Data Routing for Mobile Internet of Things Applications

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Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

June 2018

Declaration

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. Most materials contained in the chapters of this thesis have been previously published in research articles written by the author of this work (Harith Dheyaa Yahya Kharrufa), who appears as lead (first) author in all of them. The research has been supervised and guided by Dr Andrew H. Kemp, and he appears as a co-author on these articles. All the materials included in this document is of the author's entire intellectual ownership.

A) Details of the publications which have been used (e.g. titles, journals, dates, names of authors):

In Chapter 2:
"A Review of RPL and RPL-based routing protocols in IoT applications",submitted to *IEEE Internet of Things journal*, June 2018. Co-authors: Hayder Al-Kashoash and Andrew Kemp.

In Chapter 3:
"A Dynamic Cluster Head Election Protocol for Mobile Wireless Sensor Networks", *IEEE 2015 International Symposium on Wireless Communication Systems (ISWCS)* Published. Co-authors: Yaarob Al-Nidawi and Andrew Kemp. (DOI: 10.1109/ISWCS.2015.7454362).

In Chapter 4:
"Dynamic RPL for multi-hop routing in IoT applications." , *IEEE 2017 Annual Conference on Wireless On-demand Network Systems and Services (WONS)*,

Published. Co-authors: Hayder Al-Kashoash, Yaarob Al-Nidawi, Maria Quezada Mosquera and Andrew Kemp.
(DOI: 10.1109/WONS.2017.7888753).

In Chapter 5:
"A Game Theoretic Optimization of RPL for Mobile Internet of Things Applications", *IEEE Sensors Journal 18, no. 6 (2018): 2520-2530.*, Published. Co-authors: Hayder Al-Kashoash and Andrew Kemp.
(DOI: 10.1109/JSEN.2018.2794762).

In Chapter 6:
"A Performance Evaluation of RPL in Mobile IoT Applications: A Practical Approach", submitted to *IEEE Internet of Things journal*, June 2018. Co-authors: Ma Lei and Andrew Kemp.

B) Details of the work contained within these publications which is directly attributable to Harith Dheyaa Yahya Kharrufa:
With the exceptions detailed in section C, the published work is entirely attributable to Harith Dheyaa Yahya Kharrufa: the literature review necessary to construct and originate the ideas behind the published manuscripts, the novel ideas presented in the papers, the implementation of mobility management and proposed algorithms used in the Contiki OS and all the work necessary in the editing process of the manuscripts.

C) Details of the contributions of other authors to the work:
Dr Andrew H. Kemp is the co-author for all the publications listed above. These publications have been written under his supervision, benefiting from excellent technical advice and editorial, patient guidance and valuable feedback.

Yaarob Al-Nidawi and Hayder Al-Kashoash contributed with recommendations and collective study as members of the working group..

Maria Quezada Mosquera provided the hardware necessary to do practical testing and helped with the set-up of experiments.

Ma Lei provided a mobility scenario for smart agriculture applications.

Acknowledgements

I would like to thank my supervisor, Dr Andrew H. Kemp for his continuous support and guidance throughout my study. His feedback, motivation and positivity helped me through all the obstacles I faced during my research. Dr Kemp was always keen to help in both my research and professional development, I learned countless lessons from him and I am very glad and proud to have him as my supervisor.

A special thanks to my loving wife Amna for her unconditional love, support and patience. You were always there for me when I needed you, gave me strength and inspired me to keep going. I am also grateful to have my son Adam, my source of energy and motivation, he brought joy into my life and drew a smile on my face.

I would also like to thank my family, for their prayers and encouragement. Your wise council, sympathetic ear and continuous support kept me going throughout my years of study. I cannot thank you enough for all the support and guidance you provided me.

Thanks to the Higher Committee for Education Development / Iraqi Prime Minister Office for their valuable support. Without their precious help it would not have been possible for me to conduct this research. Also thanks to the state company for Internet services for allowing me to pursue further studies.

For all my friends and colleagues in the school, thank you all for your valuable support, I was really lucky to work with wonderful friends like you.

Last but not least, I would like to thank the academic staff and the research community at the university of Leeds for their advice and collaboration. Also, the staff at St. James's hospital for their help and interest in my practical testing.

Abstract

The Internet of things (IoT) represents a new era of networking, it envisions the Internet of the future where objects or “Things” are seamlessly connected to the Internet providing various services to the community. Countless applications can benefit from these new services and some of them have already come to life especially in healthcare and smart environments. The full realization of the IoT can only be achieved by having relevant standards that enable the integration of these new services with the Internet. The IEEE 802.15.4, 6LoWPAN and IPv6 standards define the framework for wireless sensor networks (WSN) to run using limited resources but still connect to the Internet and use IP addresses. The Internet engineering task force (IETF) developed a routing protocol for low-power and lossy networks (LLN) to provide bidirectional connectivity throughout the network, this routing protocol for LLNs (RPL) was standardized in RFC6550 in 2012 making it the standard routing protocol for IoT.

With all the bright features and new services that come with the futuristic IoT applications, new challenges present themselves calling for the need to address them and provide efficient approaches to manage them. One of the most crucial challenges that faces data routing is the presence of mobile nodes, it affects energy consumption, end-to-end delay, throughput, latency and packet delivery ratio (PDR). This thesis addresses mobility issues from the data routing point of view, and presents a number of enhancements to the existing protocols in both mesh-under and route-over routing approaches, along with an introduction to relevant standards and protocols, and a literature review of the state of the art in research.

A dynamic cluster head election protocol (DCHEP) is proposed to improve network availability and energy efficiency for mobile WSNs under the beacon-enabled IEEE 802.15.4 standard. The proposed protocol is developed and simulated using CASTALIA/OMNET++ with a realistic radio model and node behaviour. DCHEP improves the network availability and lifetime and maintains cluster hierarchy in a proactive manner even in a mobile WSN where all the nodes including

cluster heads (CHs) are mobile, this is done by dynamically switching CHs allowing nodes to act as multiple backup cluster heads (BCHs) with different priorities based on their residual energy and connectivity to other clusters. DCHEP is a flexible and scalable solution targeted for dense WSNs with random mobility. The proposed protocol achieves an average of 33% and 26% improvement to the availability and energy efficiency respectively compared with the original standard.

Moving to network routing, an investigation of the use of RPL in dynamic networks is presented to provide an enhanced RPL for different applications with dynamic mobility and diverse network requirements. This implementation of RPL is designed with a new dynamic objective-function (D-OF) to improve the PDR, end-to-end delay and energy consumption while maintaining low packet overhead and loop-avoidance. A controlled reverse-trickle timer is proposed based on received signal strength identification (RSSI) readings to maintain high responsiveness with minimum overhead, and consult the objective function when a movement or inconsistency is detected to help nodes make an informed decision. Simulations are done using Cooja with different mobility scenarios for healthcare and animal tracking applications considering multi-hop routing. The results show that the proposed dynamic RPL (D-RPL) adapts to different mobility scenarios and has a higher PDR, slightly lower end-to-end delay and reasonable energy consumption compared to related existing protocols.

Many recent applications require the support of mobility and an optimised approach to efficiently handle mobile nodes is essential. A game scenario is formulated where nodes compete for network resources in a selfish manner, to send their data packets to the sink node. Each node counts as a player in the non-cooperative game. The optimal solution for the game is found using the unique Nash equilibrium (NE) where a node cannot improve its pay-off function while other players use their current strategy. The proposed solution aims to present a strategy to control different parameters of mobile nodes (or static nodes in a mobile environment) including transmission rate, timers and operation mode in order to optimize the performance of RPL under mobility in terms of PDR, throughput, energy consumption and end-to-end-delay. The proposed solution monitors the mobility of nodes based on RSSI readings, it also takes into account the priorities of different nodes and the current level of noise in order to select the preferred transmission rate. An optimised protocol called game-theory

based mobile RPL (GTM-RPL) is implemented and tested in multiple scenarios with different network requirements for Internet of Things applications. Simulation results show that in the presence of mobility, GTM-RPL provides a flexible and adaptable solution that improves throughput whilst maintaining lower energy consumption showing more than 10% improvement compared to related work. For applications with high throughput requirements, GTM-RPL shows a significant advantage with more than 16% improvement in throughput and 20% improvement in energy consumption.

Since the standardization of RPL, the volume of RPL-related research has increased exponentially and many enhancements and studies were introduced to evaluate and improve this protocol. However, most of these studies focus on simulation and have little interest in practical evaluation. Currently, six years after the standardization of RPL, it is time to put it to a practical test in real IoT applications and evaluate the feasibility of deploying and using RPL at its current state. A hands-on practical testing of RPL in different scenarios and under different conditions is presented to evaluate its efficiency in terms of packet delivery ratio (PDR), throughput, latency and energy consumption.

In order to look at the current-state of routing in IoT applications, a discussion of the main aspects of RPL and the advantages and disadvantages of using it in different IoT applications is presented. In addition to that, a review of the available research related to RPL is conducted in a systematic manner, based on the enhancement area and the service type. Finally, a comparison of related RPL-based protocols in terms of energy efficiency, reliability, flexibility, robustness and security is presented along with conclusions and a discussion of the possible future directions of RPL and its applicability in the Internet of the future.

Contents

List of Abbreviations

6LoWPAN	IPv6 over Low Power Wireless Personal Area Network
ACK	Acknowledgement
AODV	Ad hoc On-Demand Distance Vector
ARSSI	Average Received Signal Strength Indication
BAN	Body Area Network
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CH	Cluster Head
CoAP	Constrained Application Protocol
CoRE	Constrained RESTfull Environments
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DAG	Directed Acyclic Graph
DAO	Destination Advertisement Object
DCHEP	Dynamic Cluster Head Election Protocol
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DODAG	Destination Oriented DAG
ETX	Expected Transmission Count
FFD	Full-Function Device
GTM-RPL	Game Theory based Mobile RPL
GTS	Guaranteed Time Slots
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force

LIST OF ABBREVIATIONS

IoT	Internet of Things
IP	Internet Protocol
KKT	Karush-Kuhn-Tucker
LLDN	Low Latency Deterministic Network
LLN	Low-Power and Lossy Network
LOAD	6LoWPAN Ad Hoc On-Demand Distance Vector
LPWAN	Low Power Wide Area Network
LR-WPAN	Low-Rate Wireless Personal Area Network
LQI	Link Quality Indicator
MAC	Medium Access Control
MANET	Mobile Ad-Hoc NETwork
MRHOF	Minimum Rank with Hysteresis Objective Function
MTU	Maximum Transmission Unit
NED	NEtwork Description
NFC	Near Field Communication
OF	Objective Function
OF0	Objective Function zero
OS	Operating System
PAN	Personal Area Network
PDR	Packet Delivery Ratio
QoS	Quality of Service
RDC	Radio Duty Cycle
RFC	Request For Comment
RFD	Reduced-Function Device
RFID	Radio Frequency Identification
RPL	Routing Protocol for Low-Power and Lossy Networks
RSSI	Received Signal Strength Indication
TCP	Transmission Control Protocol
TSCH	Time Slotted Channel Hopping
UDP	User Datagram Protocol

URI	Uniform Resource Identifier
VANET	Vehicular Ad hoc NETwork
WSN	Wireless Sensor Network

List of Symbols

I_{min}	Minimal interval size
I_{max}	Maximum interval size
$I_{doubling}$	Number of doublings to reach I_{max}
Γ	The non-cooperative game
N	Number of nodes
P_k	Node k as a player in the game
S_k	Strategies available for node P_k
A_k	Actions feasible for player P_k
$\phi_k(A_k)$	The cost for node P_k to take an action A_k
$RSSI_n$	RSSI for node n
$lastRSSI_n$	last RSSI value received by node n
K_{rssi}	Redundancy constant
$U_k(A_k)$	The utility function of node P_k
λ_k	Transmission rate
c	Safety constant
α	Weighing factor for utility function
$M_k(a_k, a_{-k})$	Mobility function of node P_k
(LQ)	Link quality cost
Mm	Mobility metric
T	Total runtime
$V_k(t)$	Velocity of node k at time t
β	Weighing factor for mobility function
$E_k(a_k, a_{-k})$	Energy function
D_m	Density Metric
T_r	Transmission range

A	Deployment area
γ	Weighing factor for energy function
$Pr_k(a_k)$	Priority function
δ	Weighing factor for priority function
H	Hessian matric
$\sigma(\lambda_k, r)$	The weighted non-negative sum
$g(\lambda_k, r)$	pseudo-gradient
$G(\lambda_k, r)$	Jacobian matrix
$\mathcal{L}_k$	The Lagrangian function
u_k, v_k	Lagrange multipliers
λ_k^*	Optimal transmission rate
λ_k^{max}	Maximum transmission rate

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Chapter 1

Introduction

1.1 The Internet of Things

New technologies are constantly changing our modern life in many ways; some of them already had a tremendous impact on education, communications, healthcare, government, environment, science, and humanity in general. The Internet is one of the examples on that and it is clearly one of the greatest inventions of all time. The Internet is the largest network of networks and it provides numerous services through human-machine interaction and machine-machine interaction. The new evolution for the Internet is to add objects to the network that can collect data using wireless sensors and actuators and communicate seamlessly using the available wireless technologies [1].

Adding physical and virtual objects or "things" to the Internet implies that networks will have a much larger number of heterogeneous devices to provide numerous new services but also raise new challenges depending on the application requirements and the limitations of the used nodes [2]. These things include sensor nodes, radio frequency identification (RFID) tags and near field communication (NFC) devices [3, 4].

Wireless Sensor Networks (WSNs) consist of a number of smart devices with limited capabilities in terms of energy, transmission power, processing and memory [5]. WSNs are playing a key element in many Internet applications especially after enabling IP networking using the IEEE 802.15.4 standard and the Internet protocol IPv6 for low-power wireless area networks (6LoWPAN) technology allowing native communication between WSNs and the Internet [6]. The 6LoWPAN adaptation layer allows objects to have IP addresses and thus makes them an active part of the Internet [7]. This integration opens the path for a large number of applications including healthcare, agriculture, smart environments, transportation, industry, military, etc. An IoT node can potentially host even more than one

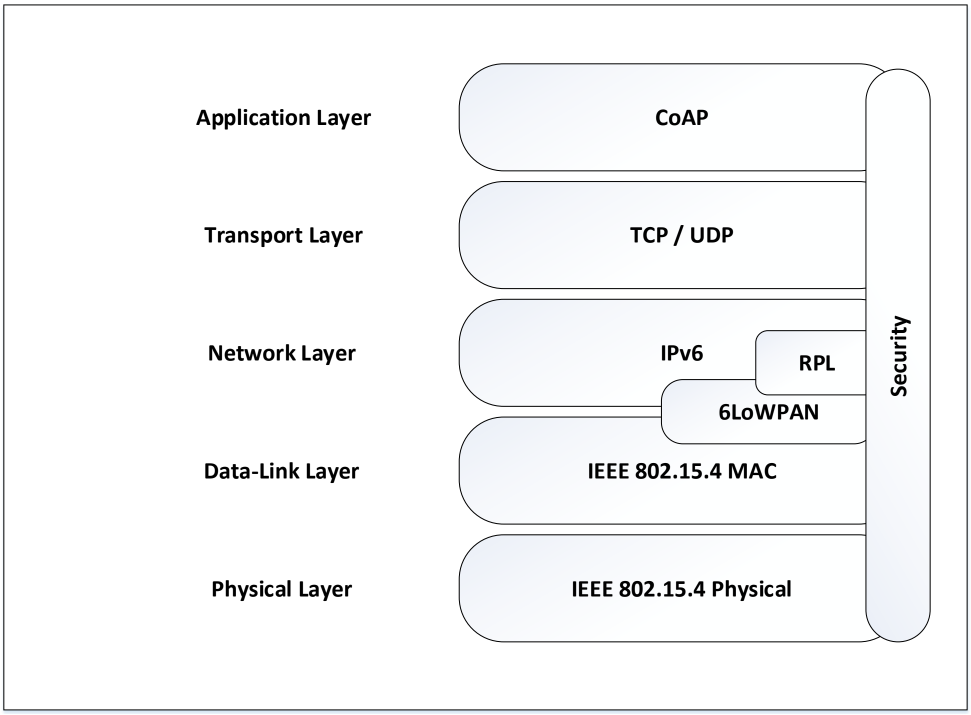

Figure 1.1: IoT Protocol Stack

application with different requirements, one of the applications may require real time data while the other requires mobility support. In order to design and evaluate routing algorithms for WSNs and IoT, many aspects have to be taken into consideration including energy efficiency, reliability, addressing scheme, flexibility and scalability. As shown in figure 1.1, the protocol stack for 6LoWPAN-enabled IoT networks uses IEEE 802.15.4 standard (or one of its variants) as the physical and data link layers, the 6LoWPAN as an adaptation layer, IPv6 and routing protocols as the network layer, UDP or TCP as the transport layer and CoAP as the application layer.

1.2 Motivation

This research is motivated by the need for efficient data routing algorithms to support the exponential growth of the Internet, and the inclusion of low powered devices that can not accommodate the existing routing protocols.

While it can be easier to deal with single-hop data routing, the need for multi-hop routing in WSN and IoT applications is indispensable. The main source of energy consumption in a sensor node is the radio transceiver [8], multi-hop networking can limit the distance between nodes and thus minimize the energy consumption as nodes no longer need to use high power to reach long distances.

In applications that require sensing large areas, multi-hop routing can save energy by deploying additional nodes that can act as sensors and relays at the same time, achieving a larger sensing area in addition to minimizing energy consumption. Examples of these applications include smart agriculture, environment monitoring, industrial applications and animal tracking.

Other applications are restricted by indoor environments, where it might not be always feasible to use single-hop networking because of obstacles. Examples of these applications include healthcare, smart buildings and military applications.

It is worth mentioning that multi-hop networking does not replace single-hop networking but rather complements it where each approach can be more suitable in different scenarios. However, the main focus of this research deals with multi-hop routing in the presence of mobile nodes.

1.3 Problem Statement

Many researchers are showing interest in WSN routing for different applications with different network requirements and numerous protocols are already available for WSN routing but there are still some issues that need to be investigated in order to cope with the fast evolution of this technology [9]. Most of the IoT standards were originally designed for static networks, making nodes' mobility one of the most challenging issues that face data routing, especially in multi-hop networks.

The IEEE 802.15.4 standard only supports mobility in the beacon-enabled mode, and even in this mode it is still not reliable in demanding applications and in dense networks. The existence of a mobile node in an IEEE 802.15.4 network affects the reliability and lifetime of the whole network, and since most of the modern applications require mobility support, an efficient mobility management approach is essential to enable reliable futuristic applications.

RPL was also designed for static networks and it still has no mobility support in its standard description, many researchers worked on enhancing RPL to enable mobility support and created a number of improved mobility-aware versions of RPL. However, even with these improvements, RPL still lacks a dynamic approach that can efficiently manage mobility in a multi-hop network.

Another problem that faces data routing is the fact that there are no efforts in literature to optimize routing efficiency in a mobile environment in terms of throughput, packet delivery ratio (PDR) and end-to-end delay. Most researchers focus on either finding a way around mobility or improving mobility management itself with hardly any considerations to applications' requirements. In addition to that, most papers rely solely on simulations and there is no actual practical performance evaluation of data routing in real IoT application environments.

One of the most challenging problems for routing in WSNs and IoT applications is node mobility, the design of IEEE 802.15.4, 6LoWPAN and RPL all assume that nodes are static. There is no mechanism to explicitly support mobility in these standards, even though many IoT applications require hybrid networks with multihop connections and mobile nodes making it essential to address mobility and tackle its additional overhead [10–12].

Low-powered nodes cannot always use GPS due to energy limitations and thus need an efficient approach to detect and handle mobility. Many solutions require changing the standard by adding extra fields for mobility support, making it no longer compatible with the original design. This research targets the problem of node mobility in the IEEE 802.15.4 and 6LoWPAN multi-hop networks without changing the original standard.

1.4 Contributions

The main contributions in this thesis can be summarized as follows:

1. Chapter 1: An overview of the Internet of things as an emerging paradigm with a brief discussion on the protocol stack and related technologies. It focusses on the IEEE 802.15.4 standard and uses it as the basis for all subsequent work. It discusses data routing in IEEE 802.15.4 and in 6LoWPAN networks outlining the advantages and disadvantages of each routing approach. In addition to that, it outlines the performance metrics used in literature and discusses the importance of using them. It also present the

theory, simulation tools and practical test beds used in this work. Finally, it lists the publications generated as part of this work and the co-authored papers resulted from collaboration with the work group.

2. Chapter 2: A literature review of work related to improving RPL for IoT applications. It presents an overview of popular IoT applications including healthcare, smart environments, transport, industry and military applications. It also outlines the routing challenges that face the applications and takes into account energy efficiency, mobility, reliability, congestion and security. It discusses papers related to overcoming these challenges underlining the advantages and disadvantages of these algorithms and their applicability to IoT applications. Finally, it introduces a summary of the review and points out general views and recommendations for future development.

3. Chapter 3: A study and implementation of an IEEE 802.15.4 clustering based routing protocol for dynamic data routing in mobile WSNs. It discusses the work related to mobile routing in the beacon-enabled mode of IEEE 802.15.4 standard with a brief discussion of the advantages and limitations of the work available in literature. It assumes a hierarchical network with no static nodes and uses a backup cluster head to expedite the process of changing parents in case of link failures (resulted from the mobility of nodes). It shows that the hierarchical topology inherits the nature of the Internet making it a good candidate for IoT development. It also shows that the IEEE 802.15.4 clustering technique has the potential to manage a large number of nodes in an energy efficient manner. Finally, it confirms that while link availability is high, the mesh-under routing approach does not guarantee reliable end-to-end delivery of data.

4. Chapter 4: A study on RPL in a mobile multi-hop IoT environment and an implementation of a dynamic enhancement of RPL (D-RPL) that uses an adaptive trickle and reverse-trickle timer, a reactive DIS messaging approach to increase responsiveness and a flexible objective function that uses expected transmission count, expected energy consumption and link quality to elect a reliable parent node. Simulations and practical testing show an improvement in energy consumption, end to end delay and PDR compared to related work.

5. Chapter 5: A game theoretic design for managing mobility using RPL is introduced, the design assumes a non-collaborative game where nodes compete to send data at high rates where mobility plays a non-voluntary action that affects link quality and signal strength for surrounding nodes. A utility function and cost functions are formulated taking into account energy, mobility and priority of nodes resulting in a final pay-off function. The optimum sending rate for each node is determined using Nash Equilibrium and the protocol is implemented and tested through simulations in real life scenarios based on blueprints and mobility patterns of actual health establishments. Results show a significant improvement in PDR, throughput, energy consumption and delay for all simulated scenarios.

6. Chapter 6: A practical implementation of RPL, mRPL and GTM-RPL using TeleOS B (Tmote sky) nodes, the experiments were made for three different applications with varied requirements. A healthcare application for hospital environment monitoring experiment was conducted in St. James's hospital in Leeds. A smart agriculture application based on robotic devices moving in a formation behind the sink nodes was conducted in an outdoor environment. A military application scenario based on the SWAT robot application was conducted in an indoor environment using one mobile sensing node mounted on a remote controlled vehicle. The practical results mostly confirm our simulations showing a significant improvement in performance using GTM-RPL compared to relevant protocols. The study also shows the impact of indoor environments on communication and routing performance.

7. Chapter 7: Conclusions from this work and recommendations for future development in the area of data routing in mobile environments.

1.5 List of Publications

1. Harith Kharrufa, Hayder Al-Kashoash and Andrew Kemp. "A Review of RPL and RPL-based routing protocols in IoT applications", submitted to *IEEE Internet of Things journal*, June 2018.

2. Harith Kharrufa, Yaarob Al-Nidawi and Andrew Kemp. “A Dynamic Cluster Head Election Protocol for Mobile Wireless Sensor Networks”, Published in *IEEE International Symposium on Wireless Communication Systems (ISWCS)*, 2015. (DOI: 10.1109/ISWCS.2015.7454362).

3. Harith Kharrufa, Hayder Al-Kashoash, Yaarob Al-Nidawi, Maria Quezada Mosquera and Andrew Kemp. “Dynamic RPL for multi-hop routing in IoT applications.” Published in *IEEE 13th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*, 2017. (DOI: 10.1109/WONS.2017.7888753).

4. Harith Kharrufa, Hayder Al-Kashoash and Andrew Kemp. “A Game Theoretic Optimization of RPL for Mobile Internet of Things Applications”, Published in *IEEE Sensors Journal 18, no. 6: 2520-2530.*. 2018 (DOI: 10.1109/JSEN.2018.2794762).

5. Harith Kharrufa, Ma Lei and Andrew Kemp. “A Performance Evaluation of RPL in Mobile IoT Applications: A Practical Approach”, submitted to *IEEE Internet of Things journal*, June 2018.

Co-authored papers:

6. Hayder Al-Kashoash, Harith Kharrufa, Yaarob Al-Nidawi, and Andrew Kemp, “Congestion Control for Wireless Sensor and 6LoWPAN Networks: Toward the Internet of Things,” Published *Wireless Networks 1-30*, Springer, 2018.

7. Yaarob Al-Nidawi, Harith Yahya and Andrew H. Kemp. “Tackling mobility in low latency deterministic multihop IEEE 802.15. 4e sensor network.” IEEE Sensors Journal 16.5: 1412-1427, 2016.

8. Yaarob Al-Nidawi, Harith Yahya and Andrew H. Kemp. “Impact of mobility on the IoT MAC infrastructure: IEEE 802.15. 4e TSCH and LLDN platform.” IEEE 2nd World Forum on Internet of Things (WF-IoT), 2015.

9. Al-Kashoash, Fadoua Hassen, Harith Kharrufa and Andrew Kemp. “ Analytical modelling of congestion for 6LoWPAN networks”. Published in *ICT Express*, 2017.

Chapter 2 Literature review

2.1 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 growing 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.

Wireless sensor networks (WSNs) play a key role in the creation 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 wireless 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

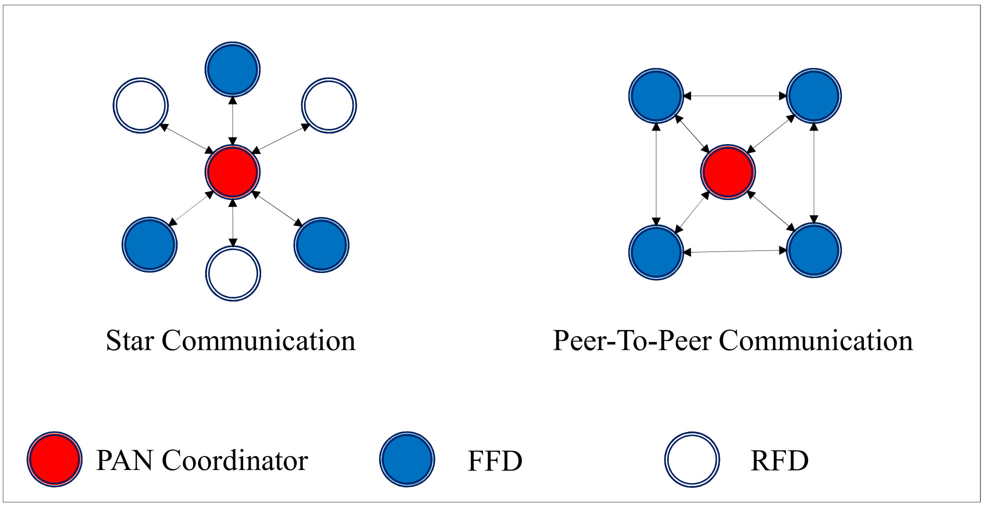

Figure 2.1: IEEE 802.15.4 Operation Modes

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. Until now, RPL is considered the de facto standard for routing in 6LoWPAN networks and IoT applications, it is a flexible and scalable protocol with both energy saving and QoS features making it a good candidate for practical deployment.

2.1.1 IEEE 802.15.4

The IEEE 802.15.4 standard provides a framework for the physical layer and MAC layer of the OSI network model for low rate wireless networks including WSNs. This standard considers the limitations of power and processing of WSNs and allows higher layer standards like ZigBee and 6LoWPAN to build their protocols based on it. This standard defines two modes of operation for network devices, the Full-Function Device (FFD) and the Reduced-Function Device (RFD). The FFD as its name suggests is capable of all network operations and can serve as a PAN coordinator, a local coordinator, or normal node. The RFD on the other hand has reduced functionality and is assumed to have low resources and is only capable of low profile applications. Figure 2.1 shows the FFD and RFD nodes in a star and a peer-to-peer topologies. The PAN coordinator is an FFD that was either preconfigured or elected by other nodes to act as the root node.

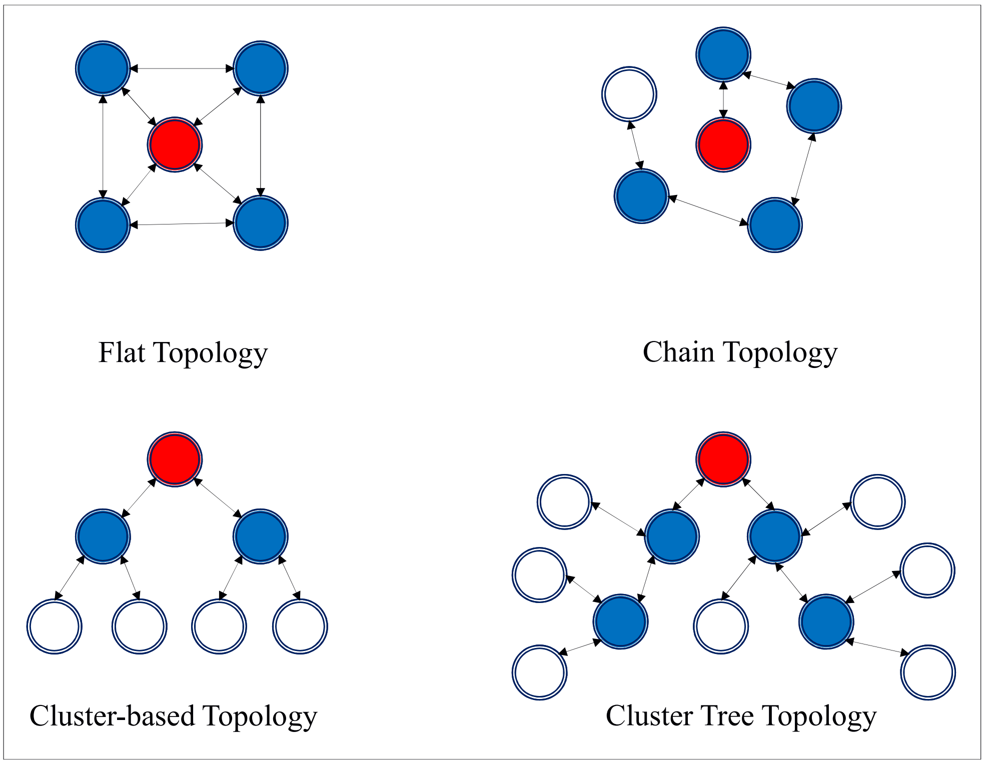

Figure 2.2: IEEE 802.15.4 Different Logical Network Topologies

Different applications require different network topologies, the use of FFDs and RFDs and their communication in the network as peer to peer or as a star can form a flat, chain based, cluster based, or cluster tree based logical topology [13] as shown in figure 2.2.

- Flat Topology: In this topology, nodes communicate to each other directly as peers using flooding to some or all neighbouring nodes. This topology is very simple and it does not have an energy saving approach [14] causing overlapping issues. Some of the flat topology protocols are SPIN [15], Direct Diffusion [16], and COUGAR [17].

- Chain Topology: Some of the nodes in this topology are elected to act as gateways; other nodes can only communicate to each other through the formed chain path to reduce flooding. The main disadvantage of this topology is the major delays especially for nodes at the bottom of the chain. Some of the chain topology protocols are Greedy routing, PEGASIS [18], and CREEC [19].

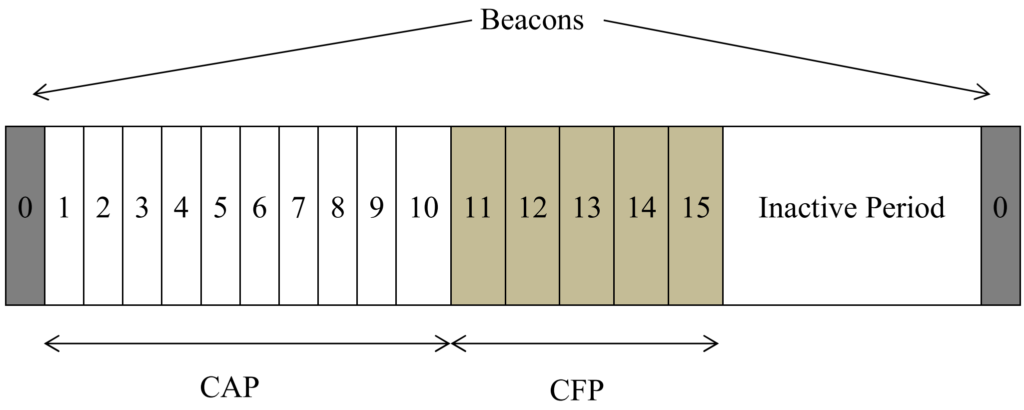

Figure 2.3: IEEE 802.15.4 super frame

- Cluster Based Topology: This topology is widely used in WSNs for different applications due to its energy efficiency, flexibility, and scalability [20]. Cluster Heads (CHs) are elected in the set-up phase based on different factors like the residual energy or distance from the sink. Nodes in each cluster send communicate through the CH and each CH communicates to the sink directly or through other clusters in a multi-hop approach. Some of the cluster based protocols are LEACH [21], HEED [22], MBC [23], EEHCA [24], BCHP [25], etc.

