Transient Multipath routing protocol for low power and lossy networks

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Abstract

RPL routing protocol for low-power and lossy networks is an Internet Engineering Task Force (IETF) recommended IPv6 based protocol for routing over Low power Lossy Networks (LLNs). RPL is proposed for networks with characteristics like small packet size, low bandwidth, low data rate, lossy wireless links and low power. RPL is a proactive routing protocol that creates a Directed Acyclic Graph (DAG) of the network topology. RPL is increasingly used for Internet of Things (IoT) which comprises of heterogeneous networks and applications. RPL proposes a single path routing strategy. The forwarding technique of RPL does not support multiple paths between source and destination. Multipath routing is an important strategy used in both sensor and ad-hoc network for performance enhancement. Multipath routing is also used to achieve multi-fold objectives including higher reliability, increase in throughput, fault tolerance, congestion mitigation and hole avoidance. In this paper, M-RPL (Multi-path extension of RPL) is proposed, which aims to provide temporary multiple paths during congestion over a single routing path. Congestion is primarily detected using buffer size and packet delivery ratio at forwarding nodes. Congestion is mitigated by creating partially disjoint multiple paths and by avoiding forwarding of packets through the congested node. Detailed simulation analysis of M-RPL against RPL in both grid and random topologies shows that M-RPL successfully mitigates congestion and it enhances overall network throughput.

Keywords: Low power lossy networks, RPL, IoT, congestion, multipath.

The preliminary version of this paper published in 2nd IEEE Asia Pacific Wireless and Mobile (APWiMob) Conference 2015, Sep. 26-28, Indonesia. In this work Packet delivery ratio (PDR) metric is used to detect congestion on forwarding nodes. Article (CrossRef Link)

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1. Introduction

Wireless Sensor Networks (WSNs) are the low power networks that comprise of distributed and self-governing sensor devices. These sensor devices are used to detect the physical environment and the network devices forward the data in multi-hops to the sink (i.e. data collector). Today, WSNs are used in various military, health care and industrial monitoring applications. WSN consists of few to several hundreds of sensor devices [1] where each device has several sensors to monitor the environment.

Low power Lossy Network (LLN) is a terminology, which refers to networks that are composed of limited power, memory and processing with lossy wireless connectivity. Examples of LLNs include Wireless Sensor Networks (WSNs) and Wireless Personal Area Networks (WPANs). It is an uphill task for the LLNs to select reliable and low latency paths to provide high data rate transfer [2, 3]. This is because of poor wireless connectivity and resource constrained nature of devices in LLNs. IETF in this regard recommends the use of routing protocol for low power lossy networks (RPL) for routing in LLNs. The design objectives of RPL includes establishing reliable routing paths, promptly reacting to link failures, utilization of minimum device energy and reduction in computational cost of routing [1].

RPL is a proactive routing protocol, which uses bidirectional links, and it builds Directed Acyclic Graphs (DAGs). The DAGs built with the help of different routing metrics and constraints [4]. Different numbers of Destination Oriented DAGs (DODAGs) construct by RPL for every root (sink) node within the network. DODAG root is a network controller node that constructs the complete DODAG. For construction of DODAG, initially the root node multicast DODAG Information Object (DIO) [5] message with initial rank value 1. The rank defines the relative positions of nodes with respect to sink within the DODAG. Apart from rank value, the DIO contains information about DODDAG ID, routing metrics, objective function, and other network information [1]. Different routing metrics, such as battery power, hop count, delay etc., used in RPL. The Objective Function (OF) in RPL determines how RPL nodes select the optimal path towards the DODAG root in a network [6]. To minimize the cost to reach the root node from any other node in the LLN, RPL uses objective function [1]. A node receives DIO message and uses this information to join the DODAG, update their rank for the selection of preferred parent. The best preferred parent uses by a child node for forwarding packets to the root node [7].

RPL provides single path routing and does not support multi-path routing. Single-path routing achieves with minimum computational complexity and resource utilization but it reduces the achievable outputs of the network [8, 9] and also greatly effects the network performance [10]. In high traffic load when an active path is congested and fails to transmit the data then multiple paths are find for data forwarding to increase the throughput. Multipath routing strives to find several paths from a source to destination. Multipath routing improves reliability, provides fault-tolerant routing and reduces congestion. Existing literature [11, 12] has identified the need for supporting multipath routing in RPL. Despite few research efforts in this domain, providing multipath routing using RPL to support high data rate applications is still an open research area.

In [11] multipath routing is proposed using cross-layer design that violates original standard specifications of RPL as a lower layer independent routing protocol. In [12], multipath extension of RPL is proposed for enhancing network lifetime by load balancing. This work extends [13] in which Multiple paths are created after congestion on path is detected using Packet Delivery Ratio (PDR). In this extended work, we use another congestion detection metric buffer size along with PDR and buffer size provide better congestion detection than PDR. Also, the congestion notification strategy of current work provides better congestion mitigation than proposed in [13]. In addition, in this work, comprehensive results presented in both random and grid topology as compared to simplistic evaluation performed in [13].

The remaining part of this paper is organized as follows; related work is discussed in section 2. Network model is presented in section 3. M-RPL protocol is presented in section 4. Simulation analysis and protocol performance is analysed in section 5. The last section concludes this paper along with future directions.

2. Related Work

RPL is a routing protocol for sensor and ad-hoc network and is more suitable in terms of energy efficiency than exisiting ad hoc routing protocols [14, 15]. In existing literature, RPL performance enhancement using multipath routing is not been investigated particularly. In this section, the existing work is surveyed in non-RPL and RPL based multipath routing scheme.

