Research Article

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American Journal of Computer Science and Information Technology

2020
Vol.8 No.2:48

DOI: DOI: 10.36648/2349-3917.8.2.48

RPL Objective Functions Evaluation For The Application Of Smart Grid AMI Networks

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Received date: May 18, 2020;**Accepted date:**June 02, 2020;**Published date:**June 08, 2020

Citation: Feroz A, Ikram AA(2020) RPL Objective Function Evaluation for the Application of Smart Grid AMI Networks. Am J ComptSci Inform Technol Vol.8 No.2: 48

Abstract

The power grid is going towards great evolution which is called smart grids(SG). It provides many other functions in addition to measure energy consumption like energy management, reliability and security with the help of different devices.AMI(advanced metering infrastructure) is an integral part of SG for two-way communication and structured in such a way that position of its nodes are fixed. Nodes used in AMI have limited power and resources and are energy constrained therefore they are considered as low power and lossynetworks(LLNS). Routing between these nodes is a major concern and our research issue. Simulation is done in COOJA in order to observe the performance of routing protocol for low power and lossy network (RPL) for AMI networks. RPL performance for medium and high density network has been simulated for two different objective functions(OF) and analyze different performance parameters. After simulation we have concluded that considering the quality, low latency and high reliability factors minimum rank with hysteresis objective function(MRHOF) gives better results as compare to objective function zero(OF0) in medium density networks. In high density network (above 100 nodes) OF0 outrun MRHOF in terms of packet delivery ratio(PDR). Average value of PDR for OF0(in high density network) is 2%to 6% higher as compare to MRHOF.COOJA simulation provide reasonable results for RPL nodes in high density networks. But due to load balancing and selection of unreliable links RPL nodes in large scale network suffers from performance degradation

Keywords: Objective function(OF); Reliability; Advanced metering infrastructure(AMI); Packet delivery ratio(PDR); Smart grids(SG)

Abbreviations

AMI: Advanced Metering Infrastructure; DIO:DODAG Information Object; DIS :DODAG Information Solicitation;DAO:DOADAG Advertisement Object; DAG: Directed Acyclic Graph;DODAG Destination Oriented Directed Acyclic Graph;ETX :Expected Transmission Count; HC: Hop Count; IOT :Internet Of Things; IETF:InternetEngineering Task Force; LLN:Low Power And LossyNetwork; MRHOF: Minimum Rank With Hysteresis Objective Function; OF: Objective Function;OF0:Objective Function Zero; PDR :Packet Delivery Ratio; RPL: Routing Over Low Power And Lossy Network; SM: Smart Meter;SG: Smart Grids

Introduction

SG is the application of energy grids to manage delivery, generation and usage of electricity. AMI is a part of SG which supports two-way communication between SM at user end to meter data management system.SG play an important role to limit electricity wastage by giving timely information to user. Communication infrastructure designing and planning of AMI is a hot research topic in academics and in industrial scale. AMI applications in SG require proper routing, low latency and a high reliability. Routing protocol used for its application must have fast routing and is capable of frequent link changes. RPL is recommended for AMI networks. In which OF is responsible for affecting the performance of routing [1]. Therefore, selection of OF is an important part for improving the performance of SG. RPL protocol is influenced by many challenges like network size, energy consumption, latency etc.

Our research is carried out in a systematic order in order to cover each and every problem related to RPL basic routing metrics. The research problem of our paper is to select the best OF RPL in the application of SG AMI networks considering different parameters under the varying density of nodes. RPL protocol implementation in Contiki COOJA is done in medium and high density networks. Objective function OF0 and MRHOF of RPL give different results when simulated in medium and high density networks. Also network performance is directly related to the type of network we use either grid or random topology [2]. Objective of our research is to find the best OF for different RPL network scenarios and compare the results in order to minimize power consumption, improve PDR, and limit network convergence time and latency. The contribution of this paper is as follows

RPL routing performance in SG has been discussed extensively in many papers. The work presented in this paper is different from the others because it mainly focuses on AMI SG network scenario by considering different parameters and topologies using RPL routing.

OF evaluation is already done in paper. But in our paper we have not only modified the basic Internet of things(IOT) network scenario but also analyzed PDR and network latency by increasing number of nodes for SG AMI application.

In the end of this paper possible enhancement of RPL for large scale network has been explained.

