by\,Source\,Node} \times 100\% \quad (2)$$

1.3 Churn Rate (CR):

Churn is a measure of the DODAG stability and dynamism, it is equally a measure of how frequently a node changes parent [18]. A higher churn rate/value indicates an unstable network which indicates an increasing number of control message traffic (DIO, DIS, and DAO), while a lower churn indicates a more stable network [19].

1.4 Convergence Time (CT)

Convergence time is the time between the first Control Message is sent (mostly by the Root Node) and the last control message is sent for the DODAG to be formed [20]. It can be further defined as the difference in time between the last control message is sent and the first control message is sent. This is represented by the equation below;

$$CT_{Time} = CM_{LastTime} - CM_{FirstTime} \quad (3)$$

Where CMFirstTime represents the time the first control message was sent and CMLastTime represents the time the last control message.

1.5 Power Consumption (PC)

Power is one of the most pressing constraints of WSN. The lifetime of the node and hence sensor network is largely dependent on how efficient this scarce resource is [21]. RPL is a power efficient routing protocol but how it utilized power is dependent on application requirement and the operational Objective Function. Power consumption with respect to MRHOF and OF0 is looked into. The estimated node power consumption is the measure of the power consumed by; Listening, Transmission, Reception, Processing which includes sensing, and Low Power Mode (Sleep Mode).

6. SIMULATION ENVIRONMENT, SETTING AND CONFIGURATION

The QoS investigation of RPL performance with respect to MRHOF and OF0 was practically demonstrated by simulation. The simulation tool of choice is the Contiki Operating System with Cooja Emulator [7]. Contiki OS is a renowned free and open source Linux based operation system vastly used by the academia and industries for simulation and experimentation exercises for the Internet of Things. Contiki Graphical User Interface (GUI) Simulation environment is called Cooja. Cooja is more of an Emulator than a Simulator because it truly makes it possible to emulate real-life motes in the most realistic way possible, hence the results obtained from the simulation of a WSN scenario in Contiki has a high degree of accuracy. Justifying this, the authors in stated that results obtained from their simulations were almost as the same as the results obtained from the physical testbed of the same experiments in spite of other external factors.

1.6 Simulation Parameter Validation

In order to ensure the simulation is in conformity with expected standards, the configurations parameters and environmental settings are similar to those in [6], though few settings were made to exactly suit the purpose of this paper. The simulation adopts the Unit Disk Graph Medium (UDGM) with distance loss. UDGM produces an intersection Tx/Rx range of equal-radius which is suitable to meet the objectives of this paper [6], [7]. This simulation strictly focused on the random topology of RPL with fixed nodes (no mobility). A total of One Hundred (100) nodes were simulated up within a 100 by 100 square meters Sensor field. Table 1 shows simulation environment configuration.

Table 1: Simulation Environment Configurations

Parameters	**Values**
Simulator	Contiki 3.0 Operating System with COOJA
Radio Medium Model	Unit Disk Graph Medium (UDGM): Distance Loss
Node Communication Range	Tx/Rx/Interference Range – 50m/50m/100m
Perimeter of Simulation	100m x 100m
Mote Type	TMote Sky

Network Layer	IPv6/6LoWPAN
Medium Access Control	CSMA/CA
Radio Duty Cycle (RDC) Protocol	ContikiMAC
No of Nodes	10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Topology	Random Node Positioning
Duration of Simulation	20 Minutes (1200s) per Simulation
Routing Protocol	ContikiRPL
Objective Functions	OF0 and MRHOF

7. RESULTS AND DISCUSSIONS

7.1 Packet Delivery Ratio (PDR)

As earlier stated, PDR is one of the metrics that represent the reliability of the DODAG. A PDR of 95% is a representation of a reliable DODAG network status. Fig 2 shows that MRHOF has a consistent and steady PDR as compared to OF0 under the same condition. Both OFs maintain the same pattern until the 40th node where the PDR of OF0 started dropping steadily and got to a minimum of 79% on the 70th node. From this low, it picked up and rose again to 100% and later dropped again to 94% on the 100th node simulation. With reference to the threshold set at 95% for a good PDR, OF0 appears not to meet the minimum threshold set in some cases, hence does not perform as well as the MRHOF which maintained a steady PDR of 100%.

