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Unveiling the Dynamics: A Performance Analysis of RPL under Congestion in IoT Network

Vikas Srivastava[1], Aditi Paul[2] and Somnath Sinha[3]
[1-2]Department of Computer Science, Banasthali Vidyapith, Rajasthan, India
Email: sriv.vikas@gmail.com, aditi23.mca@gmail.com
[3]Department of Computer Science, CHRIST Deemed to be University, Bengaluru, India
Email: ssin.mca@gmail.com

***Abstract*— The Routing Protocol for Low Power and Lossy Network (RPL) is a standardized routing protocol for resource constraint devices deployed in diverse applications in Internet of Things (IoT). RPL is the most efficient protocol which is carefully designed to meet energy efficiency of sensor nodes. However, this protocol is prone to network congestion which is one of most crucial bottlenecks of this protocol. In the current study a thorough analysis of effect of congestion on RPL routing metrics are analyzed. We have designed a congestion scenario using Cooja simulator and analyzed its effects on ETX, Power, Duty Cycle through graphs. The results of the experiments finally outline the critical parameters affected due to congestion in RPL.**

***Index Terms*— RPL Protocol, congestion parameters of RPL, ETX and congestion, RPL metrics in Cooja.**

I. INTRODUCTION

The most widely used protocol for Internet of Things is RPL which is specifically designed for lossy and low power communication termed as LLN (Low power and Lossy Network). This type of network is built with thousands of tiny sensor nodes which can create communication between multiple devices. Due to the power and storage constraints of LLN, routing is a complex task in such network. To address the challenges of this network Internet Engineering Task Force (IETF) introduced Protocol for Low-Power and Lossy Network termed as RPL. In today's era RPL is one of the most popular and widely used protocols in IoT due to its efficiency and ease of implementation in IoT applications. RPL is a type of distance vector routing supported by IPv6. Its routing mechanism follows Destination Oriented Directed Acyclic Graph (DODAG) approach to calculate the best path towards the destination [1]

One of the most demanding properties of RPL is its optimized total power and reliable data reception. The RPL metrics are available on each node and are used to estimate each neighbor node's rank to identify their position from the parents. Under DODAG, the nodes in RPL exchange a set of ICMPv6 protocol control messages which are DODAG Information Object (DIO), DODAG Information Solicitation (DIS), and DODAG Destination Advertisement Object (DAO).

DIO messages set up and maintains upward routes of RPL. DIO maintains a trickle timer to elimination duplicate control messages.

DAO messages set up downward route and advertise prefix towards node of DODAG.

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DIS messages are broadcasted by an internal or external node when it wants to join the network. Upon receiving a DIS message the neighbor node sends the DIO message back to the node.

RPL is used in diverse applications of IoT which cause variety of application-based issues. One of the most common issue is congestion. In LLN even a low-rate traffic can create congestion in highly concentrated network. Congestion hampers multiple metrics of RPL which can be identified and analyse for possible congestion control mechanisms. Th

RPL metrics: in the current study four crucial RPL metrics are considered to evaluate. These are Expected Transmission Count (ETX), Hop count, Radio Duty Cycle (RDC) and Power Consumption. These metrics are available in Contiki OS in Cooja simulator which is a open source simulator for running RPL

Expected Transmission Count (ETX): one of the most frequently used metrics is ETX that ensures link quality, reliability and congestion in a routing environment. The lesser the ETX value the better the path is optimized. A path with minimum ETX[2] value is selected by RPL for sending packets to the parent.

ETX is a measure of highest count of transmission and retransmissions desirable to deliver each packet toward destination. The ETX of sink node is always 0. ETX can be calculated by estimating the number of transmitted data packets and ACK packets received during a successful transmission :

$$ETX = 1/(Df*Dr).$$

- DF- is probability that a packet is correctly received by the neighbour
- Dr-probability of acknowledgment packet is successfully received.

