Research on Enhancing RPL for Improved Performance in IOT Networks

Hangkum Sao Chang, Maitreyee Dutta

Abstract: RPL (IPv6 Routing Protocol for Low-Power and Lossy Net- works) was developed by IETF (Internet Engineering Task Force) as the protocol for LLNs (low power and lossy networks) that comprise of resource constrained components such as those used in Internet of Things applications. Since then the research community and the industry have come up with many enhancements of RPL aimed at achieving a diverse range of objectives that include better performance under heavy traffic loads, higher throughput, lower packet loss, energy conservation, longer network lifetime, mobility of nodes and enhanced security. This paper presents a review of the various methods proposed to achieve these objectives. A comparative review and a taxonomy of these methods are presented in this paper. We aim to provide valuable insights into RPL and present the foundation for future works.

Keywords: IoT, objective function, mobility, RPL.

I. INTRODUCTION

LLNs comprise resource-constrained sensors that have limited processing power as well as memory power. These sensors sense the environment and forward their data to a border router (BR) via a network called DODAG. Due to the ease of installation and wide area coverage, LLNs have been used in several settings.

For example, in manufacturing industries can be made more secure and efficient by using temperature sensors and proximity sensors. In the area of disaster management, strategically placed sensors can upload data for early warning system, victim localization and evacuation and data analytics[1][2][3]. As seen in [4] farmers can yield greater profits through judicious use of water for irrigation with the help of water sensors in tanks that monitor water usage and soil moisture sensors that detect when and where irrigation is required.

When these LLNs are connected to the Internet, what we have is popularly known as Internet of Things.

The integration of IoT with cloud computing can lead to developments in the field of farming, forestry and livestock[5]. Better health care services can be improved by combining IoT with Big Data for health diagnosis and for monitoring various stages of cure [6].

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Also in smart homes, sensors can provide surveillance, enable users to manage and conserve energy through remote management of devices [7]. The vision of a smart city can also be achieved by improving utilities and services provided to the citizens through the use of IoT in the governance and administration of the city[8]. According to Gartner's Hype Cycle[9], IoT is in a really exciting phase, expanding each day with a number of innovative inputs that are driving its growth.

The IETF designed and standardized in [10] a routing protocol called Routing Protocol for Low Power and Lossy Networks (RPL) to be used in LLNs deployed in various scenarios [11] [12] [13] [14][15]. RPL organizes the nodes in the form of a routing graph called as DODAG (Direction oriented Directed Acyclic graph) in which the nodes form a tree like structure with a root node. DODAGs are primarily aimed for data collection from the leaf nodes and their transfer towards the root via intermediate nodes[16]. In terms of implementation of RPL, ContikiRPL [17] and TinyRPL [18] are the two most popular operating systems and most of the research work mentioned in this paper also use them.

This paper is organized into the following sections. Section II provides a brief overview of RPL. Section III classifies the enhancements into different categories according to the desired goals. Sections IV, V, VI, VII and VIII review papers that fall under different categories.

II. RPL OVERVIEW

RPL functions as a distance-vector in that it tries to find the best path for data packets based on distance. Based on the flow of direction RPL traffic can be either point-to-multipoint, multipoint-to-point or point-to-point traffic. A rank is associated with each node in such a manner that the root node has the lowest rank and its child nodes have ranks higher to it. Parent child relationships are formed according to an Objective Function(0F). During the topology formation process when a node receives a packet from one or more nodes, it selects a parent node according to the OF. IETF defined two OFs, Objective Function Zero(OF0)[19] and Minimum Rank with Hysteresis Objective Function(MRHOF) [20]. In [21] a list of metrics used for rank calculation is given.

RPL organizes the network of nodes as a DODAG. Figure 1 illustrates a simple DODAG with a single root and several leaf nodes. The structure of DODAG defines the parent child relationship between the nodes. The data collected at the leaf nodes flow towards the root DODAG root, also called as Border Router (BR) that connects the LLN to the internet.

One or more RPLs may form an RPL instance with a unique RPLInstanceId.

A. RPL control messages

DODAG is formed using ICMP control messages of which there are three types (figure 1):

a) DODAG Information Object (DIO): It is broadcasted by the root and carries the following information

i. RPLInstanceID: an 8 bit id that uniquely identifies an RPL instance.
ii. Version Number: the version number of the DODAG that gets incremented every time the DODAG gets repaired.
iii. Rank: a 16 bit rank of the sender.
iv. Grounded: a flag
v. DODAGID: a 128 bit unique IPv6 address of a DODAG.

b) DODAG Information Solicitation (DIS): This message is released by a node when it wants to be part of a DODAG. It is replied by a DIO from a neighboring node.

c) DODAG Advertisement Object (DAO): It is used to send destination information in an upward direction, to the parents. The receiver can acknowledge the DAO by sending a DAO-ACK. It carries the following information (figure 3):

i. RPLInstanceID: an 8 bit identifier of the DODAG.
ii. DAOSequence: a value that is incremented for each new DAO.
iii. DODAGID: a 128 bit address that uniquely identifies the DODAG.

d) DAO-Ack is an acknowledgment message from the receiver to the sender in response to an DAO message.

