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Article *in* International Journal of Internet Technology and Secured Transactions · April 2021
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Energy-efficient load-balanced RPL routing protocol for internet of things networks

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Abstract: This article proposed energy-efficient load-balanced RPL (EL-RPL) routing protocol for IoTs networks. In this protocol, a parent selection algorithm is proposed. It selects parent in parent list to be the next hop node toward destination node in networks based on an objective function that combines between the highest remaining energy and the total number of received packets by the parent. This can balance the load on all parents in the parents' list. Besides, the EL-RPL protocol improves DODAG construction by preventing DIO packets transmission to the nodes with the lower ranks. This will lead to save energy and hence enhance the networks' lifetime. Many experiments were performed using the OMNeT++ network simulator to evaluate the efficiency of EL-RPL routing protocol. In comparison with some existing protocol, the results ensure that the proposed EL-RPL protocol can efficiently save energy, decrease the control packets and improve the lifetime of the IoTs networks.

Keywords: internet of things; IoT; RPL routing protocol; network lifetime optimisation; energy load balancing; ELB; performance evaluation.

Reference to this paper should be made as follows: Idrees, A.K. and Witwit, A.J.H. (2021) 'Energy-efficient load-balanced RPL routing protocol for internet of things networks', *Int. J. Internet Technology and Secured Transactions*, Vol. 11, No. 3, pp.286–306.

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1 Introduction

Internet of things (IoT) refers to a massive increase in the internet and capacity to investigate, collect, and distribute data that can be converted into knowledge or information (Umamaheswari and Negi, 2017; Harb et al., 2017; Benayache et al., 2019; Thirukkumaran and Muthukannan, 2019). IoT expands the concept of the internet from a network made up of homogeneous devices such as computers to a network made up of heterogeneous devices like consumer electronics, household appliances, or wireless sensor networks (WSNs) (Elazhary, 2019; Fanian and Rafsanjani, 2019; Mahmud et al., 2019). The heterogeneous information systems can also cooperate and support common services (Le et al., 2014; Idrees and Al-Qurabat, 2017; Idrees et al., 2017; Al-Qurabat and Idrees, 2018). Different environments are proposed smart environment through a direct connection between different types of devices which is part of IoT such as low power and lossy networks (LLNs) (Oliveira and Vazão, 2016). LLNs are inherently different from standard networks because of high restricted resources where routers are restricted in terms of processing power, battery life and memory. The links are suffered from the high packet drops rate. These networks use a wide variety of communication technologies including both wired and wireless. IPv6 over low power wireless personal area networks (6LoWPAN) refer to a milestone protocol which decreases the gap between the IP world and the low power devices. It is an IP founded technology for low power wireless personal area networks (LoWPANs), for example, WSNs, that integrate IEEE 802.15.4 and the IPv6 protocols. This combination gives a new dimension in the layout of 6LoWPANs that enables a maximum inter-operability through the internet (Witwit and Idrees, 2018). In the specification of 6LoWPAN, routing is deemed one of the major issues in 6LoWPAN networks that are worth investigating.

There have been various endeavours for determining the efficiency of routing protocol for 6LoWPAN-compliant LLNs. They proposed several protocols evaluated by ROLL working group (ROLL-WG) which turned out to be unsuccessful in satisfying the requirements of LLNs. For example, the selection of path must be designed to consider the limited power capabilities, functional characteristics, and attributes of the network nodes and links. The ROLL-WG at the Internet Engineering Task Force (IEFT) has suggested protocol called routing protocol for low (RPL) power and lossy networks (Winter, 2012). RPL is a source routing protocol and distance-vector that was constructed to run above the group of link-layer techniques including IEEE 802.15.4 PHY and MAC layers (Winter, 2012; Gaddour et al., 2014). These link layers can be constrained, potentially lossy, or typically utilised in combination with exceedingly constrained hosts or router devices, such as low power wireless or power line communication (PLC) mechanisms. RPL is primarily targeting collection-based networks, in which nodes intermittently send measurements to a collection point. RPL offers a technique that enables the dissemination of information over the dynamically designed network topology. This mechanism utilises a trickle timer to enhance the dissemination of control messages (Winter, 2012). LLNs consist of huge numbers of devices which have restricted resources memory, power and battery processing.

Shortcomings

In spite of various improved RPL routing protocols are designed and achieved with several features such as delay, self-healing, a loop-free topology and load balance. Nevertheless, they are not considered energy-efficient load-balanced RPL (EL-RPL) routing protocol that can balance the load on the nodes of the parent list taking into account the remaining energy of the nodes. Besides, they have not considered the energy-efficient destination-oriented directed acyclic graph (DODAG) construction to decrease the control packet overhead over the IoT network. Whatever the case, this would result in a shorter lifetime in the IoT network.

Our protocol

This article introduced the EL-RPL routing protocol for IoT networks. In this protocol, a parent election algorithm to choose the longest lifetime parent with the minimum load in the parent list to be the next hop node towards the destination node in the network. This can balance the load on all parents in the parents' list. Furthermore, we improve the DODAG formation by inhibiting the DODAG information object (DIO) packets sending to the nodes with the lower ranks. This can lead to maintain the energy and hence enhance the network lifetime.