- Cluster Tree Topology: This topology is an extension of the cluster based topology to form a tree of clusters. The PAN coordinator initiates the tree formation by electing cluster heads, each cluster head then starts to send beacons to the neighbouring nodes until all nodes are connected to the cluster tree. This topology offers a scalable and energy efficient solution and some of the cluster based protocols applies to this topology, we proposed DCHEP [26] especially for this topology with consideration to mobility and high node density.

The IEEE 802.15.4 physical layer is responsible for managing the radio transmission and reception, channel detection and selection, clear channel assessment (CCA) link quality indicator (LQI) and received signal strength indication (RSSI). It operates at the 868 MHz, 915 MHz, and 2.4 GHz non-licensed frequency bands.

The IEEE 802.15.4 MAC layer is responsible for channel access, beaconing, and node association or dissociation. It defines two modes of operation, the beacon-enabled mode and the non-beacon-enabled mode [7]. In beacon-enabled mode, the PAN coordinator sends periodic beacons in order to synchronize communication with the sensor nodes and maintain connectivity. Beacons use the first timeslot of the super frame leaving 15 timeslots for Contention Access Period (CAP) and Contention Free Period (CFP) as shown in figure 2.3.

During the CAP which can occupy all the timeslots of the super frame, devices can communicate to each other using slotted CSMA/CA mechanism. CFP is introduced to avoid the latency of CSMA/CA, it consists of up to 7 Guaranteed Time Slots (GTS) [27] where each GTS can use one or more timeslots. Devices go to sleep mode in the inactive period of the super frame to save power. In the non-beacon-enabled mode, devices communicate to the coordinator using un-slotted CSMA/CA mechanism

2.1.2 6LoWPAN

IPv6 over Low Powered Wireless Personal Area Network working group optimized IPv6 for networks using the IEEE 802.15.4 standard. The frame size of IEEE 802.15.4 standard is limited to 127 bytes, the high overhead of the MAC protocols and the IPv6 header limits the available space for application layer data. Since that is much smaller than the MTU of IPv6 which is 1280 bytes, the MAC layer will need to fragment data packets. 6LoWPAN introduced an adaptation layer to segment IPv6 packets into smaller pieces to be used by the MAC layer. 6LoWPAN also allows header compression to minimize the overhead of IPv6 header and thus considered a crucial technology for designing IoT over IEEE 802.15.4.

6LoWPAN layer resides between the data link and network layers creating a bridge that connects the IEEE 802.15.4 standard to IPv6. One of the limitations of the IEEE 802.15.4 standard is that it supports a frame size of 127 bytes, it uses an overhead of 25 bytes leaving a maximum of 102 bytes for payload that may go down to 81 bytes with security support. In addition to that, IPv6 using UDP forces a header of 48 bytes limiting the payload even further making it between 38 and 54 bytes depending on security requirements 6LoWPAN offers header compression allowing up to 108 bytes for payload without affecting routing efficiency using RFC 6282 [28].

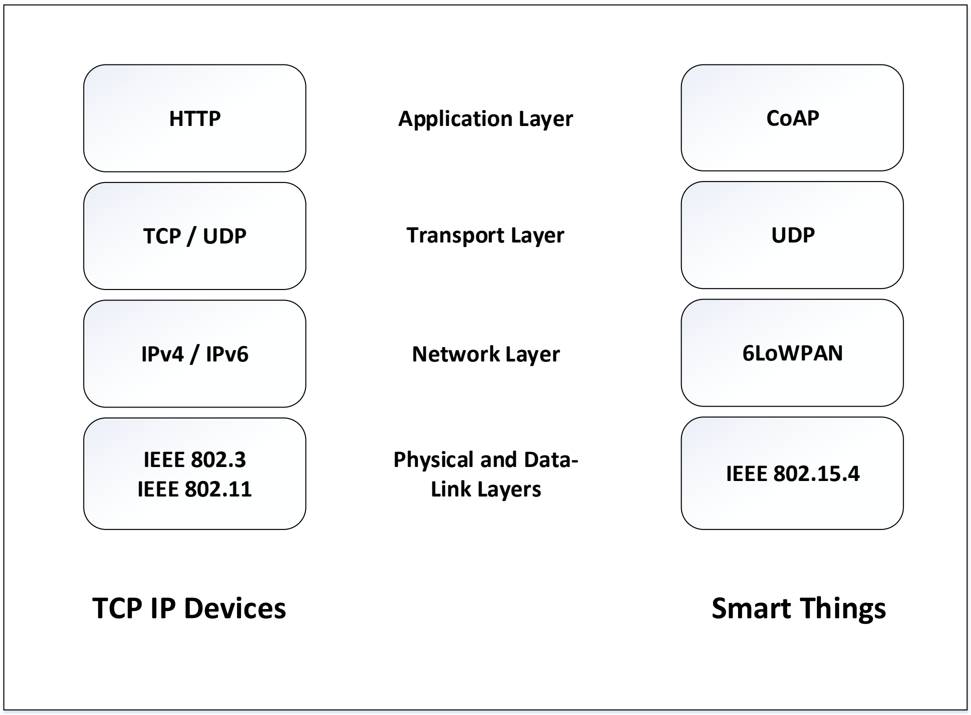

Figure 2.4: 6LoWPAN-enabled objects

Another limitation of the IEEE 802.15.4 standard is that it only supports a maximum transmission unit (MTU) of 127 bytes while IPv6 defines an MTU of 1280 bytes. 6LoWPAN uses RFC 4944 [29] to perform fragmentation and reassembly on IPv6 packets that are larger than the MTU of IEEE 802.15.4.

figure 2.4 shows the protocol stack of smart IoT nodes compared to the TCP/IP protocol stack, it also shows some of the most popular standards and protocols used in each of them. 6LoWPAN makes it possible for new smart objects to communicate with TCP/IP devices and provide revolutionized services and countless new applications.

2.1.3 RPL

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 [30]. 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.

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.

An RPL instance is a collection of DODAGs where traffic moves either from or to the DODAG root (up or down). Because a DODAG consists of edge nodes, multiple DODAGS do not share the same nodes at the same instance. RPL gives different ranks to nodes in a DODAG with reference to the DODAG root, the area of the ranks is a DODAG version [30].

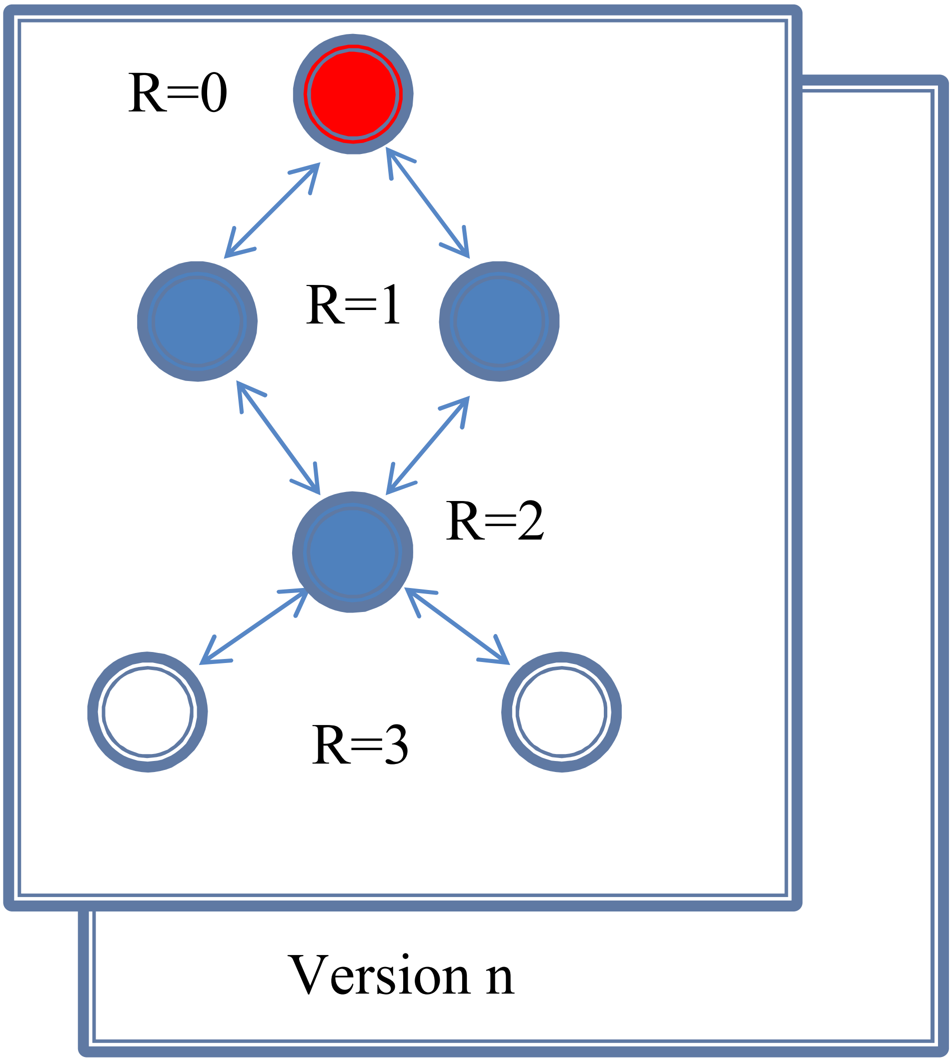

Figure 2.5: DODAG versions in RPL

The root initiates the network by broadcasting a DODAG information object (DIO), nodes receive the DIO and replay with a DODAG advertisement object (DAO). The connected nodes will in turn send their DIO messages to more nodes forming a cluster tree topology directed towards the DODAG root. Nodes can also specifically request a DIO by sending DODAG information solicitation (DIS) message to their parent node.

One of the main advantages of using RPL is the introduction of the trickle timer [31]. It 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}.

$$I_{min} = 2^n \tag{2.1}$$

$$I_{max} = 2^{n+I_{doubling}} \tag{2.2}$$

The interval n produces I_{min} (ms) which is the initial and minimum interval size of the trickle timer as shown in equation (2.1). $I_{doubling}$ decides I_{max} (ms) which is the maximum interval size of the trickle timer as shown in equation (2.2). 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.

Another advantage of RPL is that each node can have a flexible objective function that calculates a cost for each potential parent node and makes an informed decision to choose an appropriate parent. The objective function can use the rank of nodes, expected transmission count (ETX), expected energy consumption, residual energy, link quality or any other metric depending on the application requirements and the nature of the network.

Using these rules, RPL forwards data either upwards or downwards within a DODAG as shown in figure 2.5, to send data upwards, nodes should always forward to lower ranks until they reach rank 0 which is the DODAG root. To send data downwards, nodes forward to the available destinations with higher ranks.

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) [32] 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 other implementations. The second one and the arguably most popular one is the minimum rank with hysteresis objective function (MRHOF) [33] 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.

2.1.4 Transport Layer

The most common transport layer protocols are TCP and UDP, they are both used in the Internet and in most modern networks. TCP is a reliable protocol that supports end-to-end reliability by using acknowledgements and if necessary, packet retransmission. However, TCP suffers from a large header of 20 bytes making it an extra burden to the IEEE 802.15.4 payload. UDP on the other hand does not support end-to-end reliability but it has a header of only 8 bytes making it more suitable to the limited resources of 6LoWPAN networks. UDP is faster than TCP, it supports broadcasting and is the most common transport protocol in 6LoWPAN networks

2.1.5 Application Layer

The constrained restful environments (CoRE) working group has developed the constrained application protocol (CoAP) and it was standardized in RFC 7252 targeted for constrained networks to provide web services that can easily integrate with HTTP. Some of the features of CoAP are: i) It provides web services for machine-to-machine communications. ii) It allows unicast and multicast communication using UDP with the option to support reliable communication. iii) It provides basic proxy and caching services. iv) It has low header overhead. v) It deals with resources as Uniform Resource Identifiers (URIs).

The CoAP layers in the IoT protocol stack are shown in figure 2.6 , CoAP methods are similar to the HTTP methods including GET to receive information from a URI, POST to create a resource for a requested URI, PUT to update a resource, and DELETE to remove the resource. A CoAP method can use multiple transactions, transactions support reliable UDP communication using four types

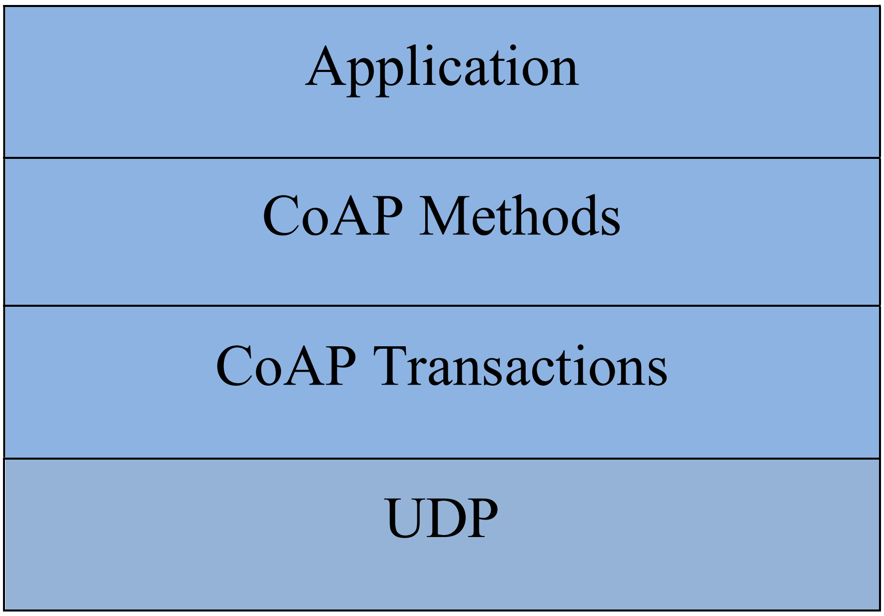

Figure 2.6: CoAP Layers in IoT

of messages, CON to send a Confirmable request that requires the receiver to send an acknowledgement, NON to send a non-confirmable message that does not require an acknowledgement, ACK to Acknowledge a received CON, and an RST to reset the message transfer if something was missing [34].

2.2 Data Routing

Data routing is the process of finding a path to send data packets from a source to a specific destination based on certain metrics and requirements, these metrics constitutes the definition of a “good” path and an efficient protocol is expected to fulfil all requirements with minimum cost. With the introduction of the 6LoWPAN adaptation layer, the layer responsible for routing acquired two new classifications, mesh-under and route-over routing [35] . As shown in figure 2.7, routing decisions are made either in the data link layer or the network layer making them either under or over 6LoWPAN layer.

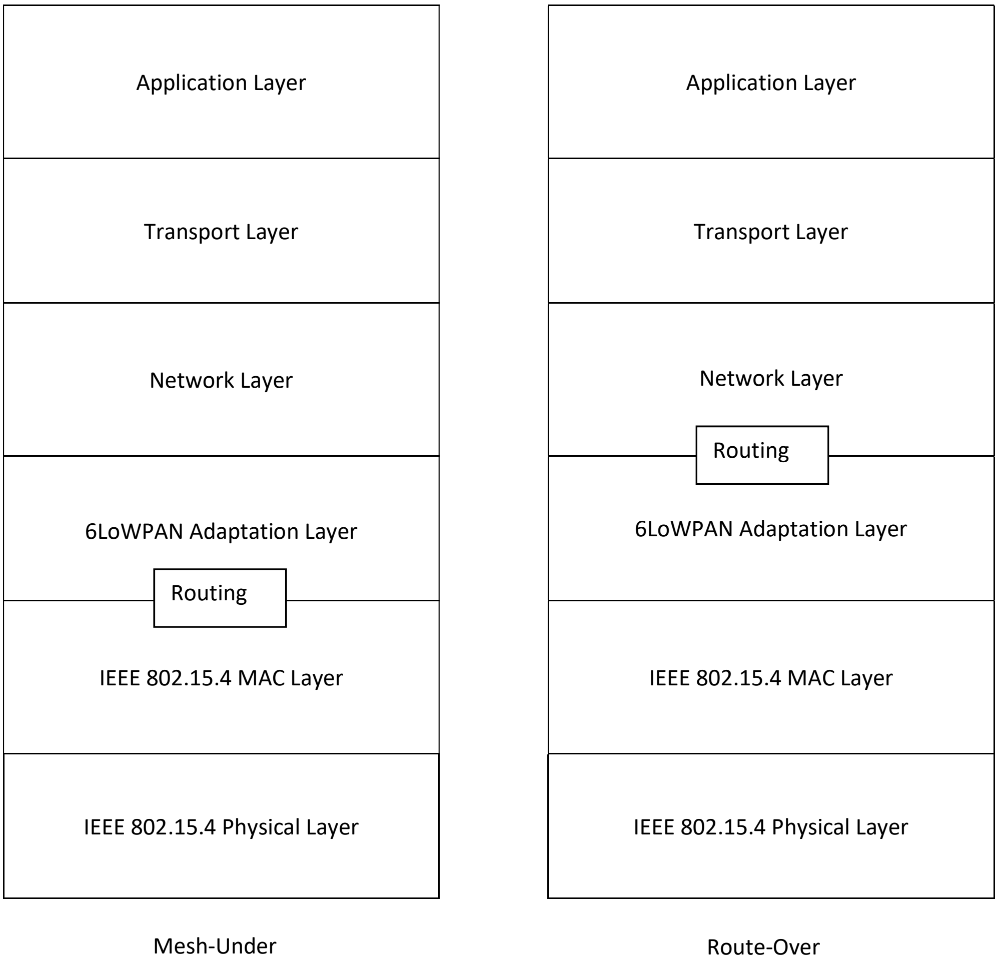

Figure 2.7: Mesh-Under Vs Route-Over

2.2.1 Mesh-Under Technique

Using the IEEE 802.15.4 standard, mesh-under routing provide clustering architecture by which nodes can send their data towards a gateway or sink node with low energy consumption and fewer collisions compared to the original IEEE 802.15.4 standard. In this technique, the overhead of routing is minimum because the network layer is not involved in routing decisions. Nodes formulate clusters where each group have a designated parent or cluster head (CH) to route data towards the sink node, the number of clusters in a network depends on the protocol used, the size of the network, the density of nodes and the application requirements.

An IPv6 packet is fragmented into smaller IEEE 802.15.4 frames and sent to the next hop which in turn forwards it to the next one until it reaches the final destination, only then it would be reassembled into an IP packet and if any frame was missing the entire packet would have to be retransmitted.

2.2.2 Route-Over Technique

In this approach, the network layer is responsible for routing decisions. This technique involves adding an extra header to transmitted packets increasing both energy consumption and transmission time. However, research shows that with the standardization of RPL, this approach proves to be more reliable and has the potential to satisfy a large number of futuristic applications [35]. It can still take the advantage of the IEEE 802.15.4 clustering technique to form its own cluster-based topology, in addition to the benefits of using 6LoWPAN allowing the use of IPv6 in each node.

At the network layer of the sending node, the IPv6 packet is fragmented into smaller IEEE 802.15.4 frames and sent to the next hop where the frames are received, reassembled into an IPv6 packet by 6LoWPAN and then forwarded to the network layer. The network layer checks the reassembled packet and determines whether to send it to the transport layer or to forward it back to 6LoWPAN with the next hop address.

2.3 Performance Metrics

Most researchers use one or more performance metrics to evaluate routing techniques and to test the efficiency of their proposed schemes. While these routing metrics can depend on the application requirements, they can still effectively give an impression of the validity and efficiency of routing protocols. The main performance metrics used in literature can be summarized in:

- **Energy Consumption**: The total amount of energy consumed by a certain node, or the average amount of energy consumed by nodes in the same network in a given period of time. This metric reflects the energy efficiency of routing protocols and algorithms as it indicates the energy required for data processing, transmission, reception and control [36]. Some papers also use residual energy, which is the amount of energy available in a node at a specific time. Knowing the residual energy in a node can help decide whether it is a good candidate to perform additional tasks [26]. Other papers also use energy tax which is calculated by dividing the number of dropped packets by the number of received packets [37].

- **End-to-End delay**: The average time required for a packet to travel from the source node to its final destination, the destination can be one or more hops away from the source. This metric gives an impression of the responsiveness of the network and sometimes the reliability and suitability of the routing protocol to use in certain applications [38, 39].

- **Latency**: The time it takes for a packet to be passed from the application layer of the source node through the transmission medium and to the next hop. This metric reflects the processing speed of nodes and the available bandwidth in the network in addition to the channel access scheme and congestion in the network [40].

- **Packet delivery ratio**: This metric represents the ratio between the number of received packets at the sink and the number of sent packets in a given period of time. This metric has a significant impact on the network performance as it reflects the energy cost endured due to loss of transmitted packets [37]. It also reflects the effective throughput of achieved at a given data transmission rate.

- **Throughput**: The total amount of received data bits in a given period of time. This metric is very important in demanding applications, a high throughput means that more data can be successfully sent to the sink node [41].

Other metrics that are less frequently used are hop count [42–44], overhead [45–47] and efficiency [48].

2.4 Simulation Tools and Test beds

In an IoT environment, devices interact with each other to provide countless services, this interaction is enabled by hardware, software and communication standards. Operating systems make it possible for IoT devices to function using various new standards and limited resources. For this reason, an IoT operating system has to support heterogeneous devices and provide reliable network connectivity in addition to special features including energy efficiency and security.

The most common operating systems used for IoT devices are RIOT OS [49], Tiny OS [50] and Contiki OS [51]. All of these operating systems have their advantages and disadvantages, however when it comes to data routing, Contiki OS is the most popular operating system. Contiki OS is an open source operating system designed for IoT devices, it supports a number of radio modules including cc1200, cc2420, cc2520, etc. It also provides duty cycling support with a number of implementations including ContikiMAC and NullRDC in addition to an implementation of CSMA, TSCH, etc. Contiki OS also provides a full implementation of 6LoWPAN, RPL, TCP, UDP and CoAP, it supports both IPv4 and IPv6 and runs on 10KB of RAM and 30 KB of ROM only [52].

While both Tiny OS and Contiki OS support a number of test beds including TelosB, WSN430, Zolertia Z1, MSB-A2 and BCM-4356. Simulation tools are still necessary to ease the testing and debugging process and provide a flexible and safe environment for experimentation. A number of simulation tools are used in literature including COOJA, TOSSIM, OMNET/Castalia, WSNet, NS2, NS3, Matlab etc.

In chapter 3, Castalia WSN simulator is used for simulating and testing the proposed protocol with realistic radio models and wireless channels [53]. It was designed to be adaptable and expandable based on the OMNET++ [54] platform. Each node in Castalia has a modular structure that enables simple modules to be added or edited separately. It provides abstract classes for MAC protocols, Routing layer, Application layer, Mobility manager, etc. Castalia uses NED language for defining modules, and C++ for defining classes and functions. It also uses configuration files (configuration.ini) for defining simulation parameter.

In chapters 4, 5 and 6, COOJA simulator is used with Contiki OS to simulate the routing process. COOJA is also a network emulator, it uses the same code for

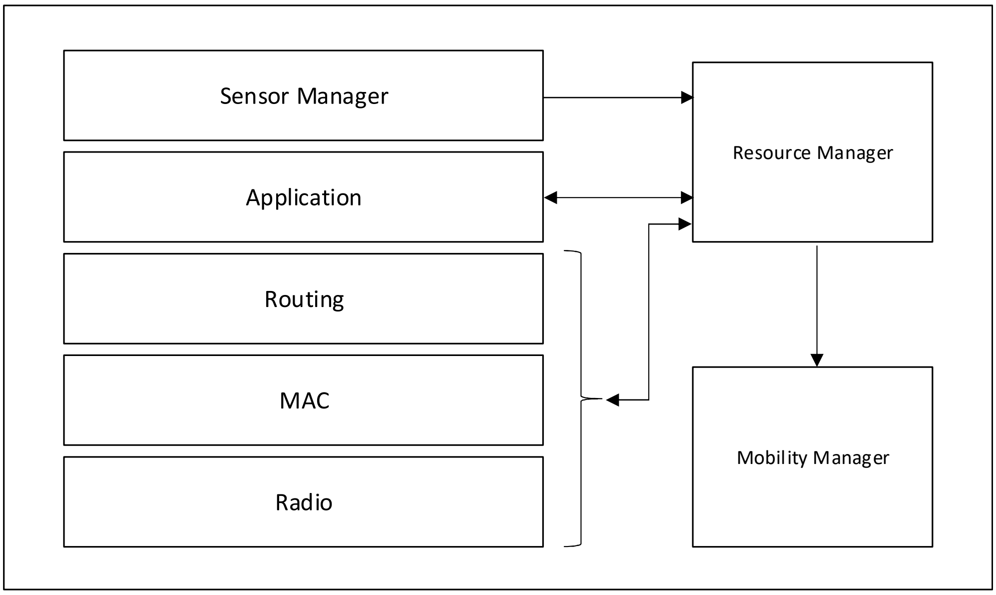

Figure 2.8: The node module in Castalia

both simulation and hardware. According to results in this work and in literature, COOJA shows an excellent emulation of real hardware and very satisfactory implementation of the wireless channel. Regarding RPL studies, COOJA is used in more than 63% compared to other simulators. Also, while COOJA and Contiki OS do not directly support mobility, a plug-in is available to define the mobility scenario prior to simulation in addition to the ability to manually move nodes during simulation.

An emulated node in COOJA is based on one of the available Contiki platforms, all COOJA simulations in this thesis use Sky platform due to its popularity and hardware availability. Figure 2.9 shows the network stack of a simulated node in COOJA and Contiki OS. These layers are also complemented with a number of tools and plug-ins including Powertrace that measures energy consumption using state tracking with up to 94% accuracy [55], a mobility plug-in that allows users to upload a mobility scenario prior to simulation and a timeline that shows a real time status for simulated nodes and the wireless channel [56].

Different platforms are available for hardware testing, TelosB (or Tmote sky) is used in this work because of its popularity in research and the support available for using it. Tmote sky nodes shown in figure 2.10 are used in around 70% of RPL

Application	Periodically send a data packet to the sink
Transport	UDP
Routing	uIPv6, RPL
Adaptation	6LoWPAN
MAC	CSMA, 802.15.4 framer
Duty Cycling	Null RDC
Radio	CC2420

Figure 2.9: Contiki node protocol stack

Figure 2.10: Tmote Sky node

experimental papers, it is supported by COOJA and available at a relatively low cost. It uses the 2.4GHz IEEE 802.15.4 CC2420 wireless transceiver, it has a USB interface for programming and features a humidity, temperature and light on board sensors with the option to add external analogue sensors.

2.5 Hierarchical routing in IEEE 802.15.4

There is a large number of WSN routing protocols with different approaches and different requirements including location-based protocols, data-centric protocols, hierarchical protocols, multipath-based protocols, and QoS-based protocols [57] [58]. All of these approaches have their advantages and limitations and they are all related to this work. However, the main focus is directed to hierarchical-based routing through clustering because it is energy efficient and it inherits the architectural nature of the Internet making it a flexible and scalable solution [59] [20].

Sensor Protocols for Information via Negotiation (SPIN) was developed by [15] for flat WSNs, it addresses the problems of flooding and overlapping using an advertisement message to advertise data, a request message to request data, and a data message that contains the actual data. Nodes need only local information about their neighbours to advertise and send data but data delivery is not always guaranteed. Direct Diffusion introduced a mechanism for the sink node to send an on-demand query to the sensor nodes specifying the type of data required. According to the type requested by the sink, nodes send their specific data using flooding. Direct diffusion is energy efficient but limited to applications that do not require periodic information [16].

COUGAR was developed by [17] to save energy by allowing sensor nodes to pick a head node to do the data aggregation process using the query plan provided by the sink. However, the extra queries consume energy at each node and because it uses some nodes as relays, it makes it harder to maintain the network if a leader node fails.

Power Efficient Gathering in Sensor Information Systems (PEGASIS) was developed by [18] for chain topology WSNs. PEGASIS forms a chain of nodes allowing each node to send data towards the sink using the chain path. It saves energy by avoiding multiple elections and formations of clusters but suffers from high delays and the bottle-neck problem.

Chain Routing with Even Energy Consumption (CREEC) changes the chain leader after each super round; the Sink predicts the cumulative energy consumption of nodes in the chain and gives them different levels based on their hop distance and decides when to change the head node [19].

The Hybrid Energy Efficient Distributed (HEED) clustering algorithm [25] selects cluster heads based on a combined factor of node residual energy and node degree. HEED overcomes the LEACH limitations by enabling multi-hop routes to the base station and having a better cluster head distribution. However the cluster formation in HEED does not ensure best coverage and it requires a lot of control packets leading to slow convergence. Using this protocol, CHs that are closer to the PAN coordinator fail sooner because of the higher load and overhead they endure. HEED also makes an assumption that all nodes have a variable transmission power which limits the applicability of using it in some applications.

In the Threshold sensitive Energy Efficient sensor Network (TEEN) [60] protocol, cluster heads broadcast two threshold values to their children nodes. These values define a soft threshold and a hard threshold for the amount of sensed data in each sensor node. If a node exceeds the soft threshold, it forwards its data to its cluster head, if it exceeds the hard threshold, it forwards it directly to the sink node. This approach ensures that cluster heads do not need to relay data that is too large. However, this protocol does not consider periodic data transmission and was only designed as an event driven routing protocol. This protocol was later improved to include more features and cope with time critical events. An adaptive TEEN (APTEEN) [61] was developed to include a periodic data transmission that is activated if no threshold was reached within a user-configured period of time. This additional functionality comes at a cost of high overhead and high energy consumption.

Some routing protocols propose a backup cluster head to improve reliability and energy efficiency like the Energy Efficient Hierarchical Clustering Algorithm (EEHCA) [24], the backup cluster head is prepared to act as a primary cluster head if the first one fails. EEHCA improves the life time of the network by introducing the backup cluster head but it also assumes that all the nodes are stationary. This protocol was improved by [62] to use multiple backup cluster heads instead of just one to further extend the lifetime and availability of a WSN also with only static nodes.

Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol is a clustering protocol that was developed in [21] to minimize energy consumption in WSNs by introducing local control in clusters and randomly rotating cluster heads. The LEACH protocol outperforms the direct routing approach in terms of energy consumption and extends the life time of the network. However, it is not efficient in larger networks because it performs single-hop transmission from cluster heads to the base station and it doesn't ensure real load balancing [63]. The random rotation of cluster heads in LEACH does not consider residual energy, meaning that all nodes need to start with the same battery level in order to efficiently distribute energy consumption.

Many routing protocols were developed for WSNs and even though most of them assume that nodes are static, there are some good efforts for designing routing protocols for mobile WSNs and specifically cluster based networks including CBR-Mobile [64], LFCP-MWSN [65], HAT-Mobile [66], LEACH-Mobile [67], M-LEACH [68], etc. CBR-Mobile is Cluster Based Routing protocol for mobile WSNs; this protocol allows mobile nodes to send their data to any available CH if they lose connection to their original CH given that there is an available time slot in the TDMA to minimize delays. CBR-Mobile lacks details on how to select CHs and it does not address the problem of interference assuming that failure to communicate can only be caused by mobility which is not a valid assumption.

LFCP-MWSN is a Location aware and Fault tolerant Clustering Protocol for Mobile WSNs, the PAN coordinator or the sink node elects CHs based on their location in the network. Then, nodes will measure their level of mobility and assign different priorities based on this information. This protocol requires nodes to be location aware and forces the network to be centralized which adds extra communication signals for CH election and re-election.

Hierarchical Addressing Tree (HAT) and HAT-Mobile where developed by [66], the HAT-Mobile introduced nodes tracking across clusters using a handover table at each CH with information about connected nodes and previously connected nodes. This protocol is not scalable due to the high memory requirements and communication overhead to maintain the handover table especially in large and dense networks. LEACH-Mobile is based on LEACH routing protocol to support the mobility of nodes by adding a membership declaration to allow nodes to join and leave clusters [67].

Various improvements were made to the LEACH protocol and a number of extended-LEACH protocols were introduced to overcome the limitations of LEACH including LEACH-Mobile, Multi-Hop LEACH and M-LEACH [69]. LEACH-Mobile is based on LEACH routing protocol to support the mobility of nodes by adding a membership declaration to allow nodes to join and leave clusters [67]. This protocol assumes a static CH and suffers from high delays caused by the association and dissociation process, and it has high energy consumption. M-LEACH supports mobility of nodes and CHs but it limits the communication to only two levels making it less scalable, it also assumes that all nodes are equipped with GPS and are location aware but this assumption is not always ideal since it consumes a lot of energy [70]. In addition to that, it requires the base station (BS) to make an informed decision and select CHs based on nodes information. This approach requires the use of extra control signals and data overhead making it less efficient in terms of energy consumption and is prone to transmission errors [64]. Various studies also introduce mobility management approaches including using LQI to detect a mobile node [71] [72], this approach helps to predict the movement of a node but needs a reliable method to distinguish false LQI readings. Other studies suggest using centralized decisions causing excessive overhead and high interference in the network [73] [74]

The Backup Cluster Head Protocol (BCHP) introduced by [25] proposes a BCH for each cluster in a hierarchical structure to maintain connectivity and take responsibility of the cluster in a reactive manner when a CH fails or leaves the cluster. BCHP is targeted for mobile networks in general and not specifically WSNs and it uses routing tables to determine a path to the destination making it less applicable for WSNs with limited resources, it also assumes that nodes are location-aware.