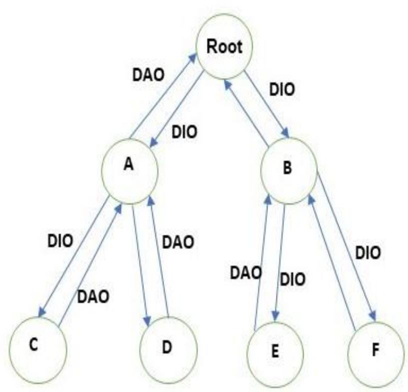

Figure 1: Structure of DODAG

B. Trickle timer

The nodes periodically send DIO messages to maintain the DODAG [22]. The rate at which the DIOs are generated is decided by the Trickle timer. The timer works in such a way so as to optimize the generation of control messages in response to changing network conditions. The interval of transmission of DIOs decreases whenever there is an inconsistency in the network topology and the interval as the network stabilizes. The timer starts with a value between Imin and Imax and it keeps on doubling as long as the network is stable until it reaches the value Imax. In case of any topology inconsistency such as a change in rank, change in preferred parent set or preferred parent, the timer is reset to Imin.

III. CLASSIFICATION OF ENHANCEMENT SCHEMES

In [23], the challenges of RPL have been highlighted such as local repair causing packet delays and trickle algorithm not being suited for fluctuating links. A lot of research has been done to enhance the working of RPL discuss to handle various challenges such as mobility, high traffic, energy consumption and improved security. We have grouped the work done into the following categories based on desired goals:

a) Mobility of nodes [16-27]
b) Load balancing under high and uneven traffic conditions [28-37]
c) Energy conservation [38-50]
d) Emergency response [51-55]
e) Security [74-86]
f) Others [87-90]

Table I summarizes the papers studied and provides a comparative analysis based on the results obtained in the simulations and parameters used to measure the efficiency of the proposed scheme. Figure 2 provides an overview of the various methods used to achieve the specified gaps in native RPL.

Out of the research publications reviewed in table I, only 5 % validated their schemes through experiments using testbeds whereas 95%of the papers relied on simulations for their study. The most widely used simulator was the Cooja simulator [24], accounting for 60% of all simulators used which was followed by NS network simulator with 17% (Figure 3).

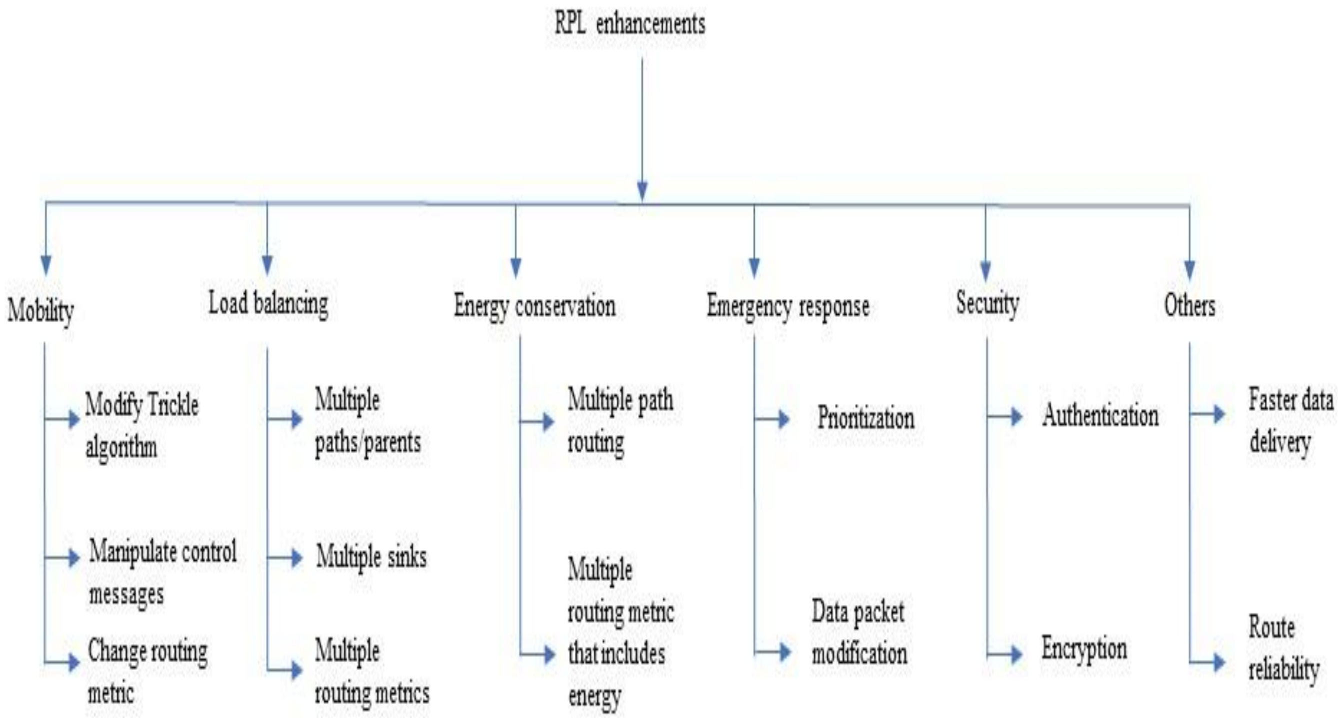

Figure 2. Classification of RPL enhancements.