In [16], multiple extension of dynamic source routing (DSR) is proposed to find the disjoint paths without any extra overhead. Each node broadcasts two route request with same ID and sequence number but using different colors. When multiple requests for route with disjoint paths are received by intermediate nodes then they marked as adjacent path with the help of color. As a result multiple requests travel to the destination and they are replied separately to the source. The source node can then use both paths for sending data.

In [17] a multipath routing scheme is presented to prolong the network lifetime by distributing the load over the network. The network is divided into districts and each district contains the interference-free row (zone). Sink node sends packet to all nodes in network and each node joins the network district based on their location. Each node then transmits packets to the sink node with their residual energy and load. The sink calculates the residual energy of each district and informs source node to forward packets through least utilized multiple districts. This helps in load and energy balancing using multiple paths.

In [18], another multipath routing protocol is presented with the objective of load balancing. It is a reactive protocol where each request contains node’s energy and hop-count. A node receiving route request message can add its neighbor in the primary or secondary path based on the combine value of neighbor energy and hop-count. Also a provision is available to mark nodes that are causing interference in the routing path. Thus the work [18] strives to avoid interference while providing load balancing and taking residual energy into account for creating multiple paths.

Load Balanced RPL (LB-RPL) [12] is an extension of RPL protocol that addresses the issue of packet loss due to buffer limitations. It aims to achieve balanced workload distribution in the network. When a node detects that the network load is increasing and the buffer size has exceeded a threshold then it holds its DIO messages. DIO holding means the delay in transmission of its DIO message. Greater the level of congestion higher will be the hold time. When the child of the congested node does not receive a DIO message from its parent then it assumes link failure. Therefore, it switches to next available parent from the parent list. As a result, the routing path changes and load over the parent node decreases. However, mitigation of congestion using DIO holding cannot immediately react towards congestion and is slow because DIO intervals are usually long (multiple minutes).

In [19], DAG-based multipath routing protocol for mobile sinks is proposed. This protocol allows a node to find alternative paths with other sinks in the network if the connectivity with primary sink is lost. The alternative link or secondary link is found using reactive on-demand approach. When a node detects link failure with primary sink, it requests another sink in the network to build a new DODAG so that the node can establish new path with that sink.

Multipath opportunistic RPL routing protocol [11] is designed to work over IEEE 802.15.4. The objective of this protocol is to provide QoS using multiple paths. It increases packet delivery ratio to minimize overhead and energy consumption. Multipath opportunistic RPL [11] uses a cross layer design approach in which RPL interacts with the underlying link layer. It uses link quality estimations and IEEE 802.15.4 is tailored to provide such information, so that better links are used in DAG formation. A node only forwards higher-priority delay sensitive data through multiple paths to increase packet delivery ratio.

In [20], a congestion avoidance multipath routing protocol with time factor for wireless sensor networks is proposed. In this protocol a new routing metric minimized delay based on ContikiMac is designed to overcome delay towards DAG root. A weights of different paths are calculated using proposed routing metric and other three metrics, including ETX, Rank and the number of received packets. A child nodes learns wake-up phase of its parent and sends packet to first awaken parent node. A part of ConitkiMac is used in this protocol.

3. Network Model

In this section, basic network assumptions, definitions and network characteristics are discussed. M-RPL is suitable for both random and grid topologies for any underlying Medium Access Control (MAC) protocol used with M-RPL. Any node in the network also forwards and originate data. RPL uses a single path between source to destination for data forwarding but M-RPL modifies the existing RPL to achieve multipath routing. It is assumed that multiple paths exist for data forwarding within the network. This is a common assumption as low power device networks such as WSN has high node density [21]. This allows WSNs to have fault-tolerance, higher connectivity and better network coverage [02, 22].

A static low power network is consider for the proposed work where nodes are not mobile. Terminologies of parent and child nodes are frequently used in a DODAG establish by RPL. Considering **Fig. 1**, the node 10 is the parent node for node 4, 7, 12 and 21 whereas it is the child node for node 6. The parent child relation is subject to network conditions depends upon objective function, link quality and mobility of nodes within the network. It is further assumed that nodes within the network has limited buffering capability to save incoming and outgoing packets from the node. The network layer receives forwarding packets from the buffer. This buffer is used in M-RPL for congestion detection purposes. M-RPL only requires the knowledge of current buffer size and does not restricts the use of small or large buffer size within sensor nodes. M-RPL uses DIO message to carry congestion notification towards child nodes. In RPL DIO messages are multi-casted after periodic intervals using trickle timer algorithm and M-RPL does not suggest any changes in the schedule of DIO messages.

Parent Table (PT) is another feature of RPL that is used by M-RPL for splitting of traffic on different paths. Each node in RPL maintains the PT that contains the list of all potential nodes and act as a parent node. When a node receives DIO messages from its neighbouring nodes then it adds them to the PT. So M-RPL uses parent table to select more than one temporary parent for splitting on partially disjoint paths.

RPL is a network layere protocol that obeys the layered principle of protocol design. It provides services only to the above layer, while RPL uses the services of lower layer. M-RPL algorithm does not change the nature of RPL. M-RPL operates on the network layer only. Both conventional layered and cross-layer techniques [11, 12] are proposed in existing literature for congestion detection and mitigation. Cross-layer solutions provide better means of congestion detection but are not generic and require changes in existing protocol stack. Therefore, both congestion detection and mitigation strategies use by M-RPL are confined to network layer.

The possible network layer metrics contributes in the detection of congestion. The congestion is detected by the hop-count, buffer occupancy, packet delivery ratio, packet arrival rate and packet service time (PST) etc. Conventionally, congestion mitigation is done by adjusting the reporting rate of source nodes at the transport layer [23]. On the other hand, network layer focus on selecting less congested paths, multi-path routing and admission control.

