Research Article

Experimental Analysis of Energy Efficient and QoS Aware Objective Functions for RPL Algorithm in IoT Networks

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Abstract

The Internet of Things (IoT) refers to smart devices with limited resources that connect to the Internet and transmit data. Routing is an important process in this structure, which can be described as the general frame of wireless sensor networks (WSNs). The Routing Protocol for Low-Power and Lossy Networks (RPL) is recommended by the Internet Engineering Task Force (IETF) to provide communication in resource-constrained networks and is designed for routing in IoT. Basically, it is the Internet Protocol Version 6 (IPv6) protocol developed based on the energy consumed by devices. The algorithm has an important place in the performance of the IoT network. In this paper, the performance of the RPL under different objective functions (OFs) is examined. OFs are symbolized and defined by detailed equations. This study provides an experimental analysis of the RPL algorithm. An overview of the RPL algorithm is also included. Finally, the RPL algorithm is simulated by a custom simulator which is performing on the application layer, created using the Python programming language. The algorithm's behaviour in terms of different OFs such as throughput maximization, energy efficiency maximization and energy consumption minimization was observed and the results were evaluated under different parameters such as packet size, number of nodes and different signal-to-noise ratio (SNR) values. Our experimental results may be useful for both researchers and practitioners working in related fields.

Keywords: Internet of Things, Wireless Sensor Network, Routing, RPL

1. Introduction

The IoT refers to the non-centralized structure created by devices that can connect to the Internet, and communicate with each others by exchanging data. In another definition [1], IoT is the technology of 'things' that transmits by collecting information over a wireless internet network. This characterization was first suggested by Kevin Ashton in 1999 [2]. The IoT structure represents an innovative technology that allows everyday objects to connect to the internet [3]-[4] and can be found in places such as smart homes, smart factories, the health industry and other systems.

The IoT includes sub-domains in terms of its scope, device, and all functions. The wireless sensor network (WSN) can be considered an IoT substructure. The WSN can be defined as networks that consist of small and cheap nodes with sensing, processing, and communication capabilities which are designed for complex monitoring operations in the geographical areas [5].

According to USNIC data, devices that work under the IoT frame will increase over the years [6] and will be used in every point of daily life to provide ease and advantage. Devices will transfer large amounts of data in terms of their transactions. However, these tiny devices have low power, lossy, and limited resources. Some devices perform under resource-constrained conditions in IoT applications [7]. Parameters such as power and throughput are instances of these limited resources.

Routing is a significant research field for wireless sensor networks as well as for standard networks. Path selection of data or processed information by specified constraints and metrics defines routing [8]. The determination of the transmission path is directly or indirectly related to various parameters. As previously mentioned, limited capacities and abilities of IoT/WSN had led to suggestions of different methods in routing. In this context, the IPv6 routing protocol RPL is proposed for resource constrained devices by the IETF working group Routing Over for Low Power and Lossy Network (ROLL) [9]. The

RPL algorithm aims to increase delivery performance in the network by providing a routing path for devices which have low power and limited resources.

In this work, we perform the incentive analysis of the RPL algorithm which is proposed in the literature. To the best of our knowledge, no experimental analysis work which is comparing routing path performance as throughput, energy consumption, and energy efficiency metrics. Many experimental studies compare the RPL algorithm with different algorithms in terms of different metrics. In this study, performance outputs of the routing path created by the RPL is observed simultaneously in terms of the mentioned metrics. We proposed different scenarios with various parameters such as packet size, SNR values. We are interested in evaluating the RPL performance and metrics to propose the most efficient OF to choose the best path to destination. In this study, analyses of energy consumption, energy efficiency, throughput behaviour, and end-to-end delay of RPL algorithm were conducted. First, the energy consumption of the nodes using different metrics and formulas was evaluated. Then the energy consumption of the overall network and energy efficiencies of nodes on generated topology was examined. The results were analysed in a Python-based network simulation environment. The rest of the paper is structured as follows: Section 2 deals with the related works of the RPL algorithm in terms of energy and other metrics; Section 3 provides an overview of the RPL and RPL basic structure; Section 4 describes OFs of RPL; Section 5 shows simulation parameters and a simulation of the algorithm; results are given in Section 6; and conclusions are provided in Section 7.