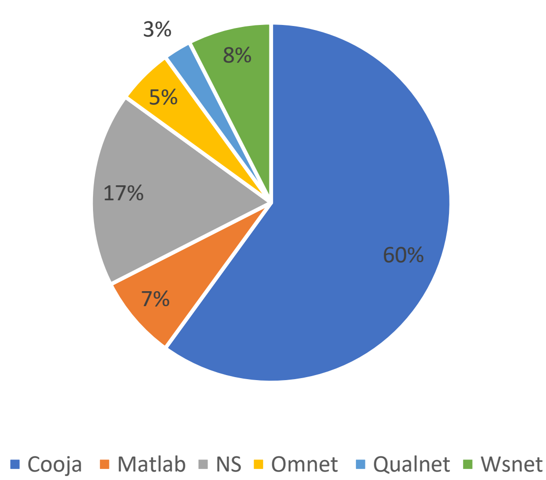

Figure 3: Simulator preference

Ref	Enhanced RPL/ Algorithm	Simulation results	Packet loss	Time delay / latency	Network lifetime	Waiting period	Energy consumption	Throughput	Packet delivery ratio	No. of hops	Idle time	RSSI	Simulator/ Experimental tool/Test bed	Operating System
[26]	SSCF	Improved throughput due to lower congestion and packet drops. Under conditions of sink mobility too, it returns better results than original RPL. Lower packet drop ratio due to better traffic management. Grid topology scenario returns better results than random topology.	yes	yes			yes	yes					Cooja simulator	Contiki
[27]	DRPL	At mobility of 5m/s the following results are observed: Lower energy consumption when compared to original RPL (RPL: more than 2 mJ/Packet, DRPL: less than 1.5 mJ/packet). PDR of D-RPL is about 78% whereas that of RPL is about 35%		yes			yes		yes				Cooja simulator	Contiki
[28]	Co-RPL	Co-RPL yields lower PDR by 45%, lowers average energy consumption by 50% and 2.5 secs cut in delay.	Yes	Yes			Yes						Cooja simulator	Contiki
[29]		Average packet loss of 1.7% which is lower than 9.6% of that of the original RPL. Packet loss increases when node speed increases. 8.1% lower energy consumption than original RPL	yes				yes	yes					MATLAB	
[30]		Provides better average end to end PDR and throughput than standard RPL. Also reduced packet overhead.						yes	yes				Real-life testbed (iMinds wiLab.)	
[31]	RRD	Improvement in PDR by 10%. Also better results with regard to number of packets sent, number of transmissions and no of packets dropped and end to end delay.	yes						yes				Cooja simulator	Contiki

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[32]	MRRD+	15% better PDR than RPL. It also returns a lower packet loss ratio since broken links are avoided and a better end to end delay since it detects movements faster than RPL.	yes	yes					yes				Cooja simulator	Contiki
[33]	ME-RPL	ME-RPL returns lower packet loss and routes are also more stable.	yes										Cooja simulator	Contiki
[34]	OF-FL	Lower packet loss ratio also leads to lower energy consumption by more than half. Average end-to-end delay reduces by about than 2 secs. It also returns better results when the speed of the node is increased.	yes				yes						Cooja simulator	Contiki
[35]	KP-RPL	PDR gets improved due to better routing among nodes. Lower positioning error also leads to lower ETX requirements.					yes		yes				Matlab	
[36]		Overhead due to increase in control messages. RPL modification leads to higher throughput (kbps) and PDR.						yes	yes				Qualnet 4.5	
[37]	mRPL +	PDR is nearly 100% whereas it is around 80% when using RPL.							yes				Cooja simulator	
[38]	M-RPL	Higher throughput and higher packet delivery ratio						yes	yes				Cooja simulator	Contiki
[39]	LB-RPL	Higher PDR and lower packet loss rate than RPL.	yes						yes				NS2 simulator	
[40]	POAF	This scheme increases the number of control messages because more nodes become parents. Compared to ETX, there is decrease in average parent load density but it yields lower packet delay.		yes									Cooja simulator	Contiki
[42]		Number of hops were reduced. Intermediate nodes got bypassed leading to energy conservation. RSSI and PDR at the receiver side also gets increased. At a height of 1.5 m, PDR touches almost 100%.							yes			yes	TI CC2420 radio on TelosB27 mote	