In M-RPL mitigation of congestion is performed by decreasing the amount of traffic in the congested region. This is achieved by splitting the forwarding traffic near the congested node on disjoint paths. The splitting of traffic is performed at the congested node or on the previous hop child nodes. M-RPL uses child nodes of the congested node to perform splitting thereby decreasing the traffic load on the congested node.

4. Multipath RPL (M-RPL)

The basic aim of M-RPL algorithm is to provide temporary multipath routing during congestion over a path.

Congestion occurs when the arrival rate of packets exceeds the forwarding rate of packets at a node. In an event based network, sudden impulse of event information is transmitted to the sink, when the critical phenomenon is triggered. Congestion generally degrades the performance of nodes that are near to the event phenomena or that are close to the sink. In the former, data loss due to congestion is one or two hops away from the event region but in the latter this loss is at several hops from the event region. Hence, congestion near the sink has adverse effects on network performance. This not only results in the loss of information but also decreases the network lifetime. **Fig. 1** shows the data reporting path of different source nodes to the sink using arrow heads. Congestion occurs at node 10 as multiple data flows converge at this node.

In the remaining of this section, the operation of M-RPL is explained in length. Operation of M-RPL is divided into two main parts: congestion detection and congestion mitigation. In M-RPL congestion is detected on any forwarding node whereas mitigation of congestion is performed by introducing multipath routing at nodes prior to the congested node.

4.1 Congestion Detection

Congestion in tree based network architecture is subject to high data rate, limited buffer size, interference and convergence of multiple traffic flow from different child nodes to a single parent. Data rate is defined based on application requirements and nature of the phenomena to be observed. Limitation of memory space (buffer) is an inherent design constraint of low power devices. Convergence of multiple traffic flows near a single destination is due to the tree based architecture used by RPL. Interference is subject to the broadcast nature of wireless communication.

The immediate result of congestion over a single path is the loss of packets due to the limited buffer storage. In M-RPL nodes constantly monitor their buffer utilization in order to detect the level of congestion at the node. Using buffer for congestion detection at the network layer has been acknowledged by various existing research efforts in ad-hoc [24] and sensor networks [25].

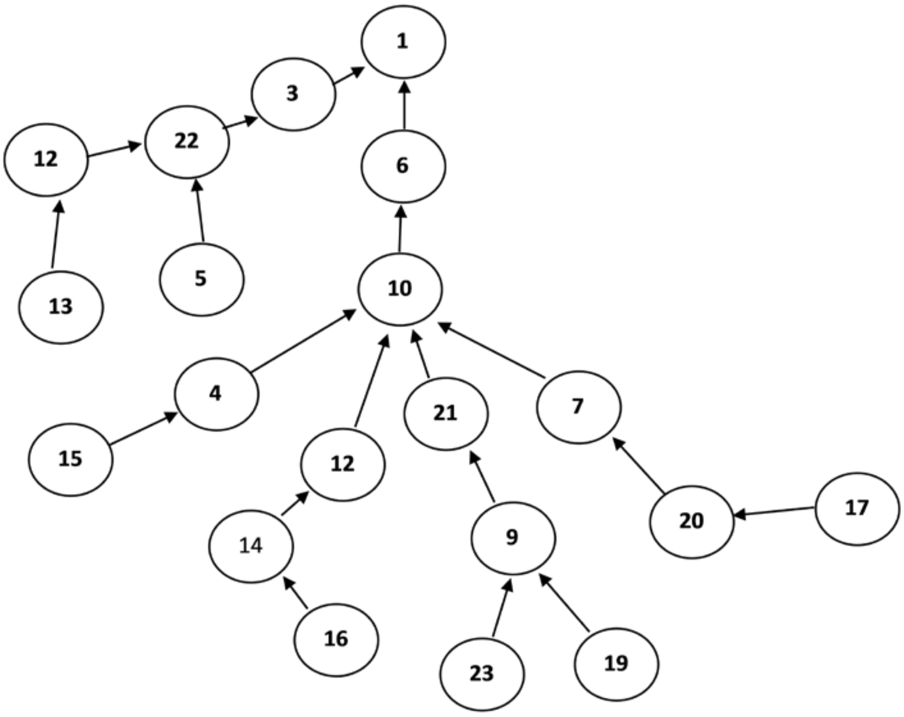


Fig. 1. Multi-hop converge-cast data forwarding in sensor networks

Another metric used for congestion detection in M-RPL is Packet Delivery Ratio (PDR) [13]. PDR can be calculated both at the parent node and at the child node. In the previous case, parent requires information related to numbers of packet sent by individual child nodes to estimate the PDR. While in the latter case, child node requires information regarding the number of packets received by the parent to estimate its PDR. M-RPL uses PDR at the parent node for congestion detection. As compared to buffer base congestion detection PDR requires more computational and communicational overhead. But PDR based congestion detection gives detailed insight regarding individual traffic flows passing through the parent node. As a result congestion mitigation can be applied aggressively on nodes sending higher data. Also PDR information can be furthered utilized for fulfilling the quality of service requirements even during congestion mitigation [26].

4.1.1 Congestion detection using buffer size

Nodes in M-RPL can act as a router as well as data originator. Each node monitors the buffer occupancy ratio after periodic intervals. Buffer occupancy changes randomly during busty traffic generated on event occurs but it is more stable and predictable during periodic data reporting by network devices. Changes in buffer occupancy are related with the availability of underlying medium, hence during congestion over a link the buffer size of intermediate nodes increases. M-RPL uses average buffer occupancy at a node during a certain Congestion Interval (CI) to detect congestion. The length of CI depicts the decision time for the detection of congestion. Very small CI means frequent congestion decisions which may not be appropriated when numbers of traffic flows passing through a node are rapidly changing.