2. Related Work

The RPL is included as standard routing protocol in the literature [10]. Researchers have proposed various models to develop the standard RPL routing protocol. The green routing protocol was proposed for the Internet of Multimedia Things (IoMT) [11]. The IoMT is a more developed version of the RPL algorithm and works by choosing one parent node according to metrics such as delay or battery consumption. The proposed algorithm takes into account minimizing of energy consumption and carbon footprint. Thus, it aims to provide Quality of Service (QoS) parameters. Chang et al. [12] proposed an energy-oriented routing protocol by improving the existing routing protocol of the RPL. The Expected Transmission Count (ETX) and remaining energy metrics were combined, generating the OF. The routing path was chosen according to this generated OF. Thus, energy consumption balance was provided not only over the nodes but also over the whole network. The proposed scheme was simulated with the Cooja network simulator and compared with previous RPL metrics. In research by Iova et al. [13], an energy aware protocol was designed to minimize global energy consumption. Their protocol works on the basis that each node consumes the same energy amount to extend network lifetime. The designed protocol specifies network bottlenecks and provides energy efficient consumption on network overall. The OF was proposed by using the Expected Life Time (ELT) metric to generate an energy balanced network. The algorithm tackles instant lifetime of nodes and bottleneck lifetime cases during the parent selection. The proposed model was simulated in WSNet with the RPL algorithm. The RPL algorithm causes significant packet losses due to reasons such as route instability. In order to prevent packet losses, a novel approach was developed by Boubekeur et al. [14]. The solutions of the problems which exist in the RPL algorithm are generally based on developing of metrics and functions. A solution was developed based on the restriction of the maximum number of child nodes during the tree generation of a node to address the RPL's route instability issue. The proposed model is called the Bounded Degree RPL (BD-RPL). As the proposed model uses control messages in RPL, it works without a link quality measure. The results were obtained by Cooja network simulation in terms of energy consumption, delay, and transmission rate. Pereira et al. [15] proposed a new routing metric for the RPL. This metric gives not only provides a reliable path selection like ETX on the network, but also important results such as load balancing and lifetime increasing on the network. Their proposed method is known as the Network Interface Average Power (NIAP). Verification of the method was done by randomly distributed homogeneous topology with the same initial battery levels. According to the results, the NIAP metric provides 24% better results than ETX in terms of network lifetime and 1% increase in packet transmission rate.

Load balancing and congestion problems in RPL were tackled by Kim et al. [16]. They stated that most of the packet losses in heavy network traffic are caused by congestion and the reason for the parent selection process in the RPL. A Queue Utilization-based RPL (QU-RPL) model was proposed by improving the RPL algorithm to solve this problem. Their aim was to increase the end-to-end packet delivery performance by balancing traffic load within a routing tree. Results were shown by comparing an RPL using the OF0 objective function called Tiny RPL based on hop count. In order to solve the issue of load balancing, Lin et al. proposed a simple power control mechanism which works by specifying the transmission power of each node according to own link and queue losses [17]. The generated OF tackles energy losses over queue and links. A routing tree is created according to the traffic load on the network and packet delivery performance is increased.

Hoghooghi et al. suggested RPL developments for static and mobile Low Power and Lossy Networks (LLNs) which provide QoS guarantee [18]. Constraints in standard OF were improved by using the Objective Function based on Fuzzy Logic (OF-FL). Performance metrics such as number of hops, end-to-end delay, and ETX were considered. The OF allows the choice of the best candidate transmission method in terms of four main criterions. Besides the OF, RPL based on the Corona (CO-RPL) mechanism was also proposed with an aim to increase service quality on dynamic and static network structures. An RPL based on Fuzzy Logic method provides improvements on the best path selection. With CO-RPL, improvements were made to QoS due to mobility difficulties in WSNs.

