



**HAL**  
open science

## Routing algorithm dedicated to environmental data collection : precision agriculture

Yibo Chen

► **To cite this version:**

Yibo Chen. Routing algorithm dedicated to environmental data collection : precision agriculture. Other. Université Blaise Pascal - Clermont-Ferrand II, 2015. English. NNT : 2015CLF22572 . tel-01228224

**HAL Id: tel-01228224**

**<https://theses.hal.science/tel-01228224>**

Submitted on 12 Nov 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

N° d'ordre : D.U : 2572  
E D S P I C : 698

# UNIVERSITE BLAISE PASCAL - CLERMONT II

ECOLE DOCTORALE  
SCIENCES POUR L'INGENIEUR DE CLERMONT-FERRAND

## Thèse

Présentée par

**Yibo CHEN**

Pour obtenir le grade de

**DOCTEUR D'UNIVERSITÉ**

**SPECIALITE : INFORMATIQUE**

Titre de la thèse:

**Routing Algorithm Dedicated to Environmental Data Collection:  
Precision Agriculture**

Soutenue publiquement le 19 Mai 2015 devant le jury :

|  |                       |
|--|-----------------------|
| M. Alain Quilliot (UBP Limos)              | Président             |
| Mme. Houda Labiod (Institut Mines-Télécom) | Rapporteur            |
| Mme. Edwige Pissaloux (ISIR)               | Rapporteur            |
| M. Fabrice Valois (INSA Lyon)              | Examineur             |
| M. Haiying ZHOU (HUAT)                     | Examineur             |
| M. Christian Germain (Bordeaux SupAgro)    | Examineur             |
| M. Kun-Mean HOU (UBP Limos)                | Directeur de la thèse |
| M. Jean-Pierre Chanet (Irstea)             | Directeur de la thèse |





*This thesis is dedicated to*

*To my parents, Wenping SUN and Qi CHEN for their love and support,*

*To my wife, Yi WANG for all her love and patience,*

*And to my thesis advisors, Prof. Kun-Mean HOU and Dr. Jean-Pierre  
CHANET for their vision, encouragement, support and guidance.*

## Acknowledgements

My education at University of Blaise Pascal has been a journey full of memories, and I cannot thank enough to the number of people who helped me during the five-year study in France.

Firstly, I would like to thank my two advisors, Prof. Kun-Mean HOU and Dr. Jean-Pierre CHANET, who have been more than supervisors to me in this foreign country. Thank you for sharing with me your knowledge, vision and passion for research. Thank you for always believing in my ability and self-motivation. I learned so much from you and I believe this valuable knowledge will be great asset for my future career as well as in real-life perspective.

I would also want to thank Prof. Houda Labiod, Prof. Pissaloux Edwige, Prof. Alain Quilliot, Prof. Haiying ZHOU, Prof. Fabrice Valois and Prof. Christian Germain for accepting to be part of my jury, for their valuable time and feedback.

I would like to thank the “Conseil Régional d’Auvergne” and the European Regional Development Funds (ERDF) which have financial supports for this thesis. I feel lucky that Irstea and LIMOS has provided me with the opportunity to become a researcher.

Big thanks to all my colleagues from Irstea and LIMOS. It was a great pleasure to share this five-year time with you. I am very thankful to Dr. Gil de Sousa from Irstea for his suggestions and help. I am very grateful to Dr. Jian-jin LI and Dr. Christophe De Vault for their kind help and precious advices. I also would like to express many thanks to present and former team members of SMIR group for their cooperation, help, countless discussion and idea exchange. Thanks to Hongling SHI, Peter DIAO, Hao DING, Xing LIU, Bin TIAN, Peng ZHOU, Khalid el Gholami. Without your help, sharing knowledge and experiences, I cannot achieve any results alone, and the time with you let me believe only team work can overcome the challenges in the real-world applied research.

I would like to thank my parents for their support and love. Thank you for encouraging me to pursue my dreams. Last, but never least, my deep gratitude is dedicate to my wife for her love, patience, support and company.

# Table of Contents

|  |           |
|--|-----------|
| Acknowledgements.....  | 4         |
| Table of Contents.....   | 5         |
| List of Figures.....   | 8         |
| List of Tables.....  | 11        |
| List of Acronyms.....  | 12        |
| <b>1 Introduction.....</b>   | <b>14</b> |
| 1.1 Overview of Wireless Sensor Networks (WSN).....  | 14        |
| 1.2 Overview of Internet of Things (IoT) and IPv6 Low-power and Lossy Network (LLN).....   | 15        |
| 1.3 Motivation.....  | 16        |
| 1.4 Structure of the thesis.....   | 17        |
| <b>2 Wireless sensor networks, Precision agriculture and Internet of Things routing protocols: state-of-the-art.....</b>           | <b>19</b> |
| 2.1 Introduction.....  | 19        |
| 2.2 Wireless sensor networks in Precision Agriculture.....   | 19        |
| 2.2.1 Resource-constrained Hardware for Wireless Sensor Network Node.....  | 20        |
| 2.2.2 WSN Node lower-layer Protocols.....  | 22        |
| 2.2.3 WSN Node upper-layer Protocols.....  | 25        |
| 2.2.4 Overview of WSN/WMSN Solutions for precision agriculture.....  | 28        |
| 2.3 Routing protocols for wireless sensor networks.....  | 29        |
| 2.4 Routing protocols for current Internet of Things (IoT).....  | 32        |
| 2.4.1 Based concepts of IPv6 Routing protocol for low power and lossy networks (RPL).....  | 32        |
| 2.4.2 Modeling and experiments of RPL routing framework.....   | 34        |
| 2.4.3 Available Internet of Things (IoT) protocol stacks.....  | 35        |
| 2.5 Optimization techniques for routing in IPv6 Low-power and Lossy Networks (LLNs).....   | 38        |
| 2.5.1 Energy-efficient metrics and Context-aware objective function.....   | 38        |
| 2.5.2 Routing metrics Composition approach.....  | 39        |
| 2.5.3 Cross-layer optimization techniques.....   | 41        |
| 2.5.4 Memory-efficient storing mode.....   | 43        |
| 2.5.5 Other related work.....  | 43        |
| 2.6 Conclusion.....  | 45        |
| <b>3 Integrating Precision Agriculture and IPv6 Low power and Lossy Network (LLN): requirement and applicability analysis.....</b> | <b>46</b> |
| 3.1 Introduction.....  | 46        |
| 3.2 A-LLNs infrastructure description.....   | 46        |
| 3.3 Deployment scenarios of A-LLNs.....  | 50        |
| 3.4 Description of traffic pattern and layer-two applicability.....  | 51        |
| 3.5 Methodology of building a low-cost IoT testbed for A-LLNs.....   | 52        |
| 3.5.1 Description of simulation experiments.....   | 52        |
| 3.5.2 Hardware testbed description.....  | 56        |
| 3.6 Preliminary result analysis of hardware testbed.....   | 58        |
| 3.6.1 Network conditions.....  | 58        |
| 3.6.2 Radio duty cycle, power consumption and lifetime.....  | 62        |
| 3.6.3 Key lessons.....   | 64        |
| 3.7 How to adapt RPL profiles to A-LLN: challenges and recommendations.....  | 65        |