The above formula depicts that ETX and PDR are inversely proportional to each other. If the PDR increases, the ETX can be 1. On the other hand, with a lower PDR, multiple retransmissions are required to successfully send a packet to the destination. This obviously increases ETX. Mobility also affects ETX. In spite of the mobility, ETX can opt a better route if the transmission is faster and links are available [3].

Hop count: another important link metric of RPL is the Hop count which is expressed as average number of hops that a data packets goes through to reach the destination. The minimum number of hops are desirable to reach a destination. Thus, hop count is a metric that selects the paths with minimum hop count. [4]

Power Consumption: it is the most important metric that is considered to analyse the performance of RPL under congestion. Power Consumption greatly varies with node density, PDR and duty cycle. Power consumption of a network is the aggregation of CPU and LPM power along with Listen and Transmit power. In Cooja simulator there are some applications like CollectView, PowerTrace and Power Tracker applications which record / estimate power consumption of network along with node wise graphical representation [5].

Duty cycle: Finally, the duty cycle represents the ratio of the estimated time slot the node is ON [6] to the length of the entire cycle. of the time a node 's signal is ON [6]. During any communication a node is alternatively switched ON and OFF for energy conservation. The total duration a node is ON and OF is combinedly called as cycle time. Duty cycle is the ratio between Active time and Cycle time of a node during a transmission. This is one the most experimented metrics in RPL as it can save energy and optimize network performance substantially.

Cause of congestion in RPL: The most promising factor of RPL is the congestion control. Congestion is inevitable consequence of DODAG construction. RPL is designed for low power lossy networks where traffic rates are moderate or low. However, RPL is used in many IoT applications where traffic is dense and congestion occurs very frequently. This creates a simultaneous issue of imbalance DODAG creation. The objective function OF of RPL uses ETX and Hop count to calculate the best route towards parent. This does not consider the buffer occupancy [7] of the neighboring nodes and hence ignores congestion near the parent nodes. Thus, under high traffic, the performance of RPL degrades due to congested parent and this causes packet loss and delay. Congestion also persists under light traffic condition due to occurrence of imbalanced load distribution among parent nodes.

In the current study we analyze the effects of congestion on RPL metrics. We have shown that the effect of congestion on certain routing metrics are intense and their variations at different scenario is considerable. Congestion is an inevitable consequence of any network which happens due to multiple factors as discussed. To execute the analysis, we opt for open- source simulator which is easy to use and designing congestion is not hazardous. Cooja simulator comes with RPL Collect file in which RPL source and sink nodes are implemented. Running this file in Cooja with Tmote Sky sensor module gives us desired environment. We use the Unit Disk Graph Medium (UDGM) as the radio medium [8].

The rest of the paper is organised as follows:

Section II represents a concise literature on RPL congestion parameters and their behaviors under congestion. Section III designs the congestion models of RPL in Cooja simulator. Section IV implements the model, Section V analyzes the model, Section VI conclude the paper with certain future scopes.

II. Literature Review

Recently, several insightful surveys on RPL have been proposed. In [9] authors proposed a load-balancing technique for reducing congestion in the 6LowPAN gateways. the technique finds the best neighbor based on minimum values of some routing metrics like link quality, hop count etc. the proposed technique is evaluated in NS2 simulator resulting higher capacity with lower overhead.

The works in [10] modelled congestion problem as non-cooperative game and proposed a solution using Lagrange multiplier data transfer rate to minimize congestion level. the work was implemented in Contiki OS and a considerable congestion reduction is proved as a result.

In [11] authors proposed a new objective function for RPL by combining ETX and Buffer Occupancy (BO) metrics for controlling congestion in both high and low traffic condition. The proposed scheme was tested in Contiki OS and results showed considerable reduction of congestion in varying network size.

In [12] a hybrid congestion control mechanism for 6LoWPAN network is developed by combining resource control and traffic control strategies the proposed hybrid model considered ETX, BO and latency as three major metrics which are optimized to reduce congestion in the network. the work showed higher performance than some existing state-of-the-art congestion techniques.

Lodhi et.al. in [13] proposed a Multipath RPL for avoiding congestion. According to this technique a node once detect congestion to the forwarding path has to follow a disjoint path temporarily provided by the technique. This technique increased the over all throughout with reduced congestion in the network.