[43]		Reduction in the number of hops that packets have to travel which in turn causes lower packet loss and energy consumption	yes				yes			yes	Yes		Cooja simulator and iMinds wiLab.t testbed	
[44]	CoAR	CoAR betters ECRM and RPL by 8.9% and 20.7%, respectively, lowers end to end delay. PDR of the CoAR is 20% whereas that of ECRM, and RPL are 27% and 50% respectively. Lower energy consumption and throughput.	Yes	Yes			Yes	Yes	Yes				Cooja simulator	Contiki
[45]	QU-RPL	QU-RPL reduces queue loss by 84% and increases PDR by 147% when compared to RPL.	yes						yes				TinyRPL	TinyOS
[46]	CA-RPL	20% reduction in packet loss 30% improvement in time delay	yes	yes							w		Cooja simulator	Contiki
[47]	CLRPL	Lower packet loss due to lower queue loss (RPL: 32 % and CLRPL: 15%). Life time increases since nodes last longer due to better packet distribution (10% increase)	yes		yes								Cooja simulator	Contiki
[48]	ELB-FLR	It requires lower overhead in terms on control messages (DIO and DIS messages). PDR of ELB-FLR is 84% whereas that of RPL is 80%.		yes					yes				OMNeT++ simulator	Contiki
[49]	CA-OF	Better PDR of 79.5 % compared to 51% and 44% respectively. Also returns better throughput and energy consumption values since less number of packets are lost due in the buffers.	yes				yes	yes	yes				Cooja simulator	Contiki
[50]		This method provides better PDR, latency and energy consumption values as the network size increases.		yes			yes		yes				Cooja simulator	Contiki
[51]	MD-RPL	Average power consumption is 3% less than RPL.					yes						Cooja simulator	Contiki

[52]	Heuristic Load Distribution algorithm	HeLD increases network lifetime by more than 47% over single path RPL and a slight increase in throughput.			yes			yes					OMNeT++	
[53]	ORP-LB	Due to load distribution, network lifetime increases. ORPL-LB returns PDR of at least 90% against 80 % of RPL. ORP-LB reduces energy consumption of energy hotspots by 40%			yes		yes		yes					Contiki
[55]		At 1pkt/min, this method results in 85%o the nodes having their power level between 54% and 56%, thus indicating better load distribution between the nodes. ETX provided better throughput of around 3% than this method since the former focuses on link quality.	yes				yes	yes					Cooja simulator	Contiki
[56]	MDMR	When compared to DD and TTDD, MDMR returns lower energy consumption and average delay values.		yes			yes						NS-2.5.	
[57]		Multiple paths increase PDR significantly over single path RPL. By distributing load, the network lifetime also gets extended.			yes				yes				WSNet	
[58]		It results in longer network lifetime and higher residual energy for the sensor nodes. Since the sink node is mobile, traffic also gets distributed between the relay/intermediate nodes.			yes		yes						WSnet	
[59]		Better PDR and energy consumption, ETX and churn values as compared to when MRHOF uses only one metric.					yes		yes				Cooja simulator	Contiki
[60]	CEEA	Returns highest success rate of 88% when compared with baseline algorithms.		Yes			Yes	Yes			Yes		NS3	Windows, Linux and OSX
[61]		Increase in overall lifetime of the network.		yes			yes		yes				WSNet	

[62]		Reduction in hop count. Lesser energy consumption when distance between nodes and root was increased and also when area of simulation was increased.					yes		yes	yes				
[63]		Provides lower latency than standard RPL. More than 50% better than MHROF with regard to PDR. Lower energy consumption than OF0 and MHROF. Improved network lifetime		Yes	Yes		Yes		Yes				Cooja simulator	Contiki
[64]	Multicriteria Parent Selection Algorithm	Better lifetime of nodes compared to standard RPL. Improved PDR ratio when the distance between nodes increases			Yes		Yes		Yes				Matlab	
[65]		When compared to ETX, this metric increases the lifetime of network by 21%. At the end of the simulation, remaining battery levels are also higher when using this metric.			yes		yes							
[66]		Native RPL suffers packet loss rates upto 55% but RPL-Probe reduces this to 12%. Energy consumption is reduced by 30%.	yes				yes						Cooja simulator	Contiki
[70]	ERGID	Provides better average end to end delay and lower loss rate when compared with other two algorithms.	yes	yes									NS2	
[71]	EARS	Emergency packets have lower waiting time and packet loss ratio(less than 1% at 100 B)	yes			yes							NS2	
[72]	EABS	Compared to other emergency methods, this method returns better average end to end delay, forwarding percentage(ratio of packets delivered to packets generated), energy consumption and network lifetime values.		yes	yes		yes						NS2	

[87]		Almost 100% Packet delivery ratio, lower delay and increase in QoS, an additional 30% increase in network life time		yes			yes		yes	yes			Cooja simulator	Contiki
[88]		Delay is reduced by about 40% for some nodes. The number of DIO messages also gets reduced.		yes									Cooja simulator	Contiki
[89]	DT-RPL	The packet reception ratio for both upward and downward traffic is more than RPL. There is also less overhead caused by fewer parent changes and global repairs.											Cooja simulator	Contiki
[90]	sRPL	More stable routes increases PDR by 20% over RPL. sRPL reduces control message overhead by 90%. However, hop count RPL results in lower latency since it chooses shortest route.		yes					yes				NS2	

Table I: Summary of RPL enhancements

IV. MOBILITY OF NODES

Wadhaj et al. compared the performance of RPL under fixed and mobile sink environments [25]. The conclusion after simulation was that RPL performs under fixed sink conditions, returning better power consumption, delay and PDR. However, in many IoT applications, the mobility of nodes is a requisite. While RPL was originally built for static networks, many studies have been made to enhance RPL to work under mobile node conditions. Any new mechanism must proposed must deal with rapid changes in the topology and update the ranks in order to avoid loops. The main methods used to optimize RPL can be grouped under the following

a. Modify the trickle algorithm
b. Manipulate the Control messages.
c. Change routing metric

In [26], the authors proposed an algorithm to ensure unhindered traffic flow rate when there is network congestion. As opposed to original RPL, the border nodes relay DIO messages to the neighboring nodes of another DODAG which in turn send the information to their own sinks. In this way, sinks keep track of neighboring sub DODAG-ID and the optimization metrics - the network size, Packet delivery ratio (PDR) and Mobility Factor (MF) that are inserted in the DIOs.