1.1 Motivation

RPL is an IPv6 routing protocol for low power and lossy networks. RPL is designed to be a simple network protocol and can be run for devices with limited resources in industrial, environmental and civil environments to support the internet vision of objects with thousands of interconnected devices across multiple networks. The original RPL routing protocol suffers from some weak points that need to be improved to increase the performance and the network lifetime. In RPL, the distance computation is absorbed by the objective function (OF). Two OF implementations have been standardised, namely OF0 and MRHOF. However, these OFs build network topologies where the bottleneck nodes may suffer from extreme unbalanced traffic load as well as increased control packets. This is a major problem for the existing OFs defined in RPL because it minimises the performance of the network and decreases the lifetime of it. In this case, energy efficiency is not achieved during the process of creating a topology called DODAGs. In addition, the RPL standard has no switch between the preferred parents (PPs) to balance the load between them. Therefore, it is possible for one PP to be allocated for several children who are adapted to exhaust all his energy and the path fails because of losing this PP, which eventually negatively impact on both the performance and the age of the network. RPL must allow one node to have many parents' nodes, but one preferred master node only functions. Traffic is transferred through this preferred main node and other original nodes are just backup copies. This, in turn, makes PPs suffer from a bottleneck problem, and their exposure to energy consumption is much greater than the other nodes within the topology. The control packet overhead needs to be decreased to save the power inside every node thus extending the network lifetime. Therefore, we need to deal with these points and improve the standard RPL routing protocol so as to save energy, decrease the control packet overhead, traffic load balancing, and extend the lifespan of the network.

1.2 Contribution

The main contributions in this article are outlined as follow:

1. EL-RPL routing protocol for IoT networks are suggested to minimise the energy consumption and extend the network lifetime. It improves the DODAG construction way by minimising the control packet overhead during DODAG construction. This can save more power for the motes and extend the lifetime of the network.
2. Propose a load balancing approach through the PP algorithm to distribute the traffic on the nodes in the PP list. The process of choosing the PP by each node is based on the remaining energy of this parent to balance the energy consumption and load among the parents and thus increase the lifetime of the network.
3. Extensive simulation experiments, using OMNeT++ network simulator, are performed to assess the efficiency of our EL-RPL routing protocol with some recent existing protocols like the IRPL routing protocol (Zhang et al., 2017) and standard RPL routing protocol in (Winter, 2012). Simulation results based on various criteria such as the network lifetime, control packet overhead, energy consumption, energy-saving ratio, and remaining energy show that the proposed protocol can give better performance than the IRPL routing protocol.

1.3 Evaluation strategy

The performance of the proposed protocol is evaluated by having four significant measurements: network lifetime, energy consumption, control packet overhead, and energy-saving ratio. The resultant performance is analysed and compared with the IRPL routing protocol (Zhang et al., 2017) and standard RPL routing protocol in Winter (2012). The proposed protocol has potentially outperformed the other technique in terms of performance metrics.

1.4 Paper layout

The structure of this paper is arranged as follow: Section 2 includes related works description. Section 3 discussed about DODAG. Section 4 talks about proposed EL-RPL routing protocol. Simulation results are explained and discussed in Section 5. Section 6 presents the proposed protocol conclusions and perspectives.

