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Quantitative Analysis and Evaluation of RPL with Various Objective Functions for 6LoWPAN

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Abstract

Objective: Wireless Sensor Networks (WSN) with IP compatibility consists of nodes that has limited resources such as reduced processing and memory capabilities, less battery life and reduced transmission range. The aim of this research work is to evaluate and implement such a routing scheme, which leads to efficient utilization of nodes and network scarce resources. **Methodology:** RPL (Routing Protocol for Low Power Lossy Network), a standard routing protocol for IP enabled WSN is considered as an efficient protocol for such network. In this research work, the performance of RPL will be analysed based on different Objective Function (i.e. Expected Transmission Count & Objective Function Zero) in various radio models (Unit Disc Graph Model - Distance Loss, Unit Disc Graph Model - Constant Loss, Multi-Path Ray-Tracer Medium) and scaled networks which makes this implementation unique and the results obtained are compatible to real time scenario. To analyse the performance of RPL with different Objective Function, various performance parameters are calculated e.g. Packet Delivery Ratio, Control Traffic Overhead, Power Consumed, Network ETX. Each of these performance parameters are compared for both the Objective Functions, to analyse which Objective Function of RPL has more efficient performance in various radio models and scaled networks. **Findings:** From the simulation results analysed, it is proved in this paper that the performance of ETX is better in comparison to OF0 for all the radio models and the scaled networks.

Keywords: 6LoWPAN, RPL, Objective Functions, OF0, ETX

1. Introduction

The utilization of wireless devices have increased extensively in today's world and with the advancement in the concept of Internet Of Things (IOT)[1], the applications for utilization of wireless devices have been diversified. Taking wireless sensor networks into consideration, devices in such networks are resource constraints because of their battery limitations, less transmission range, less processing capability etc. In order to make wireless sensor networks with limited constraints IP compatible, IETF (Internet Engineering Task Force) came with a standard called 6LoWPAN (IPV6 over Low Power Personal Area Network)[2]. In these networks an adaptation layer is used in the protocol stack, which is sandwiched between IP protocol layer and 802.15.4 standard protocol layer. The primary function of this adaptation layer is to compress and fragment the MTU (Maximum Transmission Unit) of the IP protocol stack which is 1280 octets into 127 bytes packet, which is compatible according to the 802.15.4 standard. These things are standards defined by Internet Engineering Task Force (IETF)[2] and cannot be changed or manipulated.

Utilization of limited resources in the sensor network is an important area of concern and to overcome the factors influencing over-exploitation of resources, it is important to understand them. This helps in designing and implementation of efficient protocol with reduced scarce resource utilization. Taking example of power consumption by the nodes in the network, it is well known that communication activities consumes more power in comparison to computational activities (i.e. power consumed by CPU). So it is important to focus on efficient utilization of power resources which are used by communication activities in the nodes. Similarly, WSN being lossy in nature, leads to frequent connection losses between the

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nodes in network and triggers the excess consumption of limited resources like memory, power etc[3]. So to overcome such losses and to uses the scarce resource of the nodes and the network in efficient way, selection of routing protocol plays a very important role. Efficient routing protocol reduces the power consumption of nodes in the network, transfers the data packet to the destination nodes using less hop count, less retransmission, less delay etc.

Considering the above mentioned factors IETF (Internet Engineering Task Force) has designed a routing protocol for 6LoWPAN network i.e. RPL (Routing Protocol for Low Power Lossy Network)[4]. RPL is a standard routing protocol for IP enabled wireless sensor network, with a factor called Objective Function (OF)[5], used by the nodes in the network to decide, that to whom the node should pass on the data packet so that data can reach to the destination node efficiently with less power consumption, retransmission, collision, delay, hop count etc. In this research article RPL protocol with different Objective Functions are implemented in different radio models to add realism to the simulation scenario. The performance of RPL based on different Objective Functions is quantitatively analysed using different performance parameters, which gives the clear idea of utilization of scarce resources by the nodes in WSN.

The paper is organized in the following manner: Section 2 describes the brief overview of the routing protocol RPL and discuss about the topology formation using the control messages. Section 3 describes the proposal of this research paper and explain factors considered for analysis of routing protocol. After that next sections describes the various Objective Functions explored and a brief discussion on how these Objective Functions are being calculated. To quantitatively analyse the performance of the Objective Functions, various performance parameters are explained in Section 5. In Section 6, the performance of the Objective Function in various radio models and scaled networks will be evaluated based on graphical analysis of performance parameters. At last, based on the graphical analysis, the best suited objective function for all the radio models as well as scaled networks will be declared in conclusion.