|       |  |     |
|-------|--|-----|
| 3.7.1 | RPL instances and multi-DAG .....  | 65  |
| 3.7.2 | RPL objective function and routing metrics .....   | 65  |
| 3.7.3 | Storing vs. Non-Storing Mode and DAO sending policy .....  | 66  |
| 3.7.4 | DODAG repair .....   | 66  |
| 3.7.5 | Analysis of configuration defaults and ranges .....  | 67  |
| 3.7.6 | Manageability considerations .....   | 68  |
| 3.8   | Conclusion .....   | 68  |
| 4     | <i>Modeling, optimization of RPL routing protocol for Precision Agriculture</i> .....                            | 69  |
| 4.1   | Optimization and enhancement of RPL routing framework: problem statement .....                                   | 69  |
| 4.1.1 | Simulation and analysis of uIPv6 protocol stack .....  | 69  |
| 4.1.2 | Problem statement and contribution highlight.....  | 73  |
| 4.2   | Energy-aware metrics and objective function of IPv6 Routing Protocol for A-LLNs (RPAL)...                        | 75  |
| 4.2.1 | Introduction.....  | 75  |
| 4.2.2 | Related work .....   | 76  |
| 4.2.3 | Energy-aware metrics and objective function of Routing Protocol for A-LLNs (RPAL) .                              | 79  |
| 4.3   | Scalable Context-Aware Objective Function (SCAOF) with Hybrid RPAL routing metrics.....                          | 85  |
| 4.3.1 | Related work .....   | 86  |
| 4.3.2 | An hybrid solution of resource-aware and energy-aware routing metrics composition                                | 87  |
| 4.4   | The context-aware trickle algorithm .....  | 93  |
| 4.4.1 | Introduction.....  | 93  |
| 4.4.2 | Related work .....   | 94  |
| 4.4.3 | A joint analytical Trickle model for RPL controlling messages dissemination.....                                 | 100 |
| 4.4.4 | The Context-aware Trickle algorithm for A-LLNs: CA-Trickle .....   | 104 |
| 4.5   | Integrating simulation and real world for mutual optimization: Closed Loop of Application-Simulation (CLAS)..... | 113 |
| 4.5.1 | Introduction.....  | 113 |
| 4.5.2 | Problem statement.....   | 114 |
| 4.5.3 | MAP4LLNSIM/LLNRUN4NS tool-set architecture design .....  | 115 |
| 4.5.4 | Related work .....   | 118 |
| 4.5.5 | Current progress and challenges of CLAS.....   | 118 |
| 5     | <i>Performance evaluation of routing protocol for Agriculture-LLNs: RPAL</i> .....                               | 121 |
| 5.1   | Adaptation and improvement of simulator, protocol stack and application .....                                    | 121 |
| 5.2   | Performance evaluation in simulation scenarios .....   | 123 |
| 5.2.1 | Simulation setup and designated scenarios.....   | 123 |
| 5.2.2 | Energy-aware routing metrics and SCAOF evaluation .....  | 126 |
| 5.2.3 | CA-Trickle algorithm evaluation .....  | 132 |
| 5.3   | Evaluation of RPL and RPAL routing protocols in real-world environment.....                                      | 136 |
| 5.3.1 | Testbed setup .....  | 136 |
| 5.3.2 | Evaluation results .....   | 141 |
| 6     | <i>Conclusions and future Work</i> .....   | 146 |
| 6.1   | Summary of this thesis .....   | 146 |
| 6.2   | Future work items .....  | 147 |
| 6.3   | Summary of publications.....   | 147 |
| 7     | <i>References</i> .....  | 149 |
|       | RESUME.....  | 159 |
|       | ABSTRACT.....  | 159 |





## List of Figures

|   |    |
|---|----|
| Figure 2-1 a brief taxonomy of environmental and agricultural WSN applications.....   | 19 |
| Figure 2-2 Typical architecture of WSN node.....  | 20 |
| Figure 2-3 IEEE 802.15.4 lower-layer solution.....  | 23 |
| Figure 2-4 IEEE 802.15.4-2006 devices and topologies.....   | 23 |
| Figure 2-5 ZigBee Protocol Stack.....   | 26 |
| Figure 2-6 6LoWPAN compliant stack.....   | 26 |
| Figure 2-7 Classification of Multi-path operations: node/link disjoint, interleaved, and opportunistic.....   | 31 |
| Figure 2-8 RPL DODAG topology and traffic patterns.....   | 33 |
| Figure 2-9 ZigBeeIP stack and 6TiSCH stack.....   | 36 |
| Figure 2-10 Open protocol stack and Contiki uIPv6 stack.....  | 37 |
| Figure 2-11 The loop diagram of MAC and routing interactions.....   | 42 |
| Figure 3-1 Sketch map of a modern precision agriculture system.....   | 47 |
| Figure 3-2 Schematic of LBR and smart sensor in A-LLN.....  | 49 |
| Figure 3-3 Network graph and visualizer on Cooja.....   | 54 |
| Figure 3-4 A deployment simulation in COOJA/MRM.....  | 54 |
| Figure 3-5 Measurement data of power consumption.....   | 55 |
| Figure 3-6 Measurement data of average RDC and beacon interval.....   | 56 |
| Figure 3-7 Photos of ATMEL RCB128RFA1 PCBA, Atmega128RFA1 Evaluation Kit and STK 600 with AVR JTAGICE mkII debugging tool.....  | 56 |
| Figure 3-8 Four AVR RPL router nodes deployed in ISIMA building – An indoor environment.....  | 57 |
| Figure 3-9 Atmel nodes deployed in LIMOS's office – topology snapshot in an indoor environment.....   | 58 |
| Figure 3-10 Sensor Data Collect tool and one network graph snapshot.....  | 58 |
| Figure 3-11 Time-varying network profile of current DODAG: Packet lost and beacon interval.....   | 60 |
| Figure 3-12 Time-varying network profile: Hops and Routing Metric.....  | 61 |
| Figure 3-13 Histograms of power consumption profile in our experiment.....  | 63 |
| Figure 3-14 Time-varying power consumption profiles of each node in the current DODAG.....  | 63 |
| Figure 3-15 Histograms of Radio Duty Cycle profile in our experiment.....   | 63 |
| Figure 3-16 A flow chart of adapting RPL routing platform for a specific application ..   | 64 |
| Figure 4-1 Time-varying network profile of uIPv6 protocol stack simulation: Number of DIO overhead.....   | 72 |
| Figure 4-2 Time-varying energy remained profile from uIPv6 protocol stack simulation.....   | 72 |
| Figure 4-3 Processor States.....  | 76 |
| Figure 4-4 Energy Consumption model in FSM of low-power 2.4GHz transceiver of ATmega128RFA1.....  | 77 |
| Figure 4-5 A-LLN with seven sensor nodes and one sink. SN2 has to forward the messages from SN4, SN6, and SN7 to the sink. Consequently, it will become inactive due to the energy depletion..... | 82 |
| Figure 4-6 The structure of DODAG Information Object control packet.....  | 82 |
| Figure 4-7 The formats of three adopted metric/constraint containers.....   | 83 |
| Figure 4-8 An example of DIO control packet broadcast by a RPL routing: SN2.....  | 83 |
| Figure 4-9 RPAL OF selects the neighbor with the viable ETX and the highest RE to be the preferred parent.....  | 84 |