Literature Review

A number of efforts have been made to improve the RPL performance in many applications. Researchpaper is focused on performance analysis of two OF, OF0 and MRHOF using different performance parameters. The results of this research proved that MRHOF made more reliable network than OF0.While OF0 consumes less power and has faster network convergence time as compare to MRHOF. In performance analysis of RPL in AMI based WSN has been evaluated[2]. ETX and Hop count (HC) is tested in different medium.A result shows thatETX perform better than OFO in low and medium density networks. And in dense network its performance degrades due to high packet loss rates and network congestionetc. Similar analysis is done for AMI networks in paperusing COOJA simulator. Results shows that average performance appear for AMI networks but few nodes suffer from unreliability issues and high packet loss rates [3]. These issues occur due to selection of unreliable links.InRPL performance is evaluated and proved that its performance is influenced by number of nodes, number of sink nodes and node mobility [4]. By increasing number of sink nodes energy consumption reduces to 55.86% as compare to single node.

RPL is a resource constrained routing protocol designed by Internet engineering task force(IETF) low power and lossy network ROLL group [5,6]. It constructs a tree like structure called directed acyclic graph(DAG) depending on the specific application and routing constraints. In RPL OF is responsible for parent selection by nodes and form a destination oriented directed acyclic graph (DODAG), two types of routing are done by RPL,upward routing and downward routing [3,7]. DODAG has topology information which has path from leaves to root. DODAG carries parent information in the form of DODAG information object(DIO) and DODAG information solicitation (DIS). DODAG follows three basic rules for routing which are path matrices, objective function and loop avoidance by using rank.

RPL has a mechanism in which it allow nodes to discover their neighbors carefully in order to construct optimal paths .To identify and maintain topology RPL uses four control message. RPL instance ID is an identifier within a network which is unique. DODAGs having same RPL instance ID has same OF and are used to compute the position of node within a DODAG.

DODAGID is unique and when combine with RPL instance ID design a DODAG within a network.Another one is DODAG version number which is actually a sequential counter that form a new version when incremented by root [4, 8].

Rank is also one of the topology of RPL used to define the node position with respect to DODAG root [4].RPL share information within a DODAG according to ICMPv6 control messages which areDIO allow a node to discover RPL instance [9].DIS is used when node joins a network[8,10]DODAG Advertisement Object(DAO) is used to propagate information upward along a DODAG. When nodes receive DAO it updates its routing table.

RPL can send data both upward and downward. To send data upward nodes have to keep track of their parent. While in downward routing nodes have to keep track of all the nodes below them [8,11]. DIO messages are used to build routes for parent. DAO messages are used to build routes for child. Number of upward routes are constant and has great scaling properties as compare to downward routing. Unlike upward routing downward routing doesn't scale well because number of routes of each node increases with network size. There are two objective functions specified by IETF which are OFO and MRHOF as specified earlier. Routing can be more efficient by using other metrics or combination of them. OF guide the nodes to optimize the routing within a RPL. Metrics and constraints within a RPL is defined by OF. Based on matric there are two OF;

Expected transmission count (ETX) uses hysteresis objective function(MRHOF. Hop count (HC) uses zero objective function (OFO)[8,10].

OF0 is objective function of RPL which uses rank instead of a metric to find the preferred parent. It doesn't perform any load balancing rather it route traffic upward via preferred parent.

MRHOF uses metric unlike OF0 to find the preferred parent. MRHOF works with the additive metrics advertise by the DIO messages during the routing. Firstly, it finds the minimum cost or Rank path during the routing. Secondly it switches to other path only if its Rank is smaller than the existing one[12].The metric can be divided into node metric and link metric. Node metrics include node energy and HC, link metrics are Throughput, Link quality level, Latency, ETX etc.

RPL routing is specially designed for large scale networks comprises of tiny devices with limited power and capacity. In SG RPL is considered as a suitable routing protocol for routing between smart meters (SM) and data concentrator. The main design principles of RPL routing in SG networks are:

Minimizing the memory requirements to update new neighbors in its routing table.

Routing should be less complex to facilitate low power microcontrollers.

Minimizing the routing signaling

Advanced metering infrastructure (AMI)

AMI is a bi directional communication architecture between smart meters and city utilities. It facilitates the user to give timely information about the energy usage, outage, demand side management, and power theft or meter tempering.The main structure designed for the AMI network consists of one dataconcreator, which acts as a gateway between the gathered information from SMs at home's and the utilities companies. Recently RPL routing protocol is selected for AMI networks, but it comes with some short comings like instability packet loss due to high traffic and selection of sub optimal path. In order to fulfill the requirements of low latency and high reliability in AMI networks, RPL protocol must have fast routing and capable of withstand frequent link changes. RPL protocol is the most preferable routing protocol of IPV6 for large scale networks.AMI facilitate two-way communication to get an intelligent grid. It consists of different technologies like smart meters, meter data management system, communication networks.