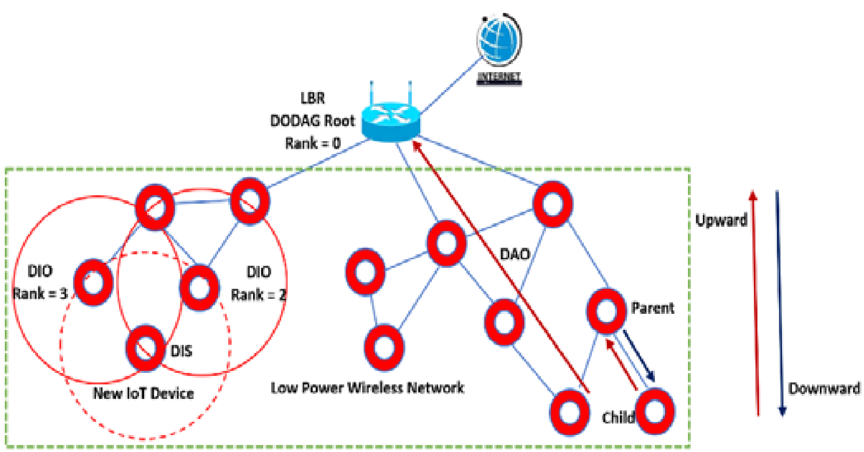
2 Related works

This section gives an overview of some existing protocols based on RPL standard like in Le et al. (2014), Oliveira and Vazão (2016), Winter (2012), El Korbi et al. (2012), Bouaziz et al. (2017), Tian et al. (2013), Marques and Ricardo (2014), Ko and Chang (2014), Djedjig et al. (2015), Iova et al. (2015, 2016, 2014), Zhao et al. (2016, 2017), Aljarrah et al. (2016), Banh et al. (2016), Ghaleb et al. (2017), Kim et al. (2016), Zhu et al. (2017), Zhang et al. (2017) and Lamaazi and Benamar (2018). Le et al. (2014) proposed a way for transmitting the sensed data through a single path from sensors to root. Nevertheless, depending on the unreliability of wireless links and the constraints of sensor nodes, a single path is not an effective strategy to cope with the demands of the performance of different applications. Therefore, the authors suggest three kinds of multipath methods depending on RPL: energy load balancing (ELB), fast local repair (FLR), and their integration ELB-FLR. The work presented by Winter (2012) suggested RPL protocol as a standard protocol for routing in LLNs. This protocol suffers from the increased overhead as well as it does not balance the load among the nodes in the parent list. In El Korbi et al. (2012), the authors proposed mobility enhanced RPL (MERPL) to improve the RPL and balance the traffic over the routes. MERPL outperforms standard RPL in terms of the stability of the path. However, authors do not utilise some major parameters such as the delay of handover, the cost of signalling, and the energy dissipation. An energy-efficient and mobility aware routing protocol named EC-MRPL is suggested by Bouaziz et al. (2017). This protocol provides permanent communication to maintain access to the nodes (MN) regardless of its location. The authors in Djedjig et al. (2015) proposed an improved version of RPL by adding the new trustworthiness meter during the creation and maintenance of the RPL. This metric is the level of confidence for each node within the network and is calculated using the components of selfishness, energy and reliability. Where through this enhanced protocol, each node is allowed to determine whether you trust other nodes while creating a topology. A pragmatic design for a balanced energy RPL is proposed by Iova et al. (2015). They construct a DAG based on the ELT scale, which is estimated by the accuracy of the lifetime of the bottlenecks. Then they propose a multi-track approach to fully exploit the DAG structure. The node exploits all of its parents, assigning its weight to the traffic of each one. In this way, power consumption is distributed on all nodes fairly between all the bottlenecks. The work in Zhao et al. (2016) proposed a new energy-based routing protocol in the region (ER-RPL), where this protocol achieves the delivery of energy-saving data without sacrificing reliability. In contrast to conventional routing protocols that were dependent on all the nodes to discover the route. In Banh et al. (2016), the authors developed other routing standards by taking into account the power consumption of the contract as a guideline because most of the routing measures used do not take into consideration the energy level of the applications, resulting in an imbalance in power consumption between the nodes. They relied on the RDC to estimate the power consumption of the mother node, based on both the power consumption and the ETX as metrics. This proposed method has achieved a better energy balance while maintaining beam delivery ratios and energy efficiency. Zhao et al. (2017) proposed a routing protocol called HECRPL based on RPL, and based on hybrid, energy-efficient cluster-parent and reliability simultaneously. Ghaleb et al. (2017) proposed an improved RPL version called enhanced-RPL. To overcome the problem of storage restrictions from the node, where the node is allowed to be distributed. The prefixes belong to the subnet on more than one parent instead of one parent. The simulation results proved that the proposed protocol outperforms the standard protocol at a rate of up to 30% concerning the delivery rate of the package and 64% in terms of overhead. Zhang et al. (2017) proposed a routing improved RPL routing protocol named IRPL to balance the energy consumption in WSNs. Topology control model is introduced to divide the communication area into equal-area rings. This energy balancing is based on the clustering algorithm in cooperation with a routing mechanism.

3 Destination-oriented directed acyclic graph

RPL is a hierarchical network. It organises the nodes in a topology called DODAGs. However, DODAG represents the essence of RPL (Le et al., 2014). The DODAG structure is similar to the group tree topology where all obstacles are collected in the root. However, the DODAG structure differs from the traditional trees. In the DODAG, each node can have more than two children, as well as the node can be connected to its brother, and supports two-way IPv6 connections between network devices. One of the relevant features of RPL routing protocol is that it combines both hierarchy and mesh topology (Bouaziz et al., 2017). RPL supports the mesh topology as it allows routing through siblings in addition to parents and children. On the other hand, RPL-based network topology is inherently hierarchical as it forces underlying nodes to self-organise as one or several DODAGs based on the parent-to-child relationship. This combination of mesh/hierarchal provides great flexibility in terms of routing and topology management (Kim et al., 2017; Wang and Li, 2014). Figure 1 shows RPL with one DODAG and one RPL instance. RPL uses the deployment of ICMPv6 messages and the trickle mechanism for the construction and maintenance of the network topology (Marques and Ricardo, 2014). In DODAG information solicitation (DIS), a new node may employ DIS to examine its neighbourhood for close DODAGs. DIO is used to build the topology of DODAG. It is broadcasted from the root towards the leaves. Every node it receives it computes its rank and then broadcasts it to its neighbours. The destination advertisement object (DAO) is used to build the routing table inside the nodes and the paths to the root and other nodes in the topology. The sender of the DAO packet will receive a destination advertisement acknowledgement (DAO-ACK) packet from the root node if the DAO is received correctly.

Figure 1 RPL with one DODAG root and one RPL instance (see online version for colours)



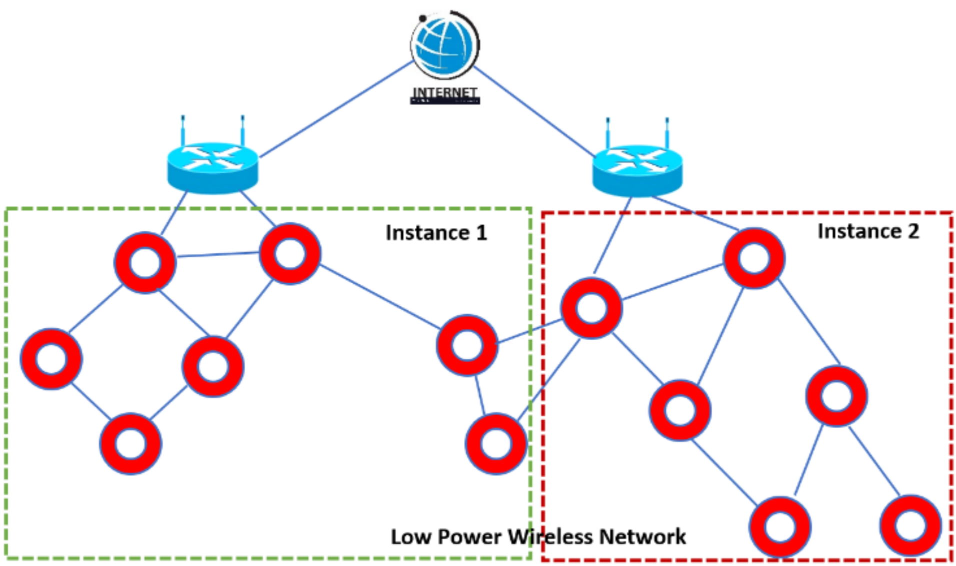
In the RPL topology, within the DODAG, there are two basic conditions to follow:

1 The rank values should increase from the LBR node to the leaf nodes and decrease from the leaf nodes to the LBR node.

2 The packets must be moved either to the upward direction towards LBR, or downwards towards the nodes, considering the rank rule.