The rest of the chapter is organised as follows: Section 2.6 categorises WSNs according to the applications they are used for, along with the requirements, design implications for each application. Section 2.7 discusses the challenges that face RPL and the approaches used to tackle them. Finally, section 2.8 presents a summary and provides technical and chronological information about the evolution or RPL and the approaches used to build RPL in its current state.

2.6 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.

This section acknowledges 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 more than 140 research papers. The approach of this review uses Google scholar with the search keyword ("allintitle: RPL -pregnancy") to search for RPL 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 chapter 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.

There are countless potential applications that can fall under the IoT umbrella, figure 2.11 shows some of the most used in literature. The general classification for applications used it this chapter 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

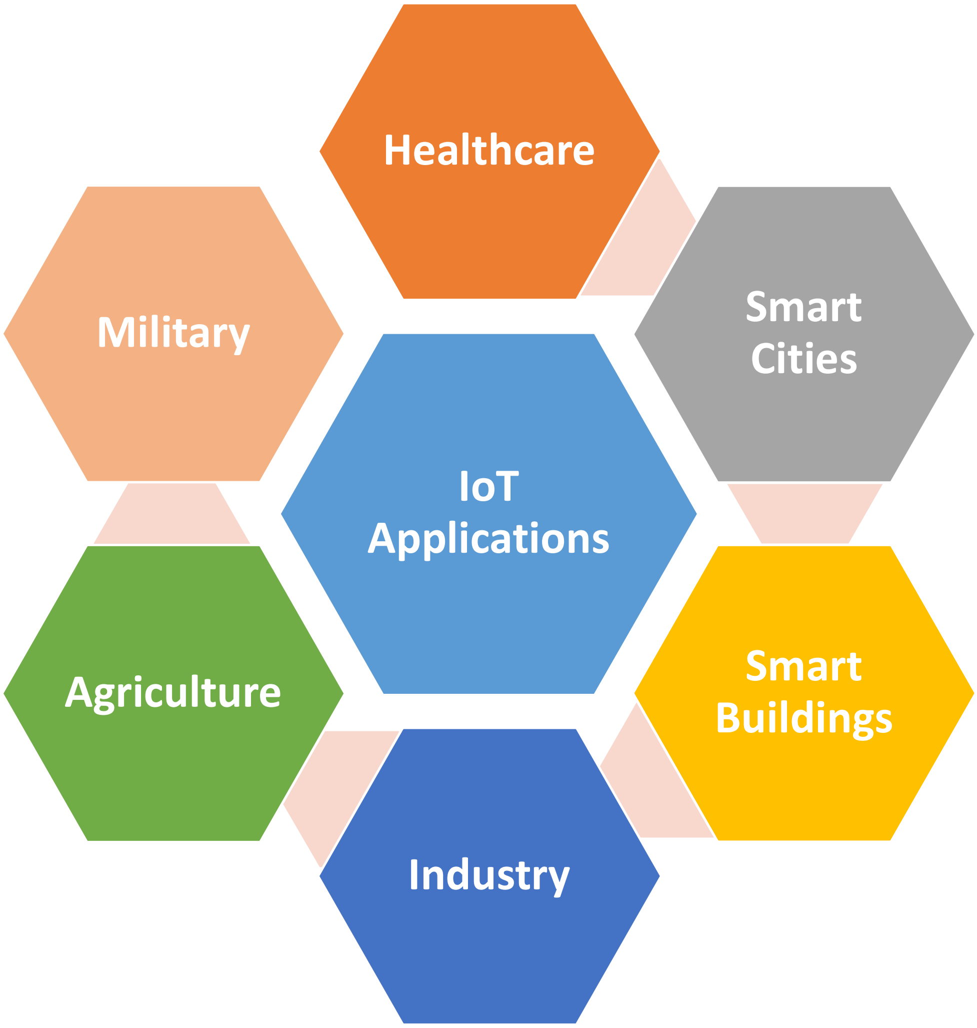

Figure 2.11: IoT Applications

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. While it is difficult to discuss all applications, the following sections present some of the popular fields for WSNs and IoT with examples from the literature.

2.6.1 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 [10, 75]. 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 [76, 77].

A study on casualty monitoring [78] 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 [79], tele-care [80], elderly and patient monitoring [81–83] and status and activity detection [84–86]. Other non-emergency applications like health environment monitoring and deaf people assistance [87] 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 [88]. 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 [89–91] 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, [92–94] sometimes accompanied by cameras and image sensors to increase the reliability of fall detection [95–97]. 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 [98], 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 chapter 6 prove that GTM-RPL can provide reliable data delivery at low costs with a high flexibility to fit many healthcare applications.

2.6.2 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 [99]. 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 [100], a wireless sensor network is used to detect problems and diseases in cattle with the aims of improving their productivity. The authors in [101] 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 [102].

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 chapter 6 show that in a mobile environment, nodes can cover large areas and communicate in a reliable and efficient manner.

2.6.3 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 [103]. In assisted driving, sensors can also detect correct lane positioning, apply emergency brakes and perform auto parking [104]. 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 [105] 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.

2.6.4 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 [106]. 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 [107]. 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 [108]. 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 [109] 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.

2.6.5 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 [110], or measure the physical state of soldiers to detect problems and measure fatigue levels using wearable devices [111]. 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.

In chapter 6, 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.

2.7 Challenges

As seen from section 2.6, 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.

2.7.1 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 [31], 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 [112], 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 [113, 114]. 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 [115]. 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 [116], 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 [117] 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 [118], 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 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 [40, 44, 119, 120].

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 [121], 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 [122], 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 [123]. 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 [124] 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 2.1

Table 2.1: RPL Enhancements for Energy Efficiency

Ref	Strategy	Advantages	Disadvantages
[114]	Contiki RPL implementation.	(i) Practical experiments. (ii) Shows a lifetime of years using Tmote sky nodes.	Takes only energy consumption into account when testing.
[115]	Using energy as a metric.	(i) Includes ETX as a metric. (ii) Considers mobile scenarios.	No improvements to RPL.
[116]	Using a cost of combined metrics	(i) Improves network lifetime. (ii) Considers industrial applications.	(i) No practical testing. (ii) No considerations for mobility.
[117]	Using collaborative approach.	(i) Uses optimization techniques. (ii) Improves lifetime.	(i) No practical testing. (ii) No throughput optimization.
[118]	Using residual energy as a metric.	Improves lifetime.	(i) Does not consider other routing metrics. (ii) No practical testing.
[119]	Using Fuzzy based metrics.	(i) Improves lifetime and throughput. (ii) Practical experiments.	(i) Does not consider mobility. (ii) Routing metrics are not optimized.
[40]	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.
[44]	Using Fuzzy logic and "Corona" strategy.	(i) Considers mobility. (ii) Improves throughput, lifetime and delay.	(i) No practical experiments. (ii) Limited mobility management.
[120]	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.
[121]	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.
[122]	RDC based energy balancing.	Improves load balancing and throughput.	(i) Marginal improvement compared to MRHOF. (ii) No mobility considerations.
[123]	Failure detection.	(i) Uses a combined cost metric. (ii) Improves lifetime.	(i) No mobility considerations. (ii) No practical experiments.
[124]	routing and aggregation for minimum energy.	Significantly improve lifetime.	(ii) Limits throughput. (ii) No mobility considerations.

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.

2.7.2 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 [125]. 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) [126] 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) [127] and the ad-hoc on demand multipath distance vector(AOMDV) [128] protocols which were not designed for LLNs and it wasn't compared to native RPL.

The authors in [129] 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 [130] 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 [131] 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 [132], 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 [105] 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 [112] 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 [133], 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 [41] 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 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 [134] 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 [45] 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++ [135] 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 [136] 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 [137] 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 [138] 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 2.2 shows a list of mobility aware versions of RPL with their advantages and disadvantages in terms of implementation and performance.

Table 2.2: RPL Enhancements for Mobility Management

Ref	Strategy	Advantages	Disadvantages
[129]	Using mobile sinks	(i) Improves lifetime. (ii) Considers multiple sinks.	(i) No improvements to RPL design. (ii) No other routing metrics used.
[130]	Sink node moves towards nominated nodes.	(i) Improves lifetime. (ii) Improves load balancing.	(i) Limited applicability. (ii) No improvements to RPL design.
[131]	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.
[132]	Including mobility status in DIO.	Improves PDR and routing stability.	Incompatible with the native RPL.
[105]	(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.
[112]	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.
[133]	(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.
[41]	Using a "Corona" mechanism.	Improves PDR, end to end delay and energy efficiency.	Limited mobility management.
[134]	Configuring mobile nodes as "leaf" nodes.	(i) Improves stability and energy efficiency.	(i) No improvements to the RPL design. (ii) Limited mobility support.
[45]	(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.
[135]	Using objective function with mRPL [45].	Higher flexibility.	(i) No improvements to mRPL. (ii) The objective function is always dependant on RSSI.
[136]	Using Kalman filter and blacklisting.	(i) Uses localization techniques. (ii) Improves PDR.	(i) Susceptible to inaccurate positioning. (ii) High energy consumption.
[137]	Adaptive timer and adaptive DIS.	(i) Improves PDR, energy efficiency and delay. (ii) Low overhead.	Marginal improvement in low mobility scenarios.
[138]	Game theoretic optimization of RPL.	(i) Improves PDR, Energy efficiency and delay. (ii) Change transmission rate according to network conditions.	-

2.7.3 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 [139].

In [140], 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 [141,142], 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 [44], 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 [119], 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 [123] 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 [143] presents an approach to detect root node failure that results in loss of all data. Most papers assume 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 [120], 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 [144–147]. 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) [148] uses a cooperative strategy for nodes with different sensing applications to save energy and reduce cost. Table 2.3 presents a summary of RPL enhancements that focus on QoS along with their main advantages and disadvantages in terms of implementation and performance.

Table 2.3: RPL Enhancements for QoS

Ref	Strategy	Advantages	Disadvantages
[140]	Passive link quality probing	Improved reliability of data	(i) Long delays caused by frequent parent changes. (ii) No mobility support.
[141]	Improving link quality estimation	Improved PDR, energy consumption and delay.	(i) No mobility support. (ii) Some conclusions do not agree with literature.
[142]	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.
[44]	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.
[119]	Fuzzy logic metrics.	(i) Improves lifetime and throughput. (ii) Conducts practical experiments.	(i) Does not consider mobility. (ii) Routing metrics are not optimized.
[123]	Link failure detection.	(i) Uses a combined cost metric. (ii) Improves lifetime and throughput.	(i) No mobility support. (ii) No practical experiments.
[143]	Root node failure detection.	(i) Allows node collaboration. (ii) Improves reliability.	(i) Increased energy consumption. (ii) Failure detection is not guaranteed.
[120]	Multiple parent nodes.	(i) Improves lifetime. (ii) Estimates link quality on multiple paths.	(i) Does not consider mobility. (ii) Incompatible with the native RPL.
[144]	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.
[145]	Implicit acknowledgements.	(i) Combines Trickle [31] and SMRF [144] algorithms. (ii) Ability to select a trade off between delay and PDR	(i) Increased delay. (ii) Increased energy consumption. (iii) High memory requirements.
[146]	Enhanced stateless multicast RPL forwarding.	(i) Improved reliability. (ii) Improved PDR and delay.	(i) Increased energy consumption. (ii) Incompatible with the native RPL.
[147]	Bidirectional multicast RPL forwarding.	(i) Improved reliability. (i) Considers bidirectional traffic. (iii) Adjustable parameters.	(i) Increased energy consumption and delay. (ii) High memory requirements.
[148]	Cooperative interaction among RPL instances.	(i) Improved reliability and energy consumption. (ii) Low implementation cost. (iii) Considers multiple objective functions	No mobility support.

2.7.4 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 [149]. Congestion leads to significant deterioration in energy consumption, reliability and delay [150]. There are different approaches to solve the problem of congestion, the most common are resource control, traffic control and hybrid schemes.

The authors in [151] 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 [46] 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 [152] 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 [153] 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 [42, 154] 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 [43, 155] 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 [156–158], 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 [159] propose using multiple routes for data delivery based on objective function metrics. In [160], the protocol uses DIO information to trigger multi-path operation only when congestion occurs.

In and [161], 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 2.4 summarizes the relevant RPL enhancements that deals with congestion along with the advantages and disadvantages of using them.

Table 2.4: RPL Enhancements for Congestion Control

Ref	**Strategy**	**Advantages**	**Disadvantages**
[151]	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.
[46]	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.
[152]	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.
[153]	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.
[42, 154]	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.
[43, 155]	Using game theory to find non-congested paths.	Improves PDR and throughput.	(i) Additional overhead. (ii) Increased energy consumption. (iii) Does not support mobility.
[156–158]	Using multiple parents.	(i) Improves throughput and energy efficiency. (ii) Achieves load balancing.	(i) Incompatible with RPL standard. (ii) Does not support mobility.
[159]	Using multipath routing.	(i) Improves throughput and delay. (ii) Achieves load balancing.	(i) Increased energy consumption. (ii) Does not support mobility.
[160]	Using adaptive multipath routing.	(i) Improves energy efficiency, throughput and delay. (ii) Achieves load balancing.	(i) Additional overhead. (ii) Does not support mobility.
[161]	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.

2.7.5 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 [162].

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.

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" [30]. 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 [163] 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

Table 2.5: RPL Enhancements for Security Features

Ref	Strategy	Advantages	Disadvantages
[163]	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.
[164]	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.
[165]	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.
[166]	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.
[167]	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.
[168]	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.
[169]	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.

is reached. Another study in [164] 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 [165] 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 [166] propose an algorithm to use signed DIO messages to detect fake rank advertisements. The algorithm was also studied and improved by [167, 168] 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 attacks. The monitoring agents are different from sensor nodes in this approach, their sole purpose is to monitor the network [169]. 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 2.5 presents the main efforts to deal with security threats using RPL with a summary of their advantages and disadvantages.

2.8 Summary

This chapter 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 2.12 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

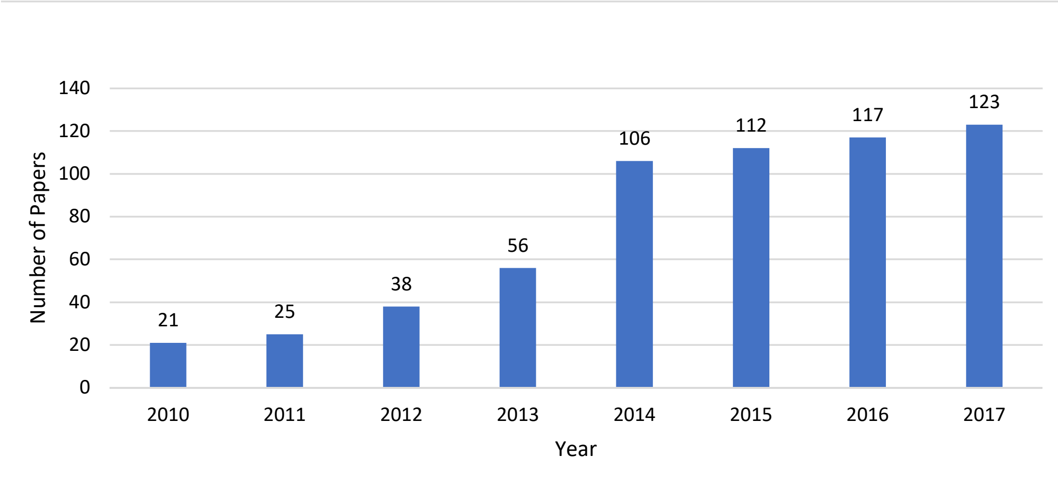

Figure 2.12: RPL research papers count

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.

Chapter 3

Dynamic Routing in IEEE 802.15.4

3.1 Introduction

WSNs consist of a number of smart devices with limited capabilities in terms of energy, transmission power, processing and memory [5]. In order to design and evaluate routing algorithms for WSNs many aspects have to be taken into consideration including energy efficiency, reliability, addressing scheme, flexibility and scalability. These requirements are even harder to accommodate in a mobile environment where some or all the nodes keep moving and losing connectivity. In a hierarchical WSN with multi-hop communication, if a CH moves away from its parent node or gateway, all of its sub clusters will lose connectivity causing a major deterioration in network reliability and efficiency.

Cluster-based topology provides a number of advantages for WSNs, it allows higher flexibility and better scalability for the network by localizing routing information inside clusters and minimizing the size of routing tables [170]. It also allows data aggregation to remove redundant data save energy and bandwidth [171]. Also, using a clustering tree allows for better load balancing and improved quality of service.

There are many efforts to improve routing in cluster-based mobile WSNs using different approaches for rotating CHs. However, the existing protocols make a number of assumptions that either limit their applications or cause high overhead making them less flexible and less sustainable [172].

A Dynamic Cluster Head Election Protocol (DCHEP) is proposed to improve the availability and lifetime of mobile WSNs using dynamic election of CHs and BCHs. The proposed protocol uses the beacon-enabled IEEE 802.15.4 standard and hierarchically elects CHs based on the beacon information and residual energy of the node. DCHEP doesn't use any extra control messages and doesn't have any extra overhead, it's rather triggered by the presence or absence of the periodic beacons and it lets every node decide whether it's a candidate for becoming a CH or not, each node has a different probability of becoming a CH that corresponds to the residual energy of the node.

DCHEP is different from other protocols because it uses a proactive approach in rotating CHs where nodes do not need a decision from a parent node but rather use their calculated probability and are triggered by the presence or absence of beacons to start the election process. It is designed to improve mobility management and assess data routing using IEEE 802.15.4 clustering scheme.

3.2 Mobility problems in IEEE 802.15.4

Mobility of sensor nodes introduce new challenges for routing and complicate the existing challenges even further, some of these challenges that affect cluster based routing are:

- Black hole problem: cluster formation sometimes leads to isolating some nodes, keeping them out of range of any CH. Mobile nodes suffer from this problem because their mobility leads them to leave the cluster area and thus disconnect from their CH which leads to deterioration in network performance and availability.

- CH mobility: when a CH disconnects from the sink node (or its parent node in cluster tree topology), it leads to major degradation in network availability, energy efficiency, etc. because it affects the connectivity of all the child nodes. Most of the routing protocols in literature assume a static CH but this assumption is not always applicable.

- Reliability: nodes that are connected to a CH may lose connectivity due to their mobility and fail to deliver packets as expected.

- Cluster maintenance: most of the mobility-aware routing protocols show interest in the formation of clusters and the election of CHs but lack the consideration of packet delivery to the sink especially in multi-hop scenarios.

- Association/Dissociation delays: when sensor nodes enter or leave a cluster, the process of adding the node or deleting it in the CH doesnt come without cost. Delays caused by this process need to be minimized especially in dynamic and dense networks.

Figure 3.1 shows a simple classification of mobility and its effects on the network. There are different mobility models for mobile WSNs including the pathway mobility model, obstacle mobility model, reference point group model, Gauss-Markov model, smooth random mobility model, random direction model, random walk model, and random waypoint model. Because of their generality, none of these models can describe accurate behaviour for all different applications. However, the random waypoint model is considered to best describe the mobility of nodes in ad-hoc and WSNs [13]. The problem with random mobility models in general is the sudden change of velocity especially at higher speeds, a node can be moving at maximum velocity and suddenly stops or change direction. Another limitation is that nodes are allowed to move freely within the simulation area where in real applications nodes can be restricted by obstacles that affect their mobility. In addition to that, the mobility of nodes are independent from each other, while in some applications like undersea monitoring or animal tracking nodes usually move in groups [173].

The random waypoint model defines the factors of mobility as velocity and direction, both factors change with respect to a specific time interval. Sensor nodes can move within the simulation area with a speed of 0 to Vmax and stays static for a random period of time before starting to move again [174].

3.3 Dynamic Cluster Head Election Protocol

3.3.1 Network Setup

In order to build the hierarchy of the network, the sink node starts sending beacons to advertise its presence, neighbouring nodes receive the beacon and send an association request to the sender setting it as their parent node. In the setup phase, connected nodes will decide whether or not to become a CH based on

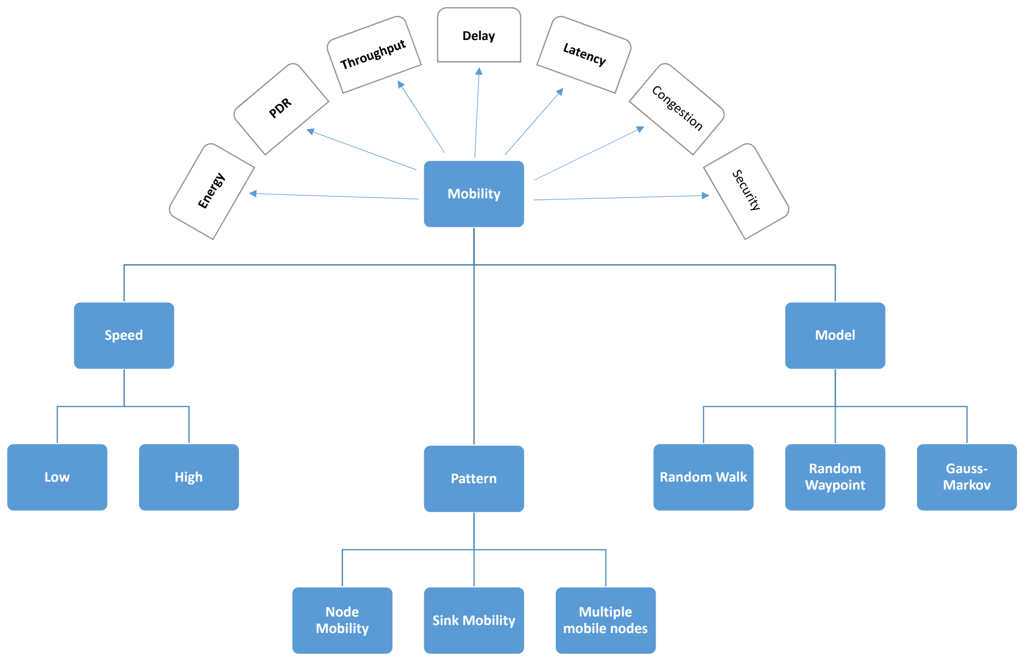

Figure 3.1: Mobility classification and effect

a Pseudo-random value that corresponds to the available residual energy. Connected CHs start to advertise their presence in the same way forming a connected tree as shown in figure 3.2.

As shown in equation (3.1), the priority of each node is calculated locally using the available residual energy and the initial energy, the connectivity takes the value of 1 or 0 and makes sure that nodes without an available path to the sink do not become CHs. The probability of becoming a CH is calculated in equation (3.2), this is triggered if a node receives a beacon for the first time or if it misses a maximum number of beacons after being connected. The preferred number of CHs is one of the most important parameters because it affects network coverage and inter-cluster interference. Selection of the optimum number of CHs for a mobile hierarchical tree WSN depends mainly on the application requirements and the speed of mobile nodes, optimization of this value for different applications is a future plan, it is given in the configuration file of each node in this simulation as 20% of the total number of nodes. Each node generates a random number using the "rand()" function and uses the value of P(CH) to determine whether or not

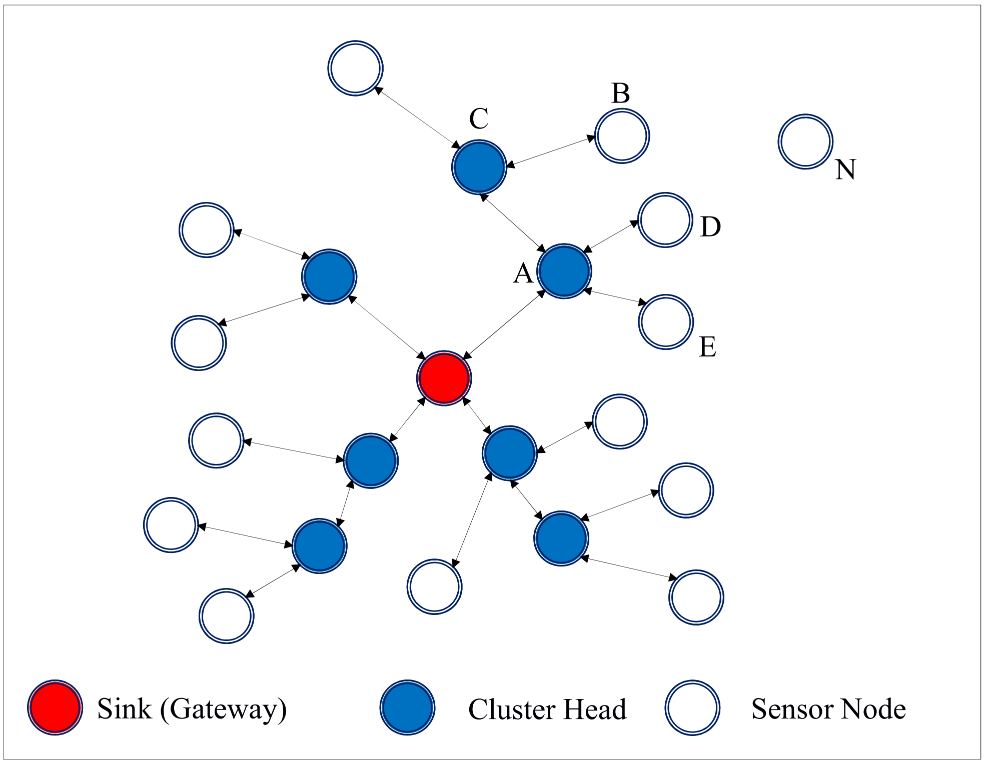

Figure 3.2: Hierarchical Architecture

to become a CH. For example, in the case of 20% ratio of CHs, the function generates five integer numbers [1-5] and the node becomes a CH if the random value was equal to 1.

$$Priority = \frac{Current\ energy}{Inital\ energy} \times Connectivity \tag{3.1}$$

$$P(CH) = Priority \times \frac{Preferred\ number\ of\ CHs}{Number\ of\ nodes} \tag{3.2}$$

Because nodes are not stationary, it is not always possible to reach all the nodes at a given time, node N in figure 3.2 is temporarily out of reach but the maintenance of clusters with each beacon and the dynamic election of CHs and BCHs makes a best effort to manage the mobility of nodes and maintain a path to the sink. Nodes that receive beacons from more than one CH join the one with best metrics and store the information of the second best as a BCH. In the event of missing a given number of beacons, the nodes switches to the BCH without a need reconstruct the whole network.

Every node waits for a beacon signal according to the IEEE 802.15.4 standard and updates its parameters based on the presence or absence of a beacon, the residual energy, and the current node status as shown in figure 3.3. Some protocols try to avoid the additional delay of using CSMA/CA but this is not possible in dense networks with high probability of collisions [27], DCHEP is targeted for dense networks so it employs slotted CSMA/CA mechanism to reduce collisions between different clusters and throughout the network. In addition to that, CHs assign a random time reference for each child node within the cluster, the nodes use this timing to communicate with their parent nodes and minimize collisions within the cluster [175].

Using the clustering tree simplifies processing at the network layer because most of the routing decisions are made in the MAC layer and each node sends information only to its parent CH while the network layer is responsible for assigning addresses and packet encapsulation/decapsulation process. The short 16-bit version of IEEE 802.15.4 standard is deployed by default to make sure that future integration with the Internet of things (IoT) is possible.

3.3.2 Network Management

Network availability and lifetime are important measures for WSNs because of the limitations in energy and processing. Availability is measured for each node to have a connected path to the sink node. To extend the lifetime of the network while ensuring an available path to the destination, the distribution of energy consumption should be fairly divided for all the nodes. Because CHs are responsible for beaconing and data aggregation, they consume more energy than normal nodes and fail sooner than others affecting both energy efficiency and network availability.

The mobility of a node or of its parent introduces another challenge to routing especially if it is a CH. The node is forced to lose connectivity from time to time and requires a mechanism to maintain the connected tree and to ensure the availability of a path to the sink. To achieve that without overwhelming the network with extra control signals and overhead, each node has to decide when and how to take action.

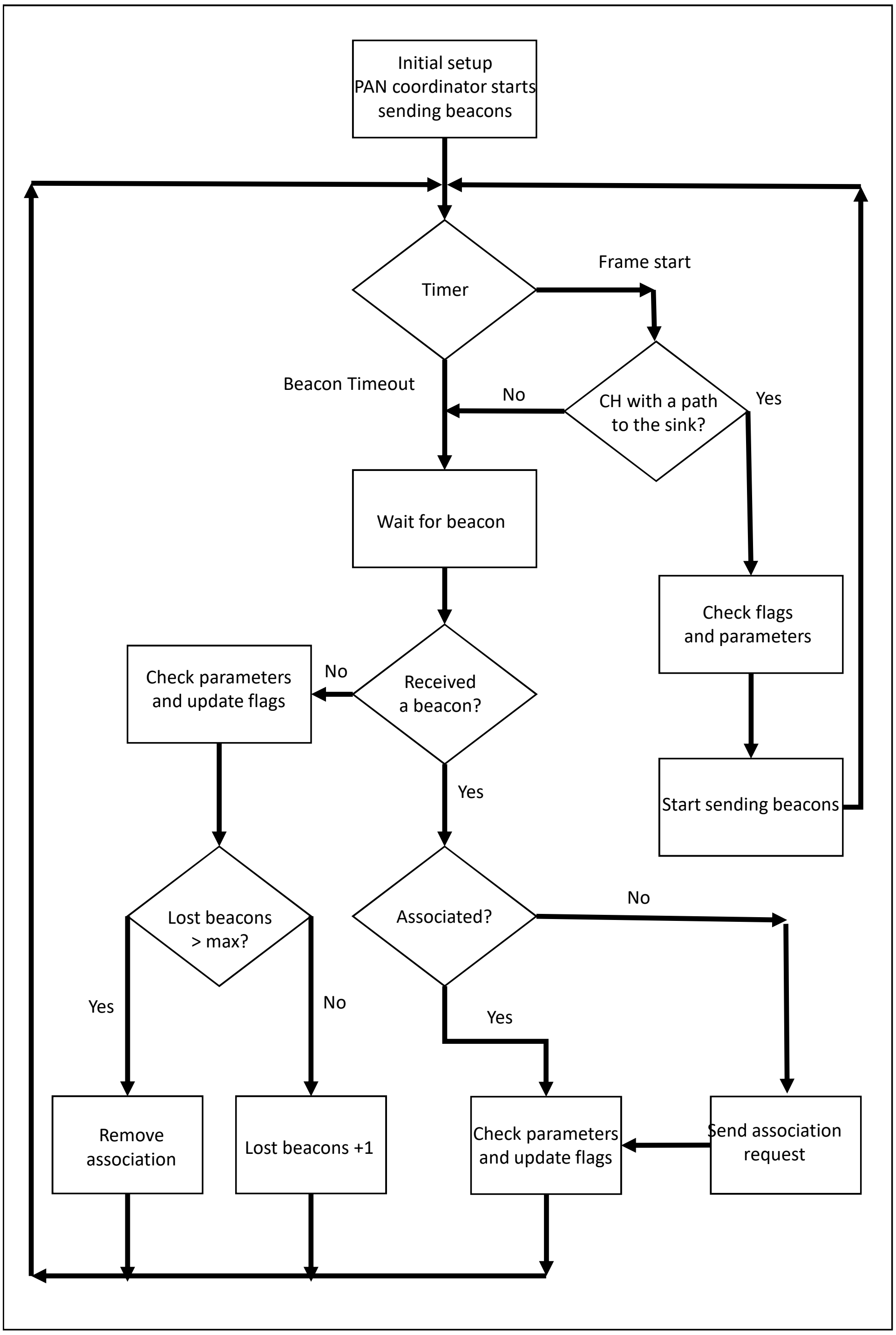

Figure 3.3: Mobility Management Flowchart

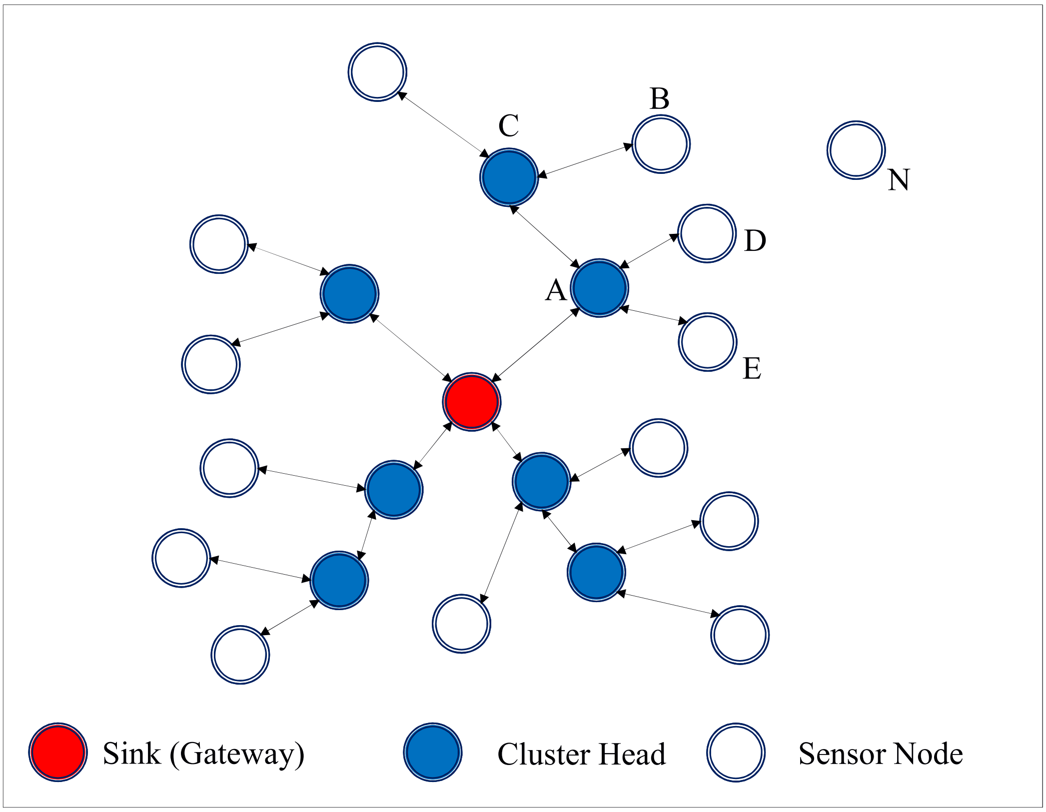

Figure 3.4: Association and Dissociation

Nodes receive periodic beacons from their parent CH to maintain connectivity and so they can operate normally. A number of factors including the mobility of nodes or the presence of collisions can result in a failure in receiving the beacon signal. When a connected node misses a beacon, it calculates its priority based on the level of residual energy to prepare for possible changes, if it misses a predefined maximum number of beacons, it dissociates from its former parent and waits for a beacon from a new one. Once connected, it uses the calculated priority value to determine the probability of becoming a CH itself as shown in figure 3.4.