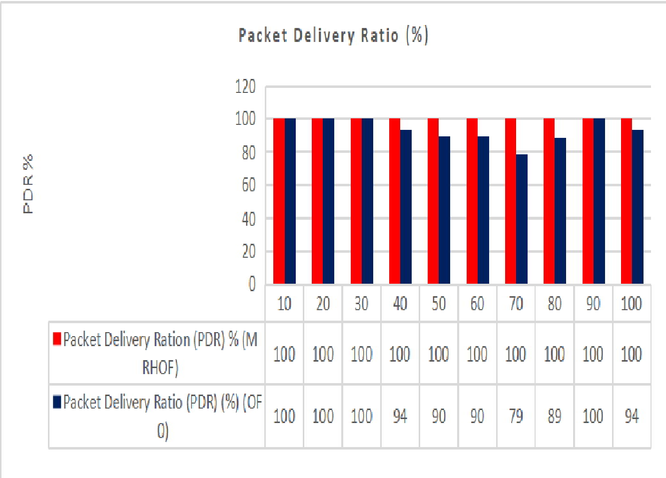

Figure 2: Packet Delivery Ratio (PDR)

The steady and reliable PDR of MRHOF is attributed to the extra computational process nodes go through to establish their ranks, routing paths and preferred parent. These process might take a little longer time and a cost on power, but once established, its PDR performance outperforms that of OF0 whose metrics computational requirements are less demanding.

7.2 Churn Rate

Fig 3 shows an increasing rate of churn with increasing number of nodes. The Churn rate of MRHOF is shown to be higher than that of OF0, again this is attributed to the metrics complexity of MRHOF as compared to OF0. While nodes with OF0 only requires to choose the least hop count to reach the Root Node without considerations for what it costs with respect to energy, hop distance, position and so on, nodes with MRHOF put all these into considerations in order to compute their rank, distance to sink and parent node. All these metrics makes the MRHOF generate a high rate of control packets which conversely leads to a high rate of churn with its high value at 35% and that of OF0 at 11% respectively. In other words, OF0 generates less churn that MRHOF and hence outperforms MRHOF.

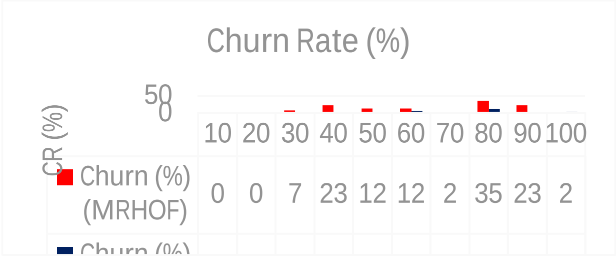

Figure 3: Churn Rate

7.3 Convergence Time (CT)

Fig 4 shows that for both OFs, Convergence time increases with increasing number of nodes. MRHOF has a sharply high value of convergence time than OF0 which means that it takes a little longer time for DODAG with MRHOF to converge than with OF0. While the minimum Convergence time of OF0 starts at 4491 milliseconds which is about 4.5 seconds and that of MRHOF starts at 5810 milliseconds, which is about 5.8 seconds at 10th node respectively. Both start-up convergence time seems to be relatively close but as the network density grows, the convergence time of OF0 increases steadily and gradually, while that of MRHOF grows rapidly and sharply. For both extremes, that is at a node count of 100 respectively, the Convergence time of OF0 is 59571 ms, which approximates to 1 minute, that of MRHOF is 134224 ms, which is a little over 2 minutes. It is observed that at both extremes, OF0 reaches convergence with over a minute ahead of MRHOF. As before, this delay is attributed to the higher metric requirements needed to be met by the nodes with MRHOF as compared to nodes with OF0. Hence, OF0 has a better Convergence time than MRHOF.

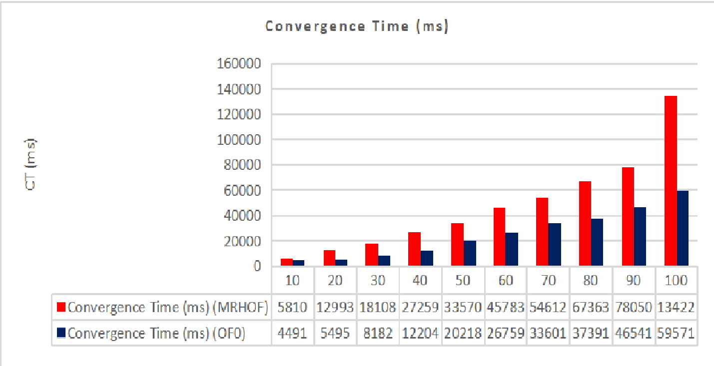

Figure 4: Convergence Time (CT)