|  |     |
|--|-----|
| Figure 4-10 The compressed format of the prefix information option .....   | 85  |
| Figure 4-11 Our proposed link color metric container format -- first solution .....  | 90  |
| Figure 4-12 Our proposed link color container and routing constraint object format --<br>second solution.....  | 91  |
| Figure 4-13 Data flow chart of original Trickle dissemination algorithm .....  | 96  |
| Figure 4-14 Pseudo-code of Trickle algorithm used in RPL routing framework .....   | 97  |
| Figure 4-15 Find the roots for equation (4.18) -- average probability of sending a<br>message in a given interval .....  | 102 |
| Figure 4-16 Percentage of bandwidth usage for DIO messages during the building of a<br>stable DODAG (Joint analytical model, BWU(DIO)).....                                      | 103 |
| Figure 4-17 Percentage of bandwidth usage for DIO messages in consecutive trickle<br>intervals .....   | 103 |
| Figure 4-18 Percentage of bandwidth usage for DIO messages in consecutive trickle<br>intervals .....   | 104 |
| Figure 4-19 Observation: Node 2 has been suppressed for two DIO cycles.....  | 106 |
| Figure 4-20 The modification of original Trickle proposed in Trickle-F .....   | 106 |
| Figure 4-21 Example of CA-Trickle operation with four synchronized nodes and one<br>new joint node .....   | 107 |
| Figure 4-22 Pseudo-code of CA-Trickle algorithm .....  | 108 |
| Figure 4-23 Schematic diagram of the start and the end the coagulable Trickle timer..  | 112 |
| Figure 4-24 MAP4LLNSim/ LLNRun4NS TOOL-SET ARCHITECTURE .....  | 116 |
| Figure 4-25 Schematic flow diagram of MAP4LLNSim/LLNRun4NS tool-set.....   | 119 |
| Figure 5-1 Protocol stack for evaluate RPAL Routing Model.....   | 123 |
| Figure 5-2 DODAG construction and initialization: SCAOF (left) and MrhOF (right)   | 126 |
| Figure 5-3 The adjustments of preferred parents controlled by SCAOF: node 7 and 9<br>change their previous preferred parents to the new ones with more remaining energy<br>..... | 127 |
| Figure 5-4 The case of 10 node network: common sensor nodes with 100% energy level<br>.....  | 127 |
| Figure 5-5 The case of 10 node network: the optional parent selection for avoiding hot<br>spot.....  | 128 |
| Figure 5-6 Interval phase of scenario 1 – The higher the degree, the interval is more out<br>of synch. ....  | 133 |
| Figure 5-7 Average cumulative energy consumption with RPL+Original Trickle and<br>RPAL+CA-Trickle.....   | 133 |
| Figure 5-8 Interval phase of scenario 2 – the higher the degree, the interval is more out of<br>synch.....   | 135 |
| Figure 5-9 Average suppressed DIO messages per node Original Trickle (left) VS CA-<br>Trickle (right), K=3.....  | 135 |
| Figure 5-10 A plan of testbed deployment.....  | 136 |
| Figure 5-11 Testbed setup: sink node and 9 IWoTCORE Ext_MiLive nodes for outdoor<br>environment experiments .....  | 137 |
| Figure 5-12 Testbed setup: photos of No.2 and No.3 deployed IWoTCORE node.....   | 137 |
| Figure 5-13 Building an indoor prototype before setting up operational testbeds.....   | 140 |
| Figure 5-14 Hop count evaluation results of 1st test and 2nd test .....  | 141 |
| Figure 5-15 Number of network churn for the testbeds in 1st and 2nd experiments.....   | 142 |
| Figure 5-16 Percentage of packets that get lost on the testbed of 11 IWoTCORE nodes  | 143 |
| Figure 5-17 Average energy usage of the testbeds in 1 <sup>st</sup> and 2 <sup>nd</sup> experiments.....   | 144 |
| Figure 5-18 Radio duty cycle of the testbeds using standard RPL model in 1 <sup>st</sup> test.....   | 144 |
| Figure 5-19 Radio duty cycle of the testbeds using RPAL model in 2 <sup>nd</sup> experiments...  | 145 |



## List of Tables

|   |     |
|---|-----|
| Table 2-1 Main features of RPL protocol .....   | 32  |
| Table 2-2 A list of routing metric/constraint objects for RPL .....                   | 33  |
| Table 2-3 RPL implementations for real-world devices .....                            | 35  |
| Table 2-4 RPL enabled simulators .....  | 35  |
| Table 2-5 Existing real-world testbeds for the evaluation of RPL protocol .....       | 45  |
| Table 3-1 Three types of key nodes in A-LLNs.....                                     | 49  |
| Table 3-2 AVR-based nodes deployed in LIMOS's office – network conditions.....        | 59  |
| Table 3-3 AVR-based nodes deployed in LIMOS's office – power profiles .....           | 62  |
| Table 4-1 Network Configuration .....   | 70  |
| Table 4-2 Network performance metrics .....   | 71  |
| Table 4-3 Descriptions of the adopted routing metrics .....                           | 88  |
| Table 4-4 Utilization of the three link color elements -- first solution .....        | 90  |
| Table 4-5 RPL ROUTING METRIC AND CONSTRAINT OBJECTS .....                             | 116 |
| Table 5-1 Traffic pattern of the nodes with different logical roles in an A-LLN. .... | 125 |
| Table 5-2 Simulation performance results comparison of scenario 1 .....               | 129 |
| Table 5-3 Simulation performance results comparison of scenario 2.....                | 131 |
| Table 5-4 Simulation performance comparison of scenario 3 .....                       | 132 |
| Table 5-5 Three main types of required measurements for statistical analysis .....    | 139 |
| Table 5-6 Same settings of three comparative experiments.....                         | 139 |
| Table 5-7 Different settings of three comparative experiments.....                    | 139 |
| Table 5-8 Remote control and fault injection functions.....                           | 140 |