When the sink begins to move, the DIO is transmitted only to its immediate neighbors so that the entire topology is not disturbed. After stabilization, the DIOs are propagated further to all the nodes in the graph.

When sinks are static, network size is decreased if the PDR falls below the threshold limit since low PDR indicates congestion in the network. The source nodes that get cut off are now forced to transmit to the sink nodes of neighboring sub- DODAGs.

In [27], the authors tried to handle node mobility using a dynamic Objective Function (OF). When a packet reaches a node, it compares RSSI of the previous packet with the new RSSI and if found lower by a constant, then the timer is reduced by half and when the timer reaches Imin, then DISs are sent to all the neighbors thus causing the root to send DIO messages to rebuild the DODAG. The trickle timer, therefore has higher intervals due to the addition of the constant done to take into account the mobility of the nodes. If the constant is not added then DIOs are sent at shorter intervals. When a node receives the new DIO message, it uses a Dynamic OF to select routing paths. The OF uses the MHROF already available in Contiki OS and also adds ETX, energy metric and the LQI. The authors did not specify how the metrics were used in the D-OF.

In [28], a method was proposed for static roots and mobile nodes, wherein the latter attach themselves to the nearest static root. It adapted the timer to issue DIO periodically without waiting for timer expiration to keep track of the location of mobile nodes. Faster the mobility of nodes, lesser the interval between DIO transmission. Each root sends a modified DIO with a special id value. Upon receiving DIOs, a node chooses the parent with the least value of that special ID. This special value is similar to the rank value in native RPL and reflects the distance from the DAG root. However, this method was not tried with mobile roots.

In [29], the rate of transmission of DIO messages is made dynamically dependent on the speed of mobility of the nodes. Imin is set in such a way that control messages will be sent when the node leaves the transmission range of its parent. The Doppler frequency is used to calculate when the mobile node will travel beyond the transmission range of the parent.

In [30], the no path DAO messages used to remove od routes are modified. The authors propose that instead of the mobile node sending the new path DAO to the parent node, their common ancestor is the one that generates and sends it to the old parent. Therefore, even if the dynamic node moves beyond the range of old parent, the DAO message reaches the old parent and the old routes gets removed from the topology.

Many IoT applications require sensor nodes to be mobile. [31] discusses a mechanism to handle mobility under single sink node conditions. It is based on RSSI, rank updating and dynamic management of control messages. A mobile node decides to change its nest hop parent when its RSSI value to the parent falls below a certain threshold. An increase in RSSI values contained in DIO messages means that the mobile node is moving towards the sink node and vice versa. Also, to reflect dynamism in the topology, smaller ranked nodes send DIOs more frequently than higher-ranked nodes.

As opposed to a single sink node, multiple sinks return longer system lifetime than a single node. In [32], the authors developed a method that enhances RPL performance under multiple sink and mobility conditions. In this method, the mobile nodes constantly monitor its links with candidate parents using RSSI values. If the new RSSI becomes lesser than old RSSI, it implies that the sink is getting further away from itself. If RSSI values increase beyond a threshold, the parent is deleted from the candidate list. Also, the timer algorithm is modified to make it dynamic, nodes closer to the sink send DIOs more frequently than those further away.

In[33], a mobility status is included in the DIO option of the DIO message to identify mobile nodes. Secondly, more than one node in the parent set have the same rank then the fstatic node is chosen as the preferred parent. Thirdly, a mobile node is forced to issue DIS messages whenever there is a change in its position.

To adapt RPL for mobility, the authors in [34] suggested that the routing metric be based on fuzzy logic that is aimed at ensuring QoS parameters like reliability and energy efficiency. The objective function is composed of four metrics- link quality, node energy, hop count and end-to-end delay. The quality of any neighbor node is based on fuzzy logic rules formed based on combinations of all the four metrics as input fuzzy variables.

To improve the positioning accuracy of mobile nodes, KP-RPL [35] uses the Kalman positioning scheme. For static nodes, native RPL is used whereas the Kalman approach is used for routing in mobile nodes. Each mobile node defines its own location using RSSI values from the anchor(static) nodes. It further refines its position using the Kalman approach. To avoid unreliable links, this approach avoids mobile to mobile routing.

Some research has also been done on RPL for VANETs such as in [36] where Lee et al. includes the parent's ID in the DIO so that a mobile node will discard any DIO that has it as the parent, thereby preventing loops. Control messages are also sent in response to topology changes and not as per the trickle algorithm.