In [14] authors proposed a multi-criteria based decision making approach to select best parent node under congestion. The proposed approach considered multiple routing metrics along with observing the traffic trends at the nodes to optimize the route. Simulation results showed that the proposed method outperformed some of the equivalent existing congestion control techniques.

Coladon et.al. in [15] proposed a new heuristic algorithm to calculate a “redundancy constant” for each node by using the neighbor count. This approach reduced unfairness of the nodes in distributing traffic equally al over the network. the proposed method was emulated in Contiki OS showing a considerable improvement on neighbor synchronization.

III. Proposed Model

In the current study we design a congestion scenario for RPL based network to understand the protocol’s behaviour under congestion states. The RPL nodes select optimized paths by using specific routing metrics which are ETX, Hop-count, Power consumption and Radio Duty Cycle. For RPL protocol, these metrics values are to be optimized to increase network lifetime. In the current study we observe and analyse the variations of these metrics by changing transmission range of the network nodes. The uniqueness of the proposed method is the creation of congestion by varying transmission ranges. Congestion can be caused due to multiple parameters among which transmission range is predominating. With varying transmission range under fixed topology, congestion scenario also changes. The proposed method focusses on variation of RPL metrics due to congestions at different transmission range.

Four congestion scenarios are created with four different transmission ranges. We started with lowest transmission range set as 40 meters and then progressively reach to 60 meters with intermediate ranges as 50 meter and 55 meters.

The topology for each environment are same and total number of nodes are also fixed. This means the node density will have no effect on the routing metric for this model.

Our aim is to understand the behaviour of the selected metrics under each environment with only variations of the transmission range. Basically, each congestion scenario only varies in the transmission range keeping other metrics constant. This helps us to understand the variation of other metrics with congestion.

The estimation of ETX and Radio Duty Cycle (RDC) is shown below:

RDC: RDC is calculated as the percentage of Transmit Duty cycle by summation of Listen and Transmit Duty Cycle of all nodes in a network.

Thus RDC= ((Transmit Duty Cycle + Listen Duty Cycle)/Transmit Duty Cycle)) *100

ETX= The Expected Transmission Count of a link is the projected number of data transmissions and retransmissions required to send a packet over that link[4].

The ETX of a multi hop link is the sum of the ETX for each link up to the destination.

ETX calculated by transmitted and received packets delivery ratios of the link. The probability of successful reach of a transmitted packet is denoted as df, whereas the probability of an acknowledgement message is received against the transmitted message is called the reverse delivery ratio, dr.

$$ETX= 1/(df*dr)$$

In the current study we analyse the variations of these metrics with varying congestion scenario.

IV. IMPLEMENTATION

In the proposed model we create four congestion scenarios with varying transmission ranges.
Congestion 1 has transmission range 40 meters for each node.
Congestion 2, 3 and 4 have transmission range 50m, 55m and 60 m respectively.
The network is built in Cooja3.0 simulator with 25 nodes among which one is sink node (node 1) and the rest are sources (Fig. 1). Simulation is run for 150 (Table I) seconds in each congestion scenario and traces are generated in each case. Topology used is Tree topology. The transmission range are 40 m, 50 m, 55 m and 60 m in four congestion scenarios. The trace files are .csv files in Cooja and have multiple routing metrics. In our study we only considered those metrics that show considerable variations due to congestion(Table II).