Large value of CI means more delay in congestion decisions that can result in increased packet drops.

If the buffer occupancy exceeds a certain congestion threshold then a notification message is sent to the child node. Congestion Notifications (CN) are sent to the child node by its parent node using periodic DIO message. Hence the overhead of extra transmission of packet is avoided by M-RPL. CN is only communicated when the average buffer occupancy exceeds threshold. As a result, all the DIOs do not carry the CN information. The reserved bit in the DIO messages are used to carry the CN.

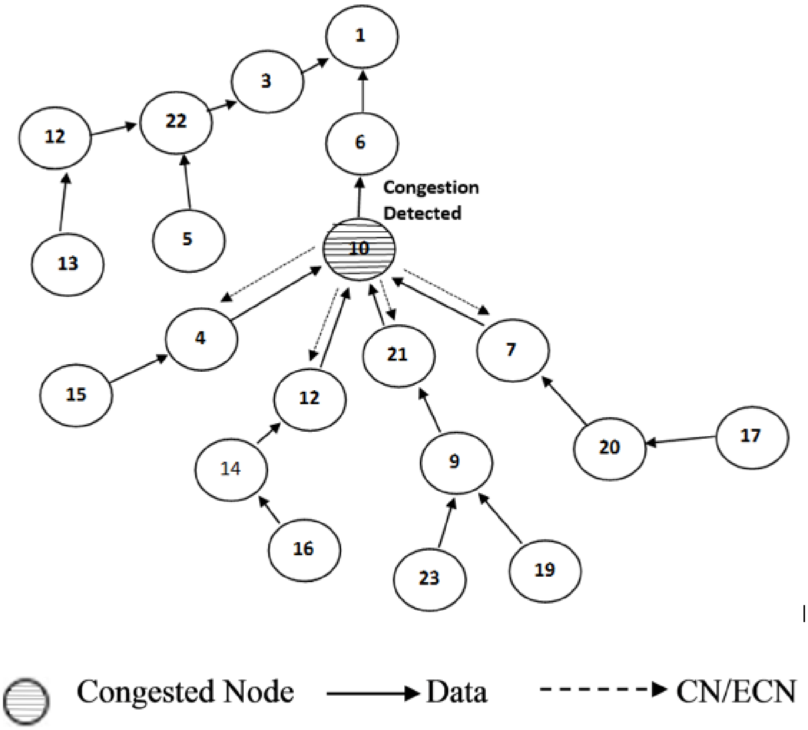


Fig. 2. Message exchange in M-RPL

In RPL, the length of DIO interval can be fixed or it can be variable. In the fixed implementation any explicit value of DIO interval is used as a result. DIO will be transmitted to all the nodes at the expiry of the interval. This causes more energy consumption if the length of DIO interval is small whereas if DIO interval is large, the reaction of RPL towards network changes will be slow.

RPL also allows nodes to adjust their DIO intervals based on network dynamics. Therefore during stable and idle network conditions DIO interval is as large as several minutes whereas during changes in network topology the DIO interval is as low as few seconds. M-RPL uses variable length DIO intervals based on network conditions, as they are more suitable for LLNs.

The length of DIO and CI are not aligned with each other. If CN is to be transmitted after the expiry of CI then the node checks the status of its trickle timer. DIO messages are generated after the expiry of trickle timer. If trickle timer is about to expire, this expire time is the remaining time, which is less than half CI then the DIO that will carry the CN. Otherwise, an Emergency DIO (EDIO) is transmitted immediately to notify congestion. In case of M-RPL, EDIO is the only extra message incorporated in RPL to notify congestion immediately because the normal periodic DIO message is not available at that time.

In **Fig. 2** a small network is shown in which node 10 observed congestion. The arrow heads represent the flow of different messages used in M-RPL. CN travels only to the child nodes of the congested node that will take necessary action for congestion mitigation.

In **Algorithm 1**. Each node calculates buffer size ($C_{buffer\text{-}size}$) and forwarding packets (Pkt_counter++) every time when it receives packets. When trickle timer is about to expire (CI Expired) then node calculates average buffer size (Avg_buff_size) and notify to child nodes if it is more than threshold value.

Algorithm1: Congestion due to Buffer_Limitation

Ensure: Congestion Detection

```
FOR EACH pkt received DO
    IF pkt_dest_address NOT EQUAL TO current_node
        obtain current buffer size ($C_{BV}$)
        increment pkt counter on for every new pkt (Pkt_counter++)
        $C_{buff\text{-}size} = C_{buff\text{-}size} + C_{BV}$ ($C_{buff\text{-}size}$ currently observed total buffer size)
    END IF
END
IF CI Expired THEN
    Avg_buff_size=$C_{buff\text{-}size}$/ $C_{Pkt\_counter}$
    $C_{buff\text{-}size}$ = 0, $C_{Pkt\_counter}$ =0; (resetting variables)
    IF Avg_buff_size > Cong_TH THEN   (Cong_TH congestion threshold)
        send Avg_buff_size to child nodes
    END IF
END IF
```