An energy efficient routing protocol was proposed by Barbato et al. [19]. The RPL based protocol is called Resource Oriented and Energy Efficient (ROEE) and multiple routing metrics were used in the proposed model. Energy amount and battery consumption metrics were created as OFs instead of only the hop count metric. The proposed ROEE algorithm was compared with basic RPL protocol in terms of metrics such as network life time, power consumption, and the number of alive nodes. In Zhao et al. [20], a model providing energy efficiency and data transmission without sacrificing reliability was proposed and called the Energy Efficient Region-based Routing Protocol (ER-RPL). The main motivation of the work was difficulty in achieving success on parameters such as reliability and energy efficiency. Improvements were made in the downward phase called the downward route discovery in the RPL. It was proposed to use only a subset of a node rather than all nodes during route discovery. This approach has been key to providing energy efficiency.

Table 1 Classification of analyzed routing algorithms

Ref.	E2E Delay	Energy Consumption	Throughput	Energy Efficiency	PDR	Num of Hop	ETX
[11]	✓	✓	✗	✗	✗	✗	✗
[12]	✗	✓	✗	✗	✗	✗	✓
[13]	✗	✓	✗	✗	✗	✗	✓
[14]	✓	✓	✗	✗	✓	✗	✗
[15]	✗	✓	✗	✗	✗	✗	✓
[16]	✓	✗	✗	✗	✓	✗	✗
[17]	✗	✓	✗	✗	✓	✗	✗
[18]	✓	✗	✗	✗	✗	✓	✓
[19]	✗	✓	✗	✗	✗	✓	✓
[20]	✗	✓	✗	✓	✗	✗	✗
E2E Delay: End-to-End Delay		**PDR:** Packet Delivery Ratio			**ETX:** Expected Transmission Count		

In Table 1, classification of analyzed routing algorithms is presented, and furthermore intended success measurements are shown. Each routing study investigate the RPL algorithm in terms of specified metrics.

3. RPL Overview

The RPL is a 6LoWPAN protocol designed for LLNs. The protocol was proposed by the IETF Roll working group and is classified as a distance vector and source algorithm in terms of its working principles and usage. It is designed in IEEE 802.15.4 PHY and MAC layers [21]. The routing path and routing tables are updated periodically because nodes propagate broadcast messages to identify changes

in the network topology. Thus, the algorithm is classified as a proactive routing algorithm. Data transmission flows such as multipoint-to-point, point-to-multipoint and point-to-point are supported by the RPL algorithm [22]. The RPL algorithm generates the network topology as a Directed Acyclic Graph (DAG). The data transmission path is optimized by a DAG root which acts as a root node, or in other words, a sink. An example of a root node is a gateway that acts as the network's exit point to the Internet. A Destination Oriented Directed Acyclic Graph (DODAG) is a multiple DAG structure which is combined of DAG trees. It consists of multiple parent nodes in contrast to standard tree structure. DODAG structure also consists of multiple paths from leaf nodes to roots [11], which is the main difference of DODAG from the standard tree structure. Figure 1 illustrates an instance of an RPL tree.
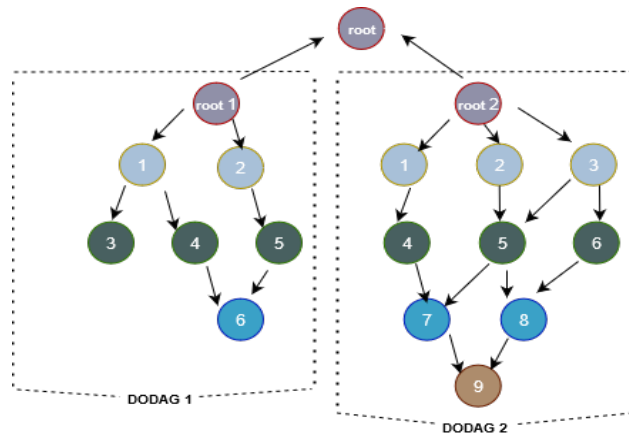

Figure 1 An RPL tree instance consisting of multiple DAGs

Tree structures consisting of nodes use identifiers for each object they contain. The RPL Instance ID is the ID of the RPL to which the DIO message is sent and the DODAG ID is the identifier number of the topology section where the RPL is sent. The DODAG Version Number and Rank provide values for nodes.