TABLE I. SIMULATION PARAMETERS

Parameter	Values
Network Layer	RPL
MAC Layer	802.15.4
Packet Size	75 bytes
Transmission/interference ranges	40,45,50,55,60/100
Topology	Tree
Simulation duration	2.5 minutes
Number of nodes	25
Type of nodes	Sky Mote
Wireless channel model	UDGM

Fig. 1. Simulation set up of congestion in Cooja

The RPL routing metrics are then analyzed to identify the effect of congestion on these. Among multiple routing metrics the sensitive ones are identified. These metrics are ETX, Hop counts, Power consumption and Duty Cycle. The variations of each routing metric with transmission ranges are observed and analyzed. Some of the crucial inferences that are derived are explained below:
ETX vs Transmission range: the effect of congestion in RPL is best observed from ETX variations. Since ETX define the ratio of packet sent and successful acknowledge received from the neighbor node, its shows an increased average value with higher congestion.
Hop-count vs transmission range: for a fixed topology hop-count varies with transmission range. If the transmission range is increased the sensor nodes come under the radio range of distant nodes which intern decreases the hop-count. Thus, in a low congested network hop-count is lower. Higher hop-count also signifies a dense network where the probability of congestion is also high.
Power Consumption vs Transmission range: In a less congested network, link failure is less which creates communication paths to the sink for a greater number of neighbor nodes. This causes increased number of nodes' participance in the communication which intern increases average power consumption of the network.
Duty Cycle vs Transmission range: Radio duty cycle of a node is the ratio of cycle time (sum of listen and transmit duty cycle) and transmit duty cycle(duration the sensor node is active mode). In the context of current congestion scenarios this parameter also varies with congestion. However, there are other factors also which paly crucial roles in controlling duty cycle.

TABLE II. CONGESTION SCENARIOS WITH VARYING TRANSMISSION RANGES AND RPL METRICS

Congestion Metrics of RPL (Cooja)													
	Average values of RPL metrics												
Transmission Range	No of Nodes	Received	Lost	Hops	Rtmetric	ETX	CPU Power	LPM Power	Listen Power	Transmit Power	Power	Listen Duty Cycle	Transmit Duty Cycle
40	25	1.091	0	2.636	1676	55.66	0.316	0.154	2.746	1.549	4.766	4.577	2.918
50	25	1.2	0	2.067	1065	37.79	0.388	0.152	3.6	1.677	5.816	6	3.158
55	25	1.235	0	1.882	1183	35.32	0.528	0.148	4.393	2.36	7.428	7.321	4.444
60		1.429	0	1.524	870.5	24.77	0.494	0.149	4.766	1.896	7.305	7.944	3.571

V. Result Analysis

After implementing four different congestion scenarios and identifying the sensitive RPL metrics which are affected, a comparative analysis is done. In this section these variations are depicted graphically.

