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Kharrufa, H, Al-Kashoash, HAA and Kemp, AH (2019) RPL-Based Routing Protocols in IoT Applications: A Review. IEEE Sensors Journal, 19 (15). pp. 5952-5967. ISSN 1530-437X

https://doi.org/10.1109/JSEN.2019.2910881

RPL-based routing protocols in IoT applications: A Review

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***Abstract*—In the last few years, the Internet of Things (IoT) has proved to be an interesting and promising paradigm that aims to contribute to countless applications by connecting more physical "things" to the Internet. Although it emerged as a major enabler for many next generation applications, it also introduced new challenges to already saturated networks. The IoT is already coming to life especially in healthcare and smart environment applications adding a large number of low powered sensors and actuators to improve life style and introduce new services to the community. The Internet Engineering Task Force (IETF) developed RPL as the routing protocol for low power and lossy networks (LLNs) and standardized it in RFC6550 in 2012. RPL quickly gained interest and many research papers were introduced to evaluate and improve its performance in different applications. In this paper, we present a discussion of the main aspects of RPL and the advantages and disadvantages of using it in different IoT applications. We also review the available research related to RPL in a systematic manner, based on the enhancement area and the service type. In addition to that, we compare related RPL-based protocols in terms of energy efficiency, reliability, flexibility, robustness and security. Finally, we present our conclusions and discuss the possible future directions of RPL and its applicability in the Internet of the future.**

***Index Terms*—Routing, WSN, IoT, RPL, mobility, game theory, 6LoWPAN, IoMT.**

I. Introduction

The Internet has evolved rapidly in the past few decades introducing countless applications in many fields including industry, transport, education, entertainment, etc. During these years, many devices, services and protocols were created and the Internet grew and is still exponentially. The next generation of this worldwide network is the IoT, where a large number of 'Things' is expected to be part of the Internet introducing new opportunities and challenges. These things include sensor nodes, radio frequency identification (RFID) tags, near field communication (NFC) devices and other wired or wireless gadgets that interact with each other and with the existing network providing futuristic applications and at the same time, creating numerous challenges for the research community to tackle.

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Wireless sensor networks (WSNs) play a key role in the creation and growth of the IoT, allowing low end devices with limited resources to connect to the Internet and potentially provide life-changing services. One of the main standards that supports low power and lossy networks (LLNs) is the IEEE 802.15.4 standard, which forms the backbone of WSNs as part of the IoT. This standard defines the physical and data-link layers of the network and provides a framework of operation at low costs.

To make these low end devices a part of the Internet, the IETF developed the IPv6 low-power wirless personal area networks (6LoWPAN) which is used as an adaptation layer that allows sensor nodes to implement the Internet protocol (IP) stack and become accessible by other devices on the network. This adaptation layers allows these nodes to implement routing protocols at the network layer and provide an end-to-end connectivity that enables countless applications. With the exponential growth of the Internet and the evolution of IoT, conventional routing protocols can no longer accommodate the large number of added nodes. For this reason, RPL was designed especially for LLNs and quickly gained popularity among the research community.

In this paper, we acknowledge the importance of RPL as the standard routing protocol of IoT and provide for the first time, a systematic review of RPL and RPL-based protocols within the context of IoT along with technical insights and recommendations for these implementations. The approach of this review uses Google scholar to search for (”allintitle: rpl -pregnancy”) in the title of a paper while removing unwanted similar abbreviation for example (”RPL” as recurrent pregnancy loss). This search comes up with more than 700 papers and patents, to make sure nothing is missed, another wider search is conducted using the phrase (IoT ”RPL” routing) to search anywhere in the article and use the years filter to categorise results according to the publication year and scroll through them to find possible candidates. This search returns more than 2900 results including papers and patents, duplicate articles are removed and then a number of papers is selected for each year where improvements where made to RPL in any aspect. Papers that mentions RPL but do not discuss its usage or do not propose an enhancement are also removed from this review. The main contributions of this paper are (i) Providing an extensive and systematic review of RPL. (ii) Discussing the efficiency of each approach in terms of applicability, energy consumption, flexibility, throughput and end-to-end delay. (iii) Providing a technical guide to assess the RPL enhancements available in the literature. (iv) Discussing recommendations for future developments.

The rest of the paper is organised as follows: Section II provides an overview of RPL in terms of design, features and problems. Section III categorises reviewed papers according to the applications they are used for, along with the requirements, design implications for each application. Section IV discusses the challenges that face RPL and the approaches used to tackle them. Section V concludes the paper and provides technical and chronological information about the evolution or RPL and the approaches used to build RPL in its current state.

II. RPL Description

RPL is a distant vector protocol designed for IPv6 low-power devices, it operates on the IEEE 802.15.4 standard with the support of 6LoWPAN adaptation layer. The routing over LLNs (RoLL) working group introduced the routing requirements for LLNs in general taking into account the resources limitations in terms of energy, processing and memory in a vision to allow large number of nodes to communicate in a peer-to-peer topology or an extended star topology [1]. This protocol creates a multi-hop hierarchical topology for nodes, where each node can send data to its parent node which in turn forwards it upward until it reaches the sink or gateway node. In the same way, the sink node can send a unicast message to target a specific node in its network.

RPL successfully and efficiently manages data routing for nodes that have restricted resources, it provides an operation framework that ensures bidirectional connectivity, robustness, reliability, flexibility and scalability. The key features of RPL come from its efficient hierarchy, the use of timers to minimise control messages and the flexibility of the objective function.

A. RPL Hierarchy

RPL builds a directed acyclic graph (DAG) with no outgoing edges as the base element of the topology, this ensure that no cycles exist in the hierarchy. The sink node starts building the first DAG making itself the ultimate DAG root, other nodes in this DAG start forming their own DAGs which are routed towards the first one making a destination oriented DAG (DODAG). RPL uses a number of control messages to build and maintain its hierarchy. The DODAG information object (DIO) is sent from the root node with information about the rank of the sending node, the instance ID, the version number and the DODAG-ID. This allows nodes to decide whether or not to act upon receiving this message, in addition to keeping valuable information about the network that can contribute to making an informed decision. The destination advertisement object (DAO) is sent from the child node to its parent (the DAG root or the DODAG root) and it contains destination information which practically informs the root that this node is still available. The root node may optionally send a DAO-ack acknowledgement if required. The DODAG information solicitation is another form of upward control messages that is used to request a DIO from the parent node, this is one of the most relevant and important features that RPL uses to maintain connectivity. Fig 1 shows the direction of RPL control messages.