The network may contain multiple DODAGs, which together form the RPL with a unique identifier, called an RPL instance identifier (Zhao et al., 2017). In this case, the network runs multiple RPL states simultaneously. But these cases are logically independent. Sometimes, it is possible to join a node to several RPL instances, but it must belong only to one DODAG within each instance (Gaddour and Koubâa; 2012; Kim et al., 2017). Figure 2 shows RPL with two DODAG roots and two RPL instances. Each node within the DODAG contains a list of identified neighbours, node ID, list of the parent(s), rank, and other parameters (Djedjig et al., 2015). The rank is an integer intended to determine the individual node position for LBR and to the other nodes. The nodes at the top of the hierarchy take smaller rank values than those below, and the root is assigned a rank of zero (the smallest rank in the whole network).

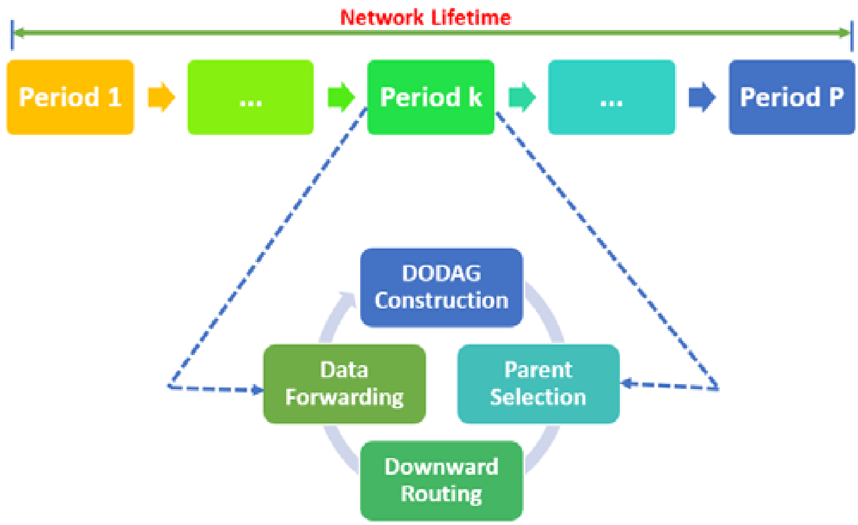
Figure 2 RPL with two DODAG roots and two RPL instances (see online version for colours)



4 EL-RPL routing protocol

In this section, we describe the proposed EL-RPL routing protocol for minimising the energy consumption in IoT networks. The network lifetime is divided into periods. Each period consists of four steps: DODAG construction, parent selection, downward routing, and data forwarding. The period refers to the amount of time required to achieve all the four steps. Figure 3 refers to the proposed EL-RPL routing protocol.

Figure 3 Proposed EL-RPL routing protocol (see online version for colours)



4.1 DODAG construction (upward routing)

All the nodes at this stage are awake and have their transmitters in listening mode for the purpose of getting the message building network DIO. The process of building DODAGs starts with transmitting DIO messages from the root node to the other nodes. The build process is explained in the following steps.

Step 1

The sink/root initialises DODAG information, the root (sink) will broadcast the first control messages DIO that contains the following information: the RPLInstanceID, DODAG identifier, version number, rank, and the OF supported by RPL that has been used to calculate the rank. All nodes within the root communication range will receive a DIO message, and then decide to join the structure or not. The decision to join the node to the graph depends on the node that meets the requirements (if it has enough power to enter the DODAG construction process). When the node meets the conditions, the join depends on the node rank: an incremental value calculated using the predefined target function (OF). Correlation requires that the node rank is not less than or equal to the node rank inside the graph. If the node does not meet the conditions, in this case, the DIO control message is ignored. These nodes that are associated will add the prefix of the sender to its list of parents and calculates the rank based on the following equation:

$$\mathrm{Rank}(\mathrm{node}) \leftarrow \mathrm{rank}\left(\mathrm{parent}(\mathrm{node})\right) + \mathrm{HopRankIncrease} \tag{1}$$

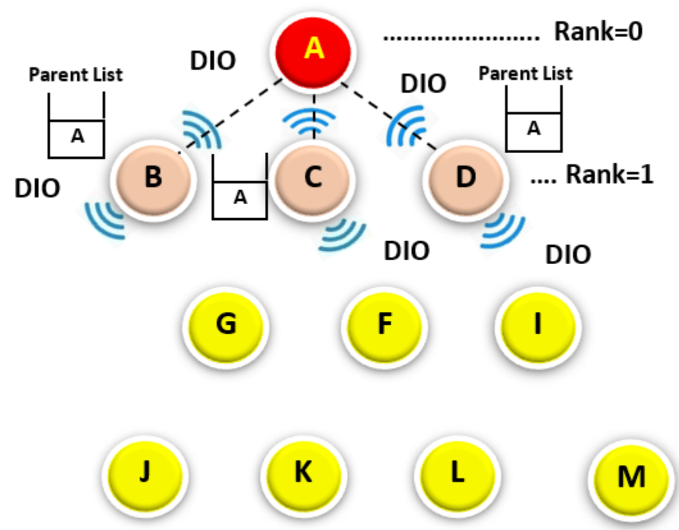
where

Rank (node)	the rank of node received DIO message
Rank (parent (node))	the rank of the parent node that sent the DIO message

HopRankIncrease is a numeric value representing the amount of increase in hops according to the objective function (OF0) followed by the RPL standard protocol, we set the value of this parameter to a value of 1.

After calculating the new rank value, the information of the received DIO message is updated with its own new rank and is broadcasted to all nodes within communication range. This is only for the first period; the other periods will exclude the nodes with lower rank values from sending the DIO message. We have adopted the size of the DIO message based on the standard protocol (128 bytes). Figure 4 shows the DIO messages broadcasting.