This way, nodes with higher residual energy will have a better chance to become a cluster head as long as they have a path to the destination. If a CH reaches a threshold value of residual energy or is disconnected from its parent, it becomes a normal node and follows the same approach in deciding its new status. This ensures that energy consumption is distributed among all the participating nodes in a controlled manner without using extra control signals leading to a better lifetime for the network. In areas where there are too many collisions and high interference with neighbouring clusters, the nodes might miss some beacons and be forced to reform the clusters in that area leading to a better formation but consuming extra power for the dissociation and association process.

3.4 Simulation Results and Analysis

The proposed routing protocol DCHEP is simulated using the Castalia WSN simulator [53]. A number of scenarios were considered according to the simulation parameters in table 3.1 to obtain results and validate the efficiency of DCHEP in terms of energy consumption and availability. Nodes are placed with a uniform distribution with the sink node at the middle, moving at a maximum speed of 2m/s using a random waypoint mobility model. Because other protocols assume a static CH or use control signals for the election process and cannot adapt to a large number of nodes, the simulation results are compared with the original standard assuming an energy aware LEACH based rotation of CHs to measure the advantages of using DCHEP especially for WSNs with high density and random mobility.

LEACH protocol uses a random probability function for each node, to determine whether or not to become a cluster head. It does not include residual energy in this decision, leading to a uniform distribution of energy consumption for all nodes regardless of their battery capacity and starting conditions. DCHEP on the other hand, considers the remaining energy to set a priority function as described in equation 3.1. DCHEP also uses backup cluster heads to minimize the number of hand-overs in case connection to the cluster head is lost.

The results obtained in figure 3.5 measure the average availability of a path to the sink node as a percentage of time. It is affected by the time needed for a node to join a cluster and by how many times it changes clusters. CHs do not send beacons unless they are connected to a parent node in order to form the cluster tree, for this reason, the fact that a node is connected implies that it has a path to the sink although it doesn't necessarily mean that it is a reliable path.

For a WSN with 100 nodes, DCHEP achieves around 40% slightly higher than the original standard, it goes up with an increasing number of nodes up to 90% for

Table 3.1: DCHEP Simulation Parameters

Parameter	Value
Simulation Area	500m x 500m
Number of Nodes	100, 200, 500, 1000
Application Packet Rate	5 Packets/Second
Mobility Model	Random Way Point, 0 to 2 m/s [176]
Simulation Time	3 Hours
Radio	CC2420
Backoff exponent	7
Maximum number of backoffs	4
Maximum number of beacons lost	4
Minimum length of CAP	440

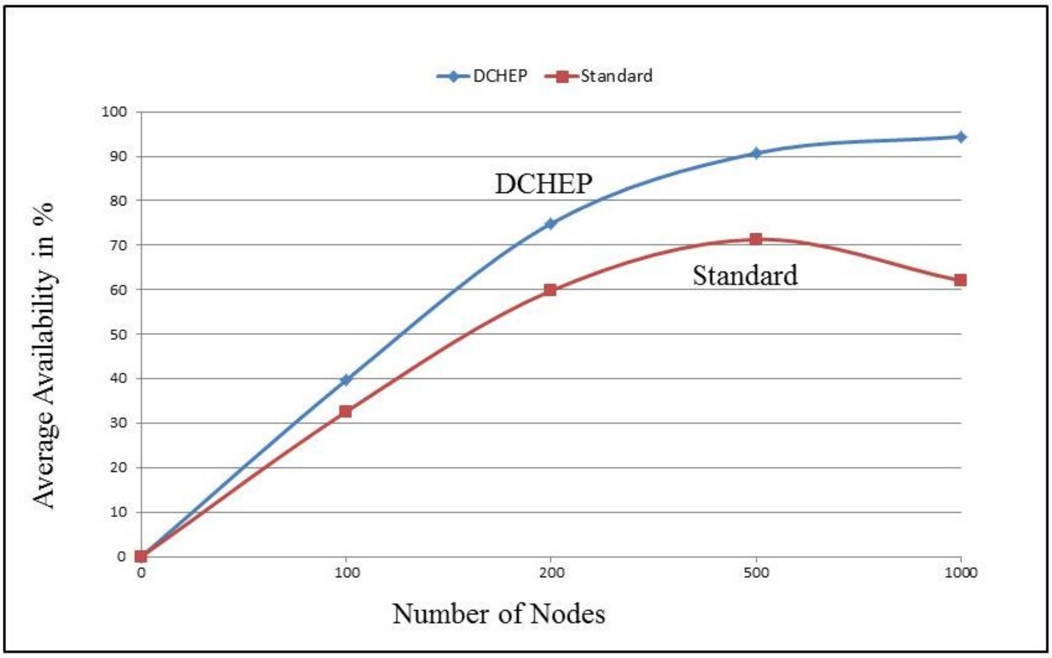

Figure 3.5: Path Availability

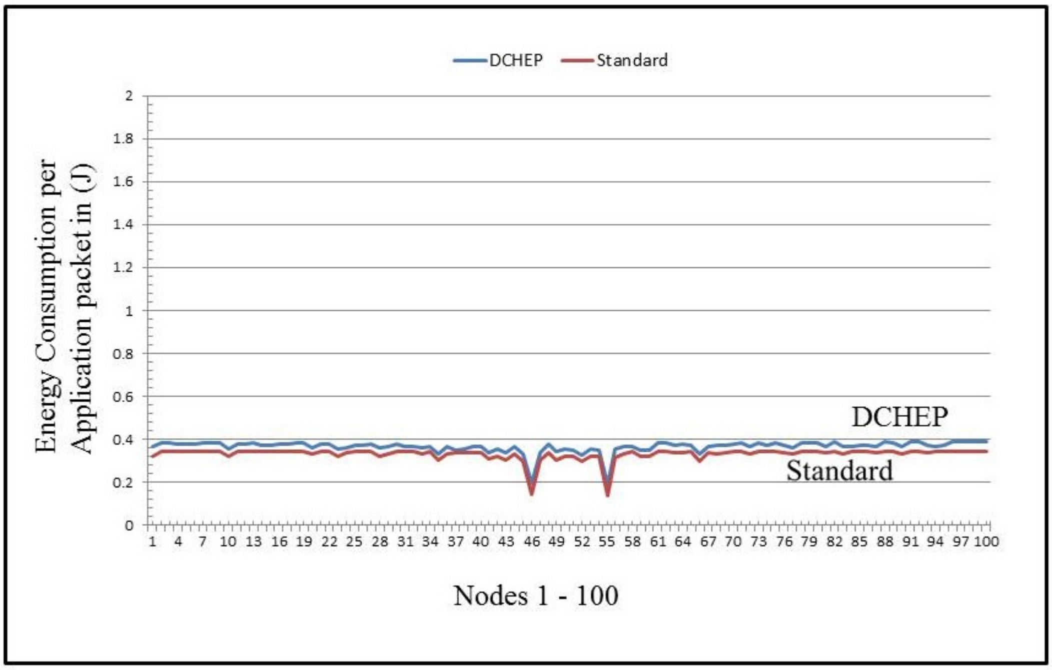

Figure 3.6: Energy Consumption, 100 Nodes

DCHEP at 500 nodes compared to the 71% of the original standard. Above 500 nodes, the availability of DCHEP keeps going higher up to 94.4% at 1000 nodes while the LEACH based rotation of CHs fail to accommodate the higher density and starts to deteriorate down to around 60%. DCHEP performs significantly better because of the efficient method of CH election and mobility management.

To measure the energy efficiency of the proposed protocol, we calculated the average energy consumption for delivering an application packet from each node. This value gives an indication of the energy efficiency and the lifetime of the network.

DCHEP and the original standard both have low availability with 100 nodes and the results in figure 3.6 show that they both have a good distribution of energy consumption but DCHEP consumes slightly more energy for delivering application packets because of the added processing in the election process. Some nodes consume less energy than others depending on their distance from the sink and their role in the cluster tree, this is directly affected by the mobility of these nodes, those who change clusters less frequently and serve as CHs for a shorter time can be seen as dips in the results and they get fewer and less obvious with

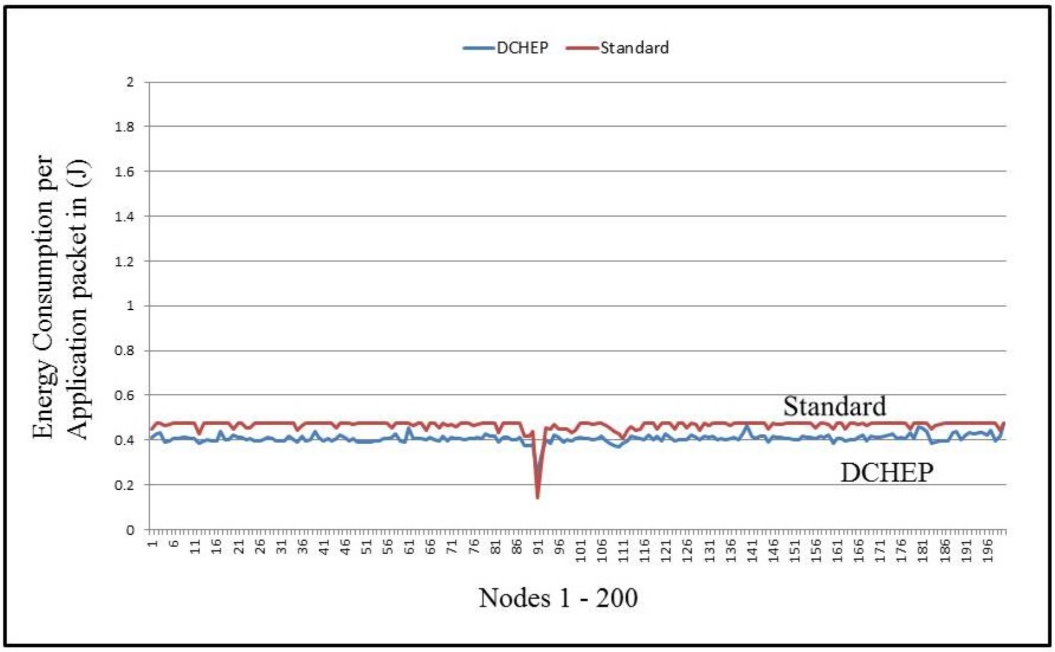

Figure 3.7: Energy Consumption, 200 Nodes

longer simulation times.

For a mobile WSN with 200 nodes, the higher density leads to more interference and more hops to the sink. As shown in figure 3.7, DCHEP outperforms the original standard consuming less energy for delivering application packets because of the improved election of CHs. The results show that DCHEP makes better decisions in selecting CHs to maintain good availability and ensure longer lifetime.

With higher density at 500 nodes, the efficiency of DCHEP becomes more obvious and the gap with the original standard increases further. The election of CHs is also affected by interference and DCHEP gains an advantage of having higher probability for nodes with lower interference to become CHs because they have a better chance to transmit and receive beacons. Figure 3.8 shows that while both protocols maintain a good distribution of energy consumption for almost all nodes, DCHEP provides a much better energy efficiency, it is also obvious that the energy consumption is going higher while increasing the number of nodes and that is due to added information sources and higher interference. The presence of backup CHs and the criteria for electing a parent node ensures better redundancy and improved load balancing.

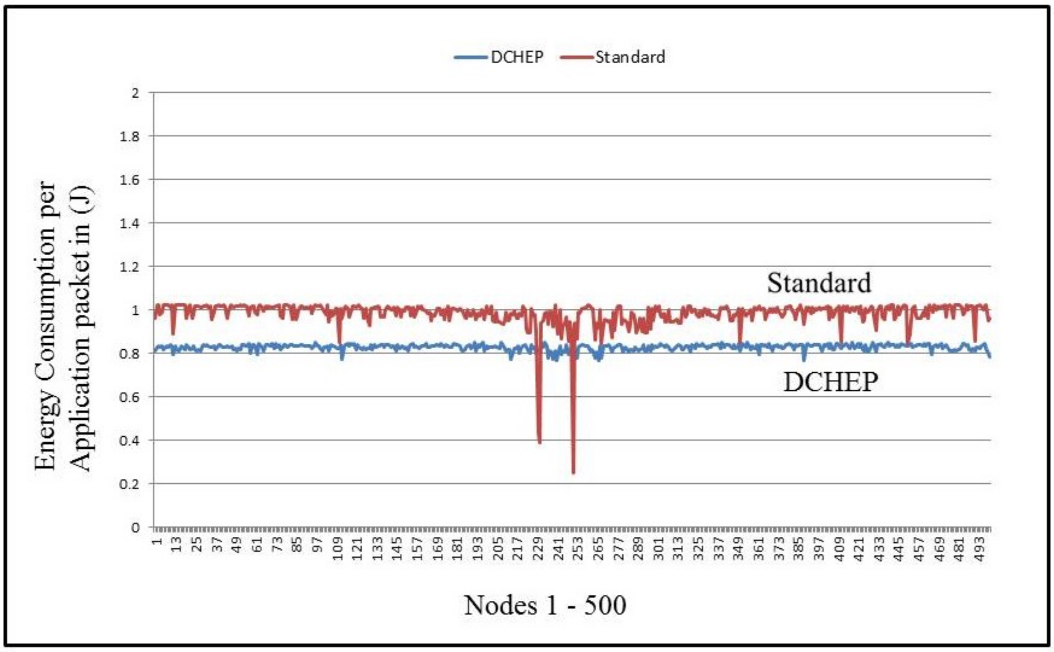

Figure 3.8: Energy Consumption, 500 Nodes

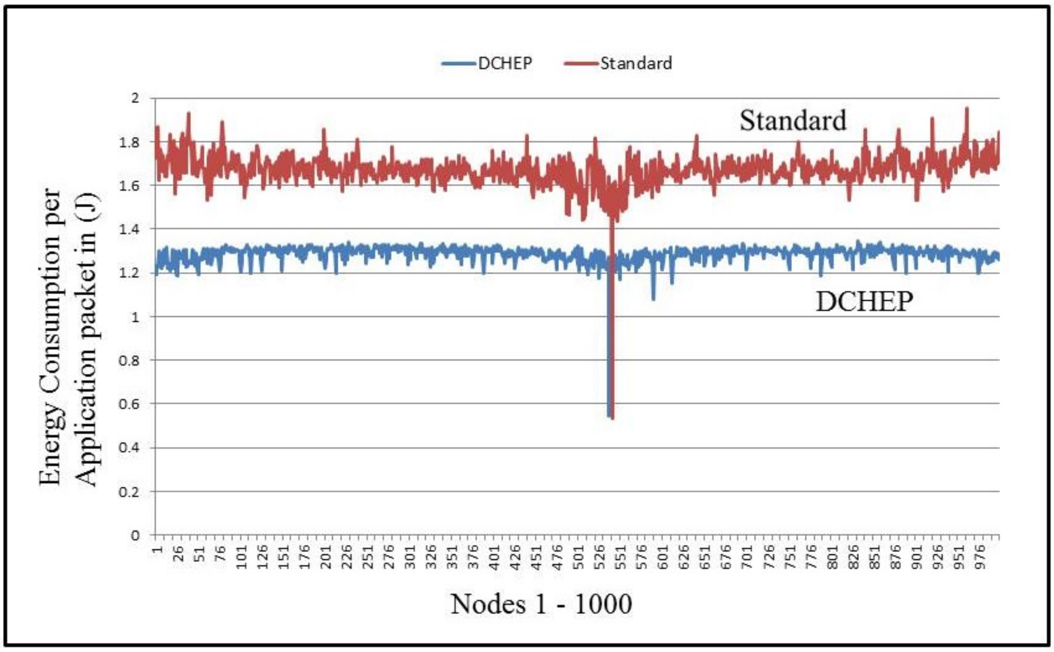

Figure 3.9: Energy Consumption, 1000 Nodes

In figure 3.9, the gap between DCHEP and the original standard increases even further. As shown earlier in figure 3.5, DCHEP maintains much better availability for a network with 1000 nodes and this gives it an advantage compared to other protocols. The high density and interference lift the energy consumption for any routing protocol but the simulation results show that DCHEP adapts much better to these changes making it a good candidate for mobile and dynamic networks. In high density networks, even though the energy consumption and path availability are improved, it still does not mean that the path is reliable to deliver data nor that quality of service is guaranteed. However, the results shown in this chapter support the general approach of clustering and the use of backup parent nodes to maintain fewer hand overs and better load balancing that leads to an improved life time for the overall network.

3.5 Summary

The Dynamic Cluster Head Election Protocol (DCHEP) is implemented to provide network connectivity for beacon-enabled mobile WSNs under the IEEE 802.15.4 standard using backup cluster heads to improve the availability and lifetime of the network when all nodes including cluster heads are mobile. Simulation results show that DCHEP maintains inter-cluster and intra-cluster connectivity in a proactive manner to distribute energy consumption among the participating nodes while maintaining connectivity.

Because of the nature of mobile networks especially with random mobility, no routing protocol can guarantee a 100% availability of a path to the sink for all the nodes but according to the simulation results DCHEP does provide and average availability of 75% and up to 94.4% in dense networks. Unlike other protocols, DCHEP is highly scalable and has an improved performance for dynamic and dense networks, it is also highly flexible and nodes can be easily added to the network at any time. DCHEP improves the availability and lifetime of the network by 33% and 26% respectively compared to the original standard.

The hierarchy of the clustering tree and the default addressing scheme of IEEE 802.15.4 makes it also a good candidate for IoT applications. This work highlights the efficiency of hierarchical routing and the importance of making local repairs. The following chapters focus on routing using and enhancing RPL which is a layer 3 protocol and is built on the IEEE 802.15.4 standard.

Chapter 4

Dynamic Multi-hop Routing in IoT Applications

4.1 Introduction

As mentioned earlier, RPL [30] is standardized as the routing protocol of the IoT [125]. It is a distance vector tree based routing protocol designed for IPv6 enabled networks, where the routing tree is built as a number of Destination Oriented Directed Acyclic Graphs (DODAG) routed towards the DODAG root. Every DODAG is formed according to the defined Objective Function (OF) which determines the routing metrics that will be used for selecting the preferred parent. RPL is described in more detail in section 2.1.3. Many applications require some of the nodes to be mobile which creates an extra challenge to routing especially when nodes move at high speeds or in an unpredictable pattern [12, 26, 177]. RPL was originally designed for static networks but there are some efforts that showed it can be used for some mobile WSNs with a few alterations and enhancements [178].

Smart city applications are various and have dynamic mobility scenarios that include static and mobile nodes. Some of these nodes can move in an unpredictable manner at different speeds. This type of mobility has a large impact on routing and it can significantly deteriorate the performance of the network. In order to satisfy the network requirements of applications with such a diverse mobility behaviour, it is imperative to have a dynamic routing protocol that can accommodate this kind of mobility and satisfy the demanding requirements of these applications.

To the best of our knowledge, none of the existing work on mobility enabled versions of RPL takes into account multi-hop routing through mobile nodes or the flexible interaction between the RPL timers and the objective function. Therefore, this chapter is motivated by these considerations to propose an enhanced dynamic version of RPL called D-RPL with a dynamic objective function called D-OF.

In this chapter, we provide realistic analysis for using RPL in mobile network based on extensive simulations for different mobility scenarios. We implement D-RPL that is an enhanced dynamic version of RPL with its own objective function (D-OF) designed for dynamic networks and compare it with existing related work taking into account different applications and mobility scenarios. The rest of the chapter is organized as follows: Section 4.2 introduces the description of D-RPL and the design of the D-OF using relevant metrics. Section 4.3 describes the simulation scenarios used to evaluate the proposed approach and provides results and analysis with regards to PDR, end-to-end delay, and energy efficiency. Section 4.4 presents the hardware implementation and testing for D-RPL using Tmote sky nodes MTM-CM5000-MSP. Finally, section 4.5 summarizes the performance of D-RPL and discusses possible improvements.

4.2 D-RPL Description

The IoT covers a wide range of applications using different standards and technologies to serve a large number of applications. These applications have different network requirements, different node distributions and different mobility scenarios. D-RPL is designed for networks where nodes can be attached to people or objects building a dynamic mobility scenario in which the DODAG formation can involve multiple mobile nodes. In this chapter, healthcare and animal tracking are presented as realistic IoT applications with dynamic mobility scenarios that require multi-hop routing to the root or gateway through mobile nodes.

The design of D-RPL includes improvements to the RPL trickle timer, a new objective function and the interaction between these two factors to manage mobile nodes in the network and improve the performance of RPL routing.

4.2.1 Timers

RPL relies on the trickle timer in sending DIO messages, if the network is stable this timer will increase exponentially to limit the number of control messages and keep a low overhead. When an inconsistency is discovered, this timer is reset to I_{min} in order to recover and repair the lost links. In D-RPL we add a control mechanism for the interval of the trickle timer based on the reception of data packets and control packets.

Algorithm 1 Trickle Timer in D-RPL

1: ***Begin***:
    Initialize trickle timer
    If (Received a packet from node n) then
        Read $RSSI_n$;
      If ($RSSI_n + K_{RSSI} < lastRSSI_n$) then
        $Trickle_I = (OldTrickle_I / 2)$
          If($Trickle_I < I_{min}$)
          $Trickle_I = I_{min}$;
        Send DIS to all neighbours;
    Resume normal trickle algorithm;
    End

Upon receiving a packet from node n, nodes read the $RSSI_n$ and compare it to the last reading from the same node $lastRSSI_n$. If the new reading is lower by a redundancy constant K_{rssi} it switches to the reverse-trickle setting and decreases the current interval to half until it reaches I_{min}. It also sends a DIS to all neighbours to assess the available options, otherwise it resumes the native RPL mechanism. This is based on the fact that a moving node is not necessarily going to leave its parent node and the decision on whether to switch to a new parent is left to the objective function. The trickle timer operation in D-RPL is defined in algorithm 1.

The idea of the reverse-trickle timer aims to gradually increase the responsiveness of RPL in a mobile environment, while keeping normal trickle operation in a static scenario. Unlike cellular handover, the reverse-trickle algorithm does not select a new contingency parent when detecting mobility, but rather ensures that nodes have updated information about their neighbours using DIS messages.

4.2.2 The Objective Function

The proposed dynamic objective function D-OF utilizes the Minimum Rank with Hysteresis Objective Function (MRHOF) that is already available in Contiki OS, and it adds other metrics in the calculation of the path cost to the destination. These metrics include ETX which is based on the expected number of transmissions required to send a packet from source to destination, the energy metric which is used as the estimated energy required to send a packet to the destination, and the link quality indicator (LQI) which is based on the RSSI. The MRHOF objective function defines a threshold for switching to a new parent and nodes only switch if the rank difference is more than 1. However, in D-OF more than one metric is used to produce the cost and changing the threshold is necessary to minimize the number of unwanted hand-overs and improve the routing performance. In this chapter, the threshold is set to 2 meaning that nodes will change parents if two of the routing metrics were better.

The proposed RSSI-based reverse-trickle timer mechanism in D-RPL aims to reduce the hand-over delay by sensing $RSSI$ values and detecting mobility or inconsistency while the proposed objective function D-OF which is responsible of parent selection aims to reduce the number of unnecessary hand-overs by comparing the calculated cost to the parent switching threshold. The integration of D-RPL and D-OF creates an optimization of these two crucial factors making it an adaptable solution for dynamic IoT applications.

4.3 Simulation Results and Analysis

4.3.1 Simulation Setup

The implementation and simulation of D-RPL has been done using the Contiki operating system 3.0 [51], with the COOJA [179] WSN simulator. Cooja has a mature and reliable implementation of RPL and although it does not normally support node mobility, it can import the coordinates of nodes through a mobility plug-in to represent mobile nodes. Mobility scenarios are generated using Bonnmotion [180], a free and widely used mobility scenario generation tool. Two different scenarios are generated to test the proposed D-RPL and compare it with relevant protocols.

RPL in its original standard, does not have an approach to handle mobility. It rather assumes that all nodes are static and it faces major deteriorations in the presence of mobility. mRPL uses a number of additional timers to detect mobility based on RSSI reading, it forces a higher overhead on the network but manages to provide good PDR. One of the disadvantages of mRPL is that it does can make unnecessary hand-overs without consulting the objective function

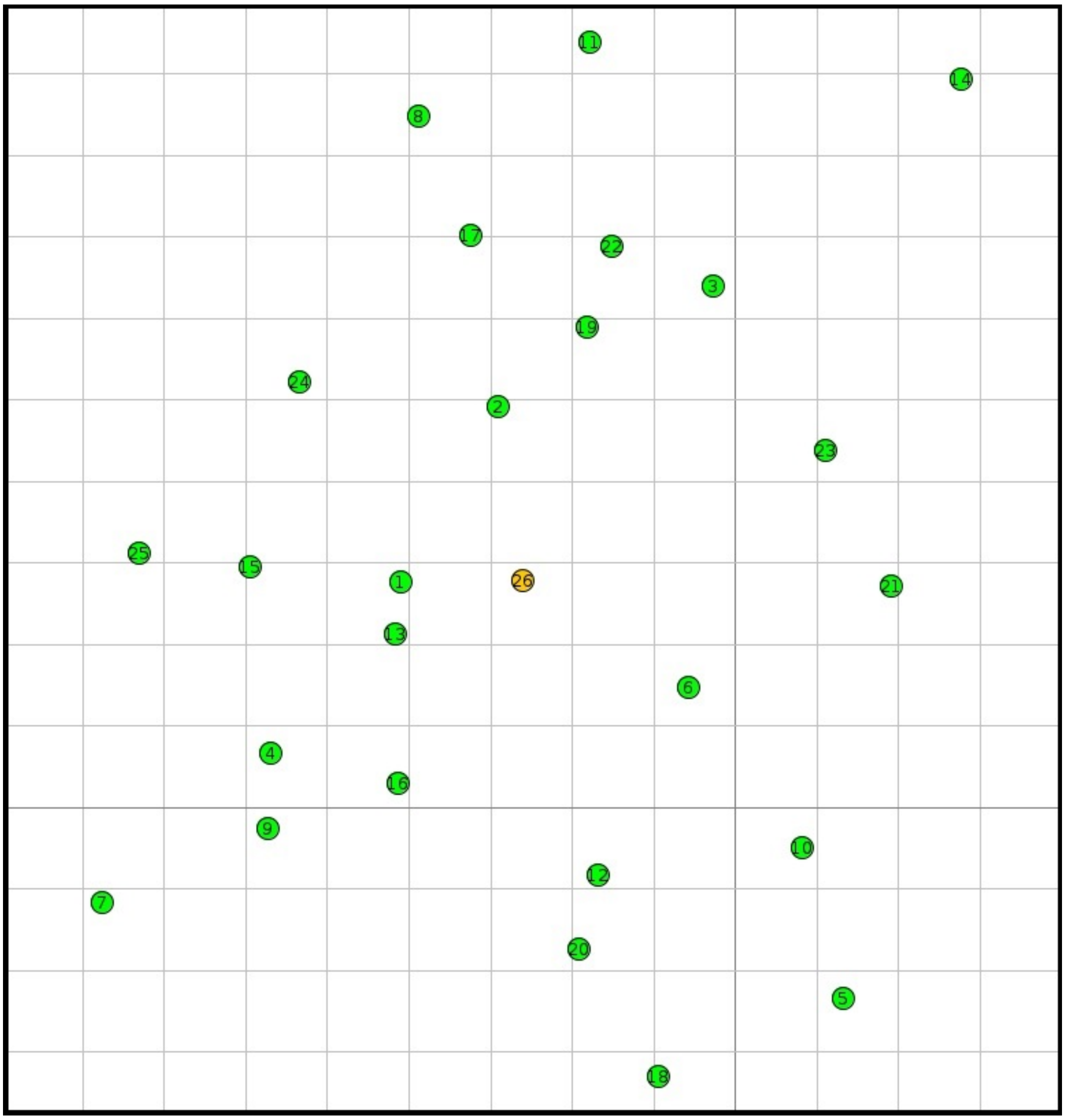

Figure 4.1: Node Distribution

metrics. D-RPL on the other hand, uses a reverse trickle algorithm to increase the responsiveness of RPL. The timer settings is triggered by RSSI readings, but instead of changing parents, D-RPL requests information from neighbours and lets the objective function make the decision to keep or change parents based on the flexible routing metrics. Also, D-RPL does not require relay nodes to be static, it assumes that all nodes are mobile with the exception of the sink node. It's worth mentioning that using mRPL gives similar results to D-RPL in scenarios where it is feasible to have static nodes in range of all mobile nodes.

Table 4.1: D-RPL Simulation Parameters

Parameter	Value
Simulation Area	150m x 150m
Number of Nodes	25 mobile nodes + 1 sink node
Transmission Range	50m
Healthcare Scenario	Random Waypoint, 0 to 2 m/s
Animal Tracking Scenario	Random Waypoint, 0 to 5 m/s
I_{min} / $I_{doubling}$	8 / 6
Simulation Time	1 hour
Radio	CC2420

We used 25 mobile nodes and 1 static sink node in a 150m x 150m simulation area as shown in figure 4.1, where the yellow node represents the static sink and the green nodes are randomly scattered mobile nodes. These nodes move based on the random waypoint mobility model at 0-2 m/s and 0-5 m/s for Healthcare and Animal tracking scenarios respectively with a maximum pause of 30s. The values of I_{min} and $I_{doubling}$ are chosen to be 8 and 6 respectively giving a minimum interval of 256ms and a maximum interval of 16s as shown in Table 4.1.

4.3.2 Simulation Results

In order to test the performance of D-RPL, we chose three metrics that reflect the efficiency of the network. These metrics are end-to-end delay, energy consumption and PDR. The end-to-end delay represents the average time required for each node to successfully send a packet from source to destination. Energy consumption represents the average amount of energy consumed to successfully transmit a packet from source to destination at each node during 60 minutes of simulation. PDR shows the percentage of delivered packets from each node compared to the total number of packets sent by the same node.

Healthcare Application

Healthcare is one of the most important IoT applications because it aims to improve patients' experience and potentially save lives. In this application, we assume that low-powered mobile nodes are attached to people, objects and equipment in a healthcare establishment and thus we consider a maximum speed of 2m/s which corresponds to human walking speed and can also be applied for other IoT applications like smart cites and smart factory management. Healthcare is estimated to dominate over 40% of the market for IoT applications by 2025 [181].

Figure 4.2 shows the percentage of the number successfully transmitted packets compared to the total number of sent packets. mRPL has high responsiveness to mobility, and the simulation results show that it provides an average PDR of 75% which is much higher than the Native RPL but around 10% lower than D-RPL. This is because mRPL was designed on the assumption that there is always a static node in range of every mobile node, however in a dynamic scenario with multi-hop communication through mobile nodes, it performs some unnecessary hand-overs causing a loss in successfully delivered packets.

D-RPL gives a PDR of around 84% using the adaptive trickle technique and its integration with the objective function which uses link quality as an indication of mobility and thus contribute in making better routing decisions.

RPL was originally designed for static networks and thus it has low responsiveness to topology changes and it has an average of 36% PDR in this scenario. Using RPL in these scenarios and comparing its results to mobility aware versions of RPL reflects on the importance of mobility management and emphasises the lack of mobility support in the design of RPL.