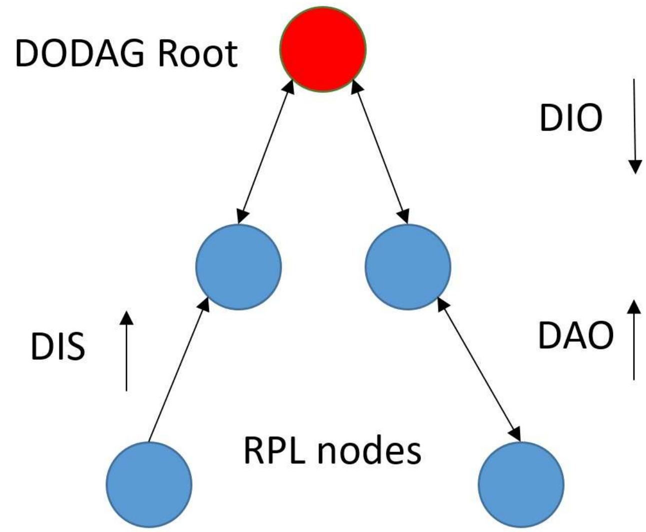

Fig. 1. Control messages in RPL

B. Trickle Timer

The trickle timer [2] is used to minimise the number of redundant control messages using an exponentially incremented interval. RPL in its original design, assumes that after the network connectivity is established, there is little need for DIO messages and thus uses the trickle timer to keep control messages only when it matters to the network. This assumption proved to be efficient in static networks but it is one of the main problems that faces RPL with the presence of mobile nodes. The main parameters of the trickle timer are I_{min}, $I_{doubling}$ and I_{max}.

$$I_{min} = 2^n \tag{1}$$

$$I_{max} = 2^{n+I_{doubling}} \tag{2}$$

The interval n produces I_{min} (ms) which is the initial and minimum interval size of the trickle timer as shown in equation (1). $I_{doubling}$ decides I_{max} (ms) which is the maximum interval size of the trickle timer as shown in equation (2). The configuration of the trickle timer depends on these variables and it is critical to select appropriate values to match the application requirements. High intervals improve energy efficiency while leading to low responsiveness while lower intervals improve responsiveness on at the cost of energy consumption and lifetime.

C. Objective Function

Each RPL node, has its predefined objective function (OF), this function carries the metrics upon which nodes select the ”better” parent among competing nodes. There are currently two objective functions presented by the IETF, the first one is Objective Function zero (OF0) [3] which is a simple and basic objective function that has only one metric, it uses the rank of the node to determine its distance from the root and selects the node with the lower (better) rank. The OF0 is designed as a general objective function used as a guide and base for

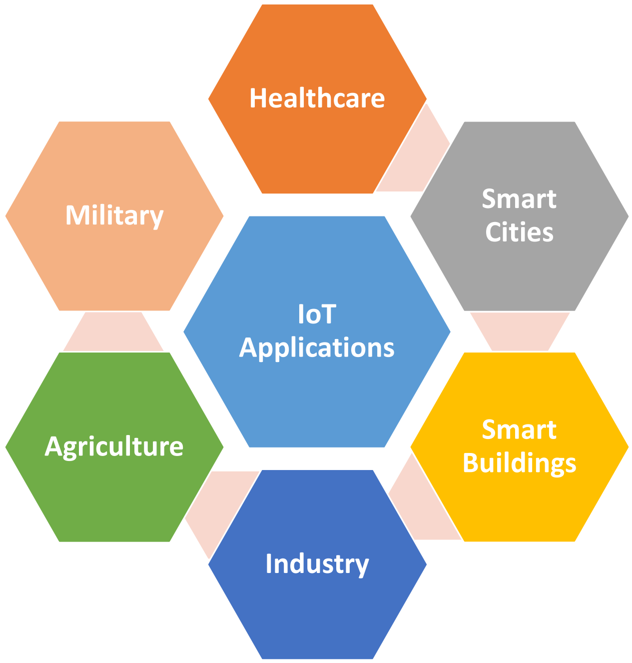

Fig. 2. IoT Applications

other implementations. The second one and the arguably most popular one is the minimum rank with hysteresis objective function (MRHOF) [4] which is based on routing metric containers. It allows the user to configure the metrics inside the metric container which is transmitted as part of DIO messages. This function uses the expected transmission count (ETX) as the default metric and provides support for using path-specific expected energy consumption as a routing metric.

III. Applications

It is difficult to list all areas that go under IoT applications, it is possible however to cover some of the common applications, with the aim to summarize their different requirements and design implications and to have a general understanding of the challenges that face their progress.

There are countless potential applications that can fall under the IoT umbrella, figure 2 shows some of the most used in literature. The general classification for applications used it this paper includes healthcare, smart environment, transport, industry and military applications. All of these applications are mentioned in literature and are popular in terms of WSNs studies and specifically RPL research. They also have their own special requirements they are looked at from different points of view. This classification highlights the requirements for IoT applications in terms of reliability, energy efficiency, security, responsiveness, scalability and mobility.

A. Healthcare

Many researchers are showing interest in the challenging and promising idea of using WSNs and the IoT in the field of healthcare, the potential of these applications is unlimited and the benefits expected are countless. Examples of healthcare applications include elderly care, patient vital status monitoring, hospital environment monitoring, emergency detection, etc.

In healthcare applications, reliability, responsiveness, security and mobility are key factors [5], [6]. The real time aspect and reliable data transmission can be crucial in case of emergency detection applications, security ensures that the privacy of patients is not breached while mobility management enables efficient operation when nodes are moving. In rehabilitation applications, inaccurate data can put the patient in a mortal peril and leads to a negative outcome where medical staff of smart equipment might use the defective data and give misguided treatment [7], [8].

A study on casualty monitoring [9] uses medical information tags to track patients in disaster scenarios, the reliability of transmitted data in this application is essential to ensure that the right actions are taken (eg. locating the nearest hospital, dispatching an ambulance or providing medical history). The same applies for fall detection applications [10], tele-care [11], elderly and patient monitoring [12], [13], [14] and status and activity detection [15], [16], [17]. Other non-emergency applications like health environment monitoring and deaf people assistance [18] may not be as critical but would still cause discomfort and in some cases health deterioration for patients.

In activity monitoring applications, the collected data reflects the usual habits of the monitored entity, the time they spend using an appliance or the exact location of a person [19]. This application and other similar applications are used to help the caretaker or the medical staff to know whether the "target" is following recommended actions. It is not usually difficult to know whether a patient is remembering to take their medication (by attaching a sensor or RFID tag on the bottle or sheet of medicine) or whether they are being sufficiently mobile. Some studies [20], [21], [22] successfully implemented wearable sensors that can identify the symptoms of many diseases including Parkinson's disease and epilepsy. However, the collection of this data and the reliable transmission through one hop or multi-hops is more challenging, keeping in mind that the privacy of patients in this case is a crucial point.

In more critical applications, like fall and emergency detection, the reliability and responsiveness of the application become more important to the patients. Falls are among the main causes of death in elderly people, the detection of such an accident and the timely reporting to the appropriate entity is a key factor in saving the patients life and preventing further developments. Accelerometers are usually used to detect falls, [23], [24], [25] sometimes accompanied by cameras and image sensors to increase the reliability of fall detection [26], [27], [28]. When a fall is detected and confirmed by image sensors, the computer makes a phone call to the emergency department or the health establishment, RSSI can also be used to give an estimated location inside the building.

It is clear that even in the same field of applications, individual application requirements can be diverse and meeting these requirements can be challenging. RPL and its enhancements are proven to be able to tackle most of these problems [29], the flexibility of RPL also make it possible to have the same routing protocol for different applications by only changing some of the configuration parameters according to application requirements. The experiments undertaken in [73] prove that GTM-RPL can provide reliable data delivery at low costs with a high flexibility to fit many healthcare applications.