Figure 4 DIO messages broadcasting (see online version for colours)



In the next periods that follow the first one, any node transmits the updated DIO message to all the nodes within the communication range except nodes in the list of parents list. This can reduce the number of control messages per node and thus reduce the consumed energy thus increasing the lifetime of the network. This participates in decreasing the control message overhead and reduces the energy consumption per node and thus increases the lifetime of the network.

Step 2

When the other grounded nodes (a node linked to the DODAG) receive the updated DIO message, it will do the following: a grounded node will check the sending node id with all node's id in its parents' list. If they exist in the parent list, the grounded node checks the rank of the node that sent the control message DIO.

If the node rank sent in the control message DIO is larger than the grounded node rank (sender node rank > grounded node rank) the receiving node updates its rank and updates the information of the DIO message and then broadcasts it to all neighbours within communication range expected nodes in the parents' list.

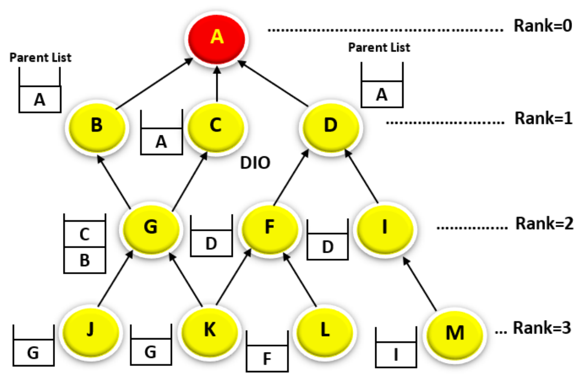
If the node rank sent in the control message DIO is equal to the grounded node rank (sender node rank = grounded node rank) the receiving node updates its rank and updates the information of the DIO message. Then, it broadcasts the updated DIO message to all neighbours within communication range expected nodes in the parents' list.

If the rank of node sent in the control message DIO is less than the grounded node rank (sender node rank < grounded node rank), the grounded node discards the DIO control message.

Step 3

The above steps are continuing until all the nodes have set their default pathways towards the DODAG root. Each node is associated with one or more of the nodes as well as it contain a list of PPs. Figure 5 shows the network after DODAG construction.

Figure 5 The network after DODAG construction (see online version for colours)



After completing phase 1, all of the nodes in the network will have at least a routing entry to its parent that hop-by-hop lead to the sink node. This represents multipoint-to-point (MP2P) forwarding model – also referred to as upward routing – where each node can reach the sink. Figure 6 shows the flowchart of the first stage DODAG construction (upward routing).

4.2 Parent selection algorithm

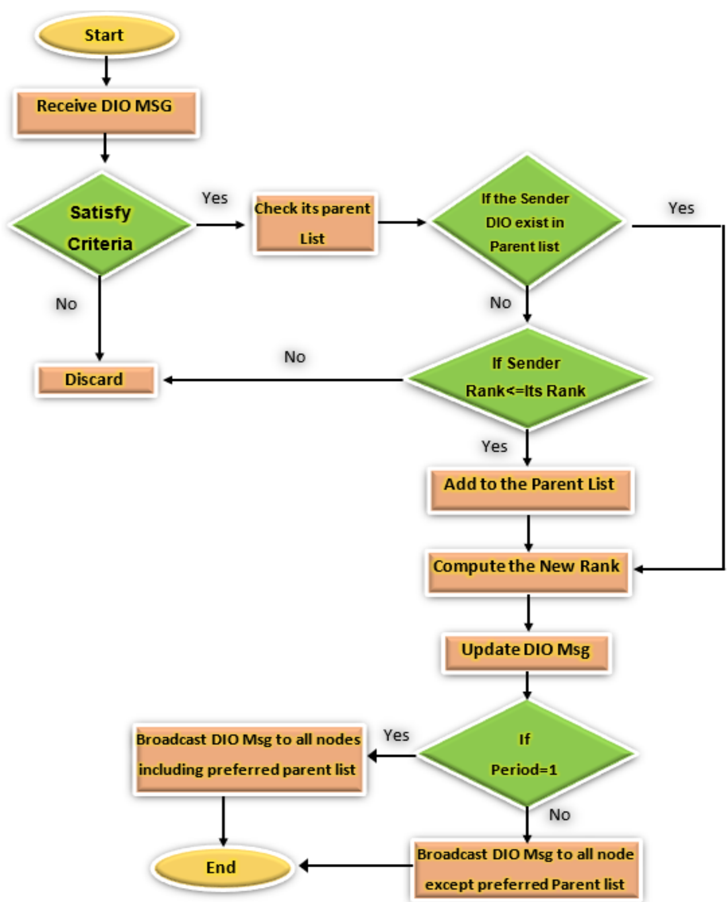
After the end of phase 1, we have a complete DODAG structure in which all the upwarding paths will be drawn. Each node within DODAG has an IPv6 address as an identifier (ID), list of parents, rank (a numeric value determines the individual position of a node for the sink and to other nodes), and other parameters. Every node requires sending control message DAO to the DODAG root (sink) to build downward paths and construct the routing table for each node. Besides, each node needs to send data packet through the intermediate nodes toward the root. This node will send DAO packet to the PP which is chosen from the list of PPs which are stored inside each node during the construction of the DODAG in the building of upwarding routing. The PP will be selected based on the OF. This OF differs from the OF used in the DODAG construction process. This function is defined as follows:

$$Fitness \leftarrow \alpha\left(\frac{E_r}{E_{in}}\right)+(1-\alpha)\left(1-\left(\frac{P_c}{\text{Max}P_c}\right)\right) \tag{2}$$

$$OF \leftarrow \text{MAX}\left(Fitness_i \in N_k\right), i \leftarrow 1, \cdots, N_k \tag{3}$$

where E_r is the remaining energy, E_{in} is the initial energy, P_c is the number of control packets, and MaxP_c is the total number of control packets that will be calculated by the summation of the control packets of all nodes in the parent list. MAX($Fitness_i \in N_k$) returns the parent id with the maximum value for the *Fitness* in equation (2) in the parents list. N_k is the number of parents in the parent list of node *k*. $\alpha \in [0:1]$.