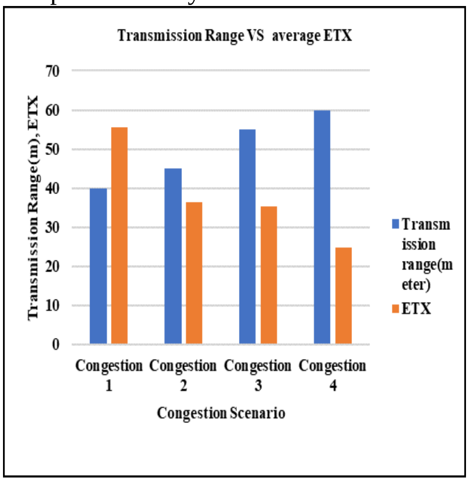

Fig. 2. Variation of ETX with congestion

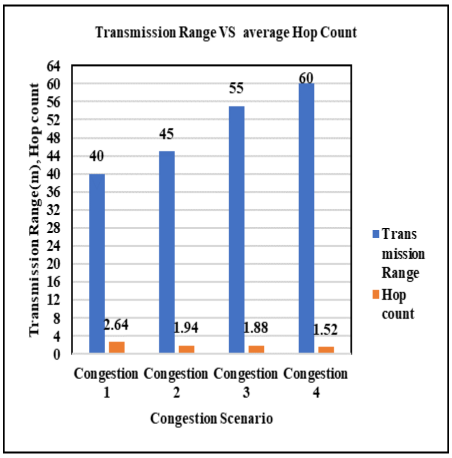

Fig. 3. Variation of average hop count with congestion

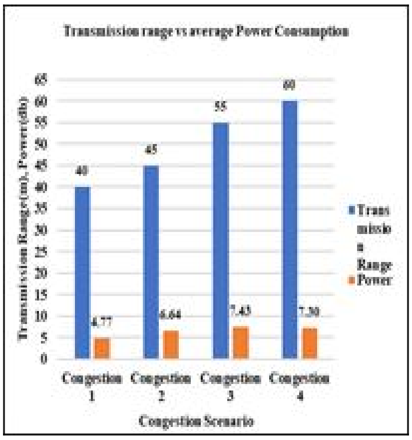

Fig. 4. Variation of average total power with congestion

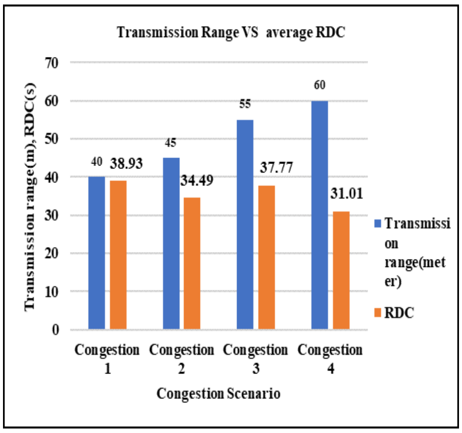

Fig. 5. Variation of average RDC with congestion

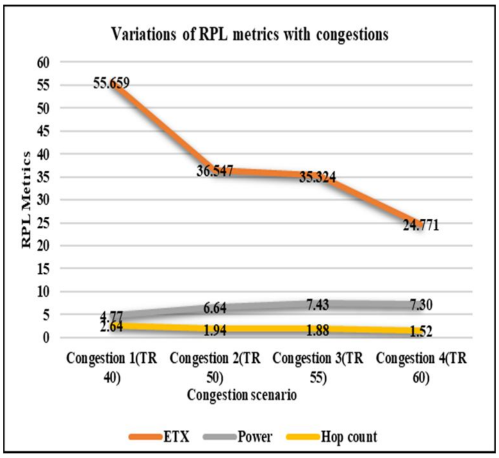

Fig. 6. variations of RPL metrics with congestions.

Fig. 2 represents the variation of average ETX with congestion. In congestion scenario 3 the value of ETX is lowest wherein it is the highest for congestion scenario 1. This is because with higher transmission range(60m) more nodes find route to the sink node and thus more packets reach the destination. Hence ETX decreases.
Fig. 3 shows that the average hop count of the network decreases as congestion decreases. This is because with increasing transmission range direct links are setup between the nodes causing lesser hop count.
Fig. 4 represents total power consumption of the network in each congestion scenario. Total power consumption increases as congestion reduces. Since the number of communications increase in a lesser congestion scenario more packets are transmitted more energy consumption of the nodes.
In Fig. 5 we plot total radio duty cycle vs transmission range. Here the value of RDC decreases in lowest congestion (Congestion 4) than the highest (congestion 1). But intermediate congestions do not affect much the RDC. This is because the RDC is a factor of other network parameters and hence transmission range cannot define the overall variation of RDC in a network.
Finally, in Fig. 6 we represent the variations of all the sensitive RPL metrics that are prominently affected due to congestion.
The result analysis shows that ETX is the most sensitive RPL metric which is affected by congestion in RPL protocol. In a low congestion state the neighbor nodes send acknowledgment for a greater number of sent packets which decreases ETX. The reverse happens with higher congestion state. At the same time with increased transmission range more direct routs are established causing lesser ETX and hop counts, higher successful communication, and thus more power consumptions in the network.
Another important observation of the current study is that considering a single metric like hop count does not explain the effect of congestion on a RPL network. To minimize congestion, multiple metrics are to be optimized at a time. This is the most crucial aspect of a network as optimizing multiple routing parameters may not always minimize congestion.