## List of Acronyms

|            |   |
|------------|---|
| 6LowPAN    | Low Power IPv6 Personal Area Network                      |
| A-LLNs     | Agricultural Low-Power Lossy Networks                     |
| AODV       | Ad-hoc Distance Vector Routing Protocol                   |
| AMD        | Agricultural Monitoring Data                              |
| CoAP       | Constrained Application Protocol                          |
| CA-Trickle | Context-aware Trickle Algorithm                           |
| DAG        | Directed Acyclic Graph                                    |
| DAO        | Destination Advertisement Option                          |
| DIO        | DODAG Information Option                                  |
| DIS        | DODAG Information Solicitation                            |
| DSS        | Decision Support System                                   |
| DODAG      | Destination Oriented Directed Acyclic Graph               |
| ETX        | Expected Transmission Count                               |
| EAMs       | Energy-aware Metrics                                      |
| IETF       | Internet Engineering Task Force                           |
| iLive      | First generation Intelligent Limos Versatile Embedded WSN |
| IoT        | Internet of Things  |
| IWoT       | Internet of Things & Web of Things                        |
| IP         | Internet Protocol   |
| IPv6       | Internet Protocol version 6                               |
| LBR        | LLN Border Router   |
| LC         | Local Controller  |
| LLN        | Low-Power Lossy Networks                                  |
| mAh        | milli Ampere-hour   |
| MAC        | Medium Access Control                                     |
| MANET      | Mobile Ad-hoc Networks                                    |
| MP2P       | Multipoint to Point                                       |
| MTU        | Maximum Transmission Unit                                 |
| ND         | Neighbor Discovery  |
| P2MP       | Point to Multipoint                                       |
| P2P        | Point to Point  |
| PA         | Precision Agriculture                                     |

|       |  |
|-------|--|
| PAN   | Personal Area Network                                      |
| PRR   | Packet Reception Ratio                                     |
| QoS   | Quality of Service   |
| RE    | Remained Energy  |
| ROLL  | Routing over Low-power and Lossy networks                  |
| RPAL  | Routing Protocol for Agricultural Low-Power Lossy Networks |
| RPL   | Routing Protocol for Low-Power Lossy Networks              |
| SCAOF | Scalable context-aware Objective Function                  |
| UDP   | User Datagram Protocol                                     |
| WG    | Working Group  |
| WoT   | Web of Things  |
| WSN   | Wireless Sensor Network                                    |

# 1 Introduction

## 1.1 Overview of Wireless Sensor Networks (WSN)

Wireless Sensor Networks (WSN) is a popular research field during the past decade. It is a highly autonomous system which has a large amount of tiny wireless devices reliably running with limited energy resources and providing valuable measurements for the observed environment. The monitoring data (i.e. temperature, air humidity, vibrations, light strength, sounds and movements) are collected by sink nodes for afterwards processing, analysis, and possible operation issued as an actuation to sensed phenomena. Durable WSN measuring the surrounding environment alleviate the need to use wires and human intervention, thus offering an easy-to-use and low intrusive manner.

Most of the current WSN nodes are possibly made within a low price so they could be intended to large-scale deployments (it is possible to see hundred, thousands even millions of WSN nodes to build the future internet with Internet of Things). WSN node is also a type of embedded system with limited resources and other constraints -- low-power (battery powered), low-range (30-100 meters), communication low-bandwidth (250 KBit/s), and small memory (few MB, sometimes even less than 100 KB). The characteristic of radio devices in WSN nodes are far inferior compared to a concurrent Wi-Fi technology, especially considering the level of transmitter power output. Thus, WSN nodes deployed over a wide area combined with short radio range leads to obligatory multi-hop function for WSN.

WSN has been testified their success by the abundance of envisioned applications. The latest literatures often discuss the following application examples: the environmental, habitat, or structural monitoring, as well the surveillance systems, such as home automation and natural disaster prevention [1]. In the near future, the application fields, such as, smart homes, smart buildings, smart cities and smart industrial plants, which serve the energy savings and the remote control [2], will become the main research topic for next generation of WSN. Moreover, the WSN in agriculture may bring out the fundamental contribution to precision agriculture (PA) [3]. ZigBee wireless communication technology provides industrial level practical solution that can meet most of the requirements of automation and monitoring system in WSN. The proposed low power ZigBee systems with multiple sensors have been discussed in more and more literatures.

Two classifications of WSN applications can be made according to their data collection pattern: time driven and event driven. The former represents the periodic reporting of the observed environmental or habitat phenomena. The later aims at recording data measurements while the WSN nodes are inquired by a designated event. Apparently, the initial application context deeply impacts on all consequent choices for selected WSN protocols.

Meanwhile, the intrinsic wireless medium natures, such as path loss, interference, shadowing or multi-path fading [4] in traditional WSN, will also influence the communication layers. A reliable WSN netstack should incorporate the mechanisms that account and leverage on the wireless medium downfalls [5]. It is a difficult but highly valuable task to analyze and afterwards create a trustworthy joint model that can improve network protocols. Furthermore, the research in the WSN domain should be definitely inspired by a real-life observations and feedbacks since it is easy to go to wrong optimization directions without setting up testbeds. Fortunately, some research advices already exist on how to conceive a running testbed [6] or how to simplify some of the research assumptions by critically observing what really matters in design goals of a specific application scenario [7]. Moreover, WSNs usually adopt a flat

structure without fixed infrastructure support. Self-organization and self-healing functions are thus huge challenges and necessities in WSNs. Namely, a set of individual WSN nodes need to independently create a fully autonomous network without human intervention or can be easily controlled, configured by the people who do not have any network knowledge. Similarly to the plug-and-play concept, WSNs should offer a deploy-and-forget experience to the final users [8]. Self-organization over the long operational periods should take the new joint WSN nodes, link breakage, and nodes disappearing due to battery exhaustion or software/hardware malfunctioning into account.

It should be noticed that, the recent development of the Power Line Communication (PLC) and energy scavenging devices can extend the classical paradigms of WSN and mitigate the issues due to limited battery energy. Nevertheless, the energy efficiency remains of the utmost importance during deploying WSNs in real world. In this thesis, such energy heterogeneity in the context of precision agriculture application will be mainly considered by the design of our routing algorithm.