Figure 4.3 shows the average energy consumption per successfully transmitted packet at each node after 60 minutes of simulation, it shows that D-RPL performs better than mRPL and much better than the native RPL. This is due to multiple factors including the fact that mobility triggers the trickle timer to be reset to its minimum value in both RPL and mRPL, while D-RPL detects mobility based on RSSI readings and this triggers a decrease in the DIO interval instead of resetting it to the minimum value and only resets it when the link is broken or no longer reliable according to the D-OF. Another factor is the higher packet loss in mRPL and RPL that leads to more retransmissions and higher energy consumption. While the total energy consumption for all three protocols is almost the same,

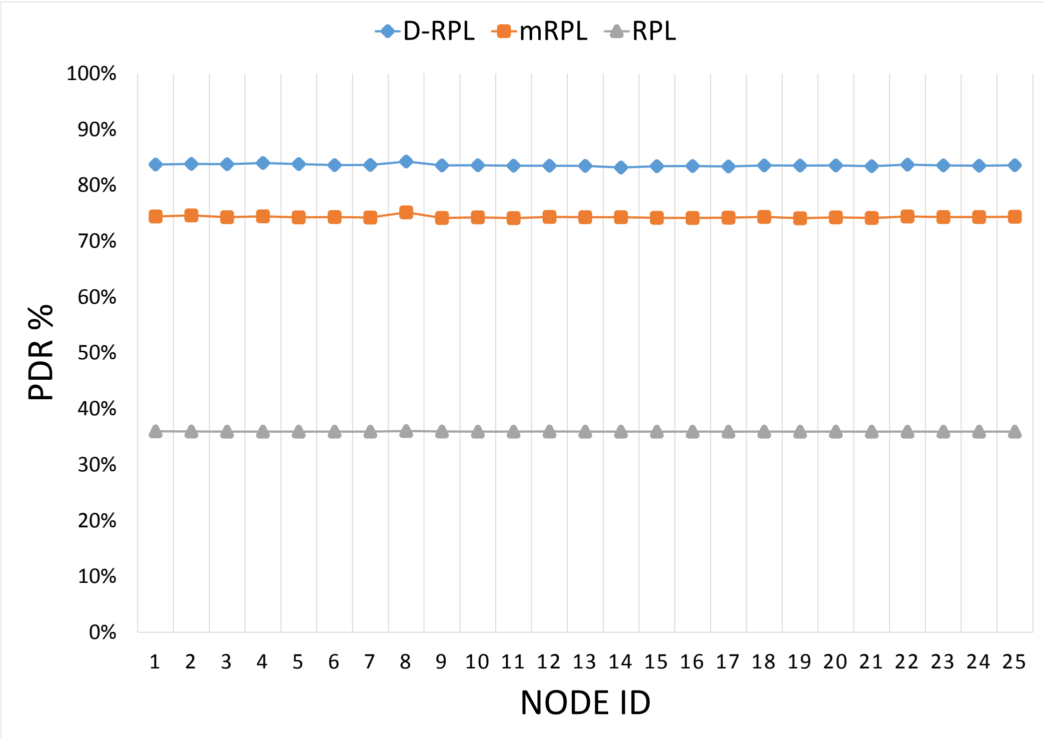

Figure 4.2: PDR - Healthcare

the efficiency of managing mobility and the ability to maintain fewer lost packets are much higher in mRPL and D-RPL, leaving the standard RPL at a significantly worse performance in mobile environment.

The end-to-end delay in figure 4.4 is similar in all three protocols with marginal difference. D-RPL performs slightly better for most of the nodes because of the better decisions in parent selection. Although all three protocols are using the same objective function, the operation of D-RPL is more flexible and less dependant on RSSI than mRPL and the native RPL leading to less delay from source to destination. This metric is based only on the successfully delivered packets and does not take into account the dropped packets and so it does not reflect the efficiency of routing unless incorporated with PDR. The end-to-end delay becomes higher with multiple hops, making it also a good indication on PDR and throughput. With a high delay, the network becomes more prone to congestion and packet loss due to insufficient buffer occupancy that is made even worse with the presence of mobile nodes. The delay is measured by adding a time stamp to each data message, and checked after being received at the sink node. At the end

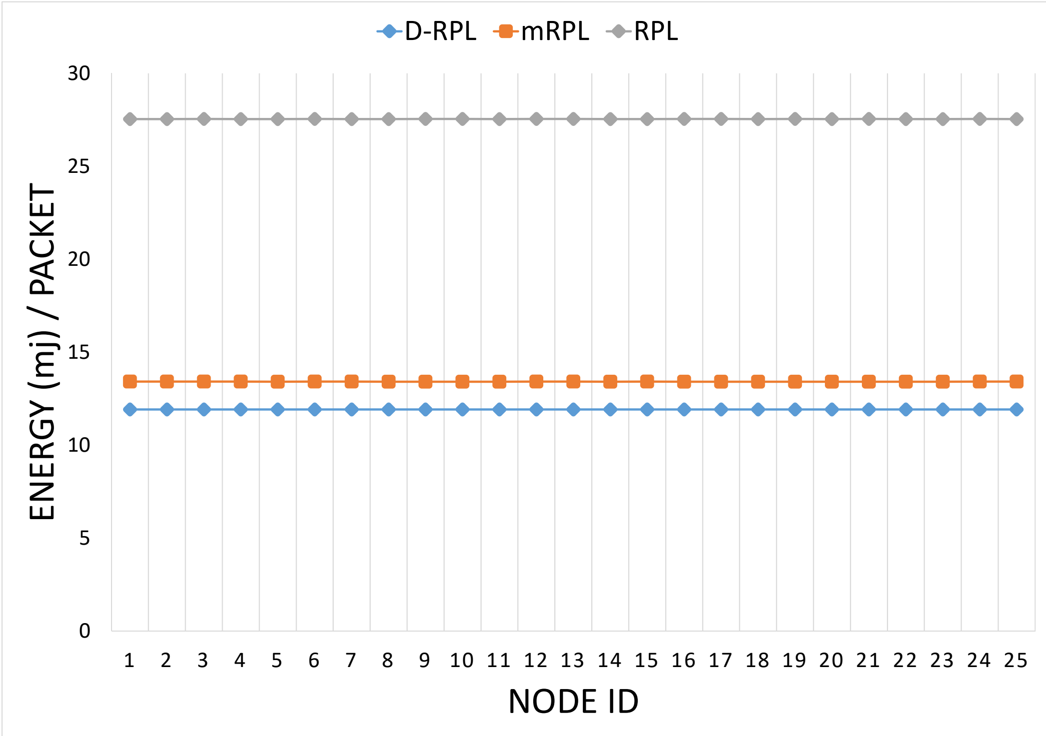

Figure 4.3: Energy Consumption - Healthcare

of the simulation, the delay is averaged for each node.

Animal Tracking Application

This application is another IoT application that aims to track a herd or a pack of animals and provide information about not only the animals themselves but also their surrounding environment. Having nodes attached to animals can cover a larger area due to their mobility. This application can also be used to detect fires in a forest or a field and provide invaluable data that can help in countless scenarios. We chose this application because it has a dynamic mobility scenario with nodes moving at relatively high speeds. It can also reflect the challenges of applications with similar mobility scenarios like sports monitoring.

Simulation results in figure 4.5 shows that D-RPL and mRPL adapt to the high mobility and provide reasonable results of around 78% and 68% PDR respectively. While the native RPL fails to catch up and provide only 35% average PDR. Similar to the healthcare application, although mRPL responds to inconsistencies quicker than D-RPL it still relies on the presence of static nodes in range

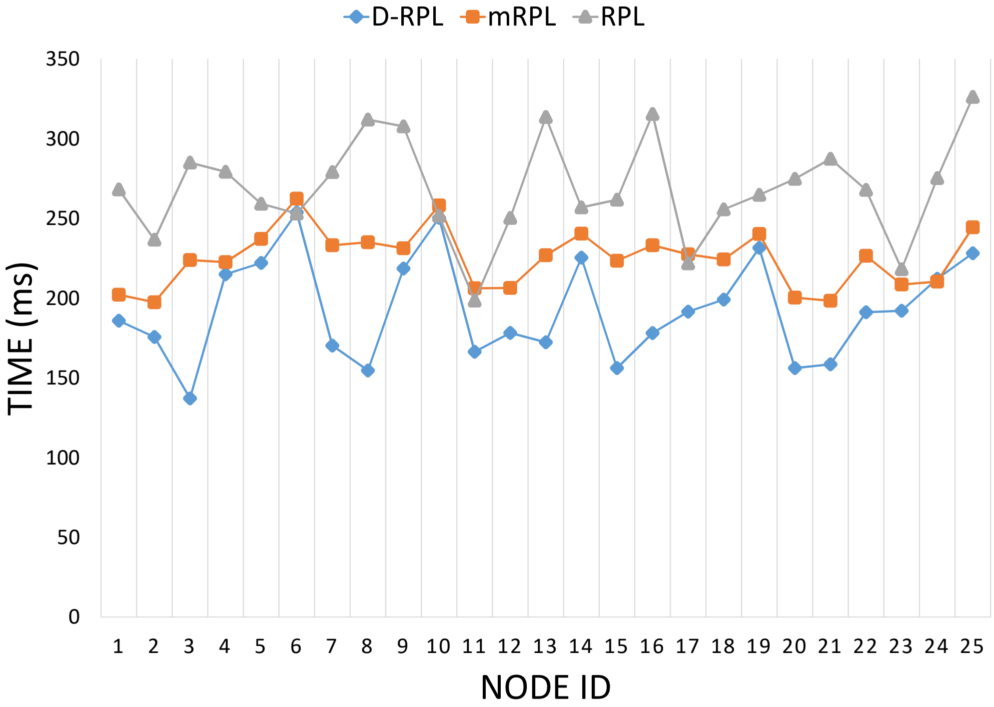

Figure 4.4: End-to-End Delay - Healthcare

and thus generates extra overhead and makes unwanted hand-overs that lead to packet loss. D-RPL can detect mobility and gradually increase its responsiveness to topology changes without the need to generate excessive control messages, it also uses the link quality threshold to make a radical change when necessary and resets the trickle timer to keep an appropriate level of redundancy. The native RPL shows a similar performance to that of healthcare applications even though nodes move at higher speeds, this is because it lacks any mobility management scheme and shows unacceptable results in any mobile scenario.

Figure 4.6 shows that RPL has the highest energy consumption per packet because of the very high packet loss caused by its low responsiveness to mobility. The performance of mRPL is much better than RPL but still fails to catch up with D-RPL because in addition to higher packet loss, the high mobility makes its trickle timer act as a periodic timer and generates high overhead. The trickle timer in D-RPL also acts more like as a periodic timer but at higher intervals that are adaptive to the speed of mobile nodes and thus has the lowest energy consumption.

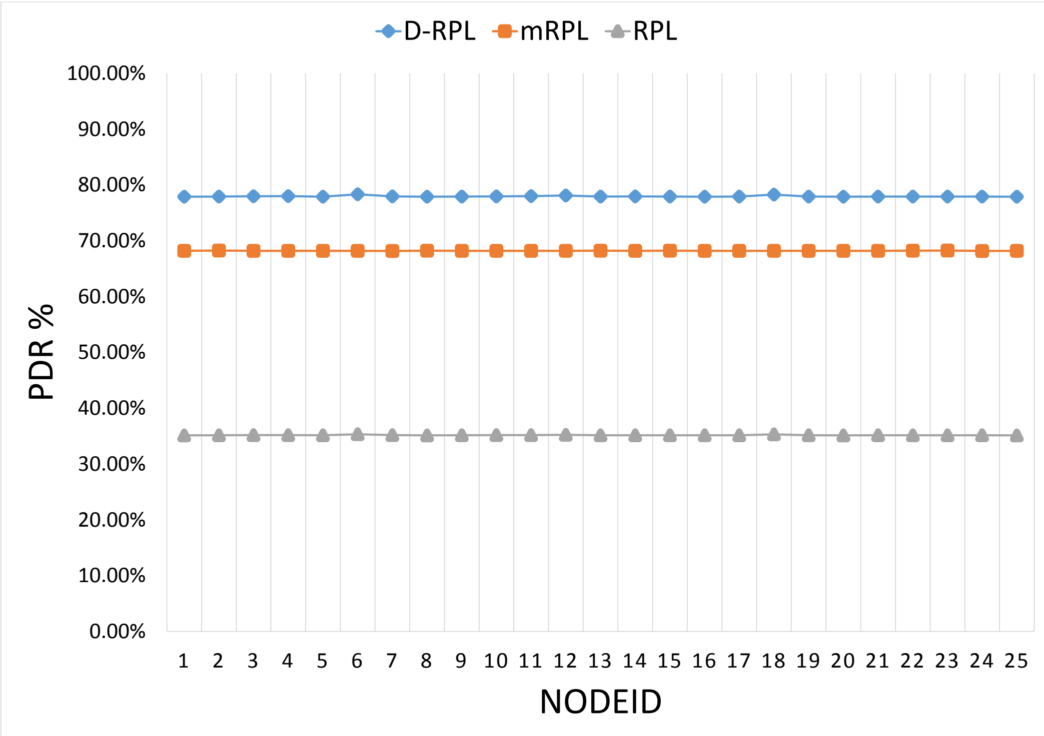

Figure 4.5: PDR - Animal Tracking

The end-to-end delay in this scenario shows that RPL, mRPL and D-RPL have similar results for the successfully transmitted packets as shown in figure 4.7. Taking PDR into account shows that D-RPL provides a higher routing efficiency and a more reliable solution. D-RPL can also achieve higher throughput and provide a reliable packet delivery that is even more pronounced when taking into account the overall performance of the network.

4.4 Practical Testing

In order to test the real performance of D-RPL, we conducted hardware testing using 10 Tmote sky nodes MTM-CM5000-MSP. The experiment was conducted in 2 environments, an obstacle-free open field and an indoor environment with obstacles. A simulation scenario is also created for comparison using a similar topology to the real hardware experiments and a similar mobility scenario. The aim of this test is to evaluate D-RPL in a practical manner and it does not reflect

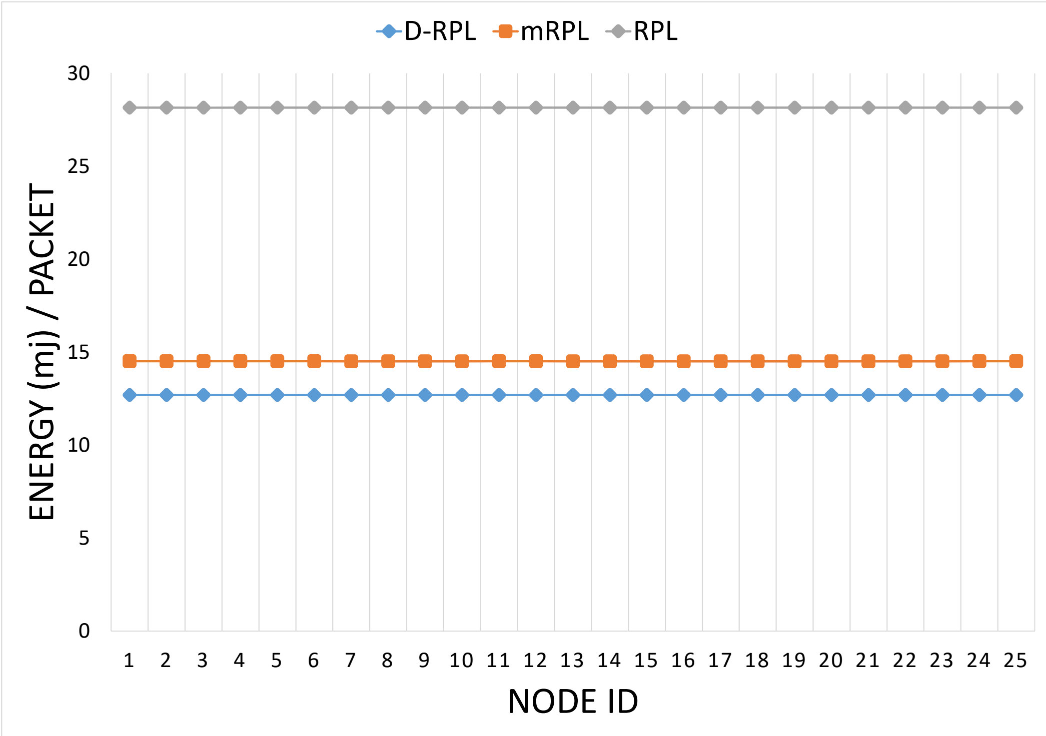

Figure 4.6: Energy Consumption - Animal Tracking

performance in a specific application. It does however give an indication of the expected performance in both indoor and outdoor scenarios.

The testing scenario involves one static sink node and nine mobile nodes moving at (0 - 1.5 m/s). Mobile nodes are connected to people moving at normal human speeds and pausing for a maximum period of 30s. Nodes are placed with a minimum overlap to ensure multi-hop communication. The sink node with ID 1 as shown in figure 4.8 is the only static node in the network, other nodes move randomly to force topology changes.

The results in figure 4.9 show that RPL achieves around 42% PDR while mRPL and D-RPL achieve around 88% and 90% respectively in simulation and both practical tests. The lower density gives the objective function less options making the difference in performance of mRPL and D-RPL down to 2% only. Higher node density increases the chance of collisions and leads to higher packet loss due to interference and congestion [182].

D-RPL depends on data packets as well as control packets to manage mobility making it adapt to topology changes. It is also less prune to inaccurate RSSI

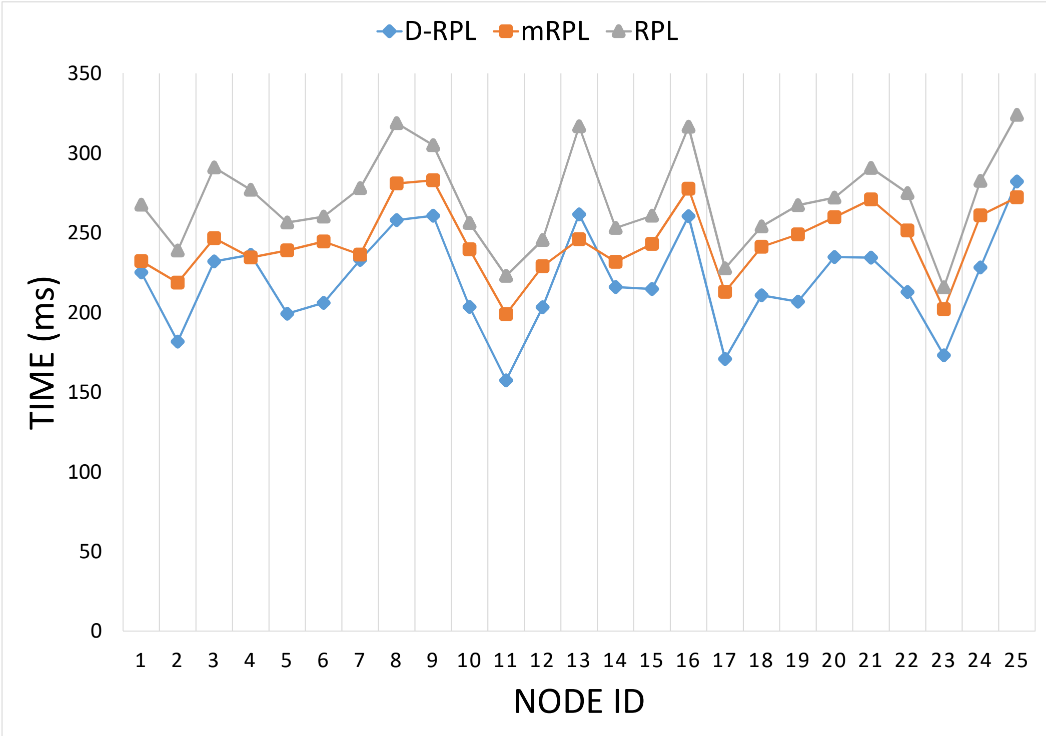

Figure 4.7: End-to-End Delay - Animal Tracking

readings because it involves the objective function metrics in the parent selection process.

The practical and simulation results are almost the same in spite of the external factors that are expected to affect practical testing. This confirms that COOJA is successful in emulating the actual hardware and providing a realistic channel model.

4.5 Summary

In this chapter, D-RPL is implemented for the dynamic applications of IoT to accommodate the network requirements and mobility demands of these applications, it is based on and compatible with RPL making it a flexible and scalable solution. Simulation results show that D-RPL improves the PDR, end-to-end delay, and energy efficiency of the network for different mobility scenarios.

D-RPL shows that it adapts to mobility changes better than relevant RPL-based protocols, achieving more than 10% improvement to PDR with better end-

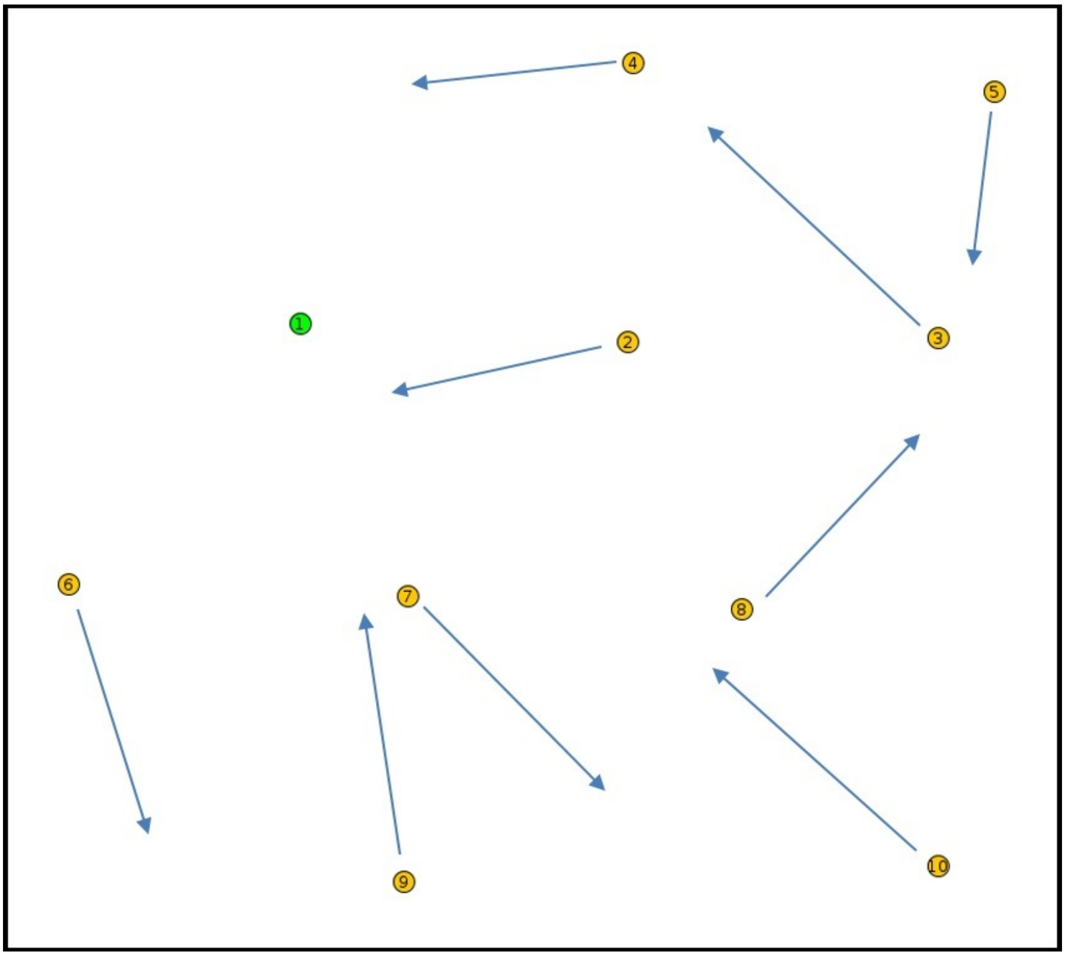

Figure 4.8: Hardware Testing Scenario

to-end delay and better energy consumption compared to mRPL. Simulation results also show the importance of the objective function and its impact on mobility management in RPL. The proposed objective function D-OF complements the operation of D-RPL giving reliable performance and efficient routing mechanism.

The design of D-RPL makes it adapt to other objective functions as well because it does not imply any metrics without consulting the objective function and uses RSSI only to detect mobility and not to make a final decision. Using the RSSI-based reverse-trickle algorithm in D-RPL leads to similar responsiveness to mRPL in low density networks. Including the objective function metrics improves the performance of D-RPL making it more efficient in highly dynamic scenarios. The optimization of the objective function to improve mobility management is

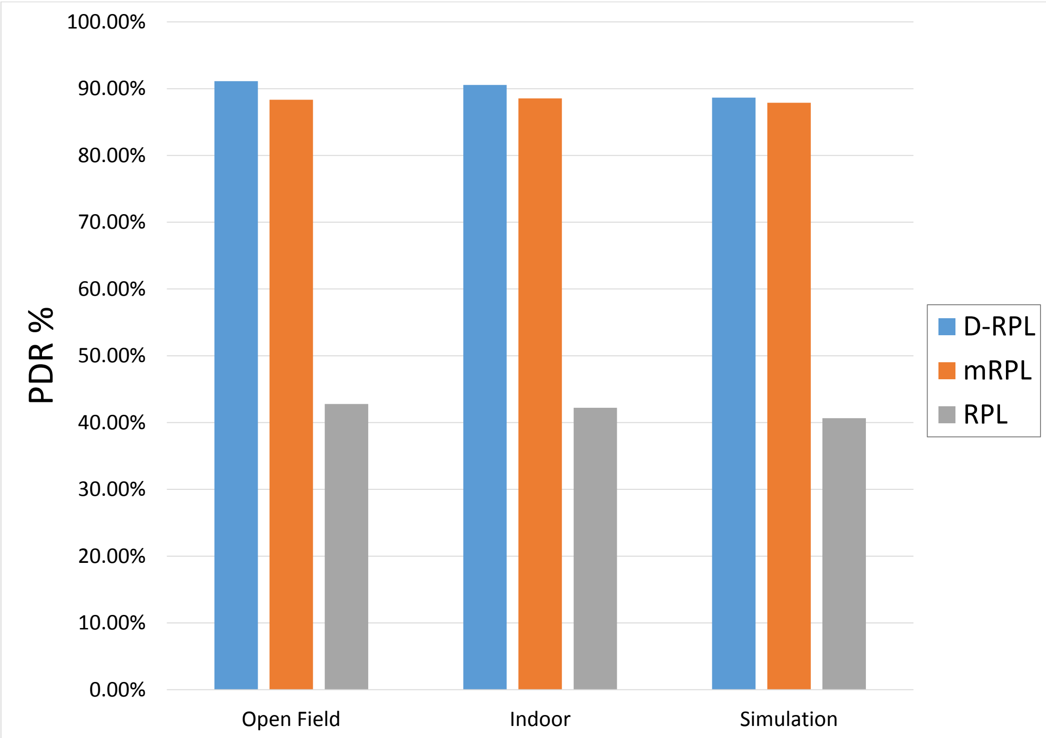

Figure 4.9: Practical Test Results

essential to achieve higher network performance.

Chapter 5

Optimized Routing for Mobile IoT

5.1 Introduction

RPL was originally designed for static networks, once the connections are established, it assumes that the network is in a steady state and does not take mobile nodes into account. There are many efforts to enhance RPL and many are successful in creating new versions of RPL that take into account the presence of mobile nodes. However, none of these efforts consider analysing and optimizing the efficiency of RPL in a mobile environment with regard to throughput, energy consumption and end-to-end delay. Therefore, in this chapter, an analytical model is provided with a proposal for a game theoretic design of RPL (GTM-RPL) using a variable transmission rate to achieve higher packet delivery ratio (PDR), lower end-to-end delay and better throughput whilst maintaining efficient energy consumption. To achieve this, a game is designed for nodes competing to send data in a mobile environment, where mobility itself serves as an involuntary action that influences decision making in all affected nodes. The payoff function is defined to assess the profit gained from increasing data transmission rate (the utility function) against the cost induced by the presence of mobile nodes (mobility function). Other factors are also taken into account in formulating the payoff function including the priority of nodes (priority function) and the energy consumption (energy function) . In order to prove the presence of at least one Nash equilibrium, a discussion and analysis are provided along with the optimal solution of the game. Then, a proposal of a novel GTM-RPL protocol based on this design and a performance evaluation in different IoT application scenarios are provided and tested using COOJA over Contiki OS in a simulation environment.

The novel contributions in this chapter are: (i) Improving and optimizing mobility management in RPL using a game theoretic approach. (ii) Introducing an adaptive transmission rate that depends on the conditions of the network and the availability of resources. (iii) Using a RSSI and link quality indicator (LQI) to assess the level of noise and the mobility conditions at each node. (iv) Adding cost functions to reflect on energy efficiency and priority, leading to an optimum transmission rate that matches the network conditions and application requirements.

The rest of the chapter is organised as follows: Section 5.3 provides a description of the native RPL and the proposed GTM-RPL with a discussion on the related aspects of the protocol and the formulation of the optimization game. Section 5.4 presents the simulation settings and results, and provides a discussion to compare GTM-RPL with relevant protocols in different scenarios. Finally, Section 5.5 presents the conclusions from this chapter.

5.2 Game Theory

While most of the tests performed in this work involved simulations and practice as explained in section 2.4, Some theoretical techniques were also used to tackle mobility and to optimize routing. Game theory was used in chapter 5 to pro-actively find an optimal transmission rate for nodes in a mobile environment leading to an improved performance. Game theory is used in different areas including politics, economy, philosophy, gaming, computer science, etc. In a cooperative game, “Players” negotiate a strategy to find an overall common profit. In non-cooperative games on the other hand, “Players” have a conflict of interest and they compete to find a strategy that allows them maximum profit. Non-cooperative games are the focus of this work as they allow individual nodes to make a decision without the need for extensive overhead. Nodes assess their environment and routing metrics to make an independent decision that nonetheless, leads to an improved profit for the single nodes and the overall network. The scenarios of using a non-cooperative game to achieve a common performance goal is further explained in chapter 5.

A non-cooperative game can be represented by $\Gamma = (N, (S_k)K \in N, (\phi_k)k \in N)$, where:

- N is the number of players or sensor nodes in the same collision space of the network, $(P_1, \ldots, P_k, \ldots, P_n), \forall k \in N$.

- S_k represents the strategies available for player P_k to take an action $A = (A_1, \ldots, A_k, \ldots, A_n) \forall k \in N$. Where $A_k = [0, \lambda_{max}]$ represents the strategy space for player P_k and thus the Cartesian product of the action sets $A = \prod_{k=1}^{N} A_k$.
- $\phi_k(A_k)$ represents the total cost for node P_k to send data at a rate of λ_k to the sink node in a mobile environment.

In order to make sure that the outcome of the game $\Gamma = (N, (S_k)k \in N, (\phi_k)k \in N)$ has an overall profit for the whole network, Nash equilibrium is used to solve the game allowing nodes to reach an optimal pure strategy s_k^* so that nodes can no longer increase their payoff by changing strategy and thus have no incentive to change it.

5.3 Game-Theory Based Mobile RPL (GTM-RPL)

5.3.1 RPL Related Aspects

As previously explained in chapter 1, a node using RPL starts its operation by waiting for a DIO message, the probability that a node receives this message in a given time depends on the number of neighbouring nodes and their trickle timer settings. Once the node receives a DIO, it sends a DAO message to the DODAG root and moves to the active state. Depending on the application, the node transmits or relays data towards the sink node and expects to receive periodic DIO messages from its parent node.

The transition states of RPL are shown in figure 5.1. The main goal is to optimize RPL so that a node can have a high probability of (b, c and d) and a low probability of (a). When an RPL node starts, it waits for a DIO and the probability that it stays in that state is represented by (a). If this node receives a DIO, then it requests association from the potential parent node and this is given a probability of (1-a). The probability of a successful association is represented by (b) and therefore, the probability of a failed request is (1-b). Once the node is successfully connected, it starts sending data towards the sink and this is denoted by a probability (c). In this state, there is a (1-c) probability of dissociation due

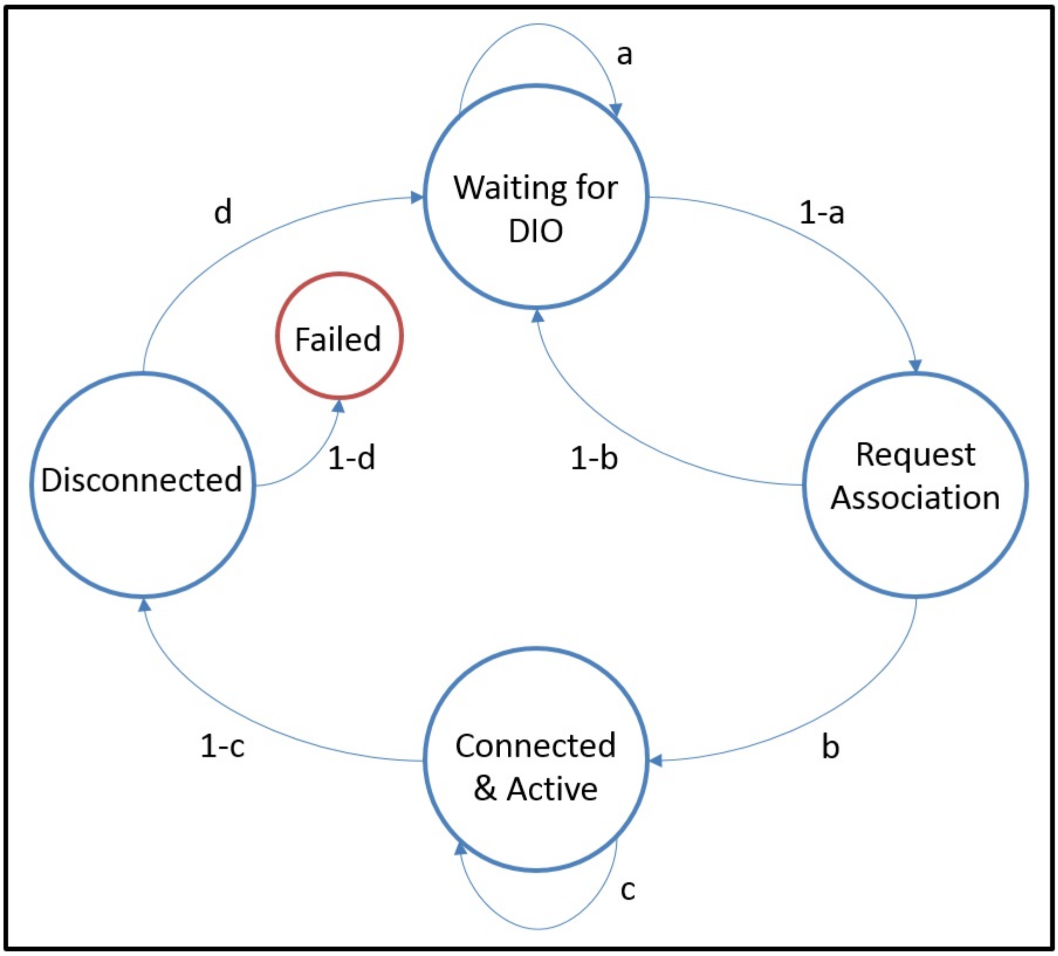

Figure 5.1: Markov chain for RPL nodes

to any reason including node mobility. Finally, there is a (d) probability that the node is still in operation and in this case, it can restart the cycle and wait for another DIO. In turn, if the energy is depleted, the node fails and cannot resume operation until it is fitted with new batteries and that is represented by a probability (1-d). With the presence of mobile nodes in the network, adaptive settings need to be added to RPL and for that reason, a non-cooperative game is formulated where nodes compete for network resources taking into account the requirements of the application and the conditions of the network.