The RPL algorithm consists of two stages: downward and upward transmission. Downward transmission provides point-to-multipoint (P2MP) and point-to-point (P2P) communication, whereas upward transmission creates point-to-point (P2P) traffic. Before these stages, it is necessary to establish the network, message transmission, and to generate the routing path by using control packages. Thus, the RPL uses tree basic ICMPv6 packet types [23].

DODAG Information Objects (DIO), are the messages sent from root node to child nodes during the downward transmission phase. Figure 2 illustrates the DIO message flow.

Figure 2 DIO message flow
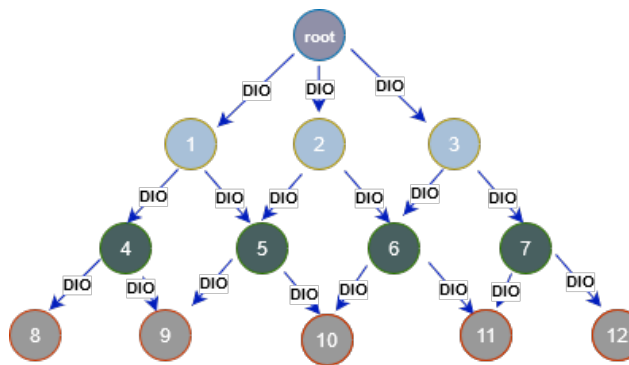
Destination Advertisement Object (DAO) are the messages sent from nodes which have no child node to root nodes during the upward transmission phase. Figure 3 illustrates this flow.

If a new node wants to join the network, it uses multicast broadcasting through the DODAG Information Solicitation (DIS) message type and chooses a possible parent according to the status of the network.

Figure 3 DAO message flow

Each node has a rank value according to its distance from the root. The rank is used for specifying the position of nodes according to roots. This value increases the further away from the root node a particular node is. The root has zero rank value on the tree. Leaf or child nodes have greater rank value than parent nodes. The rank value is a significant part of the algorithm in DODAG to prevent loops.

The algorithm starts to perform using downward transmission. The downward phase starts from the root node and ends with the discovery process on the network by DIO messages that are spread by the root node to all child nodes. DIO messages are transmitted using the Trickle Timer (RFC6206) [24]. A trickle timer is used for preventing inconsistencies that may occur due to message transmissions between nodes. In the upward stage, after spreading DIO messages, the parent selection process is conducted according to desired metrics and constraints. Each node chooses its own parent according to a calculated OF during DIO spreading. OF is necessary for parent selection of child nodes. For instance, the expected result may be minimum delay, energy consumption, or maximum message delivery rate. OF provides the desired routing path by calculating according to specified constraints and rank values. Parent selection is managed by DAO messages.

The RPL algorithm is classified according to a storage shape that is established after down and upward message transmissions and parent selection. With this perspective, the algorithm works in two basic modes: non-storing mode or storing mode. In non-storing mode, routing information is not kept by intermediate nodes but rather is stored by the DODAG root node. Route information from source to destination is determined via the root node. Packets always arrive over the root node meaning that there is no memory consumption for each node. In storing mode, each node stores route and parent information about other sub-nodes. The routing path is kept by all nodes. Path information formed during non-storing and storing modes and a general RPL view are illustrated in Figure 4.

Figure 4 RPL general view and modes

4. Objective Functions

The RPL routing protocol provides routing metrics via OFs. These functions are determined by desired routing acts such as the minimum distance path selection, the minimum energy consumption and delay, and maximum packet delivery ratio. Developments in the RPL also differ in behaviour of these functions. OF which is mainly categorized as the link and node metrics is decisive on network performance [25].

The RPL algorithm chooses the routing path according to various OFs. Link and communication quality are specified by the OF. In this work, the network model is represented by DODAG *G = (V, E),* where *V* is a set of IoT device nodes and *E* is a set of all communication links in the graph *G.* In addition, various OFs were used as routing metrics and are summarized in Table 2.