VI. Conclusion And Future Scope

In the current study a critical analysis of RPL metrics under congestion is represented. The study identifies the RPL metrics showing high variance under increasing congestion scenario. ETX, Hop-count and Power consumptions are most crucial parameters showing considerable variations under congestion. The study illustrates the less sensitive parameter as RDC which overall shows a decreasing trend as congestion decreases. But a thorough analysis shows that RDC is not a controlling factor of congestion only.
In future a more detail analysis is to be executed to represent the RDC metric's variations and controlling factors in RPL based networks. As RDC is one of the most important properties of any protocols, more intense analysis remains as the future aspects of the study.

Reference

[1] Winter, T.; Thubert, P.; Brandt, A.; Hui, J.; Kelsey, R.; Levis, P.; Pister, K.; Struik, R.; Vasseur, J.P.; Alexander, R. RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. RFC 6550. 2012. Available online: https://tools.ietf.org/html/rfc6550 (accessed on 25 January 2019

[2] A. Nirapai and S. Chantaraskul, "Centralized Control for Dynamic Channel Allocation in IEEE 802.15.4 Based Wireless Sensor Networks," Eng. J., vol. 18, no. 4, pp. 151–164, 2014.
[3] J. Vasseur;, M. Kim;, K. Pister;, N. Dejean;, and D. Barthel;, "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks," rfc 6551, 2012.
[4] Alvi, S.A.; Ul Hassan, F.; Mian, A.N. On the energy efficiency and stability of RPL routing protocol. In Proceedings of the 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, Spain, 26–30 June 2017; pp. 927–1932.
[5] F. Österlind, J. Eriksson, and A. Dunkels, "Cooja TimeLine: a power visualizer for sensor network simulation.," Proc. 8th ACM Conf. Embed. Networked Sens. Syst. (SenSys 2010), pp. 385–386, 2010
[6] Li, G., Li, F., Wang, T. et al. Bi-adjusting duty cycle for green communications in wireless sensor networks. J Wireless Com Network 2020, 166 (2020). https://doi.org/10.1186/s13638-020-01767-5
[7] Farag, H.; Österberg, P.; Gidlund, M. Congestion Control and Traffic Differentiation for Heterogeneous 6TiSCH Networks in IIoT. Sensors 2020, 20, 3508. https://doi.org/10.3390/s20123508
[8] Al-kashoash, H.A.A.; Al-Nidawi, Y.; Kemp, A.H. Congestion-Aware RPL for 6LowPAN Networks. In Proceedings of the IEEE Wireless Telecommunications Symposium (WTS), London, UK, 18–20 April 2016.
[9] Ha, M.; Kwon, K.; Kim, D.; Kong, P. Dynamic and distributed load balancing scheme in multi-gateway based 6LoWPAN. In Proceedings of the 2014 IEEE International Conference on Internet of Things (iThings), Taipei, Taiwan, 1–3 Septembar 2014; pp. 87–94.
[10] Al-Kashoash, H.A.A.; Hafeez, M.; Kemp, A.H. Congestion control for 6LoWPAN networks: A game theoretic framework. IEEE Internet Things J. 2017, 4, 760–771.
[11] Al-Kashoash, H.A.A.; Hafeez, M.; Kemp, A.H. Congestion control in wireless sensor networks by hybrid multi-objective optimization algorithm. Comput. Netw. 2018, 138, 90–107.
[12] Al-Kashoash, H.A.A.; Amer, H.M.; Mihaylova, L.; Kemp, A.H. Optimization-based hybrid congestion alleviation for 6LoWPAN networks. IEEE Internet Things J. 2017, 4, 2070–2081
[13] Lodhi, M.A.; Rehman, A.; Khan, M.M.; Hussain, F.B. Multiple path RPL for low power lossy networks. In Proceedings of the 2015 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob), Bandung, Indonesia, 27–29 August 2015; pp. 279–284.
[14] Bhandari, K.S.; Hosen, A.S.M.S.; Cho, G.H. CoAR: Congestion-aware routing protocol for low power and lossy networks for IoT applications. Sensors 2018, 18, 3838.
[15] Coladon, T.; Vučinić, M.; Tourancheau, B. Multiple redundancy constants with Trickle. In Proceedings of the Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Hong Kong, China, 30 August–2 September 2015; pp. 1951–1956.