## 1.2 Overview of Internet of Things (IoT) and IPv6 Low-power and Lossy Network (LLN)

The conventional WSNs are like isolated islands of WSN nodes that need to be merged with nowadays Internet so that their generated sensing data can be accessed. Because of the diversity of WSN protocols and systems, building a gateway for each WSN are challenging due to its complexity, flexibility and scalability. Therefore, the existing real world WSN deployments still operate independently from the rest of the world. The collected sensing data within these closed networks cannot be easily shared publicly. As the research progress related to WSN is almost done in the previous decade, especially on the conception of energy efficient, scalable, and reliable protocols, large-scale WSN deployments can be already achieved. In other words, the steady growing deployments in size have reached the anticipated goal that was set in the early conceived WSN.

Internet of Things (IoT) is a driving technology to revolutionize the current Internet by expanding it with a large number of smart objects (WSN nodes, embedded systems, smart phones, etc.) [9]. The underlying technologies will be no longer the obstructions for communication between these objects. Meanwhile, IPv6 based protocols will make possible to interconnect a huge number of smart devices (approximately  $3.4 \times 10^{38}$  available addresses), solving the long-anticipated problem of exhausted IPv4 addresses. Each smart object will be reachable through a unique IPv6 address.

The current noticeable challenge in the interconnected IoT paradigm is security issue, since smart devices will be used to monitor critical scenarios, to provide telemetric measures or even people's health information. A loophole of security might have disastrous consequences. IoT devices need to offer a high level of security robustness to protect their users from outside attacks and misconducts [10]. Furthermore, some devices in IoT operate in the unlicensed frequency band densely populated with various devices leading to a radio polluted environment. A surrounding interferer will have serious impacts on data availability. Thus, how to handle packet drops and energy waste is still an important issue and IEEE 802.15 Working Group (WG) has already proposed the corresponding solutions [11].

Similar to the role of ZigBee for WSN, standardization is a significant factor to drive smart objects to the IoT paradigm. But the current technology trend presents that open



standards are more preferable by IoT. Not like existing abundance of proprietary solutions, IoT standards can extend the acceptance of the technology at its market, and do not limit its customers in the particular services provided by vendors. IoT will continue to promote the use of open standards, and most of them are openly published [12].

As we have already known, standardization efforts relevant to WSNs are mainly the following organizations: the IEEE and the IETF. IEEE generally standardizes the physical layer and medium access protocols. The IEEE 802.15.4 proposes a widely accepted WSN global standard at MAC and PHY level for interconnecting low-power/data-rate/cost WSN nodes and actuator networks. The IEEE 802.15.4 standard for ubiquitous networks responds to a wide range of application scenarios, such as health monitoring, building surveillance and home automation [13]. The IETF comprises a large number of active WGs organized in 8 different research areas. Its WGs related to WSNs are IETF 6LoWPAN (Dedicated to providing end-to-end IPv6 connectivity in WSNs) and IETF ROLL (Routing Over Low-power and Lossy links). ROLL WG aims to cover a comprehensive number of various use cases: Home automation [14, 15], Commercial building automation, Industrial automation, Urban environments [13]. Their current progress is in the step of network routing and self-organization in Low-power and Lossy networks (LLNs) scenario. RPL (IPv6 Routing Protocol for LLNs) proposed by this WG is built over a traditional distance vector routing paradigm and can efficiently support three network traffic patterns, such as multi-point to point, point to multi-point and point to point.

### 1.3 Motivation

Thanks to the rapid advance in the domain of WSN and miniaturization of WSN node boards, Precision Agriculture (PA) (in certain contexts, it is also called precision farming) started emerging as new trends in the agricultural sector in the past few years. Generally speaking, PA system concentrates on providing the ways for observing, assessing and controlling agricultural production process, and covers a wide range from herd management to field crop production [16]. In this thesis, PA is treated as a site-specific crop monitoring application. This surrounds several different issues. One of them is environmental data collection, such as monitoring soil, crop and climate in one/multiple field(s), which are divided in parcels. Furthermore, a Decision Support System (DSS) can use these measurements for possible treatments analysis, for field-wide or a specific parcel. Meanwhile, the methods of taking differential actions can be carried out, for instance, adjusting in real-time operations such as fertilizer, lime and pesticide utilization, tillage, or sowing rate.

Precision Farming and WSN applications combine an exciting new topic of research that will greatly improve quality in agricultural production, water management and will have dramatic reduction in cost needed and environment impacts. Using a network of strategically placed WSN nodes, measurement data such as temperature, humidity, and soil moisture can be automatically monitored. For example, one WSN is able to provide precise information about crops in real time, and help to reduce water, energy, and pesticide usage, and the most important is to avoid environment pollution through the utilization of measurable fertilizer, pesticide, etc. Furthermore, the open standardized protocols, the ease of deployment and system maintenance open a door to introduce the next generation of WSN -- IoT technologies in precision farming. In addition the data about the field crop condition can be also used in the supply chain management [17].

Most of the current agro-environmental monitoring applications transmit the real-time data by wireless networks through M2M (machine to machine) support platform. Some systems use SMS, Web, WAP pattern, so that the terminal can master the information to guide the production. However, from our point of view, these earlier researches in this area stagnated and are counting on the complex Web applications on the server side. Until the appearance of 6LoWPAN adaptation layer protocol and the smart objects can connect to the IPv6-based network, the novel protocol standards is hoped to solve the existing problems and difficulties and move parts of the workload on the embedded device side.

Therefore, as the development of IETF standardization in the fields of Internet of Things (IoT) and Web of Things (WoT), their use cases will not be limited in the applicability coverage mentioned in the previous sub-sections, and PA application will become a significant and promising one in the near future. This thesis will carry out this particular study of using IoT technologies in the PA application, especially on the routing issues of Agricultural LLNs (A-LLN). According to ROLL working group's charter, RPL is conceived as general wide use routing protocol, independent from the rest of the protocol stack through propose its own self-organization mechanisms, topology structures. However, based on our evaluation experiments, the original RPL standard and existing implementation models cannot suffice the routing requirements of real-world A-LLN deployments, such as resource constraints, transmission range, network lifetime, automatic topology adjustment and resistance of highly dynamic environment caused by obstacles, adverse weather or vegetation growth.

To overcome the above challenges, the optimization mechanisms for RPL, such as energy-efficient, context-aware, cross-layer optimization techniques, and memory efficient are taken into account in this thesis. A RPL-based routing algorithm dedicated to precision agriculture application are experimented and evaluated as a part of IoT protocol stack with 6LoWPAN and CoAP (Constrained Application Protocol) in both simulation and real-world testbeds. We believe that, after a decade development, WSN has arrived to a crossroads where lots of new research challenges emerge but this is also a hard-won opportunity because IoT technologies will lead to the next generation of IP network, consequently, the IPv6 revolution could finally come to our daily life.