2. Analysis and Evaluation of RPL with OFs

Routing Protocol for Low Power Lossy network (RPL) being a routing protocol for IP enabled WSN network is still in its implementation phase[6]. The drafts and specifications published in RFC-6550 (IETF Publication) related to RPL lacks detailed implementation, it is therefore important to analyse and implement the protocol in a much careful way. Its in-depth analysis and evaluation is important to understand the performance of protocol under various parameters, so that we can determine the advantages and shortcomings of the protocol in various scenarios and implement certain modification for improving the protocol.

The most important aspect of RPL protocol is Objective Function (OF) which plays a crucial role in making a network stable with less convergence time and less consumption of scarce resources. Now RPL being a new protocol, most of the applications uses objective function OF0 (objective function zero), which basically selects the path to the destination depending on the hop count. But while dealing with low power lossy networks, objective function OF0 of RPL protocol fails to perform efficiently because of varying link quality between nodes. So in this research work a different Objective Function known as ETX (Expected Transmission Count) is implemented in RPL protocol, which consider the link quality between the nodes for the selection of path for data transmission. To analyse its performance, objective function ETX is compared with OF0 based of various performance parameters like control overhead, packet delivery ratio, power consumption, network ETX.

It is necessary and important to evaluate the performance of RPL for various interference, losses, radio propagation models etc. Since the surrounding of the sensor nodes in the RPL network will change randomly with time e.g. channel characteristics, increase in the network structure due to addition of extra nodes in the network etc., so the RPL protocol is needed to be optimized and configured for each scenario. For such an implementation, various radio propagation models are demonstrated and the performance of RPL network with different objective functions is analysed based on performance parameters. Scaling of network by increasing the number of nodes with random topology is also demonstrated, to observe the response of the RPL network based on congestion, increased traffic, collision of data etc.

3. Objective Function

Objective Function[7] can be defined as a key factor in determining the preferred parent among the contending neighbours for a particular node in RPL network.

Preferred parent is responsible for forwarding the data packet toward the root node whenever the child node has packet to send. As WSN is lossy in nature and the nodes in this network are limited in constraint, it becomes the critical responsibility of the Objective Function to select such a path for data transmission which reduces resource consumption as well as packet drops due to frequent link break. An important point to be noted is that, OF is not only used for the selection of parent, but is also used for changing the preferred parent for a particular node due to the variation in the network parameters like change in topology, link quality, node failure etc. So Objective Function steer the data traffic to different paths according to the changing network requirement. There are various Objective Functions that are used in the RPL network, the two most important Objective Functions analysed here are ETX[7] (Expected Transmission Count) and OF0[8] (Objective Function Zero).

OF0 i.e. Objective Function Zero is the most basic Objective Function used in RPL. OF0 is designed for determining the parent node among the contending neighbours which have minimum rank with respect to the root node. Initially the root node is assigned with the minimum rank and this information is multicast to the other nodes using DIO control message. Now all those nodes who receives the DIO will make the root node as a preferred parent and will assign themselves with a rank which is incremented by one with respect to the rank of the root node. This process is repeated again when these nodes further transmit there DIO forward to other nodes in the network and ranks are incremented depending on the preferred parent. Now whenever there are more than one node contending to be a preferred parent for a particular node, in that case the node with the lowest rank will be selected as the preferred parent. Therefore this Objective Functions helps in selection of the route towards the sink with minimum hop count. This Objective Function can also be called as minimum hop count objective function.