Although the application scenarios give an indication of cooperative behaviour, nodes are competing to send data at higher transmission rates, causing higher levels of noise. A node that increases its transmission rate, is maximising its util-

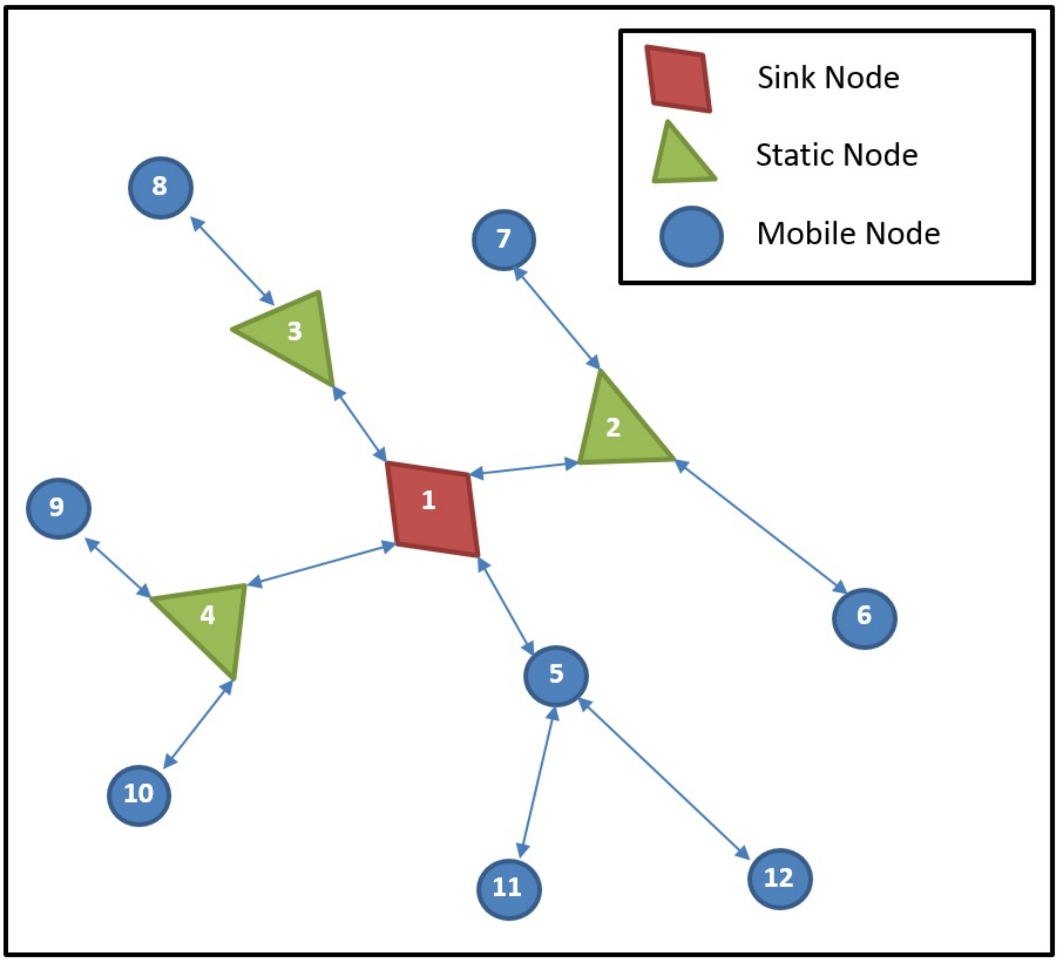

Figure 5.2: RPL topology

ity function but is also negatively affecting the utility function of other nodes. This means that increasing transmission rate will increase the payoff of the node itself, but not necessarily the collective payoff of all players. For these reasons, the game is considered a non-cooperative game with a goal to maximise gain and minimise cost for the whole network.

5.3.2 GTM-RPL Game Formulation

Assuming a network with one static sink node that serves as a gateway, a number of static nodes to ensure better coverage and a number of mobile sensor nodes as shown in figure 5.2.

Players $P = p_1, p_2, \ldots, p_n$ are competing to send data packets to the sink node while playing the mobility management game. In game theory, each action performed by a player affects the utility function of other players, actions include changing data rate, parent node, trickle settings and transmission power. The following rules define the game: (i) Each node p_k can send data at a rate of [0 , λ_{max}]. (ii) Mobile nodes have user-defined priorities $R = r_1, \ldots, r_k, \ldots, r_n$ where r_k is the priority of node p_k $\forall k \in N$. Nodes with a higher priority assume lower cost for energy consumption to allow them to send data at higher rates. (iii) All nodes share an application specific mobility metric Mm that reflects the expected mobility intensity in a specific application, and a density metric Dm that depends on the number of nodes, the coverage area of each node and the total simulation area. If these two metrics are not defined by the user, they are assumed Mm^o and Dm^o respectively. (iv) Each node can measure the RSSI of each message at the MAC layer to compute the link quality (LQ) at a given time (t). (v) Sensor nodes have limited resources with the exception of the sink node. (vi) All nodes use Contiki OS with 6LoWPAN adaptation layer and inherit their benefits and restrictions. The mobility management game is defined by $\Gamma = (N, (S_k)k \in N, (\phi_k)k \in N)$, where N is the number of players, S_k is a vector of the possible strategies for player P_k, and ϕ_k is the payoff function for player P_k. The payoff of each player represents the cost that a node P_k must endure for taking an action A_k.

1. **Players:** represent the sensor nodes in the same collision space of the network, $(P_1, \ldots, P_k, \ldots, P_n), \forall k \in N$.

2. **Strategies:** each node has a set of possible actions $A = (A_1, \ldots, A_k, \ldots, A_n) \forall k \in N$. Where $A_k = [0, \lambda_{max}]$ represents the strategy space for player P_k and thus $A = \prod_{k=1}^{N} A_k$.

3. **Payoff function:** $\phi_k(A_k)$ defines the total cost for node P_k to send data at a rate of λ_k to the sink node in a mobile environment. The payoff function is defined to include the profit (the utility function), the cost induced by mobility, the energy cost and the node priority cost as follows:

   - Utility Function $U_k(A_k)$: represents the profit of player P_k for using the strategy A_k. This function reflects the gain of increasing transmission rate λ_k as each node tries to maximise its throughput. In order to make sure that the utility function is concave and its second derivative is always negative, the utility function is defined as:

$$U_k(a) = \alpha \log(\lambda_k + c) \tag{5.1}$$

Where α is a user defined factor and c is a safety constant to make sure that there is always a defined value for the utility function, otherwise at $\lambda = 0$, the value goes to infinity. For each player, the goal is to increase transmission rate to maximize the utility function and thus the profit, taking into account the negative effects that may come with that, this trade-off is explained in the other cost functions.

- Mobility Function $M_k(a_k, a_{-k})$: this function gives a measure of the cost incurred by the presence of mobility, where a_{-k} is the actions available for all players except $P_k(P_1, \ldots, P_{k-1}, P_{k+1}, \ldots, P_n); k \in N$. In order to have a measure of mobility, $(ARSSI)$ and LQI are used to evaluate the link quality cost (LQ) as in [137]. Also, an estimated mobility metric that is application specific is used to indicate the mobility level for a given application. The calculation of this metric depends on the mobility scenario. In the simulations, the random waypoint mobility model is used because it fairly reflects the actual mobility behaviour in WSNs and IoT applications [12] [177].

$$M_k(a_k, a_{-k}) = \beta \ Mm \ LQ \ \lambda \tag{5.2}$$

Where β is a factor that can be changed in accordance with the preference of the user and the type of the application. Mm is the mobility metric and it is estimated according to the mobility scenario. In order to calculate Mm the following formula is used [183]:

$$Mm = \frac{1}{|N|} \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{1}{T} \int_{0}^{T} |V_i(t) - V_j(t)| \ dt \tag{5.3}$$

Where N is the number of node pairs in the network and is equal to the total number of nodes in the RPL topology. T is the total runtime in seconds. $V_i(t) - V_j(t)$ is the difference in speed between nodes i and j at time t. This metric is not calculated based on the actual movement of nodes because it is not possible to predict, but rather based on a generated mobility scenario using Bonnmotion [180] , a free and widely used tool for mobility scenario generation. In order to calculate LQ, extensive simulations are conducted to measure the effect of different LQ levels and the points where they can be assumed reliable in terms of packet loss and transmission delay.

- Energy function $E_k(a_k, a_{-k})$: energy consumption is one of the most important factors in many IoT applications, especially in cases where the cost of replacing batteries is high. In any application, lower energy consumption means better life span for the node itself and for the whole network. $ARSSI$ and DIS messages are used to control the trickle timer as in [137] [45] and minimize the energy consumed due to control messages. However, with regards to optimizing throughput, limitations arise from the increased energy consumption caused by sending data packets to the sink node. A higher data rate means more packet transmissions and thus higher energy consumption. Another important factor is the density of the network, higher density means more data is relayed which incurs additional packet transmissions for all nodes. The density of the network also causes higher congestion at the relay nodes leading to higher energy consumption for relaying data and retransmitting lost packets.

$$E_k(a_k, a_{-k}) = \gamma \ Dm \ \lambda \tag{5.4}$$

Where γ is the user defined weight given for energy saving requirements, Dm is the density metric of the network. In order to express the level of density in a network, this simple formula is used [184]:

$$Dm = \frac{|N| \pi T_r^2}{A} \tag{5.5}$$

Where N is the number of nodes, T_r is the transmission range for each node and A is the deployment area. In the simulations, it is assumed that the deployment area has a good coverage giving a density metric $Dm > 1$.

- Priority function $Pr_k(a_k)$: In many IoT applications, some nodes can be of higher importance than others. For example, in a healthcare application, a node that monitors the well being of a patient and informs a member of staff in case of an emergency (fall detection, health risk, etc.) is usually given a higher priority than nodes used for controlling room temperature.

The priority of nodes is set by the user to the preferred level, otherwise nodes assume $Pr_k = Pr_k^0$ as the default priority.

$$Pr_k(a_k) = \delta \; pr_k \; \lambda \tag{5.6}$$

Where δ is the user defined weighing factor, pr_k is the priority of node $k, \forall k \in N$.

The factors α, β, γ and δ are added to give higher flexibility to the design of GTM-RPL, allowing the user to customize it according to the application demands and requirements. For each player $P_k \forall k \in N$, the payoff function can be declared as:

$$\phi_k(A_k) = \alpha \log(\lambda_k + C) - \beta \; Mm \; LQ \; \lambda - \gamma \; Dm \; \lambda - \delta \; pr_k \; \lambda \tag{5.7}$$

In order to find a solution to the game $\Gamma = (N, (S_k)k \in N, (\phi_k)k \in N)$, a proof that it has a unique Nash equilibrium is required, this means that each player can reach an optimal strategy $s_k^* = \lambda_k^*$ where it has no incentive to change its strategy given that all other players maintain their current strategies.

Theorem 5.3.1 *The formulated game is a concave n-person game and it has at least one Nash Equilibrium.*

Proof: The strategy vector for player P_k can be represented by $S_k = [0, ..., \lambda_k^{max}]$. It is clear that the strategy set of player P_k is closed and bounded, meaning that the set S_k is compact $\forall k \in N$. Consider x, y to be two points in the strategy vector S_k in a Euclidean space where $S = \prod_{k=1}^{n} S_k$, the strategy set S_k is convex if for any $x, y \in S_k$ and $\eta = [0, 1]$, $\eta x + (1 - \eta) y \in S_k$ as shown in figure 5.3.

The Hessian matrix of the payoff function $\phi_k(A_k) = \alpha \log(\lambda_k + C) - \beta \; Mm \; LQ \; \lambda - \gamma \; Dm \; \lambda - \delta \; pr_k \; \lambda$ can be defined as:

$$H = \begin{bmatrix} \frac{\partial^2 \phi}{\partial \lambda_1^2} & \frac{\partial^2 \phi}{\partial \lambda_1 \partial \lambda_2} & \cdots & \frac{\partial^2 \phi}{\partial \lambda_1 \partial \lambda_n} \\ \frac{\partial^2 \phi}{\partial \lambda_2 \partial \lambda_1} & \frac{\partial^2 \phi}{\partial \lambda_2^2} & \cdots & \frac{\partial^2 \phi}{\partial \lambda_2 \partial \lambda_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 \phi}{\partial \lambda_n \partial \lambda_1} & \frac{\partial^2 \phi}{\partial \lambda_n \partial \lambda_2} & \cdots & \frac{\partial^2 \phi}{\partial \lambda_n^2} \end{bmatrix} \tag{5.8}$$

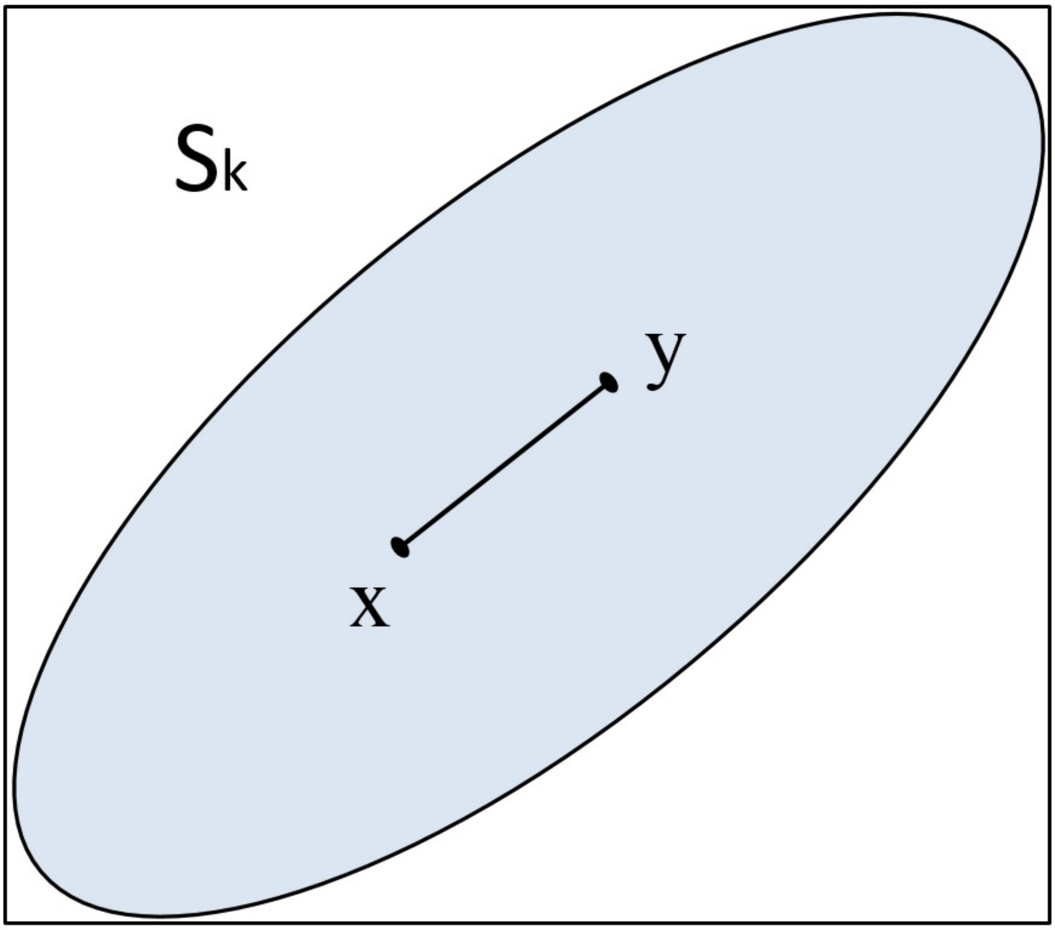

Figure 5.3: The convex strategy set $S_k \forall k \in N$

By applying the second derivative test on the payoff function ϕ_k, it is clear that the leading principal minor of the Hessian matrix is negative definite at λ meaning that it reaches a local maximum at λ as shown in equation (5.9) [185].

$$\frac{d^2}{d\lambda^2} = \phi_k''(\lambda) = -\frac{\alpha}{(\lambda_k + c)^2} \tag{5.9}$$

Theorem 5.3.2 *The weighted non-negative sum $\sigma(\lambda_k, r)$ is diagonally strictly concave if the symmetric matrix $[G(\lambda_k, r) + G'(\lambda_k, r)]$ is negative definite $\forall \lambda_k \in S$ where r is a non-negative vector [186].*

Proof: The weighted non-negative sum $\sigma(\lambda_k, r)$ can be written as a summation of $\phi_k(\lambda)$

$$\sigma(\lambda_k, r) = \sum_{k=1}^{n} r_k \phi_k(\lambda), \forall k \in N, r_k \geq 0 \tag{5.10}$$

For each fixed value of $r = (r_1, r_2, \ldots, r_n)$, a related mapping of $g(\lambda_k, r)$ is defined as gradients $\bigtriangledown_k \phi_k(\lambda_k)$.

$$g(\lambda_k, r) = \begin{bmatrix} r_1 \bigtriangledown_1 \phi_1(\lambda_1) \\ r_2 \bigtriangledown_2 \phi_2(\lambda_2) \\ \vdots \\ r_n \bigtriangledown_n \phi_n(\lambda_n) \end{bmatrix} \tag{5.11}$$

Where $g(\lambda_k, r)$ is the pseudo-gradient of $\sigma(\lambda_k, r)$ and $\bigtriangledown_k \phi_k(\lambda_k)$ is given by:

$$\bigtriangledown_k \phi_k(\lambda_k) = \frac{\alpha}{\lambda_k + C} - \beta MmLQ - \gamma Dm - \delta P_k^r, \forall k \in N \tag{5.12}$$

From $g(\lambda_k, r)$ in equation 5.11, its Jacobian matrix can be defined by $G(\lambda_k, r)$ as:

$$G(\lambda_k, r) = \begin{bmatrix} r_1 \frac{\partial^2 \phi}{\partial \lambda_1^2} & r_1 \frac{\partial^2 \phi}{\partial \lambda_1 \partial \lambda_2} & \cdots & r_1 \frac{\partial^2 \phi}{\partial \lambda_1 \partial \lambda_n} \\ r_2 \frac{\partial^2 \phi}{\partial \lambda_2 \partial \lambda_1} & r_2 \frac{\partial^2 \phi}{\partial \lambda_2^2} & \cdots & r_2 \frac{\partial^2 \phi}{\partial \lambda_2 \partial \lambda_n} \\ \vdots & \vdots & \ddots & \vdots \\ r_n \frac{\partial^2 \phi}{\partial \lambda_n \partial \lambda_1} & r_n \frac{\partial^2 \phi}{\partial \lambda_n \partial \lambda_2} & \cdots & r_n \frac{\partial^2 \phi}{\partial \lambda_n^2} \end{bmatrix} \tag{5.13}$$

Since the symmetric matrix $[G(\lambda_k, r) + G'(\lambda_k, r)] \forall k \in N, \lambda_k \in S$, is negative definite, then the weighted non-negative sum $\sigma(\lambda_k, r)$ is diagonally strictly concave and the game $\Gamma = (N, (\lambda_k)k \in N, (\phi_k)k \in N)$, has a unique Nash equilibrium [186].

5.3.3 Game Solution

To find the optimum solution of the game, the payoff function $\phi_k(\lambda_k)$ needs to be maximised by choosing an optimal strategy according to the game design. The optimal transmission rate $\lambda_k^* \ \forall k \in N, \lambda_k^* \in S$ is restricted by $0 \leq \lambda_k \leq \lambda_k^{max}$. To find the solution of the game, the Lagrangian function is defined by:

$$\mathcal{L}_k = \phi_k(\lambda_k) + u_k \lambda_k + v_k(\lambda_k^{max} - \lambda_k) \tag{5.14}$$

Where u_k and v_k are the Lagrange multipliers and the Karush-Kuhn-Tucker (KKT) [187] conditions for the maximization problem are:

$$u_k, v_k \geq 0$$
$$\lambda_k \geq 0$$
$$\lambda_k^{max} - \lambda_k \geq 0$$
$$\nabla_{\lambda_k}\phi_k(\lambda_k) + u_k\nabla_{\lambda_k}(\lambda_k) + v_k\nabla_{\lambda_k}(\lambda_k^{max} - \lambda_k) = 0$$
$$u_k(\lambda_k), v_k(\lambda_k^{max} - \lambda_k) = 0$$

The solution to the game can now be solved for each player $P_k, \forall k \in N$, the outcome λ_k^* is the optimum transmission rate depending on the state of the network and the user-defined application parameters. The value of λ_k^* can be found using equation (5.15).

$$\lambda_k^* = \begin{cases} 0 & \text{Condition A} \\ \lambda_k^{max} & \text{Condition B} \\ \dfrac{\alpha}{\beta MmLQ + \gamma Dm + \delta pr_k} - c & \text{Otherwise} \end{cases} \tag{5.15}$$

where condition A and condition B respectively are:

$$\beta MmLQ + \gamma Dm + \delta pr_k \geq \frac{\alpha}{c} \tag{5.16}$$

$$\beta MmLQ + \gamma Dm + \delta pr_k \leq \frac{\alpha}{\lambda_k^{max} + c} \tag{5.17}$$

The optimum transmission rate λ_k^* is the Nash Equilibrium for that node, $\forall k \in N$. This value changes when a node moves ($RSSI$ is affected) and when another node changes its transmission rate (LQI is affected).

5.3.4 Protocol Implementation

The proposed protocol is implemented using the Contiki operating system 3.0 [188] and the COOJA [179] network simulator. Algorithm 2 shows the basic operation of GTM-RPL. The main optimization point is the value of λ_k^*. In the simulation, the values of α, β, γ and δ are 4.7, 1, 0.05 and 0.1 respectively. These values are chosen to provide a maximum transmission rate of 4.8 pkt/s at which congestion starts to significantly affect communication. The value of Mm is 0.725 for the simulation scenarios and the Dm is 9.42 giving a reliable coverage. The

Algorithm 2 GTM-RPL operation

1: ***Initialization***:
Set α, β, γ & δ_k
Set λ_{max}
Set application metrics Mm & Dm
Set pr_k
Initialize trickle timer $I_{min}, I_{max}, I_{doubling}$
Set λ_0
2: ***Active mode***:
Read $ARSSI$
$\lambda_k^* \leftarrow equation(5.15)$
If ($ARSSI_t$ + K_{RSSI} <$ARSSI_{t-1}$) then
    Send DIS to all neighbours
    $I_t^{Trickle} = (I_{t-1}^{Trickle}/2)$
        If $I^{Trickle}$ <I_{min} then
        $I^{Trickle} = I_{min}$;
Else
    Resume normal Trickle
End

priority of nodes can take a value of [1,10] depending on the application requirements. λ_k^{max} is set to $2, 4, 8$ and 16 pkt/s and the safety factor $C = 0.1$, these values depend on the application requirement and were selected based on extensive simulations.

The value of LQ is calculated and updated at each node based on $RSSI$ and LQI and the values are mapped in figure 5.4. Lower values for LQ indicate better quality as LQ represents the cost incurred due to the link quality. The initial transmission rate λ_k^0 is set at ($\lambda_k^{max}/2$) pkt/s and then updated periodically throughout the simulation according to equation (5.15).

The mobility detection part of the protocol is also shown in Algorithm 2 and it uses the change in values of $RSSI$ as a mobility detection parameter. It sends multicast DIS messages to all neighbours and triggers the reverse-trickle timer to improve responsiveness and maintain connectivity.

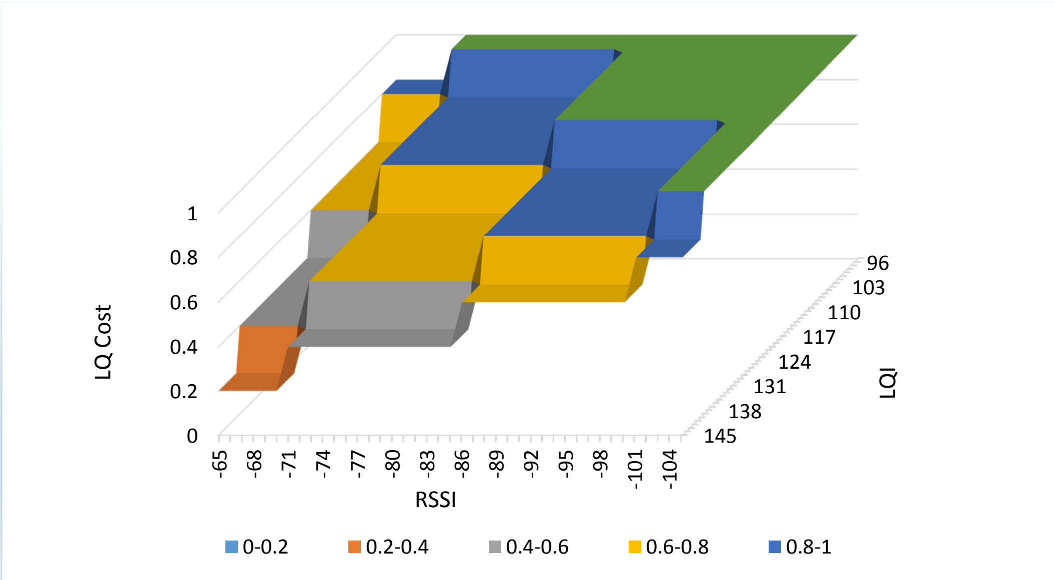

Figure 5.4: Link quality

5.4 Simulation Analysis

The simulations are focussed on two healthcare applications, the first one is patient monitoring in an elderly care unit, and the second application is hospital environment monitoring. Both applications share some of the simulation parameters provided in Table 5.1.

The proposed protocol is evaluated and compared with related protocols in terms of PDR, throughput and energy consumption using the Contiki OS and the COOJA simulator. The simulation uses a Tmote Sky platform which is emulated by COOJA, and a unit disk graph medium (UDGM) as the wireless channel taking into account noise levels and interference.

5.4.1 Elderly Monitoring

In this application, wearable sensor nodes are attached to patients in the elderly care unit shown in figure 5.5 to monitor their well being as well as information about the environment around them. These sensors read the blood pressure of patients and inform the medical staff of any abnormality. They also monitor the mobility habits of patients and provide personalized health advice. In addition to

Table 5.1: GTM-RPL Simulation Parameters

Parameter	Value
λ_{max}	2, 4, 8, 16 packets / s
Packet size	64 bytes
Simulation Area	1600 m^2
Number of Nodes	11 nodes + 1 sink node
Transmission Range	20m
Mobility Scenario	Random Waypoint, 0 to 2 m/s
I_{min} / $I_{doubling}$	8 / 6
Simulation Time	1 hour
Radio	CC2420

fall detection sensors that alarm the staff of any accidents. In the simulation, one sink node is used with three fixed sensor nodes to provide better coverage and eight mobile nodes attached to patients. In the simulation, the sensor nodes are all given the same priority of 5 and they compete to send periodic messages to the sink node. The results show a performance evaluation of the proposed GTM-RPL and compare it against the native RPL and mRPL. RPL has no way of managing mobility but nonetheless it is shown as a baseline for comparison. mRPL on the other hand has an excellent mobility management approach but it uses a fixed transmission rate and does not adapt to the mobility of nodes. For the sake of comparison, different transmission rates are used, 2 pkt/s and 4 pkt/s to show the performance at different settings.

Fig 5.6 shows the PDR as a percentage for each node, all protocols achieve high PDR (above 88%) for the first three static nodes but for mobile nodes, the native RPL goes down to around 44% at 4 pkt/s and 47% at 2 pkt/s. mRPL at 4 pkt/s achieves around 78% PDR while at 2 pkt/s reaches up to 88%. GTM-RPL achieves a similar PDR of around 88% at both transmission rates and it outperforms mRPL by more than 10% in the 4 pkt/s scenario.

Although GTM-RPL does not show an advantage against mRPL at 2 pkt/s, it

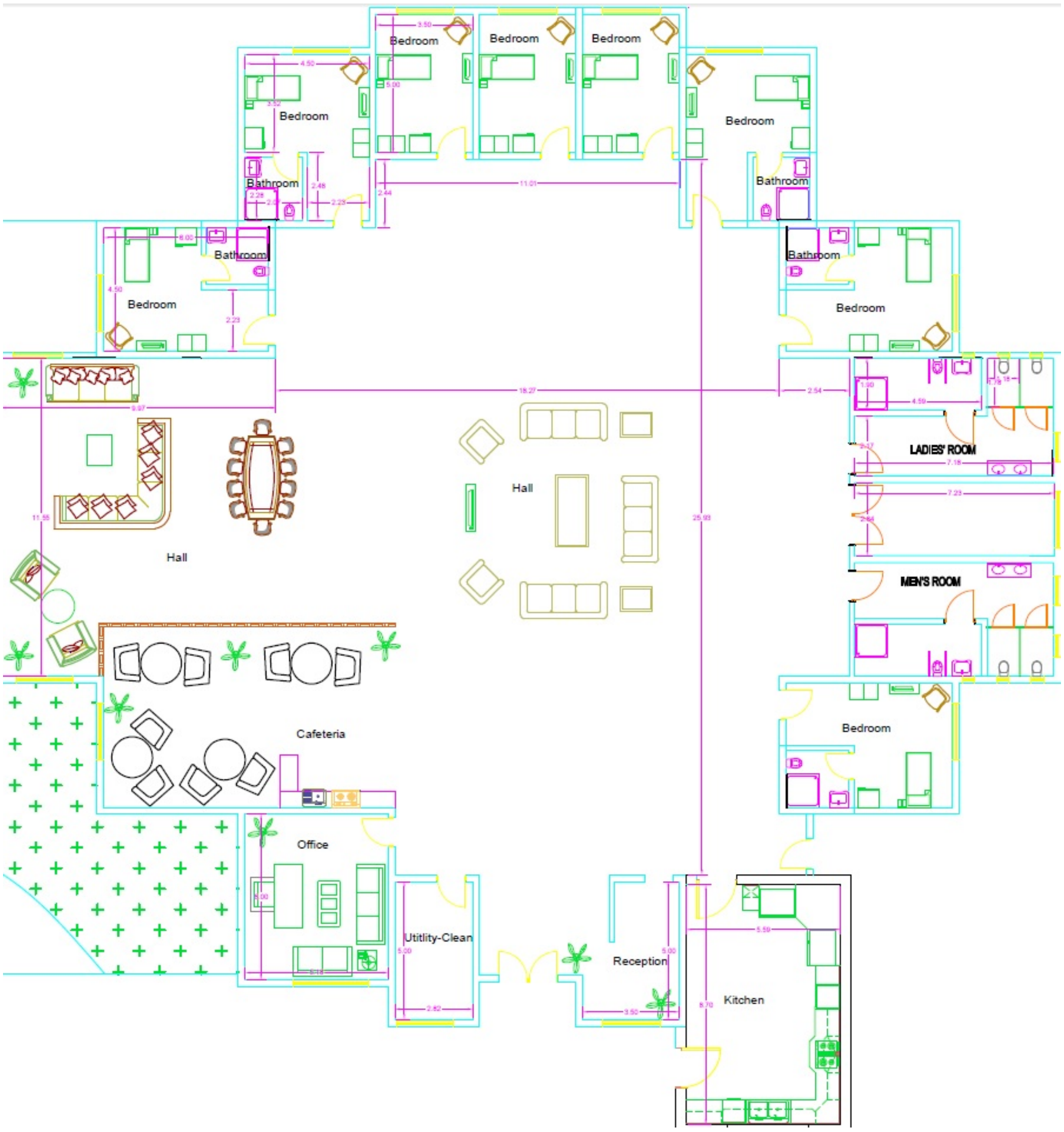

Figure 5.5: A typical elderly care unit

is clear that mRPL unlike GTM-RPL, is not trying to optimize the transmission rate. The throughput shown in figure 5.7 shows that GTM-RPL provides almost twice the size of successfully transmitted data. mRPL at (4pkt/s) is always sending at the maximum transmission rate and yet it does not show an advantage compared to GTM-RPL in terms of throughput. This is because it has a lower PDR and thus a higher number of packets are dropped before reaching the sink node.