## 1.4 Structure of the thesis

In this thesis, the work covers the following content: the consideration of the WSN supporting IPv6 connectivity, network architecture, applicability analysis of adapting RPL to precision agriculture, simulation model and testbed building and evaluation. The proposed networks can be appropriate for the large-scale deployment of WSN nodes. Moreover, the discussions and guidelines in this thesis are able to extend to other applications.

As our core evaluation work, we extend and enhance ContikiRPL [18] model of uIPv6 protocol stack in Contiki system with a set of improvements for RPL protocols as well as context-based load-balance trickle timer algorithm, self-healing and recovery mechanisms from adverse weather, and the attendant energy efficiency mechanism for prolonging the network lifetime. It should be noticed that the proposals are complied with the IETF standardization because our work focuses on the flexible and configurable parts of RPL framework. Namely, this enhanced RPL version will not obstruct the scalability of A-LLNs in IoT. Furthermore, the feasibility and effectiveness of our proposed schemes are tested and verified under Contiki/Cooja simulator [19] and the testbeds [20].

**The second chapter:** the state of the art is presented in this chapter according to our main work: application layer and routing layer. The latest literatures about WSN in precision agriculture are presented before an overview of routing protocol in WSN and IoT. We also summarize the current proposed optimization techniques and approaches for routing in LLNs. These solutions are our foundations to overcome the challenges in the routing issues of adapting Precision agriculture application to the IoT paradigm.

**The third chapter:** a detail requirement and applicability analysis for integrating precision agriculture application and IPv6 low power and lossy network (LLN) is mainly presented in this chapter. Moreover, an experimental evaluation consisting of Atmel RAVEN evaluation kit and Pandaboard is given in this chapter. The preliminary performance analysis and characterization are presented. The target of building this real-world testbed is to find out the valuable problems before the protocol adaptation and evaluation. Except adopting standardized RPL protocol and Contiki uIPv6 protocol stack, the problems caused by the ContikiRPL model, which is completely complied with ROLL standardization, are revealed. Our proposed RPL agricultural context referred to the draft of 6LoWPAN use case [21] with extra specific routing requirements presented in the Cooja simulation scenario, is summarized. The analytical study could help to clarify the key weaknesses of the LLNs environment as well have a better understanding of the dynamical environment, such as the network link and alteration of node in neighborhood. At the end of this chapter, a set of recommendations about RPL's applicability in Agricultural LLNs and testbed setup will be discussed.

**The fourth chapter:** The significant building stones of this thesis are going to be described. The impacts of resource constraints, network lifetime, automated topology adjustment, resistance of highly dynamic environment caused by obstacles, adverse weather or vegetation growth, for RPL DODAG topological structure will be considered as problem statements based on the preliminary experiments in Chapter 3. Furthermore, the analytical models and algorithm descriptions will be presented in this chapter. Our objective is to enhance the original RPL mechanisms through context-aware features and achieve the specific quality of service requirements of precision agriculture application. Correspondingly, we propose a set of locally measured routing metrics and constrains in a practical objective function, as well context-aware trickle timer algorithm, to an enhanced RPL version named as RPAL (Routing Protocol for A-LLNs) that would help to reach our goals.

**The fifth chapter:** a detail description of implementing RPAL model in the Contiki platform is presented at the beginning of this chapter. Thereafter, how to carry out the performance evaluations on simulation and real-life testbeds will be elaborated. The evaluation results of the proposed methods by measuring the well-known network metrics and properties, and the impacts on the performance of routing and application (through CoAP protocol), are assessed. Moreover, the strategic values of the IoT architecture in Agricultural information and communications technology (ICT) are discussed. Finally, the results of the tests on the setting up testbed are presented and analyzed.

**The sixth chapter:** this chapter completes this thesis by summarizing the main contributions. The final remarks motivate further possible research directions that could stem out from our work.

## 2 Wireless sensor networks, Precision agriculture and Internet of Things routing protocols: state-of-the-art

### 2.1 Introduction

The state of the art will be presented in this chapter according to our main work: application layer and routing layer. The latest literatures about WSN in precision agriculture domain are presented before an overview of routing protocol in WSN and IoT. We also summarize the current existing optimization techniques and approaches for routing in LLN proposed in a number of state-of-the-art researches. These solutions of routing issues will be our foundation to confront the challenges of adapting the routing technology in IoT paradigm to Precision Agriculture (PA) application.

### 2.2 Wireless sensor networks in Precision Agriculture

This section is concerned about the state-of-the-art ICT technologies relevant to the problems of precision agriculture and its application using WSN, which can be used to monitor the micro-climatic environments. Currently, WSN is considered as the most suitable and practical solution in this domain since wired deployment cannot cover the agricultural fields, grazing lands and monitored sites, which may reach several tens of hectares, within controllable cost. As its application is similar to the open-space monitoring, we propose a brief taxonomy of environmental and agricultural WSN applications, give in the figure below:

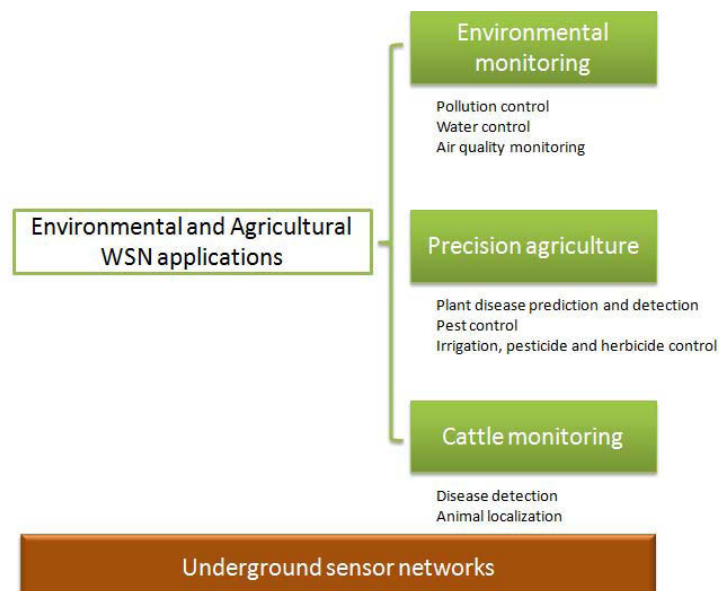


Figure 2-1 a brief taxonomy of environmental and agricultural WSN applications

In the current precision agriculture domain, a variety of applications have been developed and sensor nodes are scattered throughout the fields to monitor needed data, such as soil moisture, atmospheric temperature, light and wind strength, hours of sunshine, rainfall measurement, and humidity of the leaves. These data is the basic component of a decision

support system (DSS) that can achieve resource (e.g. water, herbicide, pesticide, fertilizer, etc.) optimization [7], disease detection and development prediction, pest control, frost protection [16], avoiding environmental pollution, intruder detection, yield prediction, fire detection, etc. In addition to these precision agriculture applications, cattle monitoring is another emerging application. The general surveillance of livestock is easy and helpful to observe cattle health status, to detect the burst of disease even plague, to localize cattle and to control end-product quality (e.g. meat, milk). Moreover, the sensor tags may save the condition information of the field crop and cattle, so it is also well suited for the development of supply chain management system.