7.2 Power Consumption

Power is the most expensive resource of the sensor node and consequently the sensor network. Running on autonomous constrained battery power, the operational longevity of a node and subsequently the sensor network depends largely on the battery power, which shares a direct propositional relationship [4]. The power consumption of the sensor node is a combination of; the Microcontroller (MCU) Processing Power, Listen Power, Transmission Power, and the Low Power Mode (LPM) Power, otherwise known as the power consumed when the node is in its sleep state. The power categories are discussed below in turn.

Microcontroller Unit (MCU) Power

This is the power consumed by the Microcontroller Unit (MCU) of the node. This unit is responsible for the processing of data packet such as packet routing, routing table formation and maintenance, management of control messages and so on.

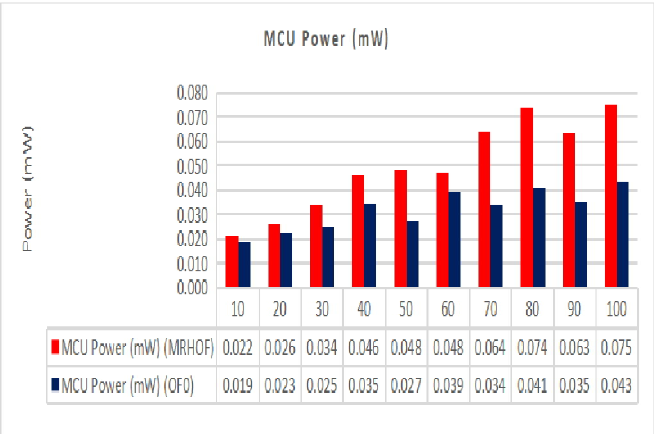

Figure 5: Microcontroller (MCU) Unit Power

Fig 5 shows a steadily increasing power consumption with increasing node number for both MRHOF and OF0. The power consumption of MRHOF is considerably higher than that of OF0. This again is as a result of the complex nature of MRHOF as compared to that of OF0.

Listen Power

This is the power consumed while the node is busy listening to the transmission medium/channel for possible transmission of data packets or control messages.

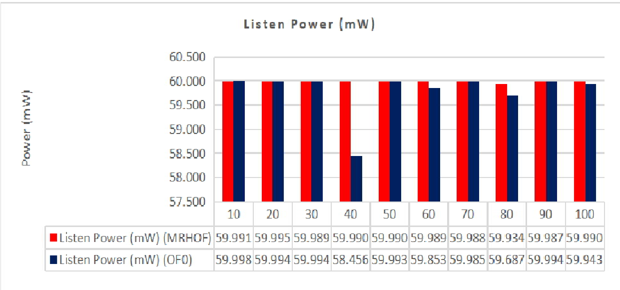

Figure 6: Listen Power

Fig 6 indicates a steady MRHOF listen power and a slightly jagged OF0 listen power at the 40th, 60th and 100th nodes, which hits its minimum at the 40th node with a value of 58.456mW. Both OFs seem to have a close listen power values for their minimum and maximum node numbers (10th and 100th nodes). Averaging both Listen powers give values of 59.984mW for MRHOF and 59.789mW for OF0, the difference of these averages gives a value of 0.195mW. This is quite a negligible value with respect to the Listen Power values. From these statistics, it is obvious that there is no much difference in the listen powers of MRHOF and OF0, though that of MRHOF is slightly higher and steadier while noting that listen operation consumes the most operational power.

Transmit Power

Transmission power is the power consumed during messages or packets transmission across the DODAG.