ETX i.e. Expected Transmission Count is basically the measure for determining total number retransmissions required to successfully transmit the data packet to the next node with an acknowledgement. It involves cross layer protocol interaction. Initially a MAC level beacon message is sent from a particular node to its neighbouring nodes. On reception of this beacon, the receiving node calculate the link quality between them, now the acknowledgement message is sent back, which also contains the information of the link quality between the nodes in forward link. On reception of the acknowledgement packet, the beacon sender node then calculate the reverse link quality. Now as the beacon sender node has both the forward as well as the reverse link quality estimation between the nodes, the ETX will be calculated by it as[9]:

$$ETX_{\text{Link}} = \frac{1}{LQ_{\text{Forward}} * LQ_{\text{Reverse}}} \quad (1)$$

In the above equation ETX_{Link} is the expected transmission count between two nodes, $LQ_{Forward}$ is the link quality between two nodes in forward direction and $LQ_{Reverse}$ is the link quality between two nodes in reverse direction. Now as the ETX information is available with the nodes, this information is transmitted to the nodes down the tree through the DIO message by the contending parents. On reception of DIO, the node will analyse the ETX information and will select the parent with minimum value of ETX. Which means the node will select that parent which require less number of data packet retransmission for successful transmission. Doing so the data packet will traverse that path which have minimum path ETX cost and it will reach to root node with less retransmission and utilizing less resources.

4. Performance Parameters

Performance parameters[10] are the factors on which the performance of Objective Functions in the RPL network will be analysed. In this research work taken, four performance parameters for the analysis. By analysing these parameters, will be able to conclude, which Objective Function performs better in different scaled networks and radio propagation models. Following is the brief description of the performance parameters taken into consideration:

- Packet Delivery Ratio (PDR): It can be defined as the ratio of total number of packets received at the root node to the total number of packets transmitted by the client nodes toward the root node. Higher the PDR of the network means that the packets lost in the network are less and the link between the nodes are stable.
- Control Traffic Overhead: It indicates the total number of control messages (i.e. the DIO, DAO, DIS messages) which are transmitter in the network for formation of DODAG and selection of preferred parent. Higher value of control traffic overhead means that the link

between nodes in the network is not stable. Due to large number of control packets flooded in the network, there will be congestion, packet collision and packet delay in the network. With the packet delay, buffering of packet at the transmitting node will increase and at the same time more power will be spent by node for checking the channel as ideal or not. So control traffic overhead directly or indirectly consumes the scarce resources of the network.

- Power Consumed: It is the measure of the average amount of power consumed by the nodes in the network throughout the network lifetime. It is important for the objective function of RPL to reduce the power consumption of the nodes, by selecting the best route among the alternatives available. Lesser the power consumption of the node, higher will be the network life time.
- Network ETX: ETX is the measure of total number of retransmission required for successful reception of data packet at receiver node. In this we take the average of path ETX cost of all the routes to the root node. Objective function with less network ETX has good network link stability, which directly states that there will be less retransmissions of data packet and less consumption of resources.

5. Simulation Results

To analyse the behaviour of RPL based on different objective function, it is important to evaluate the consumption of scarce resources of the nodes and the network. For this reason we are considering performance parameters like Packet Delivery Ratio, Control Overhead, Power Consumed and Network ETX which directly gives the information of the consumption of resources like power, memory etc. and stability of network. In this analysis we will be considering different radio models[11] e.g. UDGM (Unit Disc Graph Model) - Distance Loss, UDGM (Unit Disc Graph Model) - Constant Loss and (MRM) Multi-Path Ray-Tracer Medium. RPL with different objective function will be implemented in all the radio models and the performance of objective functions will be evaluated based on the performance parameter. For further in-depth analysis, scaled networks will also be considered, to analyse the effect of increased network size on performance parameters for various Objective Functions.

For simulating the above mentioned scenario, a special simulator known as COOJA is used which is designed to simulate WSN and have inbuilt source files for implementation of RPL. COOJA provides the freedom for user to select any radio model for simulating any WSN scenario. For result analysis, the data is taken from Log Output, Collect-View plugin and Power Trace plugin. Following Figure 1. demonstrate the topology of the nodes in COOJA simulator.

This topology will be same for all the radio models. In this topology, there are 40 client nodes and one root node. All the client nodes are sending data to the root node i.e. only upward data traffic is considered. The transmission range of each node is 50m and the interference region is from 50 to 55 m. The simulation time for all the scenarios is 10 min. and for analysing the performance of Objective Function in each radio model, graph is plotted between the performance parameters and the varying reception ratio. Following are the graphical results of performance of objective functions in various radio models:

5.1 Analysis based on Different Radio Models

5.1.1 *Unit Disc Graph Model – Distance Loss*

This model is the most basic radio model, in which each node has a transmission range modelled in a disc fashion. The two nodes are in the transmission range of each other, if there transmission regions overlap upon each other. Distance loss mentioned in the name of this radio