4.1 Throughput Maximization (P1)

In the scope of work, the throughput is represented by bandwidth and, capacity. It is a link and communication parameter between two nodes. This objective function P1, given in Equation 1, is used to find links that have maximized their capacity. Throughput should be maximized for network performance. The throughput can be represented as *B* and calculated according to the following formula:

$$B = (max) \sum_{\forall l_{i,j} \in P} \delta_{ij} \, W \log_2(1 + SNR_{i,j}) \; (bps) \tag{1}$$

where the *P* represents the set of all paths on the topology and where $l_{i,j}$ is a link over the path *P*.

$$\delta_{ij} = \begin{cases} 1, & \text{if there is a positive data flow over the link } l_{i,j} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where the δ_{ij} represents the data flow over the link, i.e., $\delta_{ij} = 1$ if there is a flow over the link and it is considered while calculating the energy consumption, $\delta_{ij} = 0$ otherwise. *W* represents bandwidth in Hertz. In this work, *W* is considered constant and $SNR_{i,j}$ is the signal-to-noise-ratio of link $l_{i,j}$ assigned from randomly selected different mean values.

4.2 Energy Consumption Minimization (P2)

Energy Consumption is the total amount of energy or power that nodes on the network spend for operations on the network. This objective function P2 as described in Equation 3 is used to find nodes that consume energy at the minimum level. Energy consumption should be minimized for all nodes. It is represented as EC and defined as follows:

$$E_C = (min) \sum_{\forall l_{i,j} \in P} \delta_{ij} \left(ETX + E_{Circuitry} + E_{Idle} \right) + \sum_{\forall l_{i,j} \notin P} \delta_{ij} \, E_{Idle} \quad \text{(joule)} \tag{3}$$

where the *ETX* is the Expected Transmission Count by RFC6551. It is frequently used in LLNs. ETX is the successful transmission of the packet from the source node to the destination and can be defined as follows:

$$ETX = Pt_{t_x} \quad \text{(Joule)} \tag{4}$$

$$t_{t_x} = \frac{\text{packet size}}{B} \quad \text{(sec)} \tag{5}$$

where the *P* in the definition is power and considered a constant.

$E_{Circuitry}$ is the energy consumption power of devices due to their individual characteristics and can be defined as follows:

$$E_{Circuitry} = P_C t_{t_x} \quad \text{(Joule)} \tag{6}$$

where the P_C is the device power value and considered a constant.

E_{Idle} is the energy consumed by devices when they do not perform any operation on the network and is defined as follows:

$$T_{remain} = T - t_{t_x} \quad \text{(sec)} \tag{7}$$

$$E_{Idle} = P_{Idle} T_{remain} \quad \text{(Joule)} \tag{8}$$

where the P_{Idle} is the power spending value of node when it is not operating.

4.3 Energy Efficiency Maximization (P3)

Energy Efficiency is defined as the output received against the energy consumed per node over a period of time under consideration [26]. It is the metric that determines the energy consumption on the network. This objective function P3, provided by Equation 9, is used to find maximum energy efficient nodes on the network. Maximizing the energy efficiency of the nodes ensures that energy consumption on the routing is minimized. Energy Efficiency is represented by E_E and defined as follows:

$$E_E = (\text{max}) \quad \frac{R}{E_C} \quad (\text{bits}/_{\text{joule}}) \tag{9}$$

$$R = B \times T_s \quad \text{(bits)} \tag{10}$$

where the R is the maximum number of bits that can be carried over the link.

4.4 End-to-End Delay Minimization (P4)

End-to-End delay refers to the time it takes for a packet to be transmitted from source to destination over the network. It also can be calculated as the sum of propagation delay, transmission delay, queuing delay, and processing delay.