Figure 6 Flowchart for DODAG construction (upward routing) (see online version for colours)



Our EL-RPL protocol used this OF to route the DAO and data packets. This can distribute the traffic load in a balanced way and it prevents the repeated selection of the same parent node for each routing decision. Besides, this will balance the energy consumption over the set of parent list and leads to extend the lifetime of the network as much as possible. Algorithm 1 illustrates the PP selection.

Algorithm 1 PP selection

Require: E_r, E_{in}, P_c, $MaxP_c$, α and N^k

Ensure: OF (the preferred parent of N)

for $j \leftarrow 1$ to N^k do

$\text{Fitness}_j \leftarrow \alpha(E_r^j / E_{in}^j) + (1-\alpha)(1-(P_c^j / MaxP_c^j));$

endfor

$OF \leftarrow MAX(\text{Fitness}_{i \in N^k}), i \leftarrow 1, \ldots, N^k;$ // select one of them randomly in the case of equality.

return OF;

The OF will be calculated for each PP before adding it to the list of PPs. Therefore, the selection of the PP who has the maximum fitness value in the list of PPs. In the case of the equality of two fitness values or more, select one of them randomly.

4.3 Build downward routing (DAO/DAO-ACK forwarding)

These types of routes are needed to support point-to-multipoint (P2MP) communication. In this stage, it will build the downward routing to draw the path between any node and the root/sink within the network to be ready to send the data towards the root. In downward routing, RPL uses DAO packets, where this type of control message is intended to maintain the downward routes and control message DAOs (DAO-ACKs). The downward routing is explained in the following steps.

At this stage, every node that has already joined the DODAG is sending a DAO message to its PP which was selected from the list of parents list based on the PP selection algorithm, to declare the destination prefixes that can be accessed through this node including its prefix.

When receiving the PP of a control message DAO, the message will be processed and the process of control message DAO depends on the operating mode supported by the RPL. There are two modes of operation for the downward paths, storage mode, and non-storage mode. We have relied on storing mode in our enhanced RPL protocol.

- If the PP receives a DAO message from one of its children, acknowledge the DAO sender with status of zero to signal the acceptance of this prefix by return control message DAO (DAO-ACK) with state 0, and store the announced prefix in its routing table along with the address of the sent node control message DAO as the prefix next hop. Figure 7 shows building routing table and control message DAO (DAO-ACK) transmission.
- If one of the PPs received DAO message and it is not able to pass this DAO message or it does not have enough space to store this prefix, it should reject the announced prefix and acknowledge the DAO sender with a DAO-ACK of status of 1 to signal the rejection of this prefix. In the case of rejection of the PP of the control message DAO sent by one of its children, the child should do the following:
    1. Lock the path leading to this PP so that the DAO messages are not sent back towards this PP.
    2. Choose another PP from the parents list and resend DAO to this new PP.

In our work, the storing mode is used in the drawing of the downward routing, where each node receives DAO message, it will store the node's address sent to it in a routing table which is in the form of a table with two fields. The first field is the node index, and the second field is the next hop or the PP of this node to use it to pass control messages or data packet toward their destinations. Figure 8 illustrates the flowchart for building the downward routing.

Figure 7 Building routing table and DAO-ACK transmission (see online version for colours)

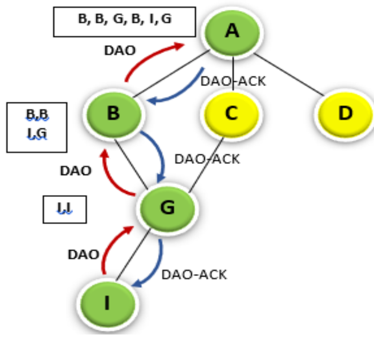
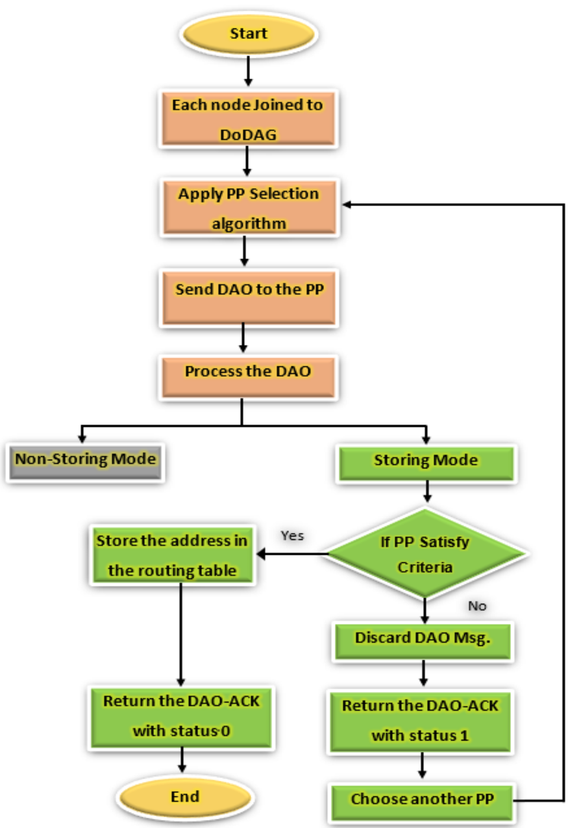


Figure 8 Flowchart for building the downward routing (see online version for colours)