AMI is a new and modern concept used in SG which can be used to control consumption pattern. It also detects power theft and tempering of electricity, inform timely to the users. However, AMI needs improvement in communication area and in analyzing data and due to its greater need in global market government companies and consumers spend a lot in AMI research and its utilization.

Routing requirements of RPL in smart grid AMI networks

RPL protocol has diverse applications in industrial, agricultural, home automation and in smart grid networks. Routing between SM and data concentrator is a crucial part in SG performance. AMI networks are sensitive to changes and has limited capacity which make them LLN. In a SG network smart meters are nodes which route data to the data concentrator. In a smart grid networks packets are route towards destination by considering the best and optimal path. In a lossy medium routing performance is inversely proportional to number of hopes. High number of hopes degrades network performance and induce delay in a system. To increase routing performance in a SG number of hops should be limited which is achieved by choosing a shortest path. Optimal path is achieved by not only consider shortest path but also consider ETX matric in IOT enabled networks.

Performance analysis of RPL in a dense network is a challenging issue due to large number of nodes. These nodes require connectivity and automation which is achieved by IOT enabled SG network [12,13].A key challenge is to stabilize the network when number of nodes or its size increases. In dense network nodes are unable to keep their routing table updated due to limited memory and storage. Therefore, they are unable to add new neighbors and its performance in a network degrade. Selection of OF for routing in a dense network is very important. The possible challenges in large scale networks are ;

Mode of transmission

RPL traffic transmission is multi point to point(MP2P), which is well defined and it is actually routing upward implemented by DIO. Downward traffic is controlled by DAO which is point to point(P2P) and point to multi point(P2MP) are not defined clearly in the literature. In large scale scenario congestion and buffer issue in DAO routing need to be solve. Storage limitation is also an issue in large case scenario. When network size increases memory consumption increases resulting in large communication overhead [9].A balance solution is required to limit memory overhead and increase node capacity.

Objective function diversification

For maintaining energy efficiency and stability in a large scale network OF need to modify. Load balancing, rapid change of preferred parent in large case scenario is very important to maintain stable routing.

Energy issues

LLN's always comes with energy consumption problems especially in large case scenario. This issue occurs because current node distance from sink node increases. Bottleneck is the major problem in large scale network resulting in reliability problems. Energy balancing and maintain quality of service is the major task in large case scenario.

Security issues

In large case scenario network security is the major problem due to large data. Tempering and hacking are major security threads which lead to degrade the integrity and limit availability of data. Different routing attacks are rank attack, sink hole attack, distance spoofing attack and neighbor attack.

Performance parameters for evaluating RPL routing in SG

Different performance parameters have been evaluated to study RPL routing requirements in SG AMI networks. Parameters under observation are

Latency is the measure of time between the packet send and receive by node. Where average latency is time used to transmit data in certain process from sender node to root node.

$$\mathrm{AA}vg\ latency = \frac{\sum(recievedT - sendT)}{No.\ of\ process} \qquad \text{——————} \qquad (1)$$

Network latency is a measure of delay or it is a time taken by certain data to reach its destination. It is measured in millisecond. Latency is actually a round trip time taken by data that has been fed into one end of the system to emerge from another end.

While PDR is the ratio of packet received to the packet sent by the receiver and sender respectively. In order to check network reliability PDR is used and its relation with ETX is inversely proportional.

$$PDR = \frac{packets\ delieverd}{packet\ sent} \qquad \text{——————} \qquad (2)$$

It is the amount of time when root node sends its first message to the time until all nodes make position in the routing table. In other words, time taken for all nodes to make DODAG.DODAG convergence time is found when all nodes are connected and reach to the root node. Formation of DODAG can be observed by sensor map feature of COOJA simulator.