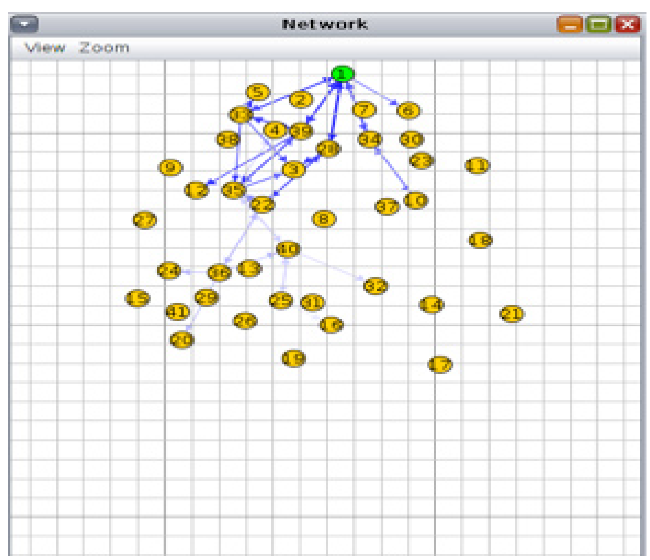

Figure 1. Snapshot of the topology taken into consideration in COOJA simulator.

model signifies that the reception ratio (the probability of successful reception of data packet considering the losses in the channel) will go on decreasing with the increase in the distance from the transmitting node. Following Figures 2, 3, 4, 5 are the graphical outputs of the performance of the Objective Functions in UDGM-Distance Loss model. Thick line represent ETX and thin line represent OF0.

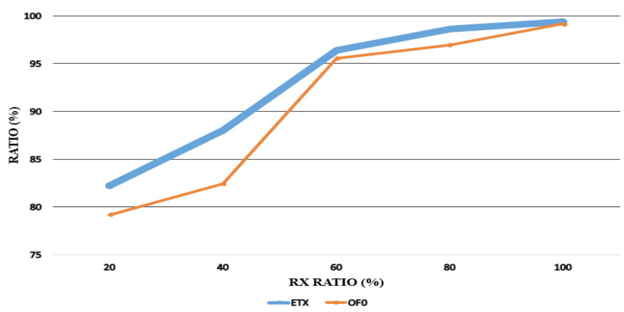

Figure 2. Graphical Output for Packet Delivery Ratio vs. Reception Ratio.

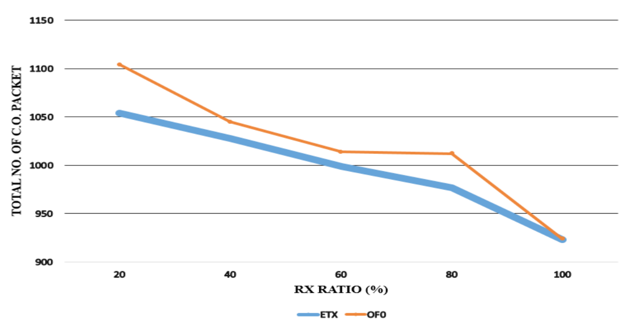

Figure 3. Graphical Output for Control Overhead vs. Reception Ratio.

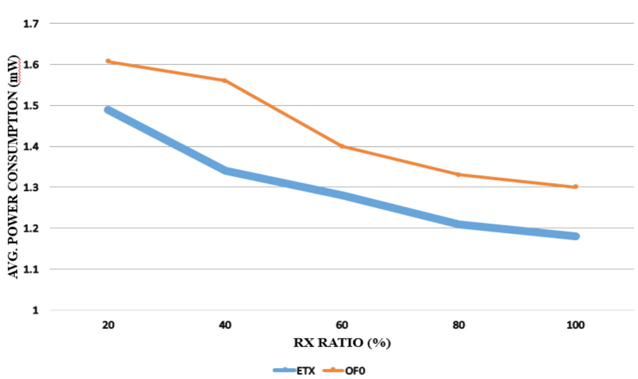

Figure 4. Graphical Output for Power Consumption vs. Reception Ratio.