Table 2 Metric notations

Symbol	Definition
B	Channel throughput
ETX	Expected transmission count
t_{t_x}	Rate of packet number that is sent by channel throughput
E_C	Energy consumption for network overall
$E_{Circuitry}$	Energy consumption power of devices due to individual characteristics
E_{Idle}	Total energy consumption amount of the device when it is idling
P_{idle}	Idle power value of devices
P_C	Characteristic power value of devices
T_{remain}	Remaining time value in the time slot of each device after processing
E_E	Energy efficiency of each node
R	*M*aximum number of bits

5. Simulation Environments

In this section, the simulation parameters and results which evaluate the performance of the RPL algorithm are presented through Python programming language. The generated custom simulator

performs on application layer. To analyse the general behaviour of the RPL under different conditions, various simulation settings were considered. The symbols and simulation parameters are shown in Table 2 and Table 3. These simulations are based on a static DODAG network topology consisting of a single root. Nodes are distributed randomly on network topology and the transmission distance between nodes is assumed as a node transmits message only to their neighbours for all scenarios.

The algorithm was simulated for different scenarios. On the constant node number scenario, 20 randomly distributed nodes were generated for network topology. The DODAG Id value was never used since the model has a single root node. Message class was generated in three basic message types: DIO, DAO and DIS. As stated in section 3.1, the identity information of each node and the RPL tree were considered. In the remaining scenarios, the number of nodes were set at 5, 7, 9, 10, 13 and 20 and all were considered static. An iteration limit of 20 was set for each different parameter and packet time interval was 0.5 seconds. SNR values used in these simulation were separated by different means. The SNR value of a link was assumed to follow an exponential process with different means and these values were generated randomly by various means. Each node had the same time slot.

Table 3 Simulation parameters

Symbol	Definition	Values
t	Simulation Time	20 iterations
L	Packet Size	[100,1000] bytes
I	Packet Interval	0,5 sec
n	Number of Nodes	[5, 20]
snr	SNR value means	[2.5, 20] dB
P	Power	1.98 Watt
W	Channel Bandwidth	$5*10^6$ Hertz
P_c	Circuitry power	0.21 Watt
P_{idle}	Idle power	0.99 Watt
T_s	Time slot	100 sec

Evaluation of the protocol was performed using performance metrics such as energy consumption, average network throughput, efficient path throughput and average end-to-end delay. Table 4 outlines the principal characteristics of the RPL simulation.

Table 4 Principal Characteristics of the RPL Simulation

Abbreviation	Definition
Algorithm	RPL
Simulation Tool	Python
Topology	Random distributed, fixed
Message Flows	MP2P, P2P, P2MP
Control Messages	DIO, DAO, DIS
Metrics	OF and rank
Mode	Non-Storing
QoS Aims	Energy consumption, energy efficiency, throughput, end-to-end delay, hop count

6. Results

This section presents the simulation results which evaluate the performance of the RPL algorithm by using Python. The simulation results are shown as the average value of different parameters and functions. The simulation time was set at 20 iterations. As shown in Table 3, the bandwidth was set to 5×10^6 Hz. Other parameters were considered constant values. Before the simulation started, source and destination addresses were specified and given as input. For each iteration, different performance metrics were calculated.

Figure 5 displays the comparison of throughput of the RPL algorithm against various SNR values ranging from 2.5 to 20 dB, and packet size is assumed to be 500 bytes. It was observed that if the algorithm was aiming for throughput maximization, the energy consumption and energy efficiency metrics acted as non-optimal. The reason for this behaviour is that the algorithm selects parents only by considering throughput without the other metrics. Also, since an increase in the SNR value also increased the signal quality, it positively affected the throughput value.
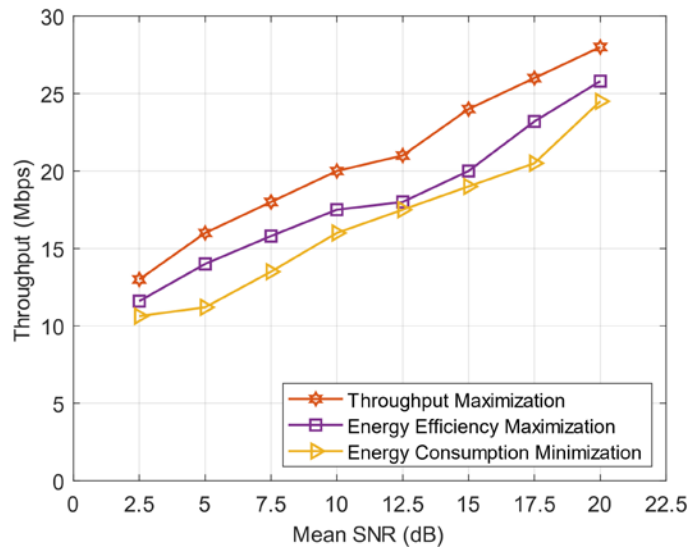
Figure 5 Throughput of selected routing paths for different SNR values under various OFs