B. Smart Environments

Applications of smart environment include smart cities, buildings, agriculture, etc. These applications typically cover large areas, making scalability, mobility management and energy consumption fundamental requirements. In addition to that, security and privacy can be also a requirement especially in smart buildings applications. The term "smart environments" is general and it can sometimes overlap with other applications, a smart healthcare environment for example can be classified as both a healthcare and a smart environment application. However, it is still useful to have it as a separate classification given that it includes many applications with similar requirements and it also attracts significant research.

In smart agriculture applications, sensor nodes are scattered around a large area to provide useful data regarding temperature, humidity and light. This data can be then used to support the decision making and can trigger automated actions or just report to the proper entity. Sensors can also be used to monitor plants and detect certain diseases, stopping the spread of diseases can have a significant economical advantage in addition to contributing to the welfare of the environment [30]. In such applications, a good coverage and a long lifetime for the network are very useful, as it usually comprises of large areas and requires long periods of time to provide meaningful information.

Other applications like animal tracking and cattle monitoring report data regarding the general environment in addition to individual animals. Attaching sensor nodes to animals can also contribute to improving sensing and communication coverage in large areas. In [31], a wireless sensor network is used to detect problems and diseases in cattle with the aims of improving their productivity. The authors in [32] introduce a water environment monitoring system using wireless sensor networks to ensure that animals always have a source of water that is safe to drink.

An even larger example of smart environments applications is smart cities, which usually comprises of a number of applications spread out in a city. One of the examples of smart cities is the city of Padova in Italy, where data from multiple applications are gathered and used to optimise the use of public resources [33].

With the typically vast area of deployment in these applications, sensor nodes face environmental challenges as well as technical challenges. Rain, snow and high temperature can affect the operation of sensors making it essential to have robust nodes that can overcome these problems and still have the ability to communicate data. In addition to that, mobility resulted from attaching sensor nodes to moving animals or unintentional mobility caused by wind or water current must be taken into account. It is good to know that mobile aware version of RPL can cope with these problems, the practical results using GTM-RPL in [73] show that in a mobile environment, nodes can cover large areas and communicate in a reliable and efficient manner.

C. Transport

There are already many sensors on some of the major roads in many countries, these sensors help in the detection of high traffic and the prevention of heavy congestions. These sensors collect data by either counting the number of vehicles or detect crashes and emergencies. In an IoT environment, these sensors can also control traffic signals, call emergency services or even raise alarms to animals crossing the road [34]. In assisted driving, sensors can also detect correct lane positioning, apply emergency brakes and perform auto parking [35]. These sensors become even more critical in the case of self driving vehicles, where sensors and cameras collect information and drive the car in a safe and efficient manner.

Long delays and errors in the information provided by sensors can easily lead to life threatening situations in both assisted driving and self-driving vehicles, reliable and real-time information are crucial factors in transport applications in addition to mobility support. Vehicle-to-vehicle and vehicle-to-infrastructure communications both face the problem of nodes moving at very high speeds, which complicates the process of routing. Also, targeted cyber attacks can provide misleading information to one or more vehicles causing disastrous outcomes, security should be taken very seriously in such applications where life threatening situations can occur.

Smart transportation can also categorized as a section of smart cities, the information provided by road sensors and in-vehicle sensors can also be used collectively by smart cities applications. This information can help in designing future roads and coming up with new traffic management strategies. RPL can be used for routing data in static on-road sensors, but very few papers discuss using it in vehicular networking. The authors in [36] use RPL in a VANET scenario, direction prediction helps in selecting a parent that is more likely to be in range. The approach is excellent and the results are promising but in order to apply RPL to this application, energy consumption has to be neglected, all aspects of RPL that save energy are removed and while energy is not usually limited in a vehicle that is usually equipped with a significantly large batteries, the use of RPL and the IEEE 802.15.4 in VANETs is still debatable.

We still believe that RPL and RPL-based protocols can contribute to the applications of smart transportation, but we also acknowledge that using it in mobile nodes travelling at vehicular speeds strips it from its energy saving advantages. We support the idea of using it for on-road sensors but we think that further improvements are necessary for in-vehicle deployment.

D. Industry

The industry sector is one of the most important drivers for technology, it has already seen radical changes in the last few decades with the introduction of new technologies, automation and robotics. In control systems, sensor nodes monitor the surrounding environment, collect data and act through actuators providing full automation and control [37]. The smart-grid application is one of the examples of closed loop control systems, with the use of WSNs, the power grid is being revolutionized to become a “smart” power grid that promises a number of improvements [38]. In renewable energy applications, the smart generation of power plays a key role in improving efficiency and facilitating the process of power generation. Renewable energy sources are gradually becoming a part of the grid, solar panels and wind turbines are generating a significant amount of power that is incorporated into the grid.

Smart metering and remote sensing introduce a transparent solution for consumers and makes it easy to track power usage and minimize wasted energy. It can also allow people to control power usage remotely making it a convenient solution as well as an economical advancement [39]. WSNs provide a solution to detect failures, locate power outages and help in isolating faults as part of the supervisory control and data access (SCADA) architecture.

Other industrial applications include safety systems, where sensor nodes detect and report abnormal events. An example of safety application is fire monitoring and control [40] where sensor nodes are used to detect fire and monitor the surrounding environment. Using the data collected from these sensors, actuators can trigger fire doors to isolate the fire area, apply automated fire extinguishing procedures or contact the fire department to seek immediate assistance.

Industrial applications require reliable communication with minimum latency, in addition to low energy consumption, security and mobility support. RPL is gaining a significant interest in the field of industrial applications as it satisfies most of the basic requirements and with the available improvements, it makes an appropriate routing solutions that is flexible, reliable and scalable. GTM-RPL furthers the performance of RPL to support mobile nodes and optimize throughput making it a promising candidate for industrial applications.

E. Military

Military applications introduce a challenging and sensitive field for any technology, it is often difficult to physically access nodes after deployment. For this reason, energy consumption is an essential metric given that changing batteries is rarely possible in war zones and hazardous areas. There are countless advantages in using sensor nodes in military applications, it limits minimizes the dangers that face soldiers and personnels by providing surveillance data, emergency navigation, disaster prevention and robotic intervention.

WSNs can also be used to detect mines [41], or measure the physical state of soldiers to detect problems and measure fatigue levels using wearable devices [42]. It is also important to note that reliability, mobility support and security are key metrics in this field of applications along with energy efficiency. Without these factors, both active and passive monitoring can become very limited and may also lead to undesired actions that are based on false data.

Using GTM-RPL [73], a scenario of a SWAT robot is introduced where a vehicular robot enters a danger location in a war zone. The robot collects data and sends it to one of the gateways through intermediate sensors, efficient routing and reliable data transmission plays a key factor in the success of the operation. RPL was tested using a practical approach along with a mobile version of RPL (mRPL) and our optimized GTM-RPL, results show that GTM-RPL successfully deliver data at higher rates with no additional costs in terms of energy.

IV. Challenges

As seen from section III, there are many aspects that routing protocols need to cover in order to fulfil the application requirements. RPL is the most popular candidate for data routing in LLNs and it has attracted a significant amount of research, many enhancements were made to RPL in literature to tackle one or more routing challenges. The main drivers for improving RPL are energy efficiency, mobility, Reliability, congestion and security.