The discussion within this section starts with the aspects of WSN node hardware and the solutions provided by the manufacturers that were investigated during the period of this thesis. An overview of communication protocols (both high- and low-level) is provided next, but the routing issues will be left to the next two sections for emphasizing the topic of this thesis. Finally, the available WSN/WMSN solutions are introduced, with a brief survey of the intelligent systems designed specifically for smart irrigation application. Since in our opinion, to address the problem of optimal crop irrigation is a more representative issue.

### 2.2.1 Resource-constrained Hardware for Wireless Sensor Network Node

Hardware domain is always a driving and active topic in research and industrial areas. The changes and possibilities in this field are fast and enormous. On one hand, the need and developing of new sensors for different application scenarios are increasing. On the other hand, the advances in miniaturization and embedded components with new features may lead to higher performance, such as bigger memory and saving more energy.

Apparently, a good design of the hardware system architecture is one crucial factor to the longevity, robustness and energy efficiency of WSN except the factors like synchronization accuracy, sample rates, precision, etc. The figure below depicts a typical WSN node architecture.

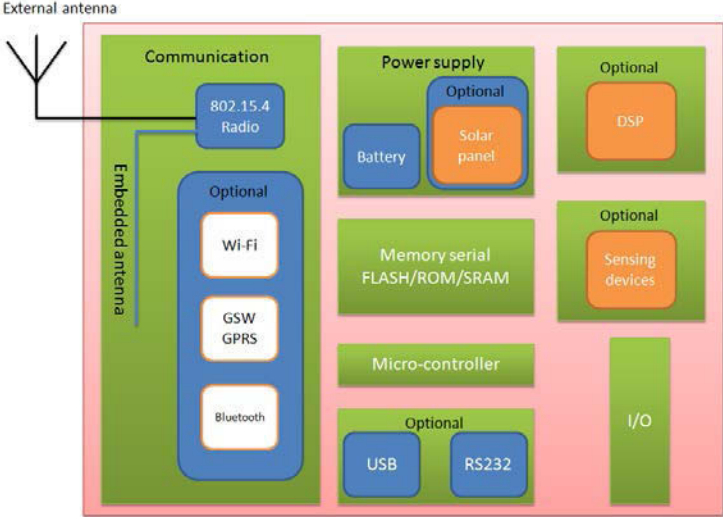


Figure 2-2 Typical architecture of WSN node

Due to the small size of WSN node, in some literatures, it is also called sensor mote or smart dust, but this type of device is often comprised of the following obligatory components, namely, Micro-Controller Unit (MCU), memory modules, power supply and input/output

component, radio transceiver module and antenna. In addition to these essential modules, one WSN node may also contain other optional components, such as sensing module, USB or RS-232 device, solar panel and DSP, or the modules for data communication.

**Processing power and memory:** are two of important resources for WSN node. However, MCU is only a low-capacity processor operated in low frequencies. Higher processing speed means higher energy consumption so certain trade-off between them is a key concern during the architecture design. It should be noted that some MCU have low-energy operation mode that means the MCU can wake its power up and return to sleep mode for extending the lifetime of the device. The current mostly used MCU are MSP430X and Atmel ATmega128X series [22]. Their processing speeds can achieve from 4 MHz to 16MHz, and their internal memories ROM ( $\leq 256\text{KB}$ ) and RAM ( $\leq 10\text{KB}$ ) are also very limited. An external memory chip device can be used to extend the storage space, but it only can be utilized for saving temporal data not for system program.

**Radio device:** provides based wireless communication to the WSN node with the characteristics such as sleep mode, low power mode, short distance and low data rate. To extend battery life, a WSN node needs to power its radio device off and go back to sleep after transmitting data to conserve energy. Except the sleep mode for power efficiency, its data rate cannot larger than 250Kbps due to its modulation techniques and specific requirements of minimizing cost and energy consumption, and its radio range is always less than 500m due to small transmission power ( $\leq 3\text{dBm}$ ).

**Antennas:** needs to be appropriate in the WSN because of the well-known constraints, for example, low cost and small size. But external antennas (e.g. Omni-directional antennas) are still commonly used in the deployment field, especially when PCB antennas cannot provide enough radio coverage.

**Power supply sources:** in WSN, the main target of power supply is often said to provide as much energy as possible at smallest cost/volume/weight/recharge time/longevity [23, 24]. As the biggest problem in WSN, energy issue cannot be solved by simply wiring WSN to the existing electrical power main cables so portable energy reservoirs like electrochemical batteries are the dominant power source for compact WSN nodes. Moreover, batteries can offer relatively high energy density at low cost. There are two types of battery, disposable and rechargeable ones. The former can only be used once like alkaline type of batteries, e.g. AA (1.5V, 1800-3000mAh). The WSN nodes on market supplied with 2AA batteries can run approximately 6 days if it is active all the time. Although the development of battery is still progressing, the lifetime of a WSN that is relied on disposable batteries is essentially finite.

Energy harvesting technologies are promising solutions of the above problem of limited battery lifetime and subsequent replacement especially where the WSN nodes are deployed in certain special circumstance. A harvester can be used as a lifetime extender for disposable batteries or to recover the voltage level of rechargeable batteries. Over the past few years, many related techniques of harvesting ambient energy have been suggested [25, 26].

Temperature differential, vibration, light and RF energy are four main sources. However, the amount of energy which can be collected from various sources is very differential and volatile. For example, in agricultural field, solar is the most commonly used source but the energy density in the outdoors environment is easily influenced by climatic condition and sun path [27]. **Solar panels:** is considered as the most adequate for energy harvesting usage in agricultural WSN applications because of its considerable amount of collected energy and its price [26]. Solar panel charging technology has been adopted by many products on the market, such as EKO node and Libelum Waspnote. The presence of solar panel cannot completely

solve the battery lifetime problem due to its low efficiency and some tradeoff versus the price, but it may after all be accepted as a solution for mitigating this limitation and prolong the field lifetime of WSN node.