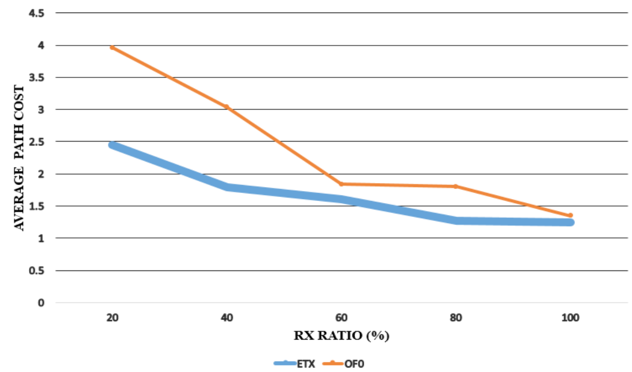

Figure 5. Graphical Output for Network ETX vs. Reception Ratio.

Figures 2, 3, 4, 5 shown before are the graphical estimation of performance parameters for both the objective function in UDGM-Distance Loss radio model. From these graphical results, it can be concluded that the performance of both the Objective Functions is pretty much similar when the reception ratio is 100%, but as the losses in the network starts to increase, the performance of OF0 declines more in comparison to the ETX Objective Function. Considering Figure 2., for high reception ratio, there will be less drop of packets in the network, which will lead to high PDR i.e. from 90 to 100 %. But as the reception ratio decreases below 60%, the packet drop in the network increases, which leads to decline in PDR. If we compare the performance of both the Objective Functions, ETX still perform better in comparison to Objective Function Zero (OF0) for lesser reception ratio.

Graph shown in Figure 3., describes the number of control overhead packets flooded in the network because of the change in reception ratio. Due to less loses in the network for high reception ratios, the transmission of control overhead packets will be less, but as reception ratio decreases, there will be packet drop because of which more control overhead packets will be transmitted in the network. If performance of both the Objective Functions are compared, ETX plays an efficient role by reducing the number of control packets because ETX consider the link quality parameter for the selection of path to the root node.

Figure 4 shows very important performance parameter, which is concerned with the power consumption of the nodes in the network. In this graph, the performance of ETX is way better in comparison to the OF0 objective function, because as analysed for Figure 3. that when the reception ratio decreases, the control overhead increases much more for OF0, which leads to increase in power consumption of the nodes. Furthermore, as the packet drop are more in OF0, buffering of packet for retransmission will also lead to more power utilization.

The last graph, which is shown in Figure 5., also proves that the performance of ETX is considerably better in comparison to the OF0. This is because, as in ETX parent nodes are selected by the children nodes based on the link quality, whereas link quality is not considered by OF0 during parent selection. This makes the value of Network ETX higher for OF0.

5.1.2 Unit Disc Graph Model – Constant Loss

This radio model is same as the above radio model, the only difference is the loss pattern in the unit disc. In this model, the loss remain constant with the variation of the distance from the transmitting node. Following are the graphical results of the performance parameters shown in Figures 6, 7, 8, 9.

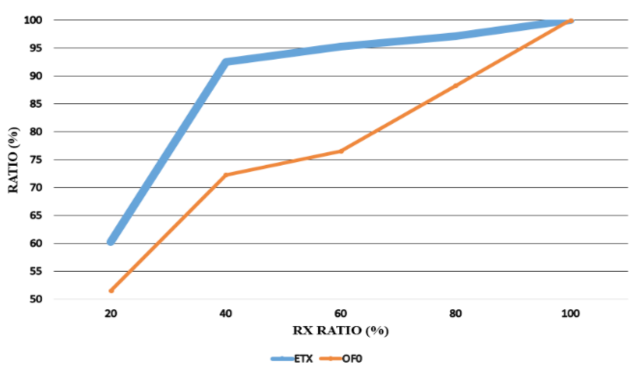

Figure 6. Graphical Output for Packet Delivery Ratio vs. Reception Ratio.

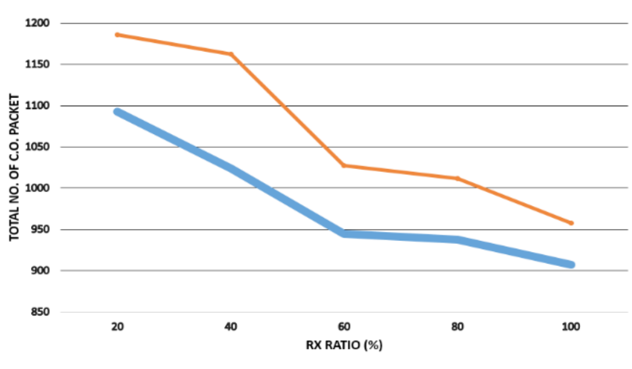

Figure 7. Graphical Output for Control Overhead vs. Reception Ratio.