A. Energy Consumption

One of the most important issues that face LLNs is limited energy, the design of the IEEE 802.15.4 and RPL both take energy consumption into account and propose methods to minimize its usage. The problem of energy consumption in RPL is addressed by the trickle timer [2], which aims to minimize the number of unnecessary control messages. However, the trickle timer is proven to have its own disadvantages dealing with dynamic environments [43], resulting in an inefficient transmission of data and high energy loss due to failed packet delivery. Many researchers take energy consumption into account when suggesting any improvement to RPL, one of the most common approaches is using energy as a routing metric in the objective function. A study also reveals that RPL in its original standard is energy efficient and nodes can last for years [44], [45]. These conclusions were based on simulations were nodes generate 40 packets/minute. Another study also uses energy consumption as a metric and confirmed the available results, they also note that energy consumption increases with higher node densities and larger networks [46]. This is to be expected as nodes in these cases suffer from a higher number of transmissions and added noise.

In a study on an energy efficient objective function targeted towards smart metering and industrial applications [47], the authors use residual energy and expected energy consumption in the objective function named smart energy efficient objective function (SEEOF). The results show 22%-27% improvement in the network lifetime when compared to nodes using MRHOF as the objective function.

The authors in [48] use a collaborative approach where nodes act as “ants” in an ant colony, the approach assumes that nodes are independent decision makers where the gain of each node is desirable for the welfare of the entire network. They also use residual energy as a metric to distribute energy consumption and thus prolong the lifetime of the network.

In [49], residual energy is used as the only metric in the objective function, while results show that it does improve the distribution of energy consumption and extend the life time of the network, it does not consider other important metrics like packet loss, latency or throughput. There are some studies

TABLE I
RPL ENHANCEMENTS FOR ENERGY EFFICIENCY

Ref	Strategy	Advantages	Disadvantages
[45]	Contiki RPL implementation.	(i) Practical experiments. (ii) Shows a lifetime of years using Tmote sky nodes.	Takes only energy consumption into account when testing.
[46]	Using energy as a metric.	(i) Includes ETX as a metric. (ii) Considers mobile scenarios.	No improvements to RPL.
[47]	Using a cost of combined metrics	(i) Improves network lifetime. (ii) Considers industrial applications.	(i) No practical testing. (ii) No considerations for mobility.
[48]	Using collaborative approach.	(i) Uses optimization techniques. (ii) Improves lifetime.	(i) No practical testing. (ii) No throughput optimization.
[49]	Using residual energy as a metric.	Improves lifetime.	(i) Does not consider other routing metrics. (ii) No practical testing.
[50]	Using Fuzzy based metrics.	(i) Improves lifetime and throughput. (ii) Practical experiments.	(i) Does not consider mobility. (ii) Routing metrics are not optimized.
[51]	Using combined metrics.	(i) Considers congestion as a metric. (ii) Improves Throughput, energy efficiency and delay	(i) Uses only Matlab simulations. (ii) Does not consider mobility.
[52]	Using Fuzzy logic and "Corona" strategy.	(i) Considers mobility. (ii) Improves throughput, lifetime and delay.	(i) No practical experiments. (ii) Limited mobility management.
[53]	Using multiple parents.	(i) Improves lifetime. (ii) Uses a multipath approach. (iii) Estimates link quality on multiple links.	(i) Does not consider mobility. (ii) Incompatible with the RPL standard.
[54]	Sinks coordination.	(i) Considers multiple sinks. (ii) Improves throughput and lifetime.	(i) No practical experiments. (ii) No mobility considerations. (iii) Incompatible with the RPL standard.
[55]	RDC based energy balancing.	Improves load balancing and throughput.	(i) Marginal improvement compared to MRHOF. (ii) No mobility considerations.
[56]	Failure detection.	(i) Uses a combined cost metric. (ii) Improves lifetime.	(i) No mobility considerations. (ii) No practical experiments.
[57]	routing and aggregation for minimum energy.	Significantly improve lifetime.	(ii) Limits throughput. (ii) No mobility considerations.

that use energy consumption as one of the metrics in the objective function, but since the main aims of these studies are to improve other aspects of routing like mobility and reliability, they will be discussed in the relevant sections. It is worth mentioning that most improved versions of RPL take energy consumption into account while not necessarily making it their main objective [50], [51], [52], [53].

Studies that aim for load balancing have a significant impact on energy consumption, distributing load reduces congestion and leads to higher throughput but it also means that the energy consumption is distributed more efficiently among nodes, giving a better lifetime for the whole network. In a study on sink to sink coordination technique [54], The control messages of RPL are utilized to adjust the sub-network size relative to other sink nodes. Simulation results show an improvement in both throughput and energy distribution among nodes in the network, leading to an improved lifetime.

In a study of energy balancing, the authors propose a method for estimating energy consumption based on RDC [55], they use this estimation as a metric for routing and achieved better distribution of energy and higher PDR. However, the improvement in energy consumption is marginal compared to using MRHOF as the objective function. In addition to that, the proposal doesn't provide any additional advantages other than marginal energy saving.

Other studies related to minimizing energy consumption use different approaches like improving failure detection to improve energy efficiency in RPL [56]. This approach uses a suffering index that reflects the cost network failures and aims to improve energy consumption by pro-actively detecting failures. Some studies propose energy harvesting techniques to efficiently transmit data. A routing and aggregation for minimum energy (RAME) technique [57] uses the information of the node with the lowest energy to regulate traffic. This approach limits throughput but is very effective in energy critical applications. Table I shows a list of energy related studies with their advantages and disadvantages in terms of implementation and performance, with a focus on implementations that take energy consumption as a priority in the design.

B. Mobility

There are several efforts on investigating routing for mobile WSNs and within the IoT applications, most of the recent work is based on RPL since it became the standard routing protocol for the IoT [58]. RPL is a flexible and scalable routing protocol and using it as a standard makes it easier to build an interoperable solution for any application making it a part of IoT. There are many efforts to improve and create enhanced versions of RPL taking advantage of its flexible and scalable design. Since one of the obvious disadvantages of using RPL is that it lacks mobility support, several researchers focus on providing solutions to accommodate mobile nodes.

The DAG-based Multipath Routing for mobile sensor networks (DMR)[59] was designed based on RPL with rank information and link quality identifier (LQI) as routing metrics, it uses a multipath approach with redundant routes and it has a DODAG maintenance and repair technique. However, RPL already covers these methods and while DMR outperforms the ad-hoc on-demand distance vector (AODV)[60] and the ad-hoc on demand multipath distance vector(AOMDV)[61] protocols which were not designed for LLNs and it wasn't compared to native RPL.

The authors in [62] evaluated the use of RPL in IPv6 WSNs through simulation of two case studies, the first case assumes two mobile sinks in a network of up to 40 nodes and the second case uses Power Line Communication (PLC) nodes which are not energy constrained to act as mobile sinks resulting in a better balance of the energy consumption throughout the network. Although this approach does improve the lifetime of the network, it does not add any improvement to RPL as a protocol and it does not consider other network metrics. Similar to the last approach, the authors in [63] present a strategy for mobile sinks in IPv6 WSNs. In this strategy, every node calculates its weight based on three metrics: number of hops, residual energy and number of neighbour nodes. The sinks look for the node with highest weight and moves towards it. This approach considers only the lifetime of the network by balancing the energy consumption, it is also limited to certain applications.