Algorithm 1: Congestion detection algorithm based on buffer overflow

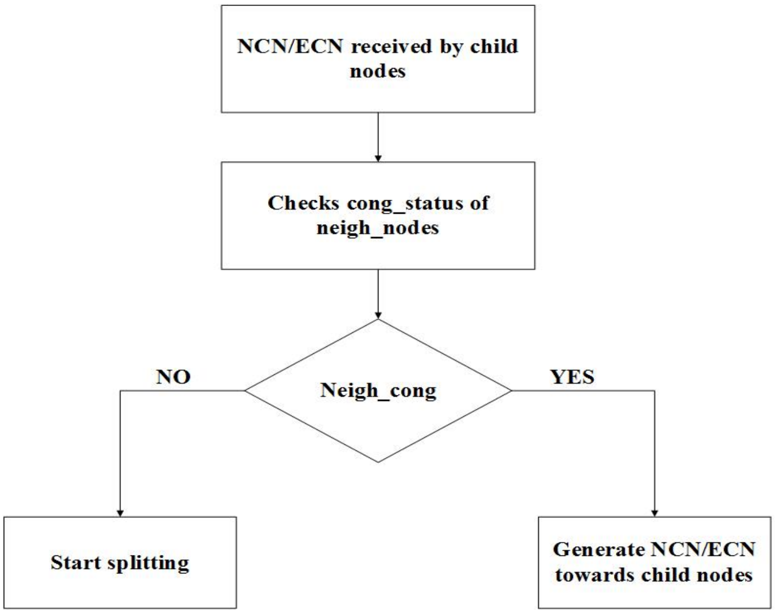
4.1.2 Congestion detection using PDR

PDR is another metric that is used by M-RPL for congestion detection. PDR is calculated by all the nodes between source and sink that are involved in the routing of information [13]. In order to calculate the PDR a node must have the information of each child node's expected data rate. In M-RPL a child node uses DAO messages for communicating its current forwarding rate to the parent node. The expected data rate at any node during the CI is equal to the aggregate data rates of all its child nodes. The use of CI and congestion notifications as explained in previous section are similar if congestion is detected using PDR.

4.2 Congestion Mitigation

The flow chart of congestion mitigation is shown in **Fig. 3**. Congestion mitigation is triggered when a child node receives a DIO message containing congestion notification. The child node that receives the DIO message starts multipath routing and split the forwarding rate into half. The child node forwards one packet to its original parent who is congested and forwards the next packet to any other node from the parent list maintained in PT. Therefore, during congestion mitigation a node drops its forwarding rate to the congested node to half.

The rest of the data is forwarded through alternate path using any other parent node. Thus the child nodes strive to reduce forwarding packets to the congested node and this helps in the reduction of the congestion at their parent node. It is possible that a child node can select another congested neighbouring node for temporary forwarding of data when its original parent has sent CN. In order to avoid forwarding packets to congested neighbouring nodes, each node also keeps the CNs of their neighbours in their PT. This does cost extra communicational or computational overhead as nodes in RPL listen to their neighbours DIO for topology maintenance. Congestion mitigation by splitting of information over two routing paths is performed on the immediate child of the congested node. The work effective, if the child's neighbours are not congested because in wireless medium access all nodes are sharing the same medium. As a result in M-RPL, the CN can be further multi-casted towards the source nodes. If the status of 50% of the neighbour nodes in the PT nodes is congested then a node receiving CN from its parent will rely this message further towards source node. Congestion notification is communicated by the congested node after every CI. If a child node does not hear CN from its parent node then it stops splitting the forwarding traffic. Fig. 4 shows the creation of multipath during congestion at node 10. The congestion notifications are sent to child nodes 4, 7, 12 and 21 which start splitting of their forwarding traffic towards the congested node. The dotted line in figure 6 represents the partially disjoint paths as a result of traffic splitting. It seems that node 4 further sends the CN to its child nodes because it's neighbour are congested.



NCN/ECN received by child nodes	=>	Congestion notification received from congested parent nodes.
Checks cong_status of neigh_nodes	=>	Child nodes check the congestion status of their neighbours through PT.
Neigh_cong	=>	If neighbour nodes are not congested then child nodes start splitting, otherwise send congestion notification to their children.