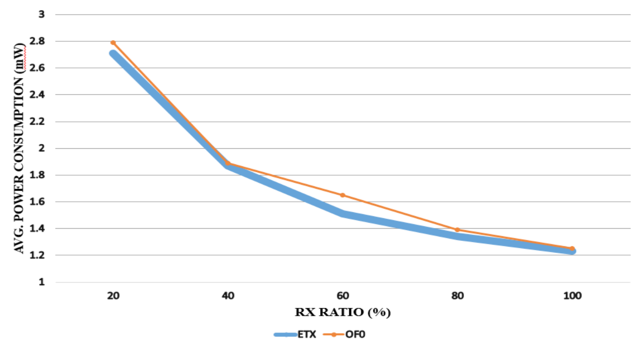

Figure 8. Graphical Output for Power Consumption vs. Reception Ratio.

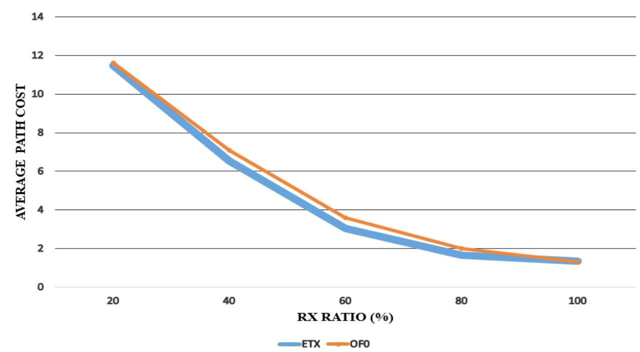

Figure 9. Graphical Output for Network ETX vs. Reception Ratio.

In above Figures 6, 7, 8, 9 thick line represent ETX, thin line represent OF0. From the graphs shown in Figures 6, 7, 8, 9, it can be concluded that the performance of Objective Function ETX is better in comparison to OF0, as it was for the UDGM-Distance loss. But the difference between the performances of both objective function is more in comparison to previous radio model. The reason is that, for previous model, nodes closer to transmitting nodes have greater reception ratio, than the nodes away from it, because of which there will be less packet drop for low reception ratios by nodes closer to transmitting node. But in UDGM- Constant loss, the reception ratio remain same for all the nodes in unit disc, irrespective of the distance from transmitting node because of which the loss will be same for all the nodes in the disc and performance of OF0 declines more because it do not consider link quality to select parent nodes.

It can be concluded from the graphs shown in Figures 6, 7, 8, 9 that because of the link quality consideration in objective function ETX, PDR will be more, which means to less packet drop and less control overhead.

Because of less congestion in network, power consumption will also be less for ETX. And finally the network ETX will also be less for Objective Function ETX in comparison to OF0 objective function.

5.1.3 Multi-path Ray-tracer Medium (MRM)

This radio model is the most realistic model for sensor network implementation. In this radio model concept like diffraction, reflection, refraction, fading are also considered. In this model obstacles can be placed in the simulating scenario, to analyze the network behavior in real-time. Figures 10, 11, 12, 13 shows the comparison of both the objective functions for all the three radio models, based on the performance parameters. In figure below, the bar with meshes represent ETX and plain bar represent OF0.

From the graphs shown in Figures 10, 11, 12, 13 it is observed that the performance of objective function ETX is best in comparison to the Objective Function Zero for all the radio models. As loses are more in MRM model, so the Objective Function ETX values are slightly less efficient in comparison to other radio models. But if overall performance is considered, ETX is the best objective

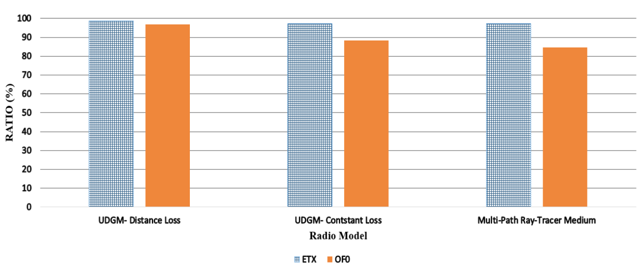

Figure 10. Graphical Output for PDR vs. Radio Models.