In [37], the soft handoff approach is proposed wherein a mobile node stays connected to its old static parent node until the new radio link to its new static parent is activated. In this scheme, the mobile node is connected to more than one parent during the handoff process as opposed to the hard handoff process in which a mobile node is connected to only one parent at a time.

V. LOAD BALANCING UNDER HIGH AND UNEVEN TRAFFIC CONDITIONS

The effect of traffic characteristics such as data rate and load distribution on routing is also profound. An unsustainable data influx can lead to a sinkhole problem wherein a node drops packets rapidly due to high incoming traffic.

The main approaches used to handle the problem of high and uneven traffic are:

a. Multiple paths/parents
b. Multiple sinks
c. Multiple routing metrics

RPL suffers when packets start getting dropped on account of high data rates. The issue of congestion avoidance was dealt with in [38]. The authors modified the original RPL to allow multipath RPL wherein the child nodes start sending packets upwards to an additional parent in case of congestion in the original parent. The use of more than one path is efficient as long as there are alternate nodes that are willing to capable to serve as viable parents. In case of unavailability of candidate parent nodes, this method does not become viable.

The performance of RPL also degrades when nodes have uneven load distribution.

One shortcoming of the original RPL is that it cannot balance the load evenly amongst the sensor nodes. To overcome this, [39] proposed an algorithm to balance the load evenly, by using multiple paths instead of a pairwise transmission model of RPL. The method relies on modifying the DIO in such a manner that a parent node informs the child nodes of congestion by sending a delayed DIO. The delay is proportional to the buffer size. Hence, more the messages received, the more the buffer size and higher the delay in sending the DIO. When a child node receives DIO from several lower ranked nodes, it builds a parent table and chooses a parent that sent the DIO earliest, which indicates that this parent has the least buffer size occupied. It chooses the second parent accordingly. Finally, the child node distributes the load between the two parents. This method requires the child nodes to perform an additional calculation to distribute the data between the parent nodes.

Load balancing is achieved in [40] by using the PAOF as an objective function that considers two metrics-ETX and parent count(number of candidate parents). If the difference between the ETX values of two candidate parents is less than the MinHopIncrease, then the candidate with the lower number of children gets selected as the preferred parent. This ensures that parent selection is diverse and no parent is overburdened. A similar modified OF was also proposed in [41] in which the candidate with the minimum children is chosen as the preferred parent.

In a majority of the papers, the factor of the height of deployment of nodes was ignored but in real life situations, it impacts the way RPL functions as shown in [42]. The authors increased the height of deployment of the nodes which led to the increased transmission range of the nodes which forced changes in the RPL functioning. The routing tables get modified in such a way that nodes that were further away are now given higher preferences as parents. The multi-hop scenario got replaced by a single hop situation because of the increase in the height of nodes deployment. The lack of physical barriers in the air leads to increased transmission ranges. Another secondary benefit was that intermediate nodes are freed from relaying packets, thus leading to energy safe. This method is applicable only in situations where there is the scope of picking the nodes from the ground and placing them at a higher level.

To redistribute uneven load and avoid sink hole problems, the authors in [43] introduced multiple sinks in the network. The redirection of packets to closer sinks causes a reduction in the number of hops that packets have to travel which in turn causes lower packet loss and energy consumption. A virtual sink node is behaves as the root of all the physical sinks. Therefore, all the nodes in the network think that they belong to a single DODAG. To synchronize DODAG id of the sub-DODAGS, a central unit is deployed. It also relays data packets between the sinks. It maintains a large routing table that it uses to find the destination node of a packet.

This method is costly as it requires embedded PCs to function as a central unit or registrar. This kind of centralization leads to the possibility of a single point of failure. Besides, this approach is useful only if the multiple sinks are placed in an optimal position. When breaking up a large DODAG into smaller subtrees, point to point connections may become longer.

In [44], multiple routing metrics -queue utilization, expected transmission count, neighborhood index and ETX- are used for congestion avoidance under heavy load conditions. The first three metrics are used to calculate a score for each parent. In the case of a tie, the neighborhood index which is indirectly proportional to the number of child nodes is used to select the preferred parent. To ensure that trickle timer responds to congestion efficiently, the timer is reset to Imin whenever congestion is detected. Only grid topology was used in the simulation. Whether similar results are delivered under random topology is an open-ended question. Queue utilization was also used in [45] to enable nodes to choose parent with lower queue utilization, which is treated as an indicator of traffic congestion. Queue information is embedded in the DIO messages.

In [46], a multicriteria metric was used for path selection-ETX, delay from the node till the root, rank of the parent and packet count received by a parent node within a time interval. The weight of each link is inversely proportional to all the four factors.

To handle high and flexible data rates, [47] proposes an objective function that depends on the rank of the parent, remaining power of the parent chain towards the root and lastly, the queue status of the parent which the authors claim avoids the thundering herd problem. Higher queue utilization implies greater convergence of data in a node which makes it unfavorable as a parent. Similarly, in [48] the energy level is also taken into account while calculating the rank of a parent. Also, to avoid congestion, the load is shared amongst parent nodes with the same hop count and energy levels.