A hybrid routing protocol for WSNs with mobile sinks [64] aimed to improve the parent selection in RPL by deploying one or more mobile sinks that move towards nodes with higher residual energy in a controlled manner to overcome the problem of depleting nodes closer to the sink. This protocol improves the lifetime of the network by balancing the energy usage among nodes. However, this approach does not consider metrics other than energy and it is only applicable in environments where it is feasible and efficient to have a controlled sink that moves in this manner. In addition to that, the authors do not provide simulation or practical results to validate this protocol.

In [65], the authors proposed a strategy to include the mobility status of each node in the DIO message, static nodes will be preferred in the parent selection process. This approach has a higher PDR and a better routes stability but as it includes the mobility status in the DIO message, it changes the standard and makes it no longer compatible with other versions or RPL. It is also limited in application to some mobility scenarios because it does not include any routing metrics in the parent selection process.

The authors in [36] proposed an enhanced version of RPL for vehicular ad-hoc networks VANETs. They included geographical information as a new metric in order to predict nodes in forward direction and select them as preferred parents to minimize the number of dissociations and reformation of DODAGs. They also modified the DIO timer to be adaptive to the speed of nodes in order to improve the handover time and thus improve the PDR and end-to-end delay. However, this protocol is tested only for data collection with only one cluster head that collects data from static road side nodes regardless of application network requirements and assuming the mobile node does not change direction. It is also aimed for VANET-WSNs and does not take into account a dynamic environment.

The authors in [43] proposed analysis of RPL under mobility using a reverse trickle algorithm. According to their proposal, mobile nodes are preconfigured with a mobility flag and are set to act as leaf nodes to make sure they do not participate in the DODAG building process. When a mobile node connects to a DODAG, it sets the trickle timer to the maximum value and periodically decreases it until it reaches the minimum value or moves to another parent. Using the reverse trickle timer for mobile nodes reduces the disconnection time and improves the detection of an unreachable parent. However, this approach assumes that there is always a static node in range of any mobile node. It also requires using different settings for static and mobile nodes making it less flexible. In addition to that, this protocol has no mobility detection scheme and it rather uses different trickle settings for mobile nodes.

In [66], the authors introduced a mobility support layer called "MoMoRo" targeted at low-power WSN applications with human-scale mobility and low traffic, it allows the nodes to send probes as soon as they observe that they are disconnected from their parent node, it also introduce a destination searching scheme by sending adaptive flood messages to detect a missing node in the data collection tree. According to the simulation results, this protocol achieves similar PDR when compared to the native RPL and to the AODV, it has less packet overhead than AODV but slightly more than the native RPL. In an outdoor practical test using three mobile nodes and one collection node, the PDR is similar to that of AODV with less packet overhead. However, this protocol cannot accommodate nodes that moves at higher speeds or require high amounts of traffic. In addition to that, the practical experiment is done using only three mobile nodes which cannot effectively show realistic results in a general manner.

The authors in [67] introduced a corona mechanism with RPL (Co-RPL) for two main enhancements to the protocol, the first one is based on the corona principle in which the network is divided into circular coronas around the DODAG root, this principle allows the nodes to find an alternative parent in a faster manner without needing to reform the DODAG, the second enhancement is the fuzzy logic objective function FL-OF that uses end-to-end delay, hop count, link quality and residual energy as routing metrics. This protocol achieves

TABLE II
RPL ENHANCEMENTS FOR MOBILITY MANAGEMENT

Ref	Strategy	Advantages	Disadvantages
[62]	Using mobile sinks	(i) Improves lifetime. (ii) Considers multiple sinks.	(i) No improvements to RPL design. (ii) No other routing metrics used.
[63]	Sink node moves towards nominated nodes.	(i) Improves lifetime. (ii) Improves load balancing.	(i) Limited applicability. (ii) No improvements to RPL design.
[64]	Deploying a contingency mobile sink.	(i) Improves lifetime. (ii) Improves load balancing.	(i) Limited applicability. (ii) No improvements to RPL design. (iii) No simulations to validate it.
[65]	Including mobility status in DIO.	Improves PDR and routing stability.	Incompatible with the native RPL.
[36]	(i) Including geographical information as a metric. (ii) Using an adaptive timer.	(i) Improves PDR and end to end delay in VANETS.	(i) Assumes that nodes do not change direction. (ii) Does not consider dynamic scenarios.
[43]	Using reverse trickle for mobile nodes.	(i) Reduces disconnection time. (ii) Improves PDR.	(i) No mobility detection scheme. (ii) Requires different settings for mobile nodes.
[66]	(i) Sending probes when disconnected. (ii) Using Adaptive flood messages.	Considers three mobile nodes.	(i) No improvements in performance compared to native RPL. (ii) Additional overhead.
[67]	Using a “Corona” mechanism.	Improves PDR, end to end delay and energy efficiency.	Limited mobility management.
[68]	Configuring mobile nodes as “leaf” nodes.	(i) Improves stability and energy efficiency.	(i) No improvements to the RPL design. (ii) Limited mobility support.
[69]	(i) Link monitoring using RSSI readings. (ii) Additional timers.	(i) Improves mobility management. (ii) Improves PDR. (iii) Considers dynamic scenarios.	(i) Uses periodic timers that cancels the need for trickle. (ii) Additional overhead.
[70]	Using objective function with mRPL [69].	Higher flexibility.	(i) No improvements to mRPL. (ii) The objective function is always dependant on RSSI.
[71]	Using Kalman filter and blacklisting.	(i) Uses localization techniques. (ii) Improves PDR.	(i) Susceptible to inaccurate positioning. (ii) High energy consumption.
[72]	Adaptive timer and adaptive DIS.	(i) Improves PDR, energy efficiency and delay. (ii) Low overhead.	Marginal improvement in low mobility scenarios.
[73]	Game theoretic optimization of RPL.	(i) Improves PDR, Energy efficiency and delay. (ii) Change transmission rate according to network conditions.	-

higher PDR, less end-to-end delay and better energy than the native RPL. However, this protocol is designed for nodes moving at low speeds of up to 4 m/s and it does not address a hybrid network with a dynamic mobility model.

Another enhancement of RPL designed for healthcare and medical applications [68] presents an evaluation of RPL for hybrid networks with both mobile and static nodes within the applications of healthcare. The authors do not introduce any enhancement to the RPL itself but rather force mobile nodes to act as leaf nodes which according to the RPL specifications cannot advertise themselves as routers and do not send DIO messages with the objective function metrics. This approach improves the stability of the network by allowing the mobile nodes to connect to the DODAG but not to act as a parent node nor to participate in the formation of the DODAG. The problem with this approach is that it assumes that there is always a fixed node in range of any other node, it also does not add anything to the design of RPL but rather evaluates using it within the given scenario.