4.4 Data forwarding

After completing the two phases of drawing the upwarding paths and downwarding paths, two basic conditions in the RPL DODAG topology must be verified from the nodes along the route. First, the values of the rank of all nodes within the DODAG topology should increase from the DODAG root down to the leaf/host nodes, as well as a decrease from the leaf's nodes up to the DODAG root. Second, the transmission of packets inside the DODAG is either up towards the DODAG root or down to the leaves nodes taking into consideration the base of increasing and decreasing the value of the rank of the nodes inside the DODAG, that is when the packet node is sent down, the sent node must have a value rank less than the node received for this packet. The node sends a packet towards the top. The sent node must have a value rank higher than the node received in the packet. As soon as the child node receives a DAO-ACK with zero status from its PP, indicating the acceptance of the destination. In this case, the child node transmits a data packet to the destination (root) through intermediate PPs. We identified the number of packets that are sent by each node, which is one packet data for each period. When the child node passes the data packet to its PP will be:

- If the PP is the destination (DODAG root), it extracts the data packet and uses it according to required application.
- Otherwise, if the PP is not the destination (DODAG root), the PP will pass the data packet to its PP as a next hop depending on his routing table toward its destination (DODAG root). This process will continue until accessing the data packet to the root node.

Algorithm 2 Trickle algorithm

```
Require: Imin, Imax and Idoubling
Ensure: I (new interval)
I ← Imin;
Start new interval;
  if (interval I expires) then
      I ← I * Idoubling;
          if (Imax ≤ I) then
              I ← Imax;
          endif
  endif
if (Trickle detects an inconsistent message) then
      I ← Imin;
endif
return I;
```

4.5 The trickle algorithm

Once the construction is completed, the maintenance begins respecting the trickle timer. This algorithm is used as a glowing timer to send control messages (DIO) periodically, to reduce the transmission of repeated messages. The interval between sent control messages is greatly increased until it reaches a fixed rate that is also called the maximum period (I_max). In other words, when DODAG settles, fewer DIO messages are sent. If an inconsistency is detected, the interval is returned to its lowest value I_min. Algorithm 2 shows the steps of the trickle algorithm.

5 Simulation results

In this section, some simulation results using OMNeT++ network simulator were conducted (Varga, 2003) to assess the performance of our proposed EL-RPL by comparing its performance with standard RPL protocol (Winter, 2012) and IRP routing protocol (Zhang et al., 2017). Table 1 gives the relevant parameters for the network simulation. The simulation is performed with four network sizes. Each network is randomly generated over the area of simulation. For calculating the consumed energy by the sensor node during the transmission and reception, we use the energy consumption model proposed by Heinzelman et al. (2002).

Table 1 Simulation parameters

Parameter	*Value*
Area of simulation	100 × 100 m
Number of nodes	20, 50, 70 and 90
Number of sinks	1
Node deployment	Random
Initial power	3 J
Energy threshold	0.017, 0.022, 0.028 and 0.036
Transmission range	50 m
Eelec	50 nJ/bit
Eam p	100 pJ/bit/m^2
Mode of operation	Storing mode
DIOIntervalMin	4
DIOIntervalDoublings	2
DIOIntervalMax	1,048
Data packet size	127 bytes
DIO packet size	128 bits
DAO packet size	64 bits
DAO-ACK packet size	32 bits
Sink position	(x, y) = (50, 0)
Mac protocol	IEEE 802.15.4 beacon-enabled mode

5.1 Performance metrics

We use the following metrics to capture the performance of our protocol and to compare it with standard RPL protocol.

5.1.1 Network lifetime

Network lifetime can be defined as the time elapsed until the first node in the network drains its power (dies).

5.1.2 Energy consumption

In order to count the average cumulative energy consumption in the network, it is computed by the following formula:

$$EC \leftarrow \left(1 - \left(\frac{\sum_{j=1}^{P} \frac{\sum_{i=1}^{n} E_i}{n}}{P}\right)\right) * 100 \tag{4}$$

where EC represents the average value of the energy consumption for each node per period, n denotes the 'number of nodes' in the network, P is the number of periods, and E_i represents the total consumed energy of node i.

5.1.3 Control packet overhead

It is necessary to decrease the number of control packets in the network to save energy and increase the performance of it. This metric is computed by taking the total number of DIO packets during the lifetime of the network and then divided on the total number of periods.

5.1.4 Energy-saving ratio

This metric represents an indication of the ability of the node to save energy during the network lifetime. It is computed as follows:

$$\text{Energy saving ratio} \leftarrow \left(1 - \left(\frac{\sum_{j=1}^{P} \frac{\sum_{i=1}^{n} E_i}{n}}{E_{in}}\right)\right) * 100 \tag{5}$$

where E_{in} refers to the initial energy of the node.

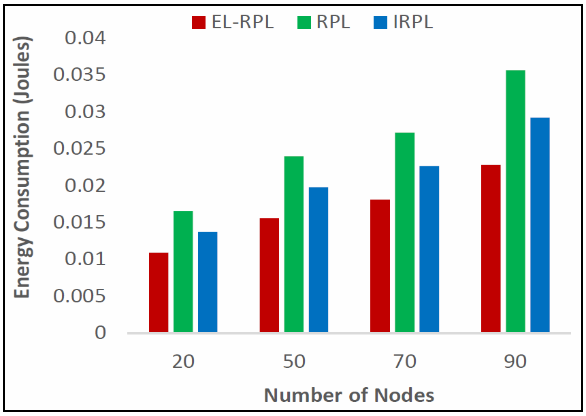
5.2 Performance comparison and analysis

This section introduces the main experiments that were performed to evaluate the proposed EL-RPL routing protocol.