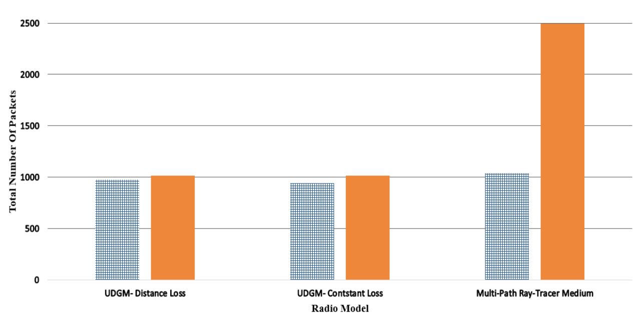

Figure 11. Graphical Output for Control Overhead vs. Radio Models.

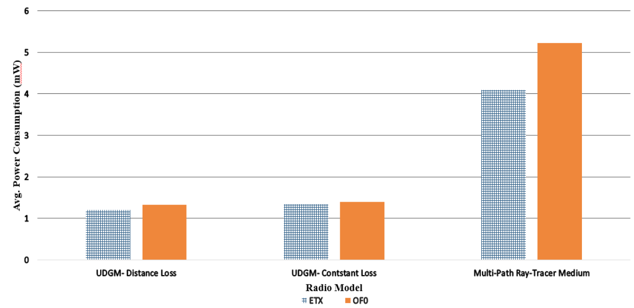

Figure 12. Graphical Output for Power Consumed vs. Radio Models.

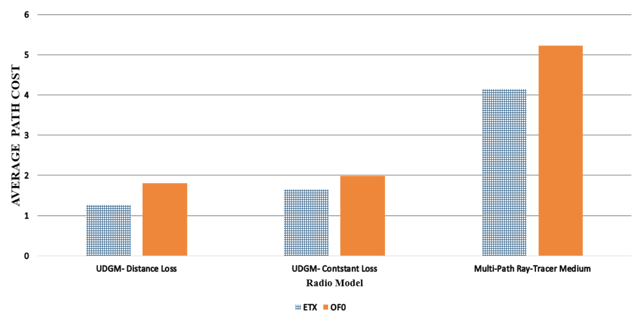

Figure 13. Graphical Output for Network ETX vs. Radio Models.

function for any radio model in comparison to OF0. As OF0 do not consider the link quality factor for parent selection, it can be seen in Figures 10, 11, 12, 13 that its performance is worst in MRM model for all performance parameters, as the losses in this radio models are random and more compared to other radio models.

The dependence of the performance parameters on each other can be observed in Figures 10, 11, 12, 13. As seen that in Figure 10., PDR for ETX and OF0 in MRM model is less in comparison to other radio models, this leads to increase in control overhead shown in Figure 11. As control messages increases due to packet loss, power consumption of nodes also increases, which can be observed in Figure 12. Lastly as the losses in the channels are more and packet drop is high, we can see in Figure 13. that Network ETX value also become high.

5.2 Analysis based on Scalability

In this analysis, the behaviour of the Objective Function is analysed by increasing the number of client nodes in the network and then based on the performance parameter, best objective function will be declared. To simulate scaled networks, the number of client nodes taken in different scenarios are 40, 80, 100, and 200. The radio model considered for each simulation is UDGM-Distance Loss. To analyse the performance of objective function, performance parameters will be plotted against the number of nodes in the network. Following are the graphical outputs of the performance parameters shown in Figures 14, 15, 16, 17. In figure shown below, thick line represent ETX, thin line represent OF0.

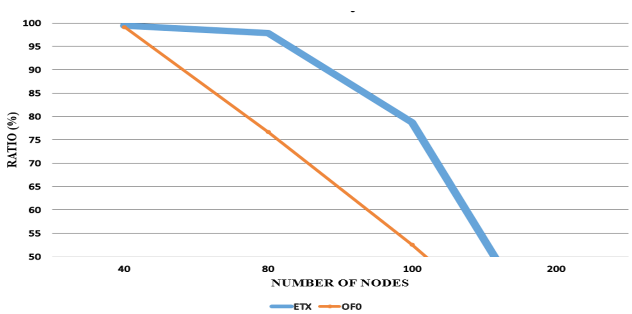

Figure 14. Graphical Output for PDR vs. Number of nodes in network.