Figure 6 shows the throughput of selected routing path for 200, 300, 400, 600, 800 and 1000-bytes packet sizes respectively. The SNR value for running this simulation was considered at 10 dB. The algorithm selected the routing path according to all three metrics. In addition, when the packet size increased, the throughput value decreased. Increasing of packet size reduced the capacity value, but the capacity optimal OF provided the highest capacity according to other objective functions.
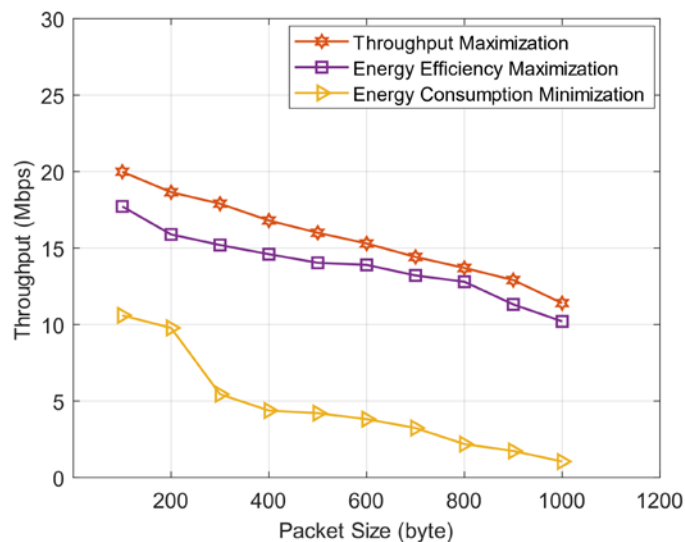

Figure 6 Throughput of selected routing paths for different packet size values under various OFs

Figure 7 illustrates energy consumption of routing paths under other throughput and energy efficiency metrics. As seen in the figure, when the SNR value increased, throughput, energy efficiency and energy consumption also increased. The algorithm selected the routing path and parent nodes according to minimum energy consumption. Thus, the energy consumption value of the path was smaller than the other metrics which were considered.
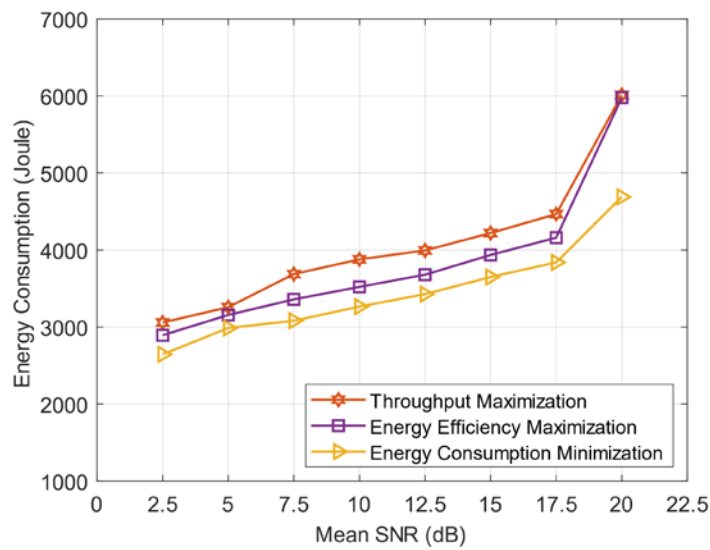
Figure 7 Energy consumption of selected routing paths for different SNR values under various OFs