In [69] the authors propose a mobile version of RPL called mRPL to manage mobility in IoT environments. This protocol aims to improve the hand-off time for mobile nodes by adding four timers to the original trickle algorithm in order to detect disconnected nodes in a smart and fast approach. The connectivity timer is responsible for detecting a loss of connectivity to the parent node. The mobility detection timer uses the average received signal strength indication (ARSSI) to assess the reliability of the connection. The hand-off timer is responsible for allocating an adaptive short period that is sufficient for sending bursts of DIS and receiving DIO replies in order to reduce the hand-off delay. The reply timer is responsible for sending replies to the mobile nodes using an adaptive period to minimize collision. This protocol is compared with the native RPL considering different simulation scenarios and the results show that mRPL outperforms the native RPL in terms of PDR, packet overhead and hand-off delay. A practical test is also conducted using Tmote-Sky nodes and the results were similar to the simulation. However, mRPL relies heavily on ARSSI values and neglects other metrics resulting in unnecessary hand overs and sometimes unreliable links establishment. This protocol is tested for only one mobile node moving at a constant velocity (2m/s) near nine static nodes and does not consider more than one mobile node or nodes moving at higher speeds. It also does not discuss the objective function of RPL and its potential to improve mobility management.

More recently, a "Smarter-HOP" version of mRPL for optimizing mobility in RPL was introduced to improve the performance of mobility management. This protocol is named mRPL++ [70] and it includes the objective function in the parent selection process to make sure that nodes are aware of link metrics other than RSSI. This approach improves the decision making by using the product of ARSSI and the ratio between the metric costs in the objective function of the competing parent nodes as the basis for parent selection. However, this protocol still suffers from the weakness points of mRPL and is still dependant on RSSI so that it cannot be neglected regardless of the objective function.

The authors in [71] present a routing strategy called Kalman positioning RPL (KP-RPL), this protocol is based on RPL and it provides robust routing for WSNs with both static and mobile nodes. In KP-RPL, two modes of communication are defined, the anchor to anchor (two static nodes) and the mobile to anchor. The first mode uses the default RPL while the second one is managed by using Kalman filter and blacklisting. Each mobile node creates an initial list of the static nodes within its range and according to the Received Signal Strength Identifier (RSSI), it blacklists those of low ETX that are considered "potentially unreliable links". This approach improves the reliability of the network by 25% according to simulation results. However, it assumes only one mobile node is moving within range of a number of static nodes and does not take into account additional mobile nodes. It also relies on positioning to estimate the position of the mobile node and performs blacklisting based on that. Inaccurate positioning can result in severe network degradation because not only the routing decision will be affected but also reliable links might be blacklisted.

The authors in [72] proposed D-RPL for multihop routing in dynamic IoT applications, aiming to improve the operation of RPL in mobile environments with dynamic requirements. D-RPL uses some of the features of mRPL in addition to an adaptive timer that works as a reverse-trickle timer when mobility is detected. It also includes routing metrics in the decision making to minimize the number of unnecessary hand overs while maintaining high responsiveness and smooth transitions. This design was also extended in [73] to optimize the performance or RPL using a game theoretic approach. The game theory based mobile RPL (GTM-RPL) uses RSSI readings to detect mobility, it also calculates an energy cost based on density, a mobility cost based on link quality level and a mobility metric and a priority cost to generate a total cost function used to adaptively change transmission rate. This approach improves the performance of RPL under mobility in terms of energy consumption, throughput and end to-end-delay, providing a flexible solution that adapts to the network conditions. Table II shows a list of mobility aware versions of RPL with their advantages and disadvantages in terms of implementation and performance.

C. QoS

Reliable data transmission is a requirement most IoT applications, this is achieved by minimizing lost packets, maximizing throughput and avoiding long delays. Achieving high QoS requires improved routing decisions, optimized transmission rates and efficient topology repair [74]. In [75], the authors present a reactive approach that uses the number of received data packets to instead of counting on control messages to send link quality updates. This approach forces nodes to change parents to measure link quality, this approach improves the reliability of transmitted data as it maintains a list of different link quality measurements for neighbouring nodes.

In [76], [77], the authors proposed a cross layer design to improve link quality estimation in RPL, this algorithm also uses an adaptive approach to achieve reliable data transmission, low energy consumption and decrease end-to-end delay compared to the native RPL. They also introduced a method to update link quality information based on priority using unicast DIS messages.

In [52], a novel objective function was introduced based on fuzzy logic, it uses a corona mechanism dividing the network into circular coronas around the DODAG root, this scheme allows nodes to easily find an alternative parent without the need to reform the DODAG. In the fuzzy logic objective function (FL-OF), it uses end-to-end delay, hop count, link quality and residual energy as routing metrics. This protocol achieves higher PDR, improved responsiveness and decreased energy consumption, it also has the ability to manage mobility at low speeds due to the corona mechanism.

A study based on merging routing metrics including ETX, remaining energy and delay introduce a new fuzzy objective function [50], the algorithm uses fuzzy logic to find a trade-off for these metrics. This algorithm was tested using practical experiments and results claim an improvement in PDR, energy consumption and end-to-end delay.

The authors in [56] use an approach to detect link failures, the algorithm (Pro-RPL) counts the number of lost packets and uses a threshold to assume a failed link. Nodes send DIO messages containing information about energy consumption and link cost, these metrics contribute to decision making where nodes select a parent that has the lowest cost. Simulation results show that this approach improves PDR and energy efficiency, however, a faster method to detect failures is needed to improve its responsiveness.

A proposal in [78] presents an approach to detect root node failure that results in loss of all data. Most papers assume

TABLE III
RPL ENHANCEMENTS FOR QOS

Ref	Strategy	Advantages	Disadvantages
[75]	Passive link quality probing	Improved reliability of data	(i) Long delays caused by frequent parent changes. (ii) No mobility support.
[76]	Improving link quality estimation	Improved PDR, energy consumption and delay.	(i) No mobility support. (ii) Some conclusions do not agree with literature.
[77]	Exploiting trickle algorithm for Link quality estimation.	(i) Improved PDR. (ii) Compatible with native RPL.	(i) Additional overhead. (ii) Increased energy consumption and delay. (iii) No considerations for dynamic scenarios.
[52]	QoS-aware fuzzy logic objective function.	(i) Improves PDR, delay and energy efficiency. (ii) Considers mobile scenarios.	(i) No practical experiments. (ii) Limited mobility support.
[50]	Fuzzy logic metrics.	(i) Improves lifetime and throughput. (ii) Conducts practical experiments.	(i) Does not consider mobility. (ii) Routing metrics are not optimized.
[56]	Link failure detection.	(i) Uses a combined cost metric. (ii) Improves lifetime and throughput.	(i) No mobility support. (ii) No practical experiments.
[78]	Root node failure detection.	(i) Allows node collaboration. (ii) Improves reliability.	(i) Increased energy consumption. (ii) Failure detection is not guaranteed.
[53]	Multiple parent nodes.	(i) Improves lifetime. (ii) Estimates link quality on multiple paths.	(i) Does not consider mobility. (ii) Incompatible with the native RPL.
[79]	Stateless multicast RPL forwarding	(i) Improved energy efficiency and delay. (ii) Potential improvement to PDR.	(i) Incompatible with RPL standard. (ii) Not flexible. (iii) No mobility support.
[80]	Implicit acknowledgements.	(i) Combines Trickle [2] and SMRF [79] algorithms. (ii) Ability to select a trade off between delay and PDR	(i) Increased delay. (ii) Increased energy consumption. (iii) High memory requirements.
[81]	Enhanced stateless multicast RPL forwarding.	(i) Improved reliability. (ii) Improved PDR and delay.	(i) Increased energy consumption. (ii) Incompatible with the native RPL.
[82]	Bidirectional multicast RPL forwarding.	(i) Improved reliability. (i) Considers bidirectional traffic. (iii) Adjustable parameters.	(i) Increased energy consumption and delay. (ii) High memory requirements.
[83]	Cooperative interaction among RPL instances.	(i) Improved reliability and energy consumption. (ii) Low implementation cost. (iii) Considers multiple objective functions	No mobility support.

that the sink node cannot fail, has sufficient power and is always in range. The root node failure detection (RNFD) uses a probabilistic approach to detect the failure of the root node or other main nodes connecting large portions of the network. It also allows node to collaborate in finding failures to improve responsiveness. Simulation results show that this algorithm has the potential to detect failures but does not guarantee that, it also introduces a control overhead leading to higher energy consumption and lower throughput.