Fig. 3. Flow chart of Congestion Mitigation

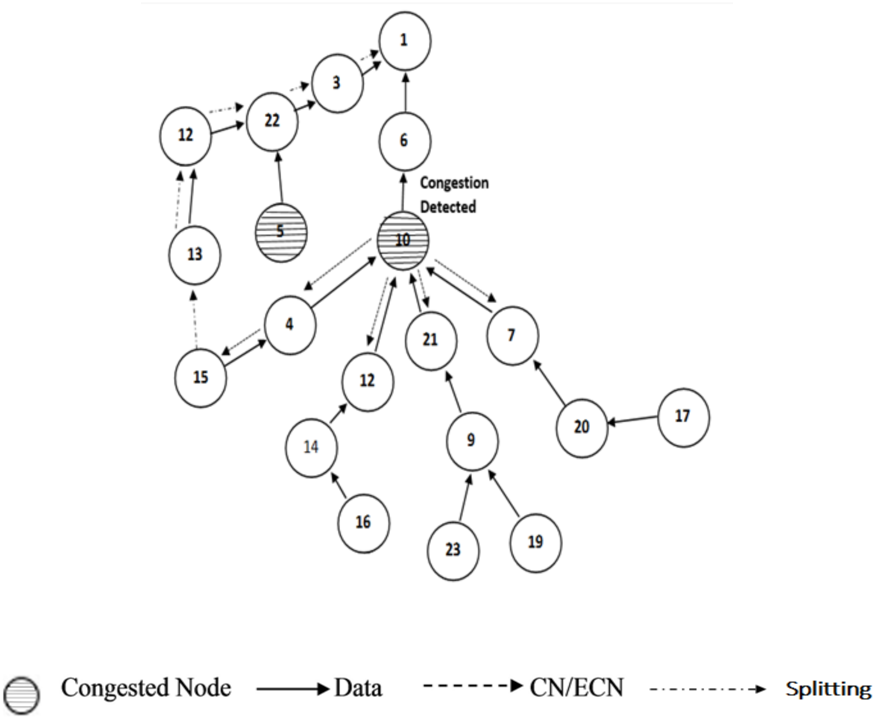


Fig. 4. Splitting on partially disjoint paths using M-RPL

5. Performance Evaluation

In this section the performance of M-RPL and RPL is analyzed in both random and grid topology. In order to test the performance of a protocol common network deployments of real-world scenarios is considered in which either arranged topologies such as grid are used or random arrangement of nodes is used. Hence, simulation in both scenarios are conducted**.** The M-RPL and RPL is simulated in Cooja [27] simulator in Contiki operating system [27]. Contiki [27] is an open source, highly portable, flexible, networked and multi-tasking operating system for low power and memory-constrained wireless internet of things (IoT) devices. Contiki OS uses the Cooja [27] simulator for simulating the performance of network and protocols. Cooja is a java-based simulator and emulator. Cooja is developed for windows and Linux platform. Cooja is examined and controlled by Contiki OS.

The sensor nodes are randomly deployed in 100x100m. **Fig. 5** shows the random topology and **Fig. 6** shows grid topology, in these figures (i.e. **Fig. 5** & **Fig. 6**) the sink node 1 is placed on the corner of the network. The circle at the bottom of **Fig. 5** and **Fig. 6** shows the event reporting nodes that are at multi-hop distance from the sink. Different nodes are uniformly, within the sensor field, generate the background traffic. Different network parameters which are used in the simulation analysis are illustrated in table I. In [12] very low data rate of two packets (i.e. 1 packet per 5 minutes) were used but it is not suitable for high data rate applications.

Table 1. Network Parameter used in simulation analysis

Parameter	Value
Network Layer	RPL/M-RPL
MAC Layer	802.15.4
Topology	Random/Grid
Simulation Time	1000s
Event reporting	900s
Objective Function (OF)	RPL-mrhof
DIO minimum interval	4 sec
DIO maximum interval	17.5 min
Data intervals (single packet per interval)	0.5,1,1.5,2 sec
Number of source nodes	2-12
TX range	20 m
Interference range	35 m
Packet size (excluding header)	50 Bytes
Tx power	0.0174W
Rx power	0.0188W
Wireless Transceiver	250kbps 2.4GHz IEEE 802.15.4
RF frequency range	Min: 2400MZz Max: 2483.5 MHz
Maximum queue length/buffer size Minimum queue length/buffer size	16 packets 0 packets

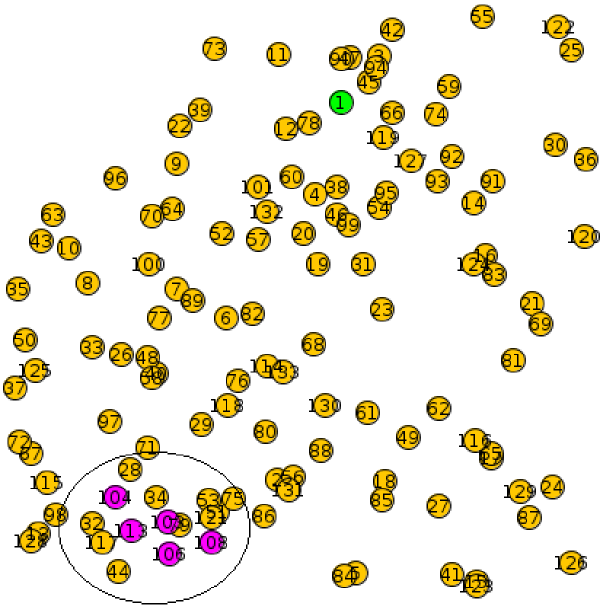


Fig. 5. Sensor network random topology used for simulation analysis

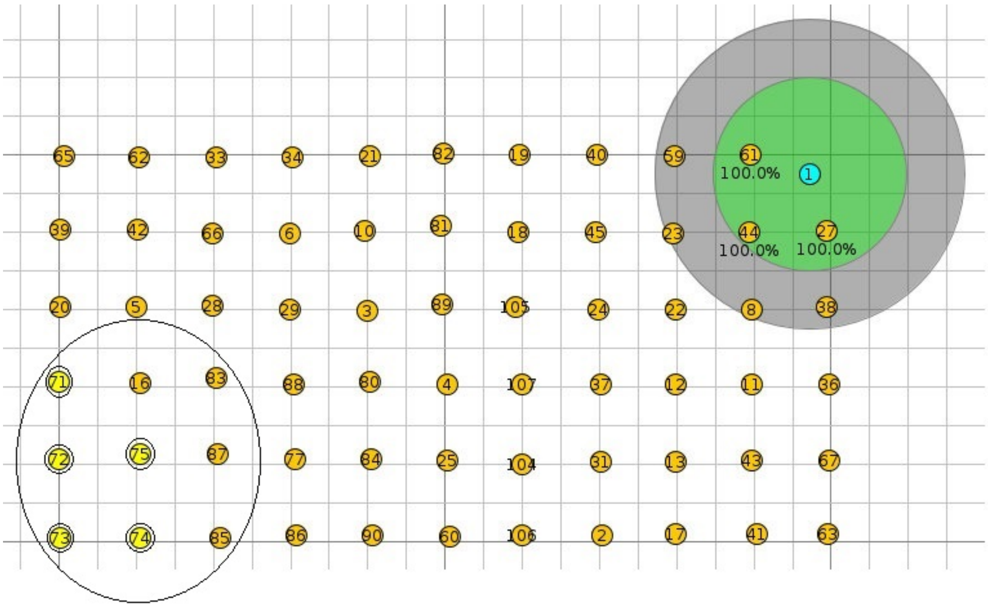


Fig. 6. Sensor network Grid topology used for simulation analysis

In the research work high data rate of one packet per two minutes and low data rate one packet per 0.5 minutes are used. The overall performance of M-RPL and RPL is evaluated by using different performance parameters which are throughput, end-to-end latency and energy. All simulations are simulated up to 1000s and reporting starts after 100s because initial time is required to converge topology. All simulation are executed for 10 times and average results are presented. Results of Grid topology are represented with name GT-M-RPL and Random topology with RT-M-RPL. Results of Grid topology is comparatively better than random topology because of position of nodes. More alternate paths are available in grip topology compare to random topology.