Figure 5.8 shows the energy consumption (mj) per packet. The native RPL

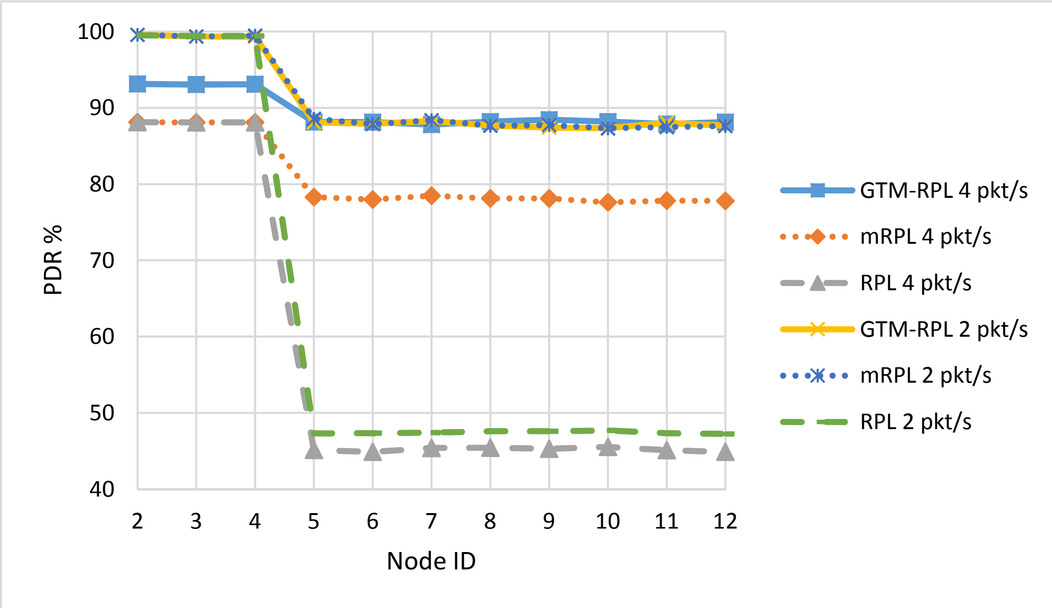

Figure 5.6: PDR

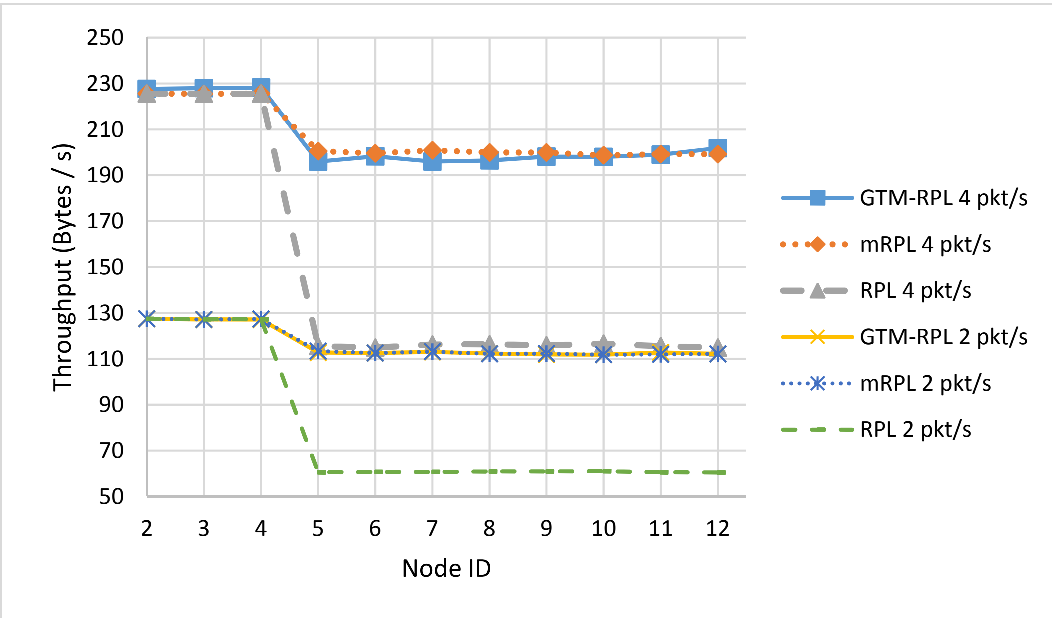

Figure 5.7: Throughput

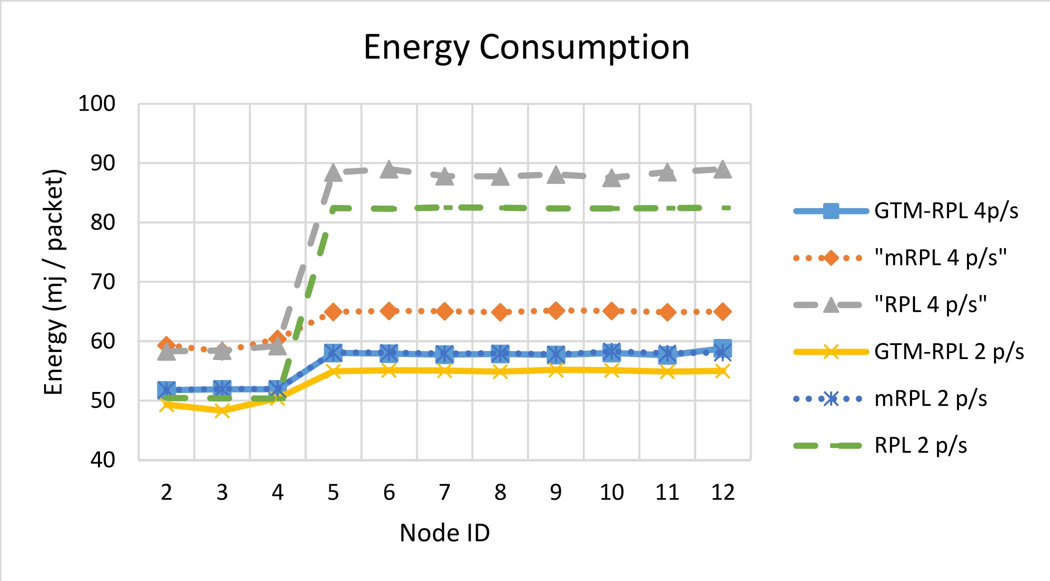

Figure 5.8: Energy consumption

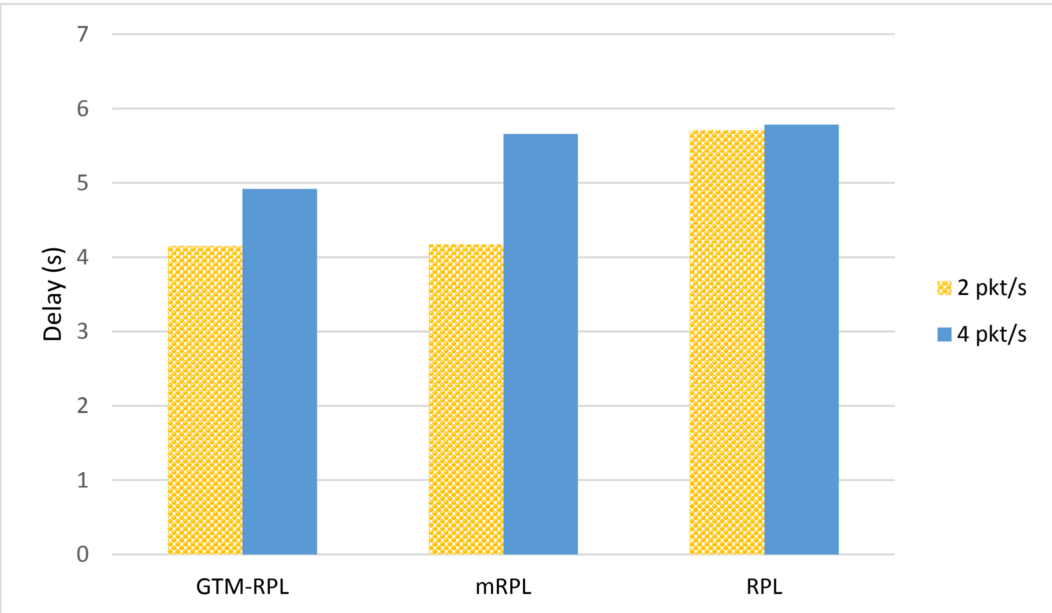

Figure 5.9: End-to-end delay

has a low PDR causing an increase in the number of lost packets and thus a high energy consumption per successfully transmitted packets. At 2 pkt/s, mRPL and GTM-RPL achieve similar energy consumption per packet but at 4 pkt/s, GTM-

Figure 5.10: Hospital environmental monitoring

RPL shows an improvement of more than 16% energy consumption for the same throughput compared to mRPL due to the higher packet loss in mRPL. Although GTM-RPL aims to maximize the data transmission rate at each node, it takes into account the mobility of nodes and the noise level caused by higher transmission rates. The presence of mobility affects the value of $RSSI$ and the transmission rates of neighbouring nodes affect the value of LQI and thus LQ, both $RSSI$ and LQ are important parameters in the selection of the optimum transmission rate.

Figure 5.9 shows the average end-to-end delay for packets travelling from the application layer of the sending node to the application layer of the receiving node. At a transmission rate of 2 pkt/s, GTM-RPL and mRPL show similar results because the number of nodes and the frequency of transmission are not high enough to cause an increase in the LQ cost. At a transmission rate of 4 pkt/s however, GTM-RPL has 15% lower average end-to-end delay compared to mRPL. The native RPL has an average end-to-end delay of more than five seconds for both transmission rates because it is less responsive to network changes and has no efficient way of managing mobility.

5.4.2 Hospital Environmental Monitoring

In this application, one sink node and 11 sensor nodes are deployed in one of St James's hospital wards in Leeds. As shown in figure 5.10, the area in the middle is not accessible leading to a different mobility limitation. Three of the sensor nodes are fixed in range of the sink node while the other eight nodes are attached to patients, equipment and staff to provide a wider sensing area and more accurate readings. The sensor nodes read a range of information including temperature, humidity and light levels and send it through the sink node to actuators in order to take an action and either fix the problem automatically (e.g. opening a window) or inform the appropriate entity, sensors also read patient data and monitor their medical condition. It is assumed that two of the patient nodes, number 5 and 6, have a high risk of emergency and thus give them a high priority of 1 while the rest of the nodes are given a normal priority of 5. Nodes with higher priority focus more on sending the data at higher rates and worry less about energy consumption compared to nodes with lower priority. This application requires high throughput because of the wide range of data and the probability of urgent incidents. For this scenario, three different transmission rates of 4, 8 and 16 pkt/s are used for testing.

The simulation results for this application are shown for three protocols, GTM-RPL, mRPL and the native RPL each at three transmission rates 4, 8 and 16 pkt/s. Figure 5.11 shows the PDR for each protocol using the three different settings. GTM-RPL uses an adaptive transmission rate that changes during operation and reaches a maximum of 4, 8 and 16 pkt/s depending on the configuration, while RPL and mRPL use a fixed value of 4, 8 and 16 pkt/s and do not change it during operation. At a transmission rate of 4 pkt/s, the results are relatively similar to the first scenario with GTM-RPL outperforming mRPL by around 10%. Using a transmission rate of 8 pkt/s, the effect of LQ becomes more obvious and GTM-RPL transmits at around 6.2 pkt/s for normal priority nodes and at 6.5 pkt/s for high priority nodes to avoid packet loss while mRPL and RPL send data at 8 pkt/s causing higher packet loss due to high noise and traffic congestion. It can be seen that GTM-RPL has an improvement of more than 25% in terms of PDR compared to mRPL. At a transmission rate of 16 pkt/s, GTM-RPL keeps the same transmission rates (6.2 - 6.5 pkt/s) given the same mobility model and the same network conditions. It is clear to see that mRPL

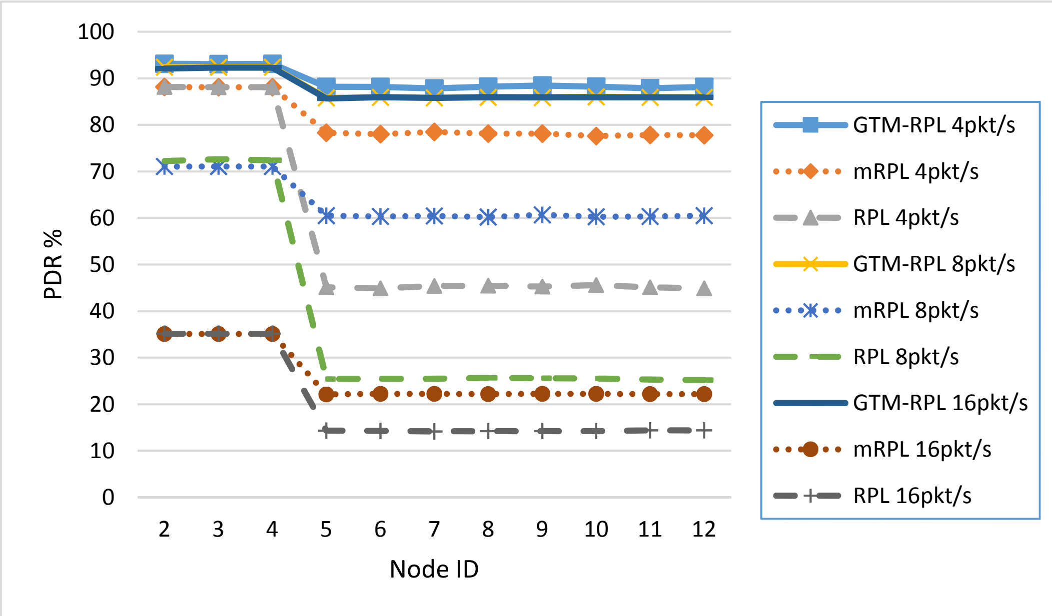

Figure 5.11: PDR

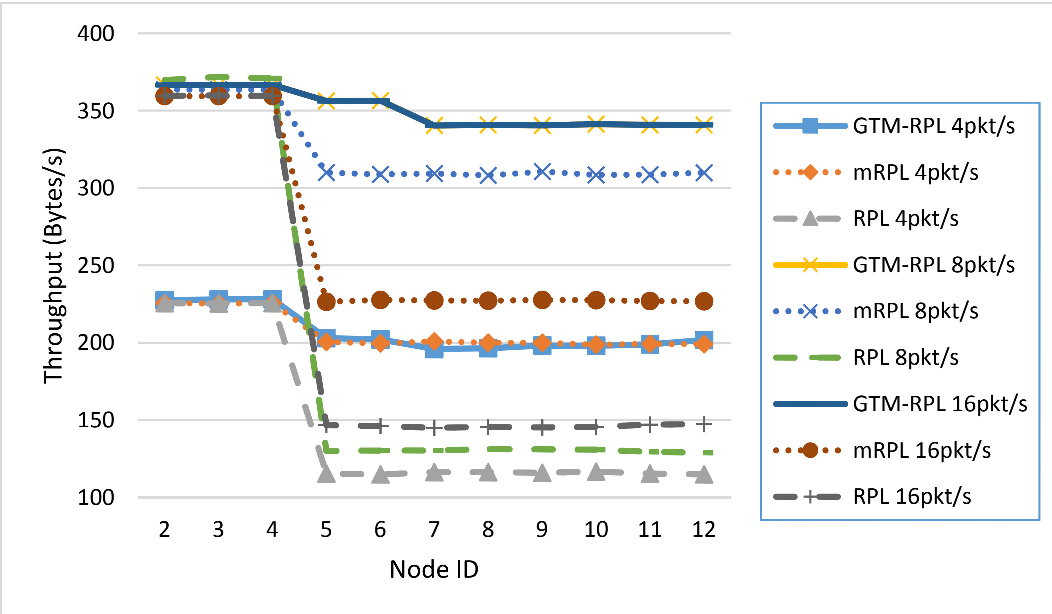

Figure 5.12: Throughput

and RPL nodes sending at 16 pkt/s have less than 25% PDR due to high noise and congestion.

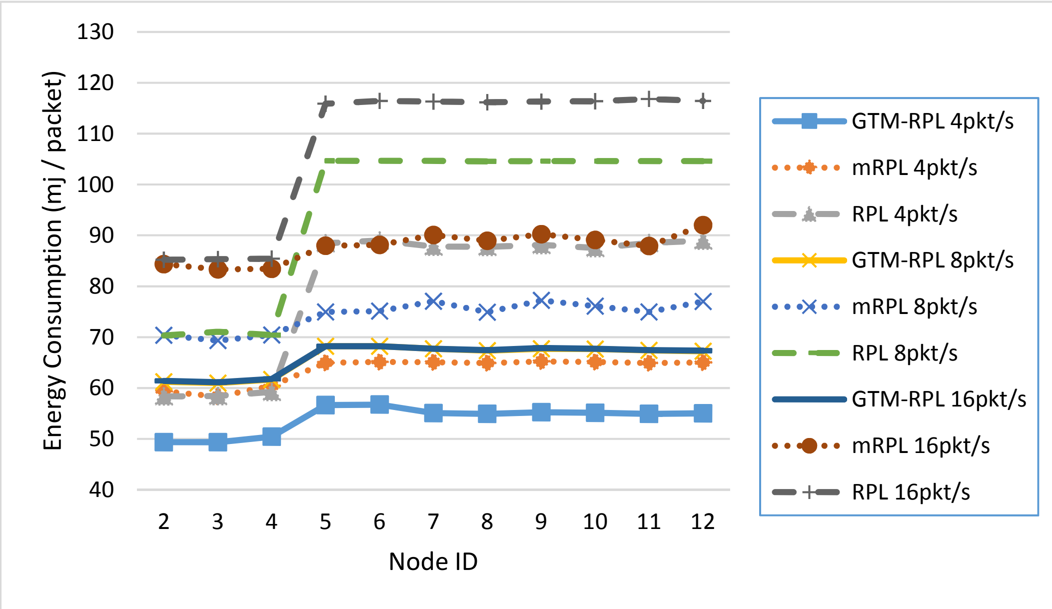

Figure 5.13: Energy consumption

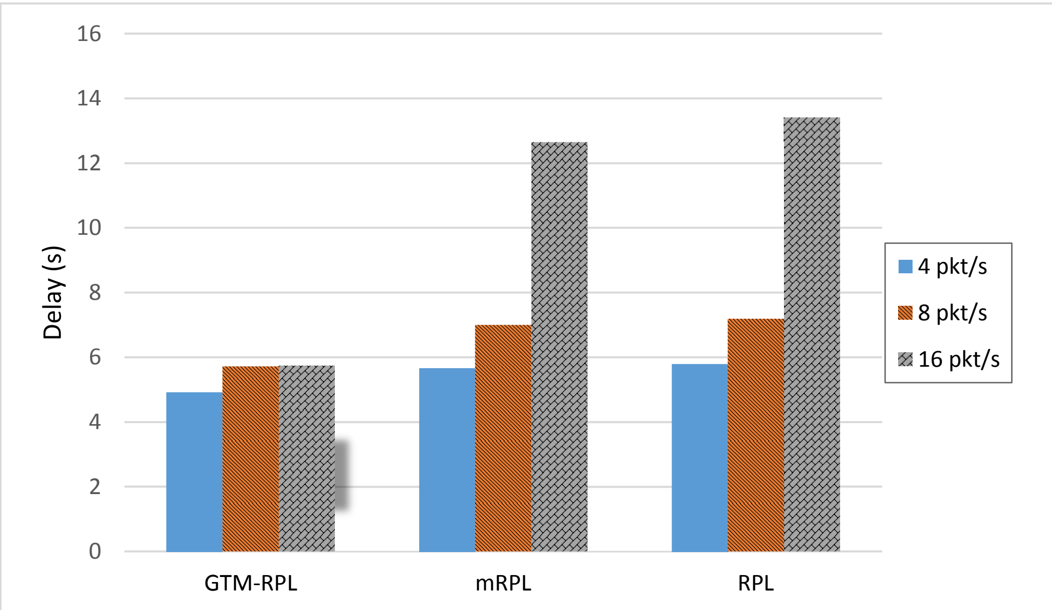

Figure 5.14: End-to-end delay

Fig 5.12 shows that GTM-RPL achieves similar throughput at a transmission rate of 4 pkt/s while GTM-RPL outperforms mRPL by 10% and 50% at transmission rates of 8 and 16 pkt/s respectively. At 16 pkt/s, mRPL has lower throughput compared to the same protocol sending at 8 pkt/s. This indicates that, although increasing the transmission rate seems like the right solution to optimize throughput. Sending data at rates that are too high can deteriorate the throughput due to significantly higher levels of packet loss. The throughput at nodes 5 and 6 show slightly higher throughput than the rest of the mobile nodes showing the effect of priority on node performance.

The energy consumption levels in figure 5.13 show that GTM-RPL maintains relatively low energy consumption for all settings outperforming both mRPL and RPL. The native RPL has a very high energy consumption per successfully transmitted packet due to high packet loss especially for mobile nodes. GTM-RPL and mRPL on the other hand do not lack the efficiency in managing mobile nodes and thus the difference in energy consumption between static and mobile nodes is less significant.

The average end-to-end delay in figure 5.14 shows the average time that a packet needs to travel from the application layer of the sending node to the application level of the destination. One of the main causes of high delay in RPL is congestion [152], and it is affected by both the presence of mobility and the transmission rate of nodes. GTM-RPL avoids congestion by managing both the mobility of nodes and their transmission rate. For this reason, GTM-RPL maintains relatively low end-to-end delay at all simulated scenarios while mRPL and the native RPL have higher delay especially at increased transmission rates.

5.5 Summary

This chapter provides comprehensive analysis for using RPL in a mobile environment. Game theory is used in this chapter to find an optimal solution for routing depending on the application requirements. The proposed approach uses a mobility metric and a density metric that are application specific parameters, to derive the mobility cost function and the energy cost function respectively. The analysis in this chapter are all based on the IEEE 805.15.4 standard and 6LoWPAN protocol stack in the presence of mobile nodes. The proposed solution is tested and evaluated using the COOJA emulator over the Contiki 3.0 OS, and compared against related protocols. Simulation results confirm the analysis of this chapter and show that the proposed GTM-RPL outperforms existing protocols in terms of PDR, throughput, energy consumption and end-to-end delay. It provides a flexible, adaptable and expandable solution for routing in IoT applications with the presence of mobile nodes achieving higher throughput whilst consuming less energy showing more than 10% improvement compared to relevant protocols. The advantage of using GTM-RPL becomes more significant in demanding applications where simulation results show that it improves throughput by 10% - 50%, with better PDR, lower energy consumption and reduced end-to-end delay. GTM-RPL offers higher performance at a lower cost taking advantage of the various parameters that contribute to the optimization game. Using $RSSI$ and LQ in addition to the improved trickle timer provides an optimized solution for routing in dynamic and mobile IoT applications.

Chapter 6

A Practical Performance Evaluation

6.1 Introduction

The IoT paradigm is quickly moving from being a dream into a reality, many IoT applications are already present especially in healthcare, smart environments and transport. While simulation tools are helpful in the design, testing and enhancement of routing protocols, a practical evaluation is essential to make sure that unexpected factors including noise, reflection and absorption do not dramatically deteriorate the performance of routing. There is no actual practical performance evaluation in the literature, in real IoT application environments, but merely a few simple tests that involve no performance evaluation.

A study of routing using the Contiki RPL implementation [114] presents an experimental test for RPL, however, it does not include any routing metrics and rather compares radio duty cycling in simulation to that in practice using Tmote sky nodes. The paper is a short paper consisting of two pages only. Having said that, this paper does show that the Tmote sky nodes can live up to several years in non-demanding scenarios.

Another study addresses data delivery in RPL [141], it presents a test in an office setting, using Contiki RPL and although the authors use performance metrics including packet loss ratio, energy efficiency and delay, the paper does not take into account mobile nodes and some of the conclusions of the paper contradicts with most research. An example on that is the statement that "Packet losses do not necessarily increase with path length (in hops)", although this might be true for nodes with low data rate, the trend of research shows a significant deterioration in packet delivery ratio for nodes more than two hops further from the sink node.

The authors in [119] conduct an experimental evaluation in an office premises with a novel fuzzy objective function, the evaluation is sound but it also does not take into account mobile nodes and only used to evaluate one testing scenario.

Using mRPL in [45], the authors conduct simulations and experimental testing taking into account mobile nodes. However, while the testing and evaluation method are sound, they are also limited to one scenario with only one mobile node and no real IoT application environment.

Another more recent study, BRPL [189], introduces the "QuickBeta" and "QuickTheta" algorithms to improve mobility management and load balancing. DT-RPL [190] uses upward and downward packets to update link quality, resulting in a more reliable end-to-end connectivity. These are the only two papers that conduct a practical performance evaluation of RPL with the presence of mobility, however, the evaluations are used only for comparing the proposed method with the original standard and they do not use an actual IoT application scenario.

In this chapter, a hands-on practical evaluation of RPL is presented in real IoT application scenarios with mobile nodes. The testing compares three routing protocols, the standard RPL in its original design, mRPL [45] which is a widely known version of RPL with an excellent approach to support mobility and our implementation of GTM-RPL, optimized using game theory and thoroughly explained in chapter 5. In these tests, Tmote sky nodes were used with 2.4GHz CC2420 RF radio, Null RDC for duty cycling, IEEE 802.15.4 MAC with an application to send periodic data towards the sink node. These nodes include 48KB flash memory, 10KB RAM and provide over 100m coverage in outdoor areas and 20m in indoor areas.

6.2 Applications

It is evident that the Internet has introduced a large number of applications that would have sounded impossible a few years ago. It has dramatically changed businesses, economy, politics, industry, transport and general life style. With the introduction of the IoT and the large amount of data to be available through connected objects, even more applications are expected to present themselves. It is changing what was previously defined as "impossible" to mere technicalities, a doctor no longer needs to be physically present to do surgery with the availability of real time communications, artificial intelligence and advanced robotics. Building are starting to manage airflow, security, supplies and sunlight using sensors and computer programs. Self driving vehicles are proving to be more of a legal issue than a technical difficulty and computers are deciding how to deal with wars and in some cases, take actions without the need for human intervention.

The range of potential applications is vast and there seem to be no indication of stopping this progress. On the contrary, it is widely accepted that IoT applications need to be encouraged by providing the required standards and protocols to make them more reliable and less costly. In this section, three different futuristic applications are selected for real hardware testing based on their importance, environmental differences and mobility scenarios.

6.2.1 Healthcare

Healthcare is one of the fields that has gained interest among the research society for many reasons, It affects people in a direct way promising to save lives, provide a better life style, introduce new treatment methods and even supply virtual doctors to treat and comfort people on demand. In addition to that, healthcare applications usually require a small area that can be made available at a local hospital, health centre, elderly home, etc.

One of the applications that are currently being studied, is the hospital environment control, optimization and infection risk assessment [191]. This application aims to deliver a healthy environment to patients in hospitals through different procedures, it includes studying infection causes and contamination sources with a plan to reduce them through controlling windows to allow sunlight to kill certain germs and dynamically controlling airflow to create a virtually quarantined area for patients with infectious diseases.

This application has the potential to deliver improved hospital environments, provide better decisions to support medical staff and patients in addition to economic benefits including faster well-being for patients and better resource management for healthcare establishments.

Simulations and practical tests are based on one of the wards at St James's university hospital in Leeds, UK. For simulation purposes, a blue print of the hospital ward is used as a reference to place and move sensor nodes, the floor plan and simulation results can be seen in chapter 5. In this chapter, the actual practical testing is presented. Figure 6.1 shows the ward and sensor nodes used for the test.

Figure 6.1: Packet Delivery Ratio - Healthcare

Sensor nodes collect information about the environment including temperature, humidity and light levels, and then send the information periodically to the

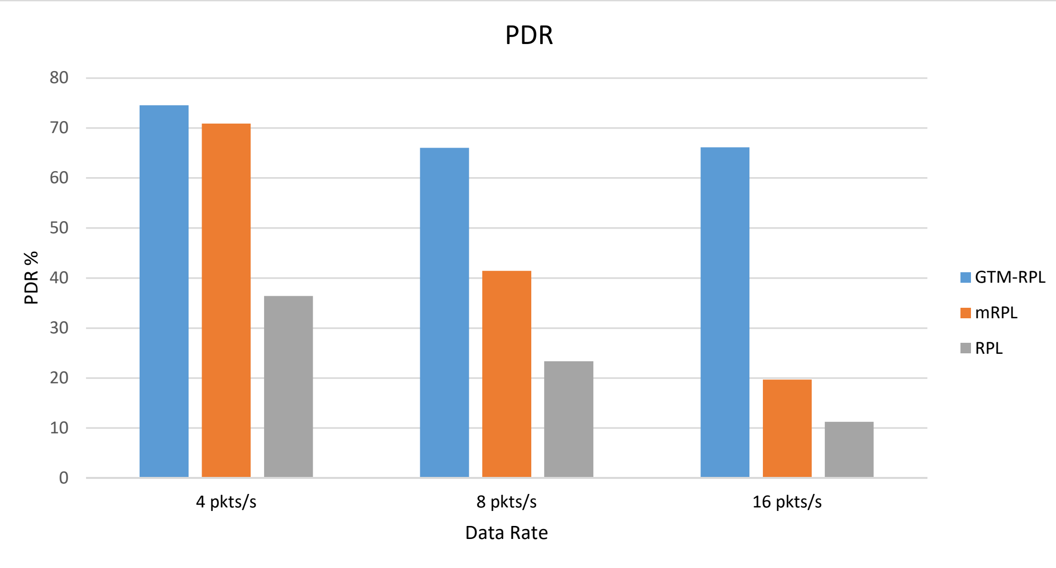

Figure 6.2: Packet Delivery Ratio - Healthcare

sink node. The aim of this test is to challenge GTM-RPL in a real environment and compare its performance to simulation results in addition to comparing it against RPL and mRPL.

Because it was essential not cause discomfort for any patient nor to discourage staff from doing their duties, nodes were placed on desks, attached to equipment or handled by non-staff members. These nodes were then manually moved following typical paths for patients and nurses, to generate the appropriate mobility scenario. Each test was done over a 60 minute period plus one minute for initialization, data was sent from 11 sensor nodes towards the sink at different rates. Nodes were configure to transmit at 4pkt/s, 8pkt/s and 16pkt/s, mRPL and the native RPL use these rates to send data while GTM-RPL uses an optimized variable transmission rate based on equation 5.15 regardless of the configured data rate. This value varies between 0-4 pkt/s depending on network conditions given that the values for α, β, γ and δ are 4.7, 1, 0.05 and 0.1 respectively. The value of Mm is 0.725 for this scenario and the Dm is 9.42.

Looking at figure 6.2, at a configured transmission rate of 4pkt/s, it can be seen that GTM-RPL has a reasonably high PDR of over 73% with mRPL at a

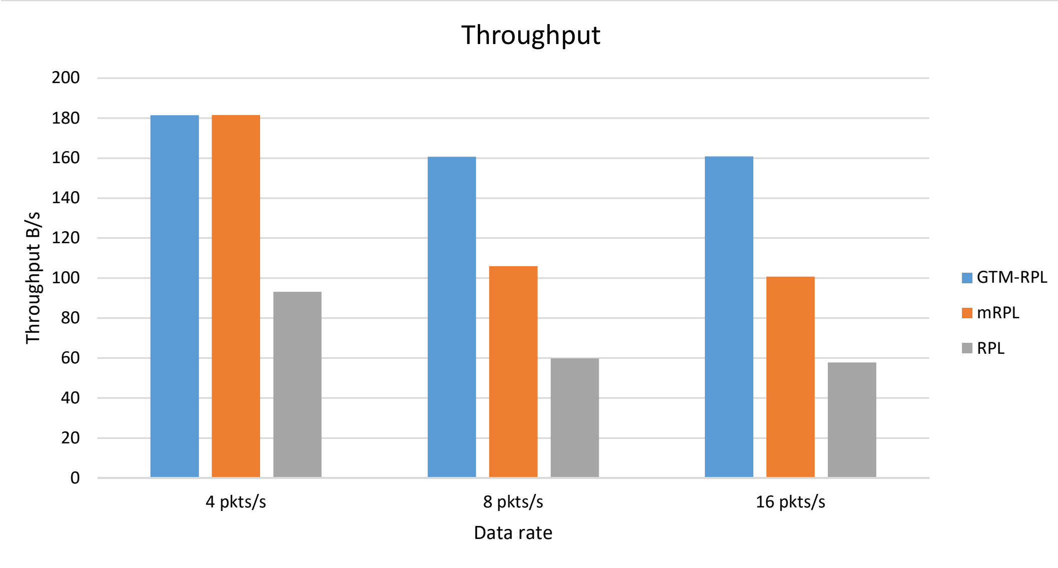

Figure 6.3: Throughput - Healthcare

slightly lower value and the native RPL with a bad performance of only 36% PDR due to the lack of mobility support. The performance of all three protocols was lower than expectations due to the special conditions of the hospital building. The thick walls and the insulation materials used in the hospital limits the effective transmission range of sensor nodes because of higher reflection and absorption rates. However, the performance of both GTM-RPL and mRPL is significantly better than the native RPL even at 4pkt/s transmission rate which is close to the optimum rate in a static network with the same settings according to extensive simulations.