Traffic congestion leads to packet loss at the node's buffer. Therefore, the buffer can be used to detect congestion as shown in the node as shown in[49]. Part of the traffic from the child nodes get diverted to another parent node. A combined metric of ETX and Buffer Occupancy is taken into account in order to facilitate both low and high data rates respectively.

Although MRHOF is considered a better OF than OF0 since it considers the link quality, it becomes less efficient when large number of nodes are used. MRHOF causes single hops that provide less ETX over multiple hops. As such, the single hop becomes a bottleneck. To tackle this problem, the authors in [50] presented an alternate routing metric in which the average ETX from source to destination is used, as a result of which the path selected will have a lower average value of ETX.

In [51], the proposed scheme called Minimum Degree RPL(MD-RPL) attempts to achieve load balancing by minimizing the degree of the DODAG formed using RPL. The node with the maximum degree and hence the maximum number of child nodes is first identified and one of its children is forced to find an alternate parent.

The proposed Heuristic Load Distribution Algorithm (HeLD) [52] proposes a scheme in which a node divides the load evenly between more than one parent located at the same depth. The scheme requires a central agent that has information on the tree topology.

Load balancing is achieved in [53] by manipulating the wake-up intervals and duty cycles of sensors. In this method, the parent nodes that forward traffic to the sink are chosen during the transmission period using anycast transmission. High load nodes increase their wake up intervals and thereby can reduce network load and duty cycle. Light load nodes do the reverse and attract traffic away from the high load ones.

VI. ENERGY CONSERVATION.

Since IoT sensors are powered by small batteries and are devoid of any power back-up, network lifetime is a critical issue in the functioning of IoT network. Network lifetime can be enhanced by conserving energy of the sensors. In [54], a comparative analysis of the impact of OF0 and MHROF on energy consumption was given. Besides changing the OF, a large number of papers have been published that propose other methods to extend network lifetime.

These methods are classified into the following groups based on the metrics used:

a. Multipath routing

b. Multiple routing metrics that include energy

In a power-constrained environment, the optimal usage of battery power is vital for system efficiency and longevity.

In [55], the authors used the nodes' remaining battery power as the node metric to decide the preferred parent and the route to the sink. A node selects that candidate neighbor as the parent which has the maximum remaining battery level. The path from the node to the sink comprises the sub-paths that incur minimum energy. Xu et al. also incorporated the energy level to calculate the rank of a node [56].

The residual energy of a battery was also used to calculate the ELT (Estimated Lifetime)metric in [57]. A node with low ELT is identified as a bottleneck i.e. a node that dies before others. In this paper, each node calculates it impact on a bottleneck. Further, the load gets divided among parents that have minimum impact on bottlenecks present in the path toward the destination. Saad et al. proposed a method that involves mobility of the sink node in an attempt to increase the lifetime of the overall network [58]. A mobile sink reduces the number of hops which in turn helps save energy of the nodes.

In [59], instead of using a single metric, two metrics- ETX and energy - were used to in the MRHOF objective function. Both the metrics were given equal weight. This method performed better than OF0 and MRHOF as well. The simulations were performed under light to medium density network conditions.

In [60], the author proposed a method for dealing with delay-sensitive data in a wireless sensor network. Routing is based on a hierarchy of metrics with the energy used as the first metric. Routing paths are chosen based on residual energy from source to sink. A routing node is removed from the path if its initial energy level falls below a certain threshold. If two nodes offer the same energy incentive, then the second attribute of link reliability is used, which is then followed by throughput value.

In [61], the authors proposed using multi-path routing to divide the traffic among multiple paths. Parent selection was done using the expected life expectancy of the nodes as the metric. The preferred parent also changes only when it ran out of energy to maintain the stability of the topology and save energy on control messages. Energy is also wasted when DIO messages are lost in noisy environments, leading to non-optimal DODAGs. This problem has been resolved in [62] in which a node receiving a DIO from a sender also checks out the parent ID of the sender. If the latter is an appropriate candidate, it is chosen as the parent instead of the DIO sender. This requires a slight modification in the DIO by appending the sender's parent ID in the control message. In[63], the composite metric includes both minimum no of hops and ETX since the latter alone may lead to longer routes with more number of hops. In the case of a tie between two routes, the standard deviation method is used to find the better route. The more stable route is considered to have a lower SD. To solve the problem of network partitioning due to energy depletion, [64] proposes the selection of parent node using multiple criteria- ETX, ETT, residual energy. The weight of each criterion is formed from a pair-wise comparison matrix based on the Analytical Hierarchical Process (AHP).

Energy conservation may need to make a trade-off with efficient routing. In [65], Capone et al. have proposed a way to strike a balance between energy conservation and routing in the form of a metric called L2AM. This metric is a composite metric of ETX as the measure for link quality and remaining battery power to take into account the energy aspect.

In native RPL, link quality is estimated using a probing scheme that sends unicast DIO messages to each neighbor which is energy-consuming. To reduce the energy expended during link quality estimation, the authors in [66] used a novel scheme called RPL-Probe based on the multi-armed bandit to measure link quality. This method is reactive to sudden topology changes caused by node mobility.

In the next two papers, the issue of energy conservation has been tackled with from a macro perspective i.e from a framework point of view wherein solutions proposed are implemented at higher levels.