The collective throughput of random and grid topology are observed at the sink, is shown in **Fig. 7** and **Fig. 8**. Five source nodes are generating one packet per second from the event region for 900 seconds. Packets are dropped and congestion occurs as the traffic converge on certain nodes near the sink. Throughput of RPL is persistently lower than M-RPL because the single paths used by RPL get congested. On the other hand, M-RPL splits traffic near the congested node over different paths resulting the decrease in congestion and increase in 40% throughput than RPL**.**

The **Fig. 9** shows the average throughput which is observed at the sink node for M-RPL and RPL under different packet intervals of 0.5, 1, 1.5 and 2 seconds. Lower packet interval means higher data rate whereas higher packet interval means lower data rate. Throughput of M-RPL is significantly better than RPL, according to **Fig. 9**, because of all packet generation interval and of multi-path routing. It is observed from **Fig. 9** that as the data rate is decreased (1 pkts per two sec) the performance of RPL gets better because congestion is not severe.

The average end-to-end delay of RPL and M-RPL is shown in **Fig. 10**. The latency of both the protocol is high because the devices which are using in simulation have very low duty cycle therefore nodes spent most of their time in sleep mode compared to active mode. It is noticed that initially the delay of M-RPL is similar to RPL.

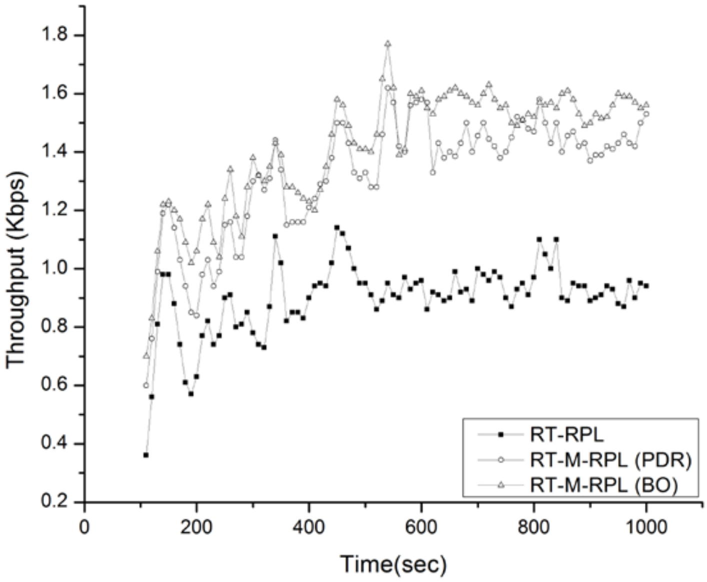


Fig. 7. Average throughput of RPL, MRPL in Random topology

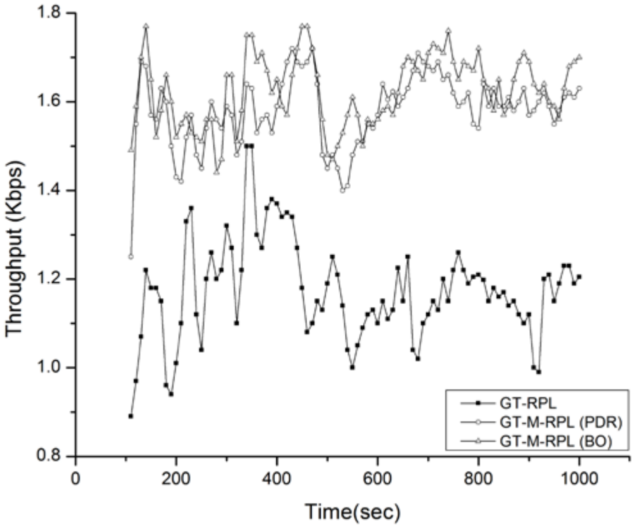


Fig. 8. Average throughput of RPL, MRPL in Grid topology

The similar delay of M-RPL and RPL is because M-RPL initially establishes a single path for data routing as defined by RPL. However, after the detection of congestion at any congested node data splitting start resulting in the creation of multiple routing paths. At the start of data splitting the latency of M-RPL is slightly greater than RPL because multiple paths are

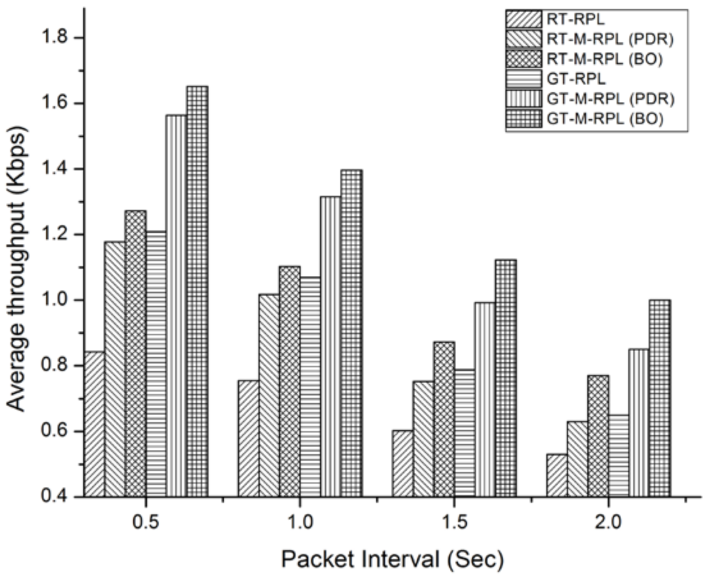


Fig. 9. Average throughput of RPL and M-RPL under different packet generation intervals