Expected number of transmission is to send the information to the destination or root node. ETX value of different nodes are given in the table. Nodes with one hop away from root node and lossless path has ETX value equal to 1. It means that ETX also helps to calculate link quality of two neighbor nodes and is defined as

$$ETX = 1/_{Df * Dr} \text{ where; Df=forward delivery ratio,} \qquad (3)$$

Dr=reverse Delivery ratio

The energy consumption of sensor nodes in our IOT environment can be calculated using power trace. Smart grids network has fixed or grid node position but we have extended our research to study nodes behavior in random topology by changing nodes and sink position. LPM is used when node is in sleeping mode. Radio transmit and listen is related to power when there is communication of nodes. CPU power is related to level of node processing and mathematically we can calculate energy consumption as

$$Energy\ consumption(ml) = \frac{[(CPU * I_{CPU}) + (RX * I_{TX}) + (LPM * I_{RX}) + (LPM * I_{LPM})] * voltage}{R\_TIMER} \qquad (4)$$

After simulation of nodes different values are shown in power trace. Total energy consumption of whole process can be calculated from equation 4.

Simulation and results

COOJA simulator has been chosen because it allows developers to run and simulate large wireless networks[14]. COOJA helps to find power consumption of each node and behavior of nodes can be studied through graphical user interface [15,16] .

Contiki provides RPL routing protocol for low power and lossynetworks. In the experiment we have created an IOT sensor based environment to study RPL performance in SG. The nodes position does not change during simulation in grid topology. Root node is responsible for data gathering and network initialization. The root node should not face any power problem whereas sub nodes are battery powered in practical scenario. All child nodes have same initial power and configuration.

Table 1 shows simulation values used in each topology. We have created grid topology where sink nodes and sender nodes have fixed position and in random topology sender nodes are scattered in an area of 700m and their relative position from sink node is different. RPL based AMI Network has emulated with one sink node and smart meters are scattered with in an area of about 700m side.

Table 1:RPL performance has been analyzed considering the following parameters under two OF (OF0, MRHOF).

Parameters	Value
OS	Contiki 2.7
Area	700m
Nodes Layout	Random, grid
Radio medium Model	UDGM (unit disk graph model)
No of nodes	Medium density(21-81)High density (100,125,150,160)
MAC layer	IEEE 802.15.4
Network Protocol	Contiki RPL
Objective Function	MRHOF,OF0
Application	Examples/ipv6 /RPL collect
Mote Type	SKY

- Network latency by increasing number of nodes and reception ratio(Rx).
- PDR in medium density network for OF0 and MRHOF with different packets per minute.
- Network convergence time (grid, random) for OF0 and MRHOF in medium density network
- Average power consumption (grid)
- PDR in a dense network (random, grid) for OF0 and MRHOF.

Performance parameter analysis in medium density networks

DODAG Convergence time calculation in medium density network is observed in grid as well as in random topology. Convergence time is measured when sensor map shows DODAG. In grid topology observation has been made on different nodes like 25,49,81. In grid topology both OF has almost same convergence pattern, but OF0 has less convergence time as compare to MRHOF.OF0 convergence time is almost same at nodes 25 and 49 and increase linearly by increasing number of nodes.

We therefore analyze convergence time at different nodes with random position as shown in Figure 1. MRHOF convergence time is high as compare to OF0 this is because it’s OF process is more complex than OFO. Another reason of having different convergence time is because of the ETX in MRHOF, which take longer time to process as compare to HC in OF0.We also concluded that node position greatly affects the convergence time. In grid both OF0 and MRHOF has same convergence time but in random they have different behavior as shown in **Figure 1**.

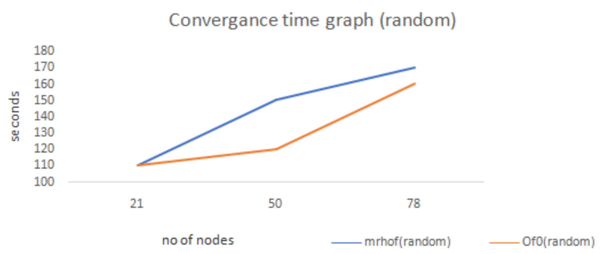

Figure 1: Network convergence graph (random).

For analysis of average power consumption of medium density network, we have selected nodes 21,50 and 78. Average power consumption is shown in Figure 2which shows OF0 consumes less power as compare to MRHOF. This is due to the complexity of ETX metric as compare to HC[1]. DODAG formation in MRHOF takes longer time and consumes higher power as compare to OF0.

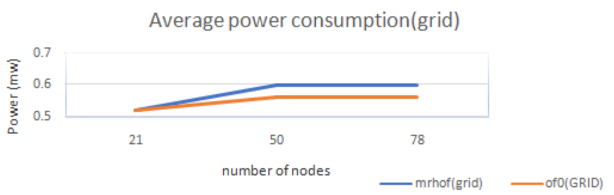

Figure 2: Average power consumption (grid) of medium density network.