In [53], the authors propose a multipath routing approach where nodes use multiple parents and transmit their data across all the available links. It uses an estimated lifetime metric (ELT) to divide transmission among node according to their residual energy and ETX. The metrics combination ensures a more reliable connection compared to using MRHOF or OF0, in addition to improving load balancing and energy efficiency performance.

Other studies introduce multicast techniques to improve routing reliability [79], [80], [81], [82]. These studies propose a stateless multicast RPL forwarding (SMRF), an enhanced SMRF (ESMRF) and a bidirectional SMRF (BMRF) to control multicast messages in RPL. The experiment results show that these protocols have the potential to outperform the trickle algorithm, they also claim that by using link layer broadcast and link layer unicast they ensure higher reliability. However, this improvement in reliability comes at a high cost of energy consumption and delay.

Another approach for ensuring QoS and connection reliability, is the use of multiple instances that is part of the original RPL description but is rarely discussed in research. This approach allows using different logical topologies of RPL at the same time where each "instance" or topology can use unique QoS requirements. An algorithm called cooperative-RPL (C-RPL) [83] uses a cooperative strategy for nodes with different sensing applications to save energy and reduce cost. Table III presents a summary of RPL enhancements that focus on QoS along with their main advantages and disadvantages in terms of implementation and performance.

D. Congestion

One of the most challenging aspects in multi-hop routing is congestion, as the number of hops increases the accumulated data causes congestion especially at the node level. With multiple nodes transmitting at high rates, the risk of congestion becomes greater and both the wireless channel and the nodes' buffer become congested [84]. Congestion leads to significant deterioration in energy consumption, reliability and delay [85]. There are different approaches to solve the problem of congestion, the most common are resource control, traffic control and hybrid schemes.

The authors in [86] propose a duty cycle aware congestion control (DCCC6) for controlling traffic in 6LoWPAN networks, it uses RPL to handle routing and adjusts its traffic based on RDC and buffer occupancy. This protocol is tested using 25 nodes in a random deployment, simulation results and practical results show an improvement in performance in terms of energy consumption and delay, this approach successfully mitigates congestion in RPL networks. Similarly, the authors in [87] introduced three schemes for congestion control called Griping, Deaf, and Fuse. These schemes use queue length, buffer length and a hybrid combination of them respectively. According to simulation results, the last scheme (Fuse) which uses a combination of queue and buffer length outperforms the other two in managing congestion.

One of the problems of the aforementioned schemes is that they do not support node priorities or application priorities, the authors in [88] introduced a game theoretic framework to use an adaptive transmission rate in sensor nodes. The game formulation is aware of the buffer occupancy, energy consumption and node and application priorities. Simulation results show that this scheme improves the performance in congested networks in terms of throughput, delay and energy consumption.

In resource control strategies, the authors in [89] introduce a congestion control algorithm that detects least congested paths based on buffer occupancy. This proposal was designed for CoAP/RPL networks and was compared to the CON and NON transactions in CoAP. This approach improves the performance of the network in the presence of congestion, however, it becomes counter productive when used in non-congested networks. It is also worth mentioning that this algorithm uses "eavesdropping", to passively listen to received packets leading to high energy consumption.

In [90], [91] the authors follow a load balancing approach, they use a queue utilization scheme where nodes send congestion information using DIO messages. This approach successfully achieves load balancing and improves the performance in congested networks. Similarly, the authors in [92], [93] propose a game theoretic approach that contributes to the parent change decision. In this algorithm, the parent node sends a DIO when it detects congestion and the child node uses the congestion information to change parent. Simulation results show that this approach achieves up to 100% throughput improvement in highly congested networks compared to the native RPL.

Other load balancing schemes were also used in [94], [95], [96], distributing the load on different routes through multiple parents. According to simulation results, these algorithms successfully avoid congestion and significantly improve the energy efficiency and throughput. However, these protocols change the standard of RPL by creating new control messages and changing the DODAG formation procedure, making them incompatible with the native RPL. The lack of interoperability is a problem in IoT applications and RPL nodes are expected to be flexible and scalable, these are important factors in making it the popular choice for IoT routing.

Another approach to mitigate congestion is using multipath routing, the authors in [97] propose using multiple routes for data delivery based on objective function metrics. In [98], the protocol uses DIO information to trigger multi-path operation only when congestion occurs.

In and [99], the authors introduce a congestion alleviation scheme based on grey theory, it uses buffer occupancy, ETX and queuing delay in a multi attribute optimization approach. It also uses a utility function to maximize throughput in non-congested situations making it a hybrid solution that combines both traffic control and resource control. Table IV summarizes the relevant RPL enhancements that deals with congestion along with the advantages and disadvantages of using them.

E. Security

Most IoT applications require a certain level of security, depending on the type of the application, the area of deployment and the sensitivity of transmitted information. In general, IoT applications are expected to have integrity, confidentiality, availability, privacy, authentication and trust. There are many attacks that can easily target sensor nodes taking advantage of the relative simplicity of their hardware, seeking gain by exploiting their data or just blocking their services. From a routing perspective, the most common attacks that face sensor nodes are denial of service (DoS), man in the middle, spoofing, black hole, sink hole, worm hole and Sybil attacks [100].

According to the the RPL standard in RFC 6550, Three security modes are defined:

- Unsecured: Control messages are sent without any security measures.
- Pre-installed: Nodes use a pre-installed key to join a network.
- Authenticated: Nodes use a pre-installed key to join the network as a leaf node, nodes then request an authentication message that allows them to operate as routers.

TABLE IV
RPL ENHANCEMENTS FOR CONGESTION CONTROL

Ref	Strategy	Advantages	Disadvantages
[86]	Duty cycle aware congestion control.	Improves energy efficiency and delay.	(i) Does not consider using uncongested routes. (ii) Reduces throughput. (iii) Does not support mobility.
[87]	Using queue length and buffer length to mitigate congestion.	Improves PDR and energy efficiency.	(i) Does not consider using uncongested routes. (ii) Does not support mobility.
[88]	Adaptive transmission rate.	(i) Improved PDR, energy consumption and delay. (ii) Supports node and application priorities.	(i) Does not consider using uncongested routes. (ii) Does not support mobility.
[89]	Detecting least congested paths using bird flocking technique.	Improves PDR in the presence of congestion.	(i) Increase energy consumption. (ii) Becomes counter productive in non congested scenarios. (iii) Does not support mobility.
[90], [91]	Sending congestion information in DIO.	(i) Achieves load balancing. (ii) Improves PDR and energy efficiency in congested routes.	(i) Does not adapt to non-congested scenarios. (ii) Does not support mobility.
[92], [93]	Using game theory to find non-congested paths.	Improves PDR and throughput.	(i) Additional overhead. (ii) Increased energy consumption. (iii) Does not support mobility.
[94], [95], [96]	Using multiple parents.	(i) Improves throughput and energy efficiency. (ii) Achieves load balancing.	(i) Incompatible with RPL standard. (ii) Does not support mobility.
[97]	Using multipath routing.	(i) Improves throughput and delay. (ii) Achieves load balancing.	(i) Increased energy consumption. (ii) Does not support mobility.
[98]	Using adaptive multipath routing.	(i) Improves energy efficiency, throughput and delay. (ii) Achieves load balancing.	(i) Additional overhead. (ii) Does not support mobility.
[99]	Using grey theory to mitigate congestion.	(i) Improves energy efficiency, throughput and delay. (ii) Uses an adaptive transmission rate to maximize throughput. (iii) Supports node and application priorities.	Does not support mobility.