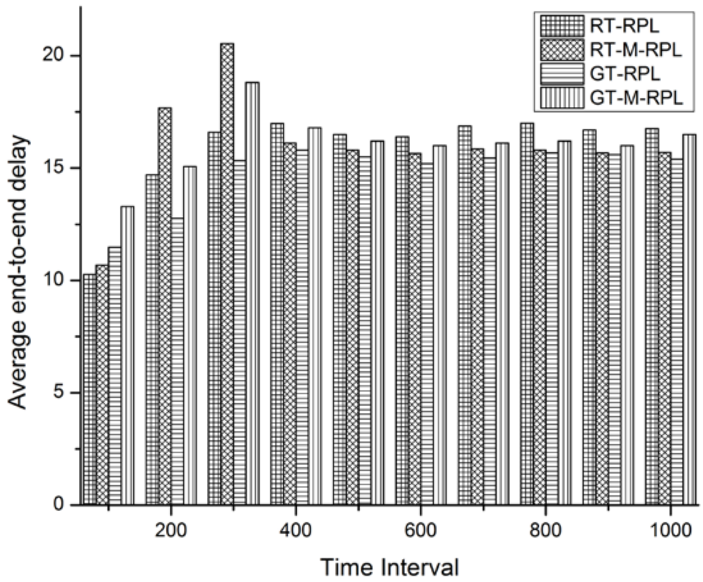


Fig. 10. Average end-to-end delay observed at sink node

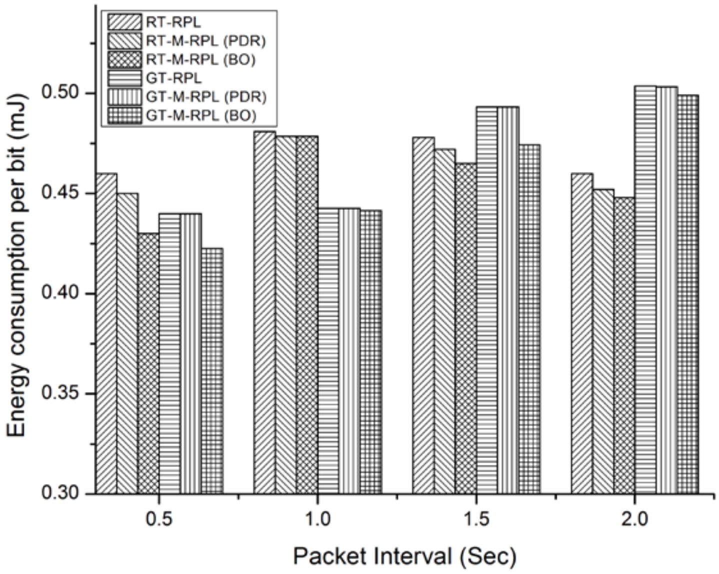


Fig. 11. Average per-bit energy consumption of RPL and M-RPL at different packet generation intervals

introduced. It is also observed that the delay of RPL decreases and becomes similar or less than M-RPL because data is continuously reported and congestion becomes persistent that forces RPL nodes to change their parents. This results in change of network topology and also results in increased delay. Thus as data is continuously reported the end-to-end delay of M-RPL stabilizes and becomes less than RPL.

Fig. 11 shows the average per-bit energy consumption of M-RPL and RPL at different packet generation intervals. Per-bit energy is calculated by dividing total energy expenditure by total number of bits transmitted/received within simulation time. RPL has higher packet drop ratio, which results in wastage of energy on unsuccessful transmissions. Despite the fact that M-RPL creates more than one path by splitting of traffic flows as congested node. The M-RPL has lower per bit energy consumption than RPL. M-RPL has higher packet delivery ratio and less packets are dropped that results in decrease of energy wastage.

6. Conclusion

RPL is the standard protocol recommended by IETF for IPv6 based LLNs. The current standard of RPL supports single path routing. In this research work, Multipath extension of RPL is proposed termed M-RPL.The proposed protocol is aimed to provide higher throughput compared to RPL using temporary splitting of traffic flow after congestion is detected. M-RPL has proposed two methods for congestion detection at the network layer using either buffer size or PDR. Intermediate nodes on the routing path are responsible for congestion detection. Once it is detected by any node, it is used either implicit or explicit measures to notify congestion to its child nodes. The previous hop (child nodes) based on the congestion notification start data splitting by forwarding alternate packets to any neighbouring node apart from preferred parent. This helps in reducing congestion on the congested parent node and results in the creation of partially disjoint paths.

Detailed simulation analysis of M-RPL with RPL is performed in grid and random topologies. According to the conclusion of performance analysis it is stated that M-RPL significantly increases the throughput of RPL with the introduction of multi-path routing. Also, energy consumption of M-RPL is slightly improved as packets loss are reduced which cause wastage of transmissions. The end-to-end latency of M-RPL is similar to RPL which highlights that the selected multi-paths are not un-optimal paths and are established only when required. The average packet delivery rate observed using RPL at different data rates is approximately 53% whereas M-RPL achieves 64% and 74% delivery rate with buffer size and PDR based congestion detection methods, respectively. In future, M-RPL can be enhanced to support mobile network scenarios and it can be extended to support routing to multiple sinks.

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