We have performed number of simulations in order to observe PDR on different reception ratio like at 25,50,75 and 100.Transmission ratio remain at 100%. The graph in **Figure 3** clearly shows that MRHOF has higher PDR at same packets per minute than OF0.At low data rate like at 10 packets per minute both OF has same PDR value. But when data rate exceeds MRHOF dominates OF0.By analyzing result we conclude that maximum difference occurs at 30 packets per minute. At 30 packets per minute difference is quite double as compare to 70 packets per minute. At Rx=100% PDR value is quite low as compare to others. But the difference in PDR is maximum at 100 percent reception ratio. Network quality is best when PDR is equal to 1. MRHOF makes more stable and reliable network as compare to OF0.

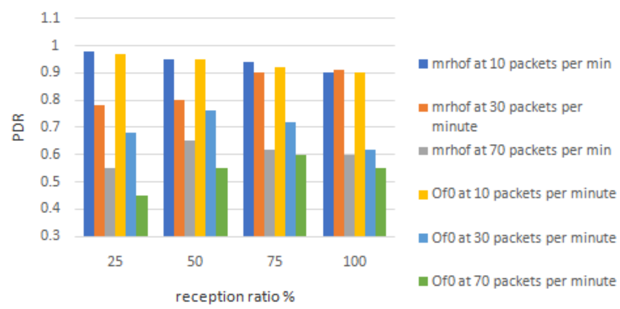

Figure 3:PDR performance for different Rx.

Performance parameters analysis in high density networks

Smart grid network comprises of thousand or more meter connected to each other through a single root [4]. In order to analyze large case scenario, we have selected nodes 100, 120 and 150.PDR performance has analyzed by taking RX=60,80 and 100 for both objective functions. **Figure 4** shows 100 nodes in grid topology simulated under COOJA simulation network

Figure 4: COOJA simulation scenario for dense network.

In **Figure 5** and **6** we have analyzed that there is a direct increase of PDR against reception ratio. Best PDR is when number of nodes are 100 in grid topology. The graph clearly shows that OFO PDR for same number of nodes is higher as compare to MRHOF. Average value of PDR in OF0 is 2%to 6% higher as compare to MRHOF.

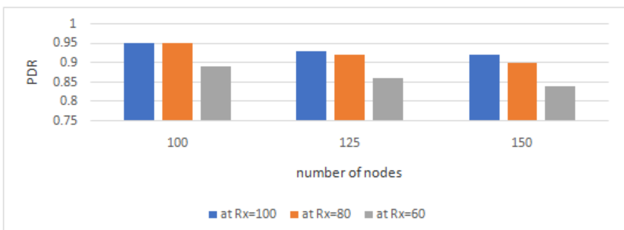

Figure 5: Analysis of PDR for MRHOF in a dense network.

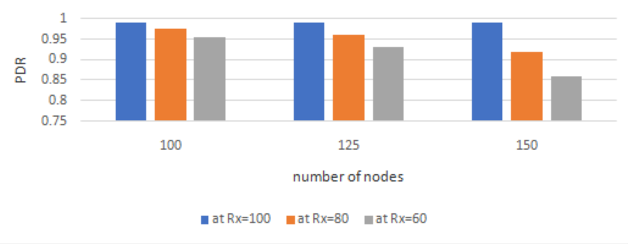

Figure 6: Analysis of PDR for OF0 in a dense network.

Network latency calculation

Network latency is an important parameter in order to observe network performance. OF0 and MRHOF are compared based on latency. In **Figure 7** we observe that MRHOF perform better than OF0.This is because ETX choose best path for routing. Different Rx values i-e 30 50 70 90 and 100 are used in the simulation against latency. Comparison of both objective function can also be done by connecting hardware and fix both transmission and reception ratio to 100%. Date rate can be varied against latency to observe and compare both OF.

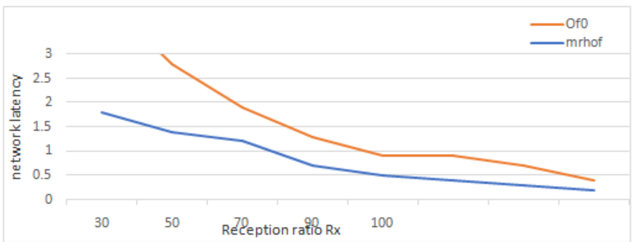

Figure 7: Network Latency Graph

Network latency for high density networks is evaluated in **Figure 8**. which shows that by increasing number of nodes OF0 gains high latency as compare to MRHOF in grid topology. This is because ETX considers details of a link and find best path for routing.