In [67], an architecture is proposed to conserve energy in IoT applications such as healthcare, smart city and smart transportation. Sensors transmit data only when an event occurs and lie in sleep mode. Data from the sensors is stored and analyzed in the cloud. The resources on the cloud are also allocated based on the amount of data generated which depends on the number of active sensors.

In [68], the sensors are classified as relevant, irrelevant or redundant according to the data they provide to a particular task such as water level monitoring task. Except for the task-relevant sensors, the other sensors are allowed to go to sleep state. Thus, energy gets saved without compromising the QoI.

VII. EMERGENCY RESPONSE

The possibility of employing IoT in an emergency is also an ongoing area of research. When emergencies arise, data from emergency sites need to be forwarded on a priority basis. Data from non-critical sensors can be delayed or discarded altogether to free routing paths from traffic congestion. In these situations, there is sometimes a tradeoff between energy optimization and time delay. Yang et. al [69] analyses how IoT can improve emergency response operations by improving situational awareness and providing the following abilities to monitor and trace resources and personnel involved in emergency response operations.

In [70], Dijkstra's method is used as a greedy approach to calculate the least time delay from the node to the root node. It removes the problem of ignoring valid paths as seen in other emergency algorithms by using Dijkstra's method.

In [71], data are divided into three categories: emergency, general and non-emergency. Higher priority is accorded to emergency data packets which are put in a separate queue and forwarded first.

In [72], the data packets are modified to contain an emergency flag and a deadline of the packet. Those emergency packets with a minimum deadline are forwarded first. A separate queue is maintained for emergency packets. Regular packets are queued in a separate queue wherein they are forwarded according to LIFO policy. Emergency packets flow through shortest paths whereas regular packets are forwarded through longer paths.

[73] states that packet loss is a major problem in emergencies and that the in-built RPL mechanism of ACK messages causes traffic overhead. Maalel et. al proposed using the overhearing mechanism in wirless sensor networks to detect packet loss. If the sender does not overhear its neighbor forwarding its packet to the next hop, then it assumes that the packet has been lost and retransmits the original packet on the next best link as indicated by the Link Quality Indicator (LQI). Rather than wait for the ACK control message from the receiver, the sender relies on the overhearing mechanism. However, this proposed scheme has not been tested on a simulator.

VIII. SECURITY

An IoT infrastructure is vulnerable to a wide range of attacks that can result in depletion of sensor batteries, theft of information and manipulation traffic direction among others. [74] presents the various attacks that occur across different layers. With the deployment of IoT networks in a wide variety of settings, it becomes vital to secure the network. A general set of security requirements in the context of IoT is given in [75]. Authentication and encryption are the two most popular security solutions.

Authentication is required to check the validity of the devices. Further communication is allowed only if the devices pass the authentication test. In [76], the authors provide a three-stage authentication scheme that is based on mutual authentication. A two-way authentication scheme based on the public key cryptography RSA is given in [77]. Mutual authentication schemes are proposed in [78], [79] for M2M communication in 6LoWPAN networks. In this scheme hybrid cryptography for authentication and flexible key establishment. A lightweight attestation and authentication method is proposed in [80]. Another lightweight authentication protocol is proposed in [81] which is based on IKEv2 protocol [82] and

Encryption is used to ensure secure end-to-end communication. Due to resource constraints in IoT networks, lightweight encryption based security solutions have been proposed like compressed IPsec [83] and compressed DTLS [84]. A physical layer encryption scheme in which the phase of a signal is manipulated by a keystream is proposed in [85] while a transport layer security solution is presented in [86].

IX. OTHER OBJECTIVES

Besides the objectives mentioned so far, researchers have also attempted to improve some factors in the DODAG. [87] presents a dynamic route selection based on application requirements. Fuzzy logic is used to select an Objective Function from a set of four OFs based on the requirements of the applications during run time. For example, if the priority is on reliability, the OF includes ETX whereas if the minimum delay is the requirement, then the OF includes hop count as a metric. If energy consumption is a concern, the fuzzy system includes remaining energy as a metric.

To achieve faster packet delivery, in[88] the routing metric incorporates the next- hop delay. The candidate node with the least delay is chosen as the parent node.

RPL was originally designed with upward traffic from the sensors to BR in mind. In [89], RPL is modified to use downward along with upward traffic for estimating link quality in the form of ETX. In normal RPL, ETX is measured by the child based on upward traffic. Whereas in this method traffic the packet received from the parent is used by the child to measure ETX. Three bits MAC header is used to pass information about the link quality downwards.

To improve the reliability of routes, Yang et al. proposed a new routing metric that measures the stability of nodes and helps in building more stable routes [90].

X. CONCLUSION

This paper reviews contributions aimed at overcoming native RPL gaps related to mobility, security, high traffic and emergency events. A classification of schemes based on the desired objectives and methods used is also provided in this paper. We also present a comparative analysis of the proposed schemes to serve as a blueprint for future research.

Today, a lot of research is being done on RPL. Researchers need to make a trade-off between various parameters. For example, mobility enhancements demand additional data and calculations that shorten the battery lifetime of the low battery nodes. Future research, therefore, needs to consider the overhead cost when proposing any scheme or solution.

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