Figure 8 demonstrates the energy efficiency of nodes over the routing path. While generating the routing path, nodes choose the most energy efficient node as the parent node. The higher the SNR value, the higher the communication quality and transmission performance. Accordingly, the number of bits sent per unit energy increased.
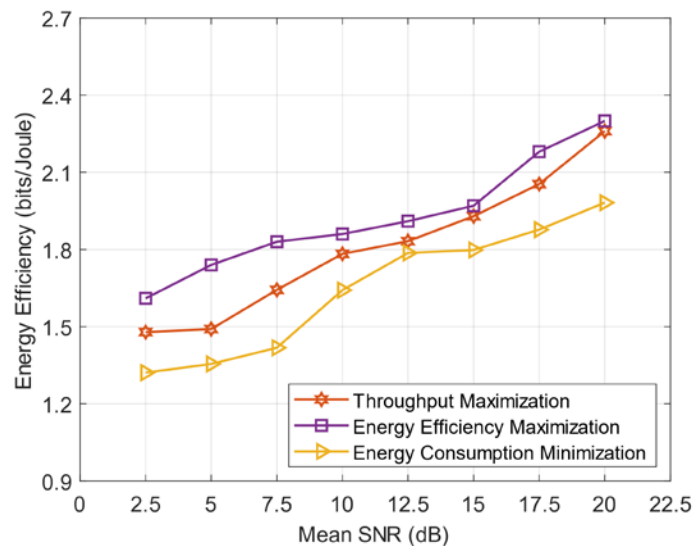

Figure 8 Energy efficiency of selected routing paths for different SNR values under various OFs

Figure 9 shows the comparison of end-to-end delay of any randomly selected routing paths in the RPL tree for 5, 7, 9, 10, 13, 15, 17, and 19 node counts, respectively. From source to destination, end-to-end delay increased when the node number increased. As the number of nodes increased, the number of unit transactions on the network increased and the queuing, processing, transmission, and propagation delay increased accordingly.

7. Conclusion

The RPL is a significant routing protocol used in low resource networks. It determines the routing path in the communication and data exchange of devices in the network in accordance with intended performance metrics. The RPL protocol, which works in both storing and non-storing mode, can be
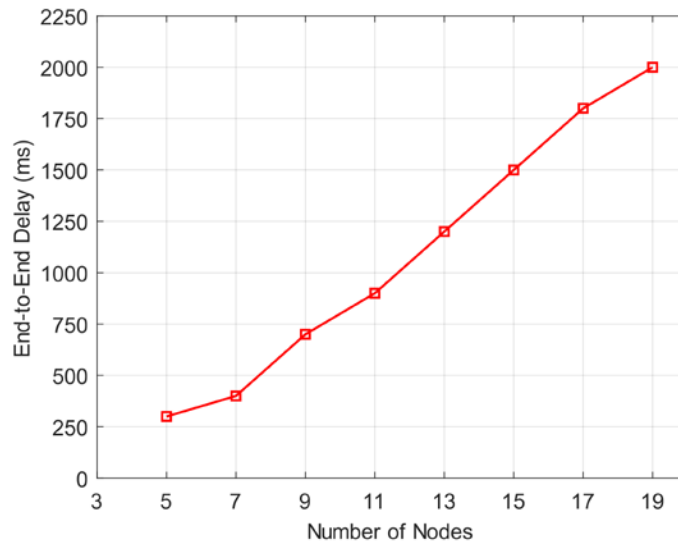
Figure 9 End-to-end delay of selected routing paths for different numbers of nodes in the RPL tree

developed in many ways. Since the root node stores all routing path information in non-storing mode, it creates an exponential storage of path information in memory, which can increase memory cost. In this article, an overview of the RPL algorithm which works on IPv6 networks was provided and the parent selection principles were explained. OFs used during parent selection were also defined. The algorithm was simulated using the Python programming language and by simulating different OFs via various parameters such as packet size, SNR values, and number of nodes. The RPL algorithm behaviour was observed by throughput maximization, energy efficiency maximization, energy consumption minimization, and end-to-end delay OFs and results were evaluated.

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