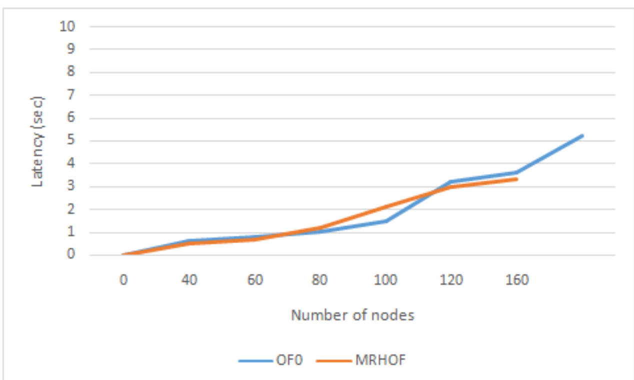

Figure 8: Network latency observation for high density network

Results and Discussion

After analyzing different performance metrics, we conclude that RPL performance is directly related with number of nodes and network topology. From the simulation results it is concluded that MRHOF give better results as compare to OF0 in terms of network reliability.OF0 consumes less power and has less convergence time as compare to MRHOF.OF0 perform better with limited power in random or mobile topology. In our work we have seen different results of PDR, energy consumption and network latency by using COOJA simulator which also works as power visualizer. RPL performance was also evaluated in dense network. PDR is evaluated for OF0 and MRHOF. Results show that RPL under dense network in grid topology has better PDR in case of OF0 as compare to MRHOF. Results show that OF0 experiences higher latency as compare to MRHOF. When network size increases number of hops increases.From our results we have summarized the following conclusions

RPL performance analysis is done using several scenarios and network parameters like network density, routing metrics, physical topologies.

For large scale AMI networks, ETX has higher latency than HC

OF0 consumes less power as compare to MRHOF.

In medium density network MRHOF made more reliable and stable network than OF0 due to high PDR.

In dense network OF0 is preferable over MRHOF.

RPL protocol satisfies its routing performance in AMI application through an appropriate OF.

Possible improvement and proposed solution

We have simulated IOT network scenario for SG AMI networks using the basic OF to study the behavior of nodes in different scenarios. After simulating in different mediums and topologies, we came to know that RPL need improvement. In light density networks nodes need lesser convergence time so there is no problem of load balancing. As density of nodes increases beyond 100 nodes it takes a lot of time to make DODAG.When number of nodes increases in a network ETX value of whole path is larger as compare to a long single hop.Such long hops cause bottleneck in a network. In order to reduce problems of higher convergence time, latency and energy consumption unnecessary features of RPL should be limited.In past many authors proposed methods to increase RPL performance in SG AMI networks by adding new metrics in basic RPL OF. By doing so they eliminate many problems of congestion and unreliability issues but resulting in larger DIOs causing routing errors.Assigning multiple weights to these metrics is another problem. Our proposed solution is to eliminate unnecessary features of RPL in SG networks in order to make it more efficient for routing. Hence lexical combination is more effective than additive approach.Load balancing and energy efficiency problem can be reduced by using cross layer approach as explained in paper [18]

Conclusion and Future work

In our research work we have used RPL protocol and test it under different network scenario in order to observe its feasibility in SG AMI networks. AMI networks in SG application need high reliability and low latency. RPL protocol provide these requirements by selecting suitable objective function. We have studied different performance parameters by changing different OF. We came to know that MRHOF outrun OF0 as it has high reliability and low latency but it consumes more power than OF0.Performance evaluation of RPL in a dense network revealed that while using OF0 PDR is better than MRHOF. COOJA met all the requirement of routing and provide control over simulation. From our findings we came to know that network scale and density of flows have appreciable impact on the network performance. In future our goal is to enhance and add configuration in basic RPL parameters to participate well in SG applications

Author Contributions:

Ayesha Ferozdesign the paper and do the methodology. Ayesha Ferozwrite the paper. Dr Ata-ul-Aziz-Ikramsupervise the research work.

Funding

This research received no external funding.

Acknowledgments

We are thankful to the anonymous reviewers for giving us their precious time and useful suggestions to improve the overall quality of this paper

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability

The [COOJA simulations] data used to support the findings of this study are available from the correspondingauthor upon request.

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