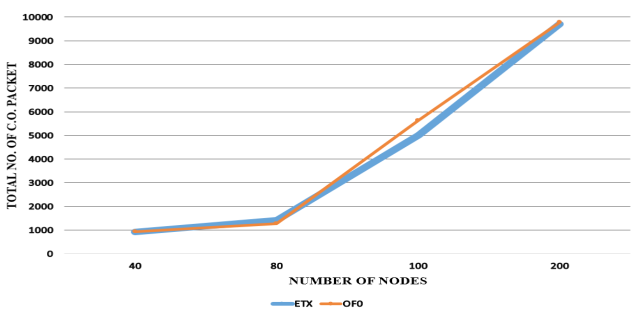

Figure 15. Graphical Output for Control Overhead vs. Number of nodes in network.

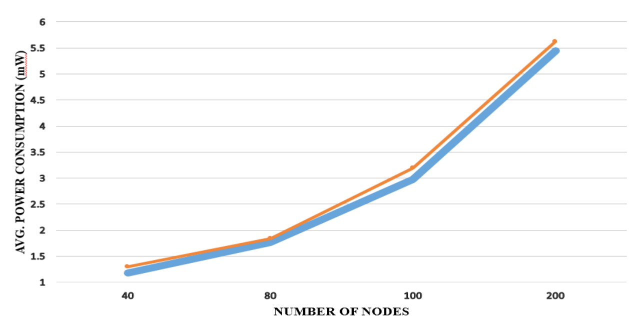

Figure 16. Graphical Output for Power Consumption vs. Number of nodes in Network.

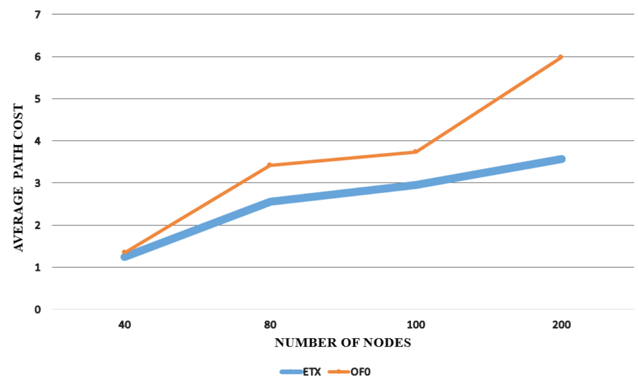

Figure 17. Graphical Output for Network ETX vs. Number of nodes in network.

From the graphs in Figures 14, 15, 16, 17 it can be analysed that performance of both the objective function declines with the increase in the number of nodes in the network. The reason for this decline is that, with the increase in the number of nodes in the network, the transmission of data packet will increase, which will lead to collision of packets in the network and decrease in PDR. Due to loss of packets in the network, more control overhead packets are generated, which further creates congestion in network. Now due to large transmission of data and control packets in network, the power consumption of nodes will increase, due to buffering data packet, sensing of channel to be ideal or not etc. At last due to collision in data packets, Network ETX will also increase. It can be determined for the above graphs that, the performance of ETX is still better in comparison to OF0 because the losses in ETX network is due to excess transition of data packet, but in case of OF0 losses are due to excess data transmission and lack of link stability between the nodes.

6. Conclusion

In this paper, the framework for analysing the performance of RPL with different objective function is presented for various radio models and scaled networks. For quantitative analysis, different performance parameters are taken into consideration, which directly gives the information about the scarce resources of the nodes and the network. Performance parameters considered are PDR, Control Overhead, Power Consumption and Network ETX. All these parameters are interrelated to each other i.e. change in one parameter brings change in the other parameters.

From all the graphs analysed for different performance parameters in various radio models as well as scaled networks, it can be clearly understood that performance of objective function ETX is better in comparison to the performance of OF0.The main reason for this is the consideration of link quality for the selection of preferred parent, during the formation of DODAG by ETX objective function whereas in case of OF0, the hop counts with respect to the root node is considered. So it is concluded that the performance of ETX Objective Function is better in comparison to Objective Function Zero in any radio models and scaled networks.

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