Moreover, the harvested energy needs to be stored by some methods, such as super-capacitor (also named by ultra-capacitor or double-layer capacitor) and rechargeable batteries, to maintain power throughout the night and during cloudy days. But no matter which energy storage approach is adopted, there always exist limitations and problems, for example, Lithium-ion battery has limited number of cycles to charge/discharge (500-1000) problem, and super-capacitor has the limitations of high cost and low specific energy/cell voltage.

To sum up, as the decreasing prices of the WSN node and its peripheral devices, the ability to set up IoT testbeds containing hundreds of nodes becomes a real possibility. There will be more emerging technologies, for instance, new energy harvester, more powerful MCU with lower energy consuming. WSNs will be soon suggested and combined with daily life in the near future. Currently, although the advancements of these techniques are extremely fast, several issues caused by aforementioned constraints of WSN nodes (e.g. limited processing power, bandwidth and lossy connection link, and energy), such as QoS, energy efficiency, robustness and lifetime of WSN, and the most important, the special requirement brought by agricultural applications, are still very challenging and waiting to be solved.

## 2.2.2 WSN Node lower-layer Protocols

On one hand, the aforementioned hardware techniques are necessities for WSN, but they are not sufficient to exploit everything in WSN efficiently. On the other hand, communication protocols designed to handle complex interconnection in WSNs and maintain reliable and flexible data delivery process from each sensor node to the gateway/edge router towards the external networks are important part in this domain. Communication is the main work in an organized network since it represents the basic packet transmissions and receptions. Especially, communication also represents the most intensive process in terms of energy consumption issue. Many works have been done in this field to provide efficient, practical and careful design for establishment of reliable WSNs.

WSN communication protocols could be roughly divided into two types: lower-layer protocols and upper-layer protocols [28]. From the view of OSI model architecture, lower-layer protocols are typically responsible for the basic communication, connection maintenance and channel access functions, whereas upper-layer protocols manage the end-to-end data delivery between two sides' application-layers. Under the spotlight of the emerging framework of Internet of Things (IoT), we can easily make these two protocol divisions like the existing Internet. But as our discussion goes deeper, the two protocol classes are clearly developed and standardized by different organizations. On one hand, for example, IEEE 802.15.4 working group is devoted exclusively to the solutions for low-power wireless personal area networks (WPAN) [29] and it has become the core technique in this domain. On the other hand, upper layer protocols which are built upon IEEE 802.15.4 solution have more different options and possibilities, such as ZigBee protocol stack and 6LoWPAN solution. It should be noted that current upper-layer solutions have the tendency for provision of seamless and efficient IPv6 connectivity of WSN nodes into global Internet infrastructure, so it is able to drive WSN to the era of IoT.

IEEE 802.15.4 (version 2006) standard will be briefly presented in this subsection. As we knew, it comprises Physical (PHY)/Medium Access Control (MAC) layers that are corresponding to the physical layer and the data link layer of the OSI model. However, our

contribution on lowermost protocol layer is MAC layer, for environmental monitoring and WSN applications in agriculture are almost exclusively adopting the effort of IEEE 802.15.4 working group.

2.2.2.1 General overview of IEEE 802.15.4

The overall goal of IEEE 802.15.4 standard is to provide the WPAN solution for simple, low-cost and low-data-rate connectivity among widely spread devices, typically autonomous and without direct involvement of end-users [30]. This description includes different forms of sensor nodes in WSN, thus most of the available commercial WSN solutions use IEEE 802.15.4 standards as a basis for their MAC/PHY realization.

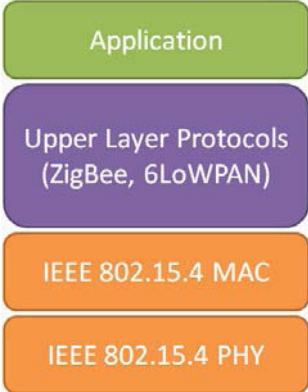


Figure 2-3 IEEE 802.15.4 lower-layer solution

The IEEE 802.15.4-2006 standard defines two types of network device: Full-Function Device (FFD) and Reduced-Function Device (RFD). The differences between these two are in the functionality they offer and the role in the network they are able to serve. FFD has more computing power, larger memory storage, sustain longer battery power supply, etc. Thus FFD is capable of serving any of the three network roles: PAN coordinator, coordinator and network device.

In contrast, RFD offers only a minimal set of functions defined by the standard and is able to perform only a role of network device. By the standard-defined constraints, RFD can only associate to a single FFD at a time so the communication between RFDs can only proceed if the intermediate FFD is involved. Using FFD and RFD devices, two different topologies are envisaged by the standard (cf. Figure 2-4): i) star topology, and ii) peer-to-peer topology. Both topologies are introduced in the initial standard and preserved throughout standard upgrades. Also, both topologies require at least one FFD device included in the network as a PAN coordinator.

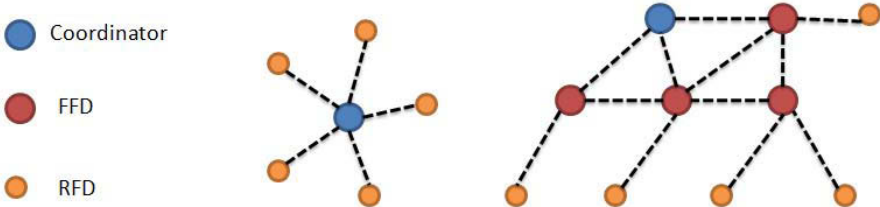


Figure 2-4 IEEE 802.15.4-2006 devices and topologies

The star topology consists of a single PAN coordinator, a FFD device that can communicate directly with all other involved devices. Thus the PAN coordinator is the central network point which is responsible for establishing, organizing and maintaining all the



network communication. Apart from the PAN coordinator, other devices can be either FFD or RFD. However, they are all required to communicate only via the central PAN coordinator.

In contrast to the star topology, the peer-to-peer topology allows direct communication between the network devices. Like the aforementioned star topology, it still requires at least a single FFD to serve as a PAN coordinator. However, the multi-hop routing of network messages using this topology is independent of the PAN coordinator and is performed autonomously by each involved device. This ability allows for larger areas to be covered by the network with more complex structures such as mesh network and cluster-tree, but routing is not directly supported by this standard and an additional upper layer is required.

#### *2.2.2.2 IEEE 802.15.4 PHY layer*

Over the years, several IEEE 802.15.4 PHY layers solutions are proposed and standardized, typically differing