To the best of our knowledge, all RPL enhancements in the literature use the "Unsecured" mode, the "Authenticated" mode is not specified in details in the standard, it requires a "companion specification to detail the mechanisms by which a node obtains/requests the authentication material" [1]. It is surprising however that the "Pre-installed" mode has not been implemented in literature. Since there are no studies on security as an RPL internal mechanism, a number of studies on RPL attacks and their mitigation are presented in this section.

A DOS attack that forces the trickle timer to reset by causing inconsistencies in the DODAG, this results in a loop of DODAG reformation and global repair. This type of attacks prevent nodes from handling data packets and deprive them from their energy used for pointless repairs. An IETF standard proposal in RFC 6553 [101] considers using a threshold for the number of allowed trickle resets per hour. This solution does not solve the problem of dropped data packets but at least, it limits the energy wasted for DODAG reformation after the threshold is reached. Another study in [102] improved this idea and proposed an adaptive threshold that depends on the network conditions and type of attack. The strategy shows a significant performance improvement in terms of energy consumption.

A study in [103] proposed an intrusion detection system (IDS) to detect the problems of black hole and grey hole attacks where malicious nodes silently drop all or some of the data packets. The algorithm detects malicious nodes by monitoring the number of DIO messages, packet loss and delays. According to their results, this approach successfully prevents malicious nodes from participating in the DODAG formation process.

In case of a sink hole attack, where a node advertises itself with a high rank to attract data from neighbouring nodes, the authors in [104] propose an algorithm to use signed DIO messages to detect fake rank advertisements. The algorithm was also studied and improved by [105], [106] to cover spoofing and replay attacks.

A more recent study on detecting version number attacks in RPL claims that sensor nodes cannot cope with cryptographic messages and thus introduce a monitoring strategy to detect

TABLE V
RPL ENHANCEMENTS FOR SECURITY FEATURES

Ref	Strategy	Advantages	Disadvantages
[101]	Limiting trickle resets using a fixed threshold.	(i) Improves energy efficiency. (ii) Improves DODAG stability in case of DoS attacks.	(i) Decreases throughput. (ii) Does not use RPL security features.
[102]	Limiting trickle resets using an adaptive threshold.	(i) Significantly improves energy efficiency. (ii) Improves DODAG stability in case of DoS attacks.	(i) Additional overhead. (ii) Does not use RPL security features.
[103]	Using IDS to create white and black lists.	(i) Isolates malicious nodes successfully. (ii) Improves network trust.	(i) High overhead. (ii) Does not use RPL security features.
[104]	Using signed DIO messages to detect sink hole attacks.	(i) Detects and drops malicious DIOs. (ii) Improves network trust.	(i) Additional overhead. (ii) Does not use RPL security features.
[105]	Using geographical information to detect spoofed DIOs.	Potentially mitigates spoofing attacks.	(i) Not validated. (ii) Requires location awareness. (iii) Does not use RPL security features.
[106]	Using geographical information with layer 2 keys.	Potentially mitigates replay attacks.	(i) Not validated. (ii) Requires location awareness. (iii) High overhead. (iv) Does not use RPL security features.
[107]	Distributed monitoring architecture.	(i) Mitigates version number attacks. (ii) Potentially locates the attacker. (iii) Scalable solution.	(i) High overhead. (ii) High deployment cost. (iii) Does not use RPL security features.

attacks. The monitoring agents are different from sensor nodes in this approach, their sole purpose is to monitor the network [107]. This approach implies that a high overhead is added to the network because of the added monitoring nodes. However, the results show that this approach mitigates the problem of version number attacks and presents a scalable solution with the potential to identify and locate an attacker or a group of attackers. Table V presents the main efforts to deal with security threats using RPL with a summary of their advantages and disadvantages.

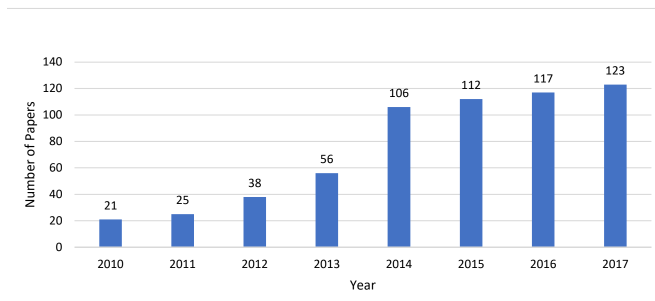

Fig. 3. RPL research papers count

V. CONCLUSIONS

This paper presents a systematic review of RPL-based routing protocols, with technical insights and evaluation for the different implementations of RPL and the optimisation approaches in literature. It also discusses the current state of RPL, with regards to its applicability and efficiency in IoT applications.

Our study shows that RPL is gaining increasing interest with more topics being covered every year since its standardisation. In the first few years (2010-2013), the main focus was on studying RPL and improving energy saving without worrying about missing functionalities. In later years however (2014-2015), the focus changed towards adding functionalities and improving the core design of RPL. Mobility, congestion, multi-path routing, load balancing and QoS witnessed extensive studies that produced a number of invaluable improvements to RPL. Currently (2018), many researchers accept RPL as the routing protocol for the IoT. Thus, research is moving forward focussing on industrial uses of RPL, cross-layer design and security-enabled RPL. Figure 3 presents the number of IEEE research papers in each year since 2010, it is clear that after its standardization in 2012, RPL is receiving increasing interest in research and implementation. It is quite clear from the vast number of papers on RPL that the research community sees it as a promising protocol that can be if not already is a key player in the Internet of the future. The simulation results and practical implementations of RPL show that it can be efficiently used in different applications including but not limited to healthcare, smart environments, transport, industry and military applications. It is not easy to find a single adaptation of RPL and declare it as the ultimate routing protocol but many of the protocols presented in this review are interoperable and backward compatible with the native RPL. This also proves that the original design of RPL was successful in creating a flexible and scalable basis. Having said that, it is also worth mentioning that some of the design features that are documented in the original standard RFC 6550 and RFC 6551 including multiple instances and version numbers were rarely investigated in literature, while some of the potentially game-changing functionalities including mobility support and congestion control were not mentioned in the original standard. It is our belief that RPL can significantly benefit from a new standard design that takes into account its current state and opens the door for new optimisation studies.

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