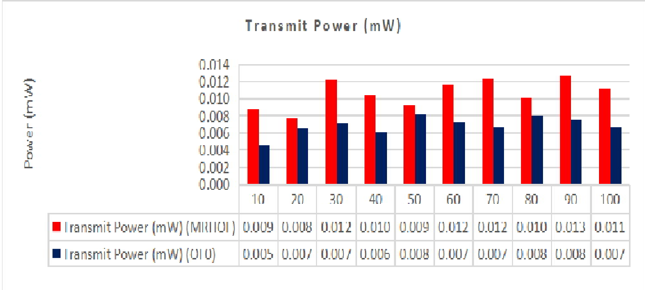

Figure 7: Transmit Power

Fig 7 shows that transmission power increases gradually with increasing number of nodes for both MRHOF and OF0. As compared to the power consumed during listen operations, the transmission power is relatively very small if not negligible. This makes more sense when comparing the highest power consumed by transmission and listening operations – the highest transmission power is 0.013mW, which is that of MRHOF. This value is fairly far from 1mW. On the other hand, the highest listen power is 59.998mW. The difference between both powers is 59.985mW. This obviously indicates how negligible transmission power is as compared to listen power. While pointing that the power consumption for transmission and reception is approximately the same in an idle state, MRHOF transmission power is also shown to be higher than that of OF0. This is again being resulting from the complexity of MRHOF metrics as compared to OF0, which only depends on hop count.

Low Power Mode (LPM) or Sleep-State Power

The LPM or Sleep power is the power consumed when the node is in its lowest operational state, which is also known as the sleep state. In this state, the node is not totally turned off but sleeping, it wakes up as quickly as possible upon receiving beacon signal indicating the presence of a packet to be sent, receive or transmit. In the LPM power mode, the node conserves the most power.

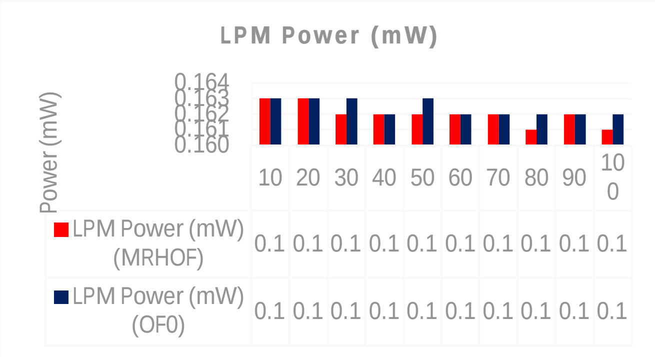

Figure 8: Low Power Mode

Fig 8 shows a dropping LPM power consumption over time for both MRHOF and OF0 with MRHOF dropping most sharply even though they had the same power consumption at the least number of node that is 10 nodes. In both cases, the LPM Power value varies between 0.161mW to 0.163mW, which signifies a fairly close and steady power between both OFs. The lowered value of MRHOFs LPM Power at the 80th and 100th nodes is as a result of the steady state attended upon convergence as compared to OF0 that may attain convergence much earlier but has a higher LPM Power.

8. CONCLUSION AND FUTURE WORK

From the simulation results, it is shown that MRHOF has a steady and sustained PDR in all nodes variation with a value of 100% while OF0 dropped to a minimum of 79%, while noting that the higher the PDR value the more reliable the DODAG is, hence MRHOF has a better PDR performance compared to OF0. The Churn Rate measured the stability of the network; it is shown that MRHOF has a higher Churn Rate; 35%, compared to OF0; 11%. This means that the flood of control messages, which results in the frequent change of parent nodes across the DODAG, is minimal in OF0, hence OF0 build a more stable DODAG compared to MRHOF. The Convergence Time measured network delay. The figures show that OF0 has a lesser Convergence Time of 59571ms or 59.571 seconds compare to that of MRHOF, which reached a high of 134224ms or 134.224 seconds. This is expected, as the metrics complexity of MRHOF is higher than that of OF0. From the figures, MRHOF power consumption for processing and transmitting data packets is higher than that of OF0. While they almost share similar value for Listen power where that of OF0 was at some points uneven to a low of 58.456mW and that of MRHOF remained steady at 58.456mW. As earlier stated, these steady power consumption values of MRHOF results from its metrics complexity compared to that of OF0. On the contrary, the power consumption at LPM (Sleep) mode for OF0 is higher than that of MRHOF. This is so because, after a rigorous metrics computation by nodes to select parents, routing path and rank, a more relaxed operational states is attained which impacts on the LPM power values especially when there is no active operation by the node. The opposite is the case of OF0. In conclusion, for applications that target data accuracy and integrity and less concern on timing, MRHOF should be used, while for applications that consider speed and timing, as pressing factors, OF0 should be used. With respect to this analysis, the future work including proposing an enhanced OF to improve the network operational lifetime.

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