5.2.1 Energy consumption

The energy consumption has an important impact on the lifetime of nodes. It is mainly related to messages transmission and reception, processing (CPU) and idle state or overhearing. The average energy consumption for each node and each period is computed according to equation (4). Figure 9 illustrates the energy consumption in Joules for different network sizes. As shown in Figure 9, the EL-RPL routing protocol consumes less energy in comparison with the RPL and IRPL protocols. Our protocol saves energy from 34% up to 36% and from 20.5% up to 22% compared to the RPL and IRPL, respectively. When the number of nodes increases, the consumed energy increases due to the increased communication cost of the dense network. However, the proposed EL-RPL protocol saves more energy than the RPL and IRPL protocols in spite of the increase in the number of nodes constituting the network that lead to extend the lifetime of the network.

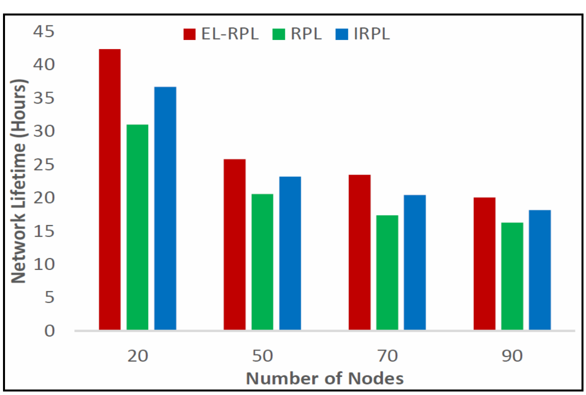
Figure 9 Energy consumption for different network sizes (see online version for colours)



5.2.2 *Network lifetime*

In this experiment, we assess the proposed EL-RPL routing protocol from the network lifetime point of view. As illustrated in Figure 10, the EL-RPL routing protocol provides a significant increase in the network lifetime compared with the RPL and IRPL protocols. This is due to the reduced energy consumption by our EL-RPL protocol compared with RPL and IRPL protocols (see Figure 9). The EL-RPL routing protocol extends the network lifetime from 23.3% up to 36.6% and from 10.4% up to 15.5% in comparison with the RPL and IRPL, respectively. It can be seen that the lifetime of the network will be reduced when the density of the network increases due to the increased communication cost.

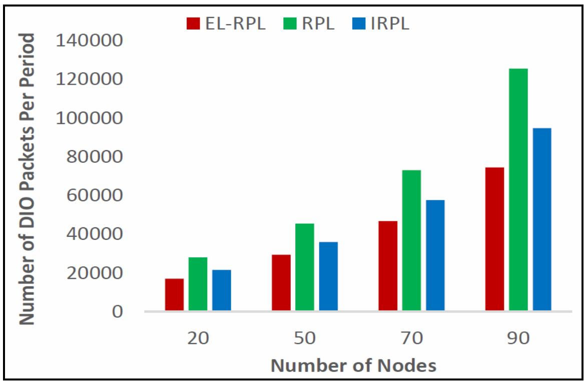
Figure 10 Network lifetime (see online version for colours)



5.2.3 Control packet overhead

This section studies the effect of the number of control packets on the performance of our EL-RPL protocol. Figure 11 shows control packets overhead per period. The EL-RPL routing protocol decreases the number of control packets from 38.9% up to 40.6% and from 20.9% up to 21.4% in comparison with the RPL and IRPL, respectively. It can be seen from the results that the EL-RPL routing protocol decreases the number of control packets due to the improvement in the DODAG construction compared to the RPL and IRPL protocols. The number of control packets overhead increases when the density of the network increases.

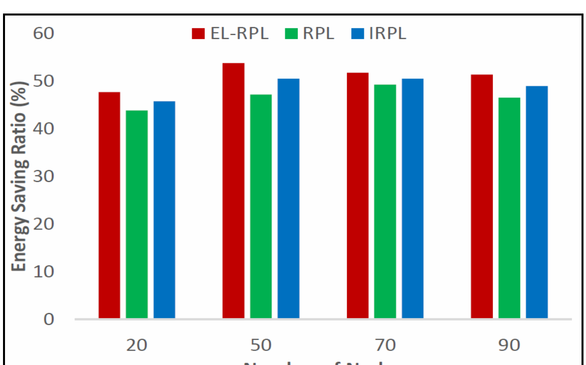
Figure 11 Control packets overhead (see online version for colours)



5.2.4 Energy-saving ratio

In this experiment, the energy-saving ratio inside the node is investigated. It represents an indication of the ability of the node to conserve energy during the network lifetime. It is calculated according to equation (5). Figure 12 shows the energy-saving ratio for different network densities. The EL-RPL routing protocol saves energy from 8.8% up to 9.2% and from 4.2% up to 6.6% in comparison with the RPL and IRPL respectively. It can be shown from Figure 10 that the EL-RPL routing protocol has a higher energy conservation rate than the RPL and IRPL protocols and for different networks sizes.

Figure 12 Energy-saving ratio (see online version for colours)



6 Conclusions and perspectives

This article suggests an EL-RPL routing protocol for IoT networks. A PP selection algorithm is suggested to distribute the load among the parents in the list of parents. The DODAG construction is enhanced through preventing sending DIO packets to the nodes with the lower ranks. This will lead to save energy and hence enhance the network lifetime. The proposed protocol provides an energy-efficient routing way in conserving the batteries power of the low power nodes in LLNs. Many experiments were performed using the OMNeT++ network simulator to evaluate the efficiency of EL-RPL routing protocol compared to two protocols: RPL and IRPL. The results ensure that our proposed protocol can efficiently save energy, decrease the control packets, and improve the lifetime of the IoT network compared to other protocols. In the future, we plan to combine between the different metrics to generate a new OF for selection and persistence of routing paths. The proposed protocol could be improved by considering the reliability of routing. Real experiments would be one of our future objectives to assess the efficiency of the enhanced RPL protocol.

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