At a configured transmission rate of 8 pkt/s, GTM-RPL still uses the optimized rate that can vary between 0-8 pkt/s but it peaks at around 5pkt/s in the conditions of this experiment. mRPL and the native RPL both use a steady transmission rate of 8pkt/s but show a significantly deteriorated performance due to higher noise levels and congestion. While mRPL has the ability to efficiently tackle the mobility problem, it cannot pro-actively adapt the transmission rate to the network conditions and suffers from high packet loss. The native RPL is not designed to handle mobility and at higher transmission rates, this problem

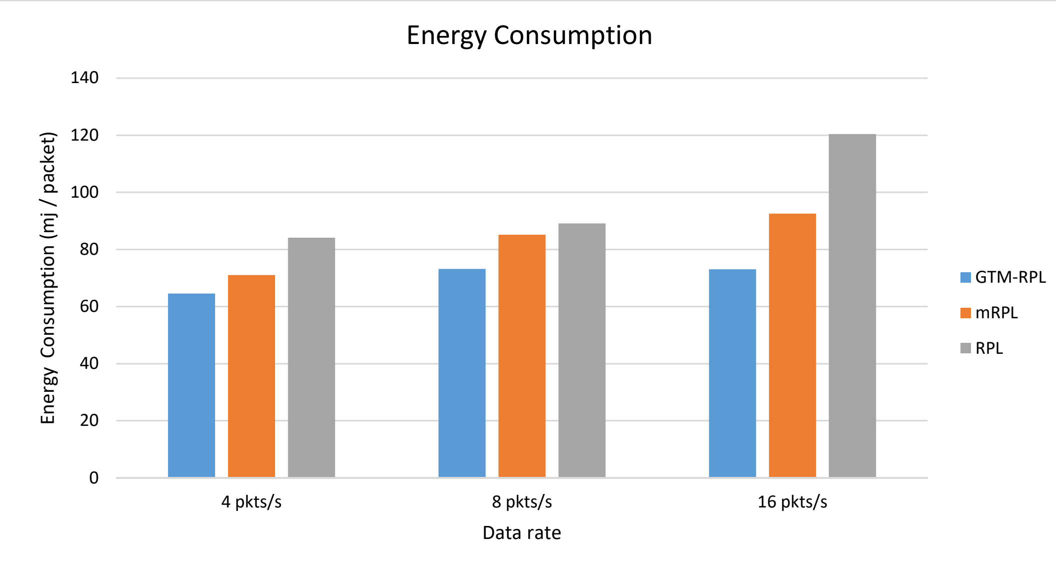

Figure 6.4: Energy Consumption - Healthcare

becomes even greater showing impractical performance.

Using a 16pkt/s transmission rate results in even worse conditions for both mRPL and the native RPL for the same reasons and at this point, it is clearly not a wise decision to configure these nodes with higher data rates unless they are using an adaptive approach similar to GTM-RPL which in turn shows a steady performance.

Figure 6.3 shows the average node throughput in all three protocols, with data rates lower than 5pkt/s, GTM-RPL and mRPL deliver similar throughput, at higher data rates however, the performance of mRPL deteriorates due to much higher packet loss. The native RPL algorithm suffers from the same problem as mRPL, in addition to its lack of mobility management making its performance even worse.

Although mRPL does perform well at 4pkt/s transmission rate and even slightly outperforms GTM-RPL by up to 0.5% is some cases, figure 6.4 shows that the energy consumption per successfully transmitted packet is also higher than GTM-RPL. This is due to the fact the mRPL is sending at a higher rate than GTM-RPL, but the higher packet loss that mRPL suffers from leads to a similar throughput but higher energy consumption. The native RPL consumes more energy and provides a lower throughput even at a transmission rate of 4pkt/s. GTM-RPL consumes less energy in all scenarios and provide similar throughput to mRPL at low data rates and higher throughput at data rates over 4 pkt/s.

In this application, GTM-RPL proves to be a flexible and adaptive solution that gives better results at low costs and is therefore a good candidate for similar applications. This scenario can also apply to any indoor area with the need for multi-hop communications in a mobile environment.

6.2.2 Smart Agriculture

The quality of vegetables and fruits is directly related to the well-being of people, in addition to the economic improvements that can create countless new opportunities and open the door for new investment. The Internet of things lays the ground for futuristic applications that have the potential to achieve all that in addition to gaining more data for future exploitation.

The application is chosen based on an IoT study that involves using robots to patrol farms or fields to collect data, these robots are equipped with an artificial intelligence software that allows them to create formations and move as a group following by leader node [192]. The formation depends on the sensing range, transmission range and area of the field. The main advantage of this scheme is to cover large areas and have a collectively large sensing area, it also makes it more reliable to read information from multiple sensors rather than depending on one source only. For the purpose of testing, nodes were carried by friends and colleagues and moved across Woodhouse Moor in Leeds. Nodes where moving at similar speeds that change only when direction is changed to patrol the whole area.

This is one of the applications that have a unique mobility scenario making it an interesting candidate for testing the performance of GTM-RPL and analyse the results. One of the issues that make this application special, is the fact that nodes are mobile but almost static in relation to each other. Nodes move at similar speeds, at steady distance from each other and thus are almost static in relation to each other most of the time. This is a good opportunity to test the performance of GTM-RPL in an almost static environment, which is expected to be higher than other protocols given the optimized adaptive transmission rate.

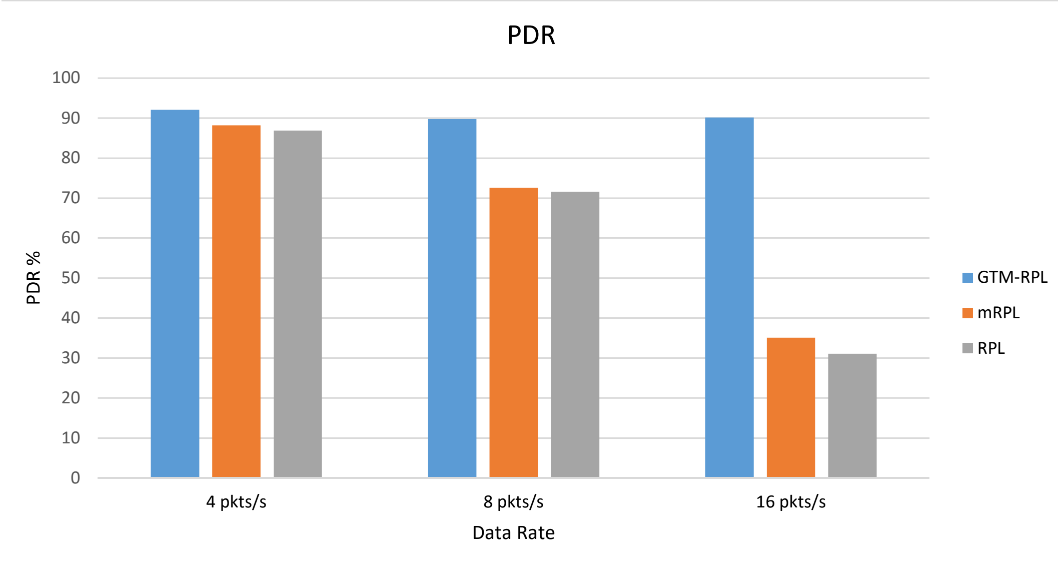

Figure 6.5: Packet Delivery Ratio - Smart Agriculture

The values for α, β, γ and δ are 4.7, 1, 0.05 and 0.1 respectively. The mobility metric Mm is 0.1 for this scenario and the Dm is 9.42.

Figure 6.5 shows the PDR for GTM-RPL, mRPL and the native RPL using three configured transmission rates, 4 pkt/s, 8 pkt/s and 16 pkt/s. mRPL and the native RPL use a steady transmission rate while GTM-RPL uses an adaptive value that changes dynamically according to network conditions and peaks at the configured transmission rate. Using a data rate of 4pkt/s, all three protocols perform well as the configured transmission rate is close to an optimum rate for a similar topology in a static scenario. Also, nodes are moving at similar speeds and the effect of mobility is only visible when robots are making a turn, causing some sensors to be out of coverage for a short period of time. The performance of GTM-RPL slightly outperforms that of mRPL and the native RPL at this data rate. These results totally agree with simulations because of minimum interference and absorption in open space outdoor environments.

At a transmission rate of 8 pkt/s, the PDR performance of mRPL and the native RPL goes down to 72.55% and 71.59% respectively while GTM-RPL keeps a steady performance of 89.75% PDR. The game-theoretic adaptive algorithm

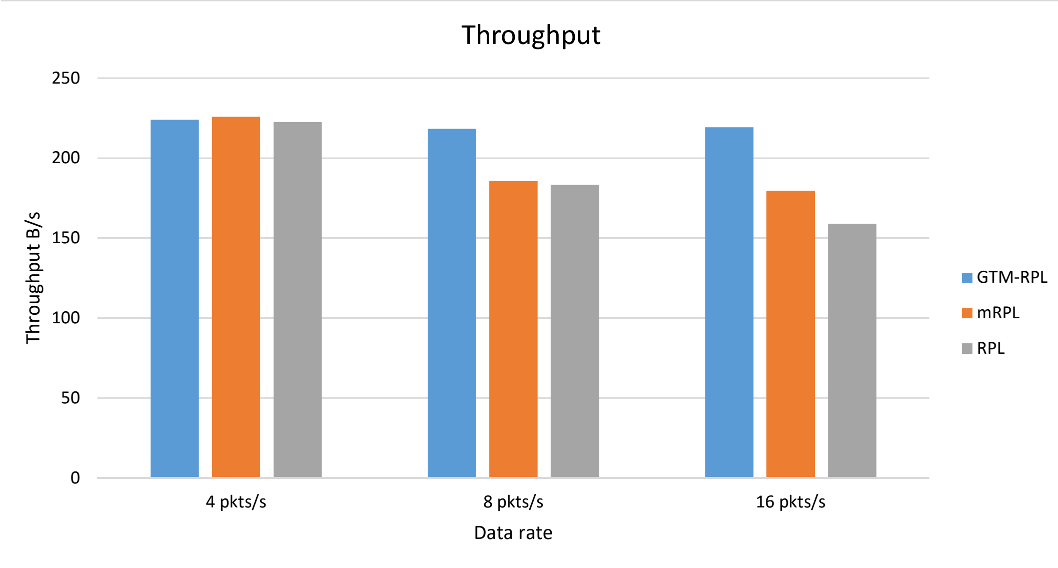

Figure 6.6: Throughput - Smart Agriculture

used in GTM-RPL uses LQI to detect mobility and congestion in the network, it makes sure that a minimum number of packets are dropped while mRPL and the native RPL need to be adjusted with a different value for each scenario to perform reasonably even in static networks.

As expected, at a 16 pkt/s transmission rate, the PDR of both mRPL and the native RPL becomes even worse because of the increased noise and congestion, While GTM-RPL does not suffer from these problems.

The throughput in figure 6.6 shows similar performance for all three protocols at rates below or equal to 4 pkt/s. It is also worth mentioning that mRPL has a slightly better throughput than GTM-RPL in this test even though the latter has a better PDR, this is due to the steady transmission rate of 4pkt/s in mRPL as compared to the varying rate used in GTM-RPL. The effect of lost packets is even more recognizable at higher data rates, the performance of mRPL and the native RPL seems to deteriorate with increasing transmission rate after a certain threshold even in static networks. GTM-RPL solves the problem of mobility and incidentally avoids congestion by using the LQI metric in the game theoretic design.

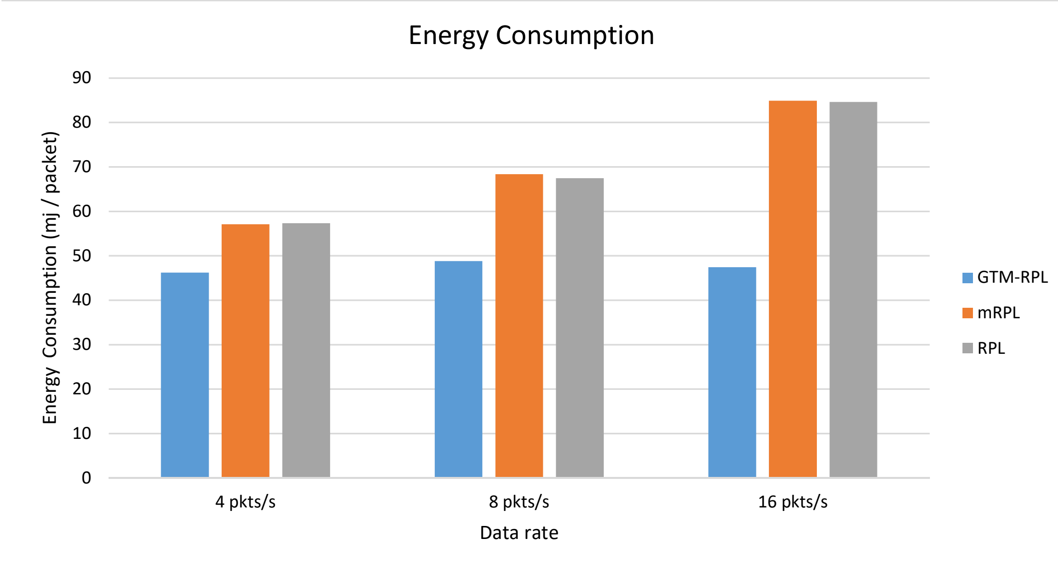

Figure 6.7: Energy Consumption - Smart Agriculture

The good performance of mRPL and the native RPL in terms of throughput comes at a high cost in terms of energy consumption. Figure 6.7 shows that even at a transmission rate of 4 pkt/s, GTM-RPL has a 20% improvement in energy consumption compared to other protocols. The energy wasted for unsuccessful packet transmissions is minimum in GTM-RPL, leading to a longer life span for the network at a negligible cost in terms of throughput.

At higher data rates, the gap in performance becomes even wider and in the extreme case of sending at a maximum rate of 16 pkt/s, GTM-RPL shows a 45% improvement in energy saving compared to other protocols. Because this is a practical test, it is worth mentioning that the measured energy consumption is accurate to 94% [55]. Nonetheless, the error rate is low enough to neglect in most cases but is useful to keep in mind while looking at some of the results.

In this application, it is clear that GTM-RPL can cope with the network requirements and provide a good performance that outperforms relevant protocols. These results also indicate that in case of additional requirements (eg. security features), GTM-RPL is less prone to deterioration caused by the added overhead. It does not mean that GTM-RPL is more “secure” than other RPL protocols,

Figure 6.8: Tmote sky node as a SWAT Robot

but it can accommodate security measures more efficiently due to the fact that it can provide higher throughput.

6.2.3 Military Applications

Military personnel, police officers and all people working in war zones or dealing with security threats occasionally face mortal danger finding themselves in an unfriendly area with unknown threats. Technology has always been helpful in minimizing these hazards and it is very important to find more solutions that can potentially save lives.

One of the popular military applications is the SWAT robot, which is usually a mobile robotic device equipped with sensors or cameras. A SWAT robot can go into areas that are marked as “unsafe”, collect information about the environment, send data to inform the tactical team and possibly even take an action [193]. One of the key challenging problems that face this application is communication [194], it is clear that having a robot inside an unfriendly building without communication is useless to the team.

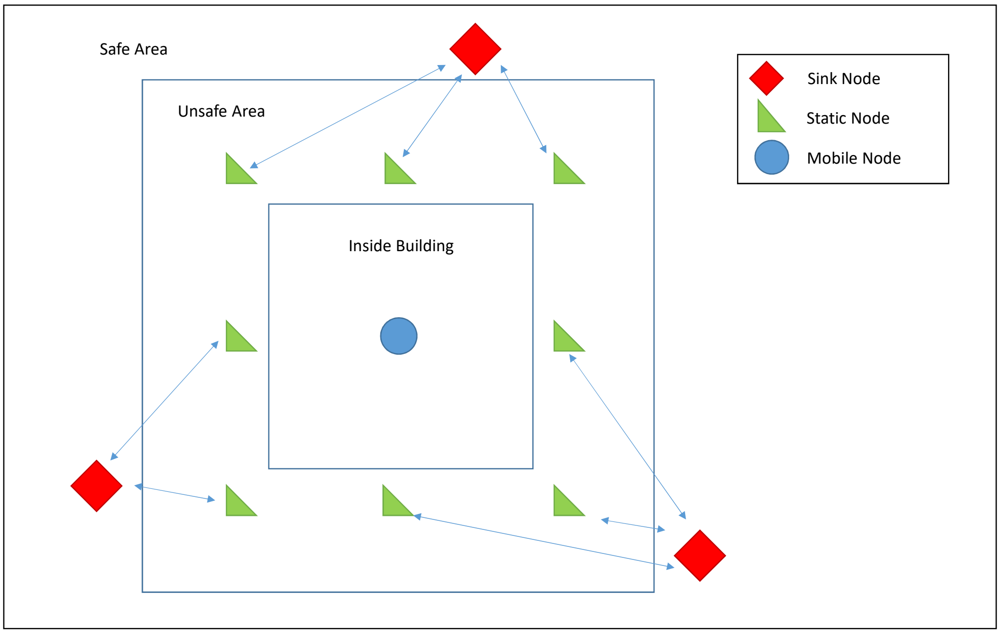

Figure 6.9: SWAT Robot Scenario

This application has challenging requirements, power efficiency is essential because it is usually not possible to change batteries. Reliable connectivity and the ability to send relatively large amounts of data is also a necessity, it can make the difference between a successful or a failed operation. It also requires multi-sinks and has a unique mobility scenario with only one node moving for most of the time. These conditions also make it a good application for testing GTM-RPL and relevant protocols in a practical manner.

Tmote sky nodes were used for this test, the mobile node was attached to a remote controlled vehicle as shown in figure 6.8, while eight nodes were scattered around the testing area and three sink nodes were placed outside the danger zone as shown in figure 6.9. The tests were done inside one of the university of Leeds buildings making sure that the testing area is surrounded by walls and that static nodes and sink nodes are placed outside these walls.

For this test, the values for α, β, γ and δ are 4.7, 1, 0.05 and 0.1 respectively. The mobility metric Mm is 0.25 for this scenario and the Dm is 9.42. As is the previous tests, mRPL and the native RPL were tested using 4 pkt/s, 8 pkt/s and 16 pkt/s. GTM-RPL uses the adaptive transmission rate that maximizes at

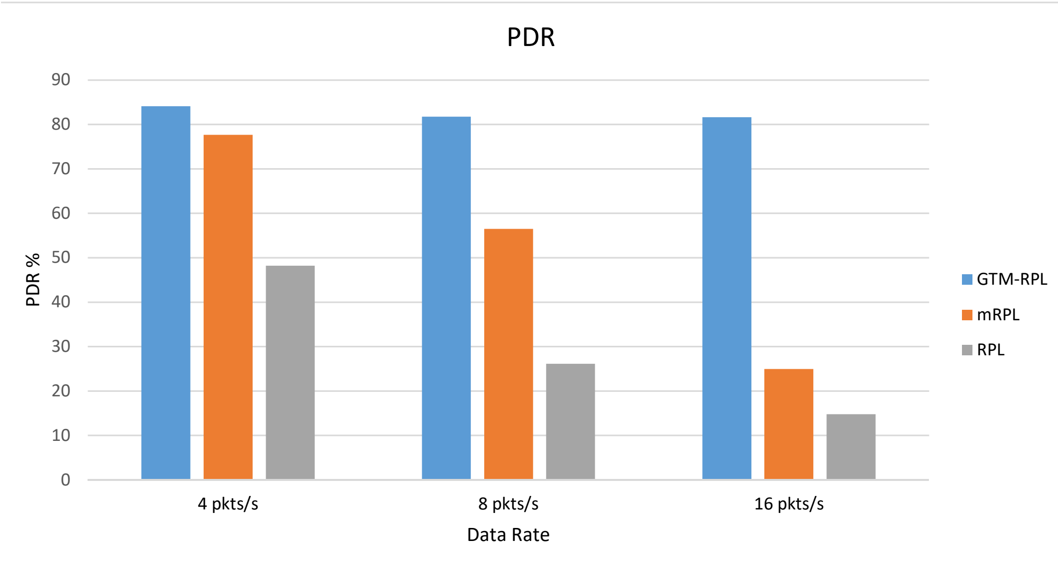

Figure 6.10: Packet Delivery Ratio - Military

4 pkt/s, 8 pkt/s and 16 pkt/s respectively.

Figure 6.10 shows the PDR for GTM-RPL, mRPL and the native RPL. Although there is only one mobile node is this scenario, it is forced to change parents many times during operation and use multihop communication to reach the sink node. The native RPL achieves 48% PDR only at a transmission rate of 4 pkt/s, while mRPL and GTM-RPL achieve 77% and 84% PDR respectively. The practical results are slightly lower than the COOJA simulations due to indoor interference and absorption, but have the same trend nonetheless.

At an 8 pkt/s transmission rate, mRPL and the native RPL achieve only 56% and 26% PDR respectively while GTM-RPL maintains its high PDR by using the adaptive transmission rate that depends on the network conditions, the link quality and mobility of nodes. As expected, increasing the transmission rate even higher has little effect on GTM-RPL but causes higher packet loss in mRPL and the native RPL.

Figure 6.11 shows the average throughput in bytes per second for the mobile node. The trend of practical results agrees with expectations in this case, GTM-RPL and mRPL have similar results at 4 pkt/s with GTM-RPL perform-

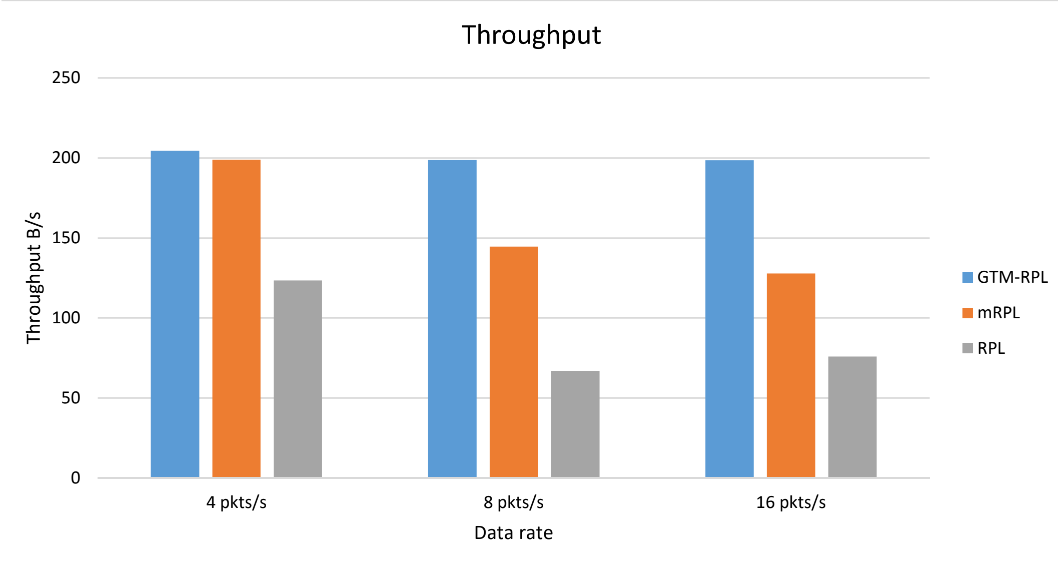

Figure 6.11: Throughput - Military

ing slightly better. The native RPL having no means of managing or detecting mobility shows a significantly lower performance. Increasing the configured transmission rate to 8 pkt/s has the expected negative effect on both mRPL and RPL while GTM-RPL maintains a variable transmission rate and does not suffer from high packet loss.

Configuring nodes with higher packet transmission rates only worsens the performance of mRPL and the native RPL. Although it does not improve throughput in GTM-RPL, it does increase the potential of GTM-RPL to deliver higher throughput in networks with less challenging conditions.

In figure 6.12, the energy cost per successfully transmitted packet is shown. At low data rates, mRPL performance is close to GTM-RPL in terms of throughput, but GTM-RPL always outperforms it in terms of energy consumption. At a transmission rate of 4 pkt/s, GTM-RPL offers an improvement of 9% in energy consumption compared to mRPL and 28% compared to the native RPL.

It is not difficult to spot also that the performance gap becomes wider after increasing the configured transmission rate. Since energy consumption is one of the most important metrics in military applications, the improvements that

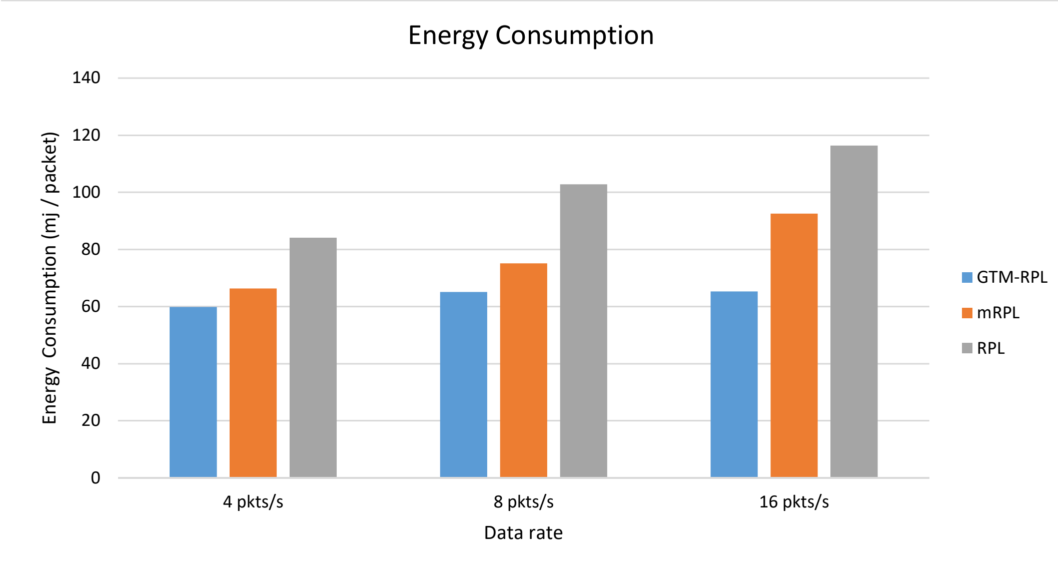

Figure 6.12: Energy Consumption - Military

GTM-RPL offers becomes even more necessary and comes at no additional cost.

6.3 Summary

This chapter follows a practical approach to test RPL and evaluates its performance in real IoT applications. It takes into account, different scenarios with different application requirements and challenges including mobility of nodes, outdoor and indoor environments and deployment restrictions. While in general, COOJA and Contiki provide a reasonably good simulation environment, the practical testing faces more challenges especially in indoor environments. Some hospital wards show unanticipated challenges due to high insulation making it especially difficult to deploy WSNs in a hospital where thick walls and insulated rooms limit the range of nodes to a few meters. Practical results in other scenarios are almost identical to simulations results, showing that COOJA and Contiki do provide accurate simulation of the wireless channel, and only lacks accuracy in special situations where unanticipated circumstances present themselves. The testing includes deployment of three versions of RPL, the first one is the native

RPL which was designed for static networks, the second one is mRPL which provides an excellent mobility management scheme to RPL and the third one is our optimized protocol GTM-RPL that provides energy and throughput optimization based on a game theoretic approach. Results show that even in worst case scenarios, the proposed GTM-RPL algorithm outperforms the native RPL and mRPL algorithms in terms of energy consumption, packet delivery ratio and throughput.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This section concludes the thesis by outlining the main findings of this work and presenting recommendations for development. It also shows solid contributions with regards to studying and managing mobility in WSNs and IoT applications. In chapter 3, a dynamic cluster head election protocol (DCHEP) is implemented for beacon-enabled mobile WSNs using IEEE 802.15.4 standard. The proposed approach uses backup cluster heads to improve the availability and lifetime of the network assuming that all nodes including cluster heads are mobile. Simulation results show that DCHEP successfully manages mobility inside clusters in a proactive manner maintaining low energy consumption and high responsiveness to changes. DCHEP guarantees up to 94.4% path availability in dense networks and improves energy consumption by 26% compared to the original standard. However, it does not guarantee QoS requirements and even though it shows an available path to the destination, it does not promise successful data delivery. This work investigates routing in a hierarchical topology and recommends using it in IoT applications. However, it also confirms that layer 3 routing (eg. RPL) is preferred in IoT applications where reliable connectivity and QoS requirements are usually needed.

In chapter 4, a dynamic RPL (D-RPL) is implemented with an adaptive trickle and reverse trickle timer to track mobility in multi-hop networks without the need to compromise energy consumption. It also uses a reactive DIS control to trigger parent changing depending on RSSI readings from received packets. A dynamic objective function D-OF that uses ETX, energy consumption and link quality is also proposed in this work to improve decision making in the parent selection process. Simulation results show that D-RPL successfully manages mobility and improves PDR, end-to-end delay and energy consumption. It also concludes that further optimization is required to fulfil IoT application requirements.

Chapter 5 presents a game theoretic approach to optimize RPL for mobility management in IoT applications and find an optimal transmission rate adaptive to the mobility scenario, application requirements and network conditions. It uses a mobility metric that is application specific and a density metric that depends on the number of nodes, transmission area and deployment area. These two metrics are used to generate a cost function for mobility and energy consumption. It takes into account the priorities of sensor nodes as well in calculating the final pay off function. To improve mobility management itself, GTM-RPL uses $RSSI$ and LQ cost in addition to the improved trickle algorithm resulting in a responsive, adaptive and efficient scheme. GTM-RPL improves PDR, throughput, end-to-end delay and energy consumption in all tested scenarios and outperforms relevant routing protocols.

A practical experimentation in real-life IoT applications using RPL, mRPL and GTM-RPL is presented in chapter 6. The experiments consider three different applications: (i) Hospital environment monitoring. (ii) Smart agriculture using mobile robots. (iii) Military SWAT robot application. The experiments show that it is easy to deploy RPL and RPL-based protocols using Tmote sky nodes and confirms simulation results in most cases. It also shows that thick and insulated walls in hospitals make it more difficult to deploy sensors due to the high absorption and reflection in these areas. Practical results show that even in worst case scenarios, GTM-RPL outperforms relevant protocols in terms of PDR, throughput and energy consumption.

The design of RPL aims to allow reliable and energy efficient routing for LLNs. Interoperability is one of the crucial aspects of RPL that makes it such a popular routing standard. With the implementations and proposals found in literature, it is noted that many of RPL-based protocols are not backward compatible with RPL. Changing the structure of DIO messages for example is a common cause of incompatibility. This problem can be clearly observed in mobility management implementations. The fact that RPL has no mechanism of its own to manage mobility is worrying and can even be crucial enough to stop RPL being adopted for IoT applications.

The energy consumption side in RPL is quite satisfactory as most papers do consider it and results agree that RPL is an energy efficient routing protocol. From a QoS point of view, RPL maintains a high performance with the use of its flexible and interoperable objective function. With regards to congestion, we believe that there are excellent efforts published to mitigate this problem but it is still worth reviewing the RPL standard and proposing a standardized mechanism to alleviate congestion. To tackle the security challenges, we believe that routing layer security needs to be addressed, the RPL standard also needs to revise the security features and at least propose a mechanism to implement the "authenticated" mode of RPL. The standard in RFC 6550 maintains that the "unsecured" mode does not necessarily mean that the network is not secure as transport layer security can still be used with this mode. Nonetheless, a mechanism for implementing security as part of the standard will be a great advantage to RPL in our opinion.

With regards to mobility, the problem is studied extensively and many proposals introduce efficient mobility management including mRPL [45], D-RPL [137] and GTM-RPL [138]. All of these protocols successfully and efficiently tackle the problem of mobility at human speeds and are also compatible with RPL. However, we strongly recommend adding a mobility management mechanism in the RPL standard due to the importance of this problem. We also recommend our GTM-RPL for consideration in the mobility management standard proposal due to the high performance, flexibility and efficiency of using it. It is our belief that RPL will continue to be deployed in IoT applications and highly recommend a new revision considering congestion, security and mobility management.

7.2 Future Work

A summary of future work recommendations based on this work is presented in this section:

- An implementation of RPL with routing layer security using the "preinstalled" mode with an assessment of reliability and recommendation on using the "authenticated" mode. Transport layer security like IPv6 security can also be implemented and tested with RPL and GTM-RPL to assess the impact of security overhead on routing. The performance of GTM-RPL also needs to be tested for security enabled networks. Some of the existing intrusion detection systems that can be used for testing are SVELTE [165], Specification-based IDS [195], NIDS [196] and DEMO [197].

- Considering mobility issues in LPWAN networks which face even more constraints than 6LoWPAN networks in terms of both node and link limitations. In addition to that, an assessment of using 6LoWPAN and LPWAN along with a comparison of their mobility management schemes can be very useful for future implementations. Applying both standards to different mobility scenarios can clearly present the advantages of each one of them especially in scenarios with extreme mobility like VANETs.

- Considering a scenario with two-way traffic using GTM-RPL with real life application where users can send requests to specific nodes through HTTP and CoAP application protocols. The original design of RPL assumes that traffic is moving upwards in the direction of sink node, it is interesting to see how GTM-RPL can cope with high load in both directions.

- A full revision of the RPL standard to propose a mechanism for handling mobility is very important, we recommend using our proposed GTM-RPL for it's reliability, efficiency and flexibility. We also hope that congestion and security are addressed in more details in the new RPL standard. Submitting a draft RFC with an enhanced trickle algorithm and additional fields for mobility status, congestion flag and security features can make a significant step towards the deployment of RPL.

- Deploying GTM-RPL to a practical application and measuring its performance over a long period of time (A year for example), to have a realistic view of its robustness and reliability. Practical data provides more tangible results and gives a better understanding of the challenges that face practical deployment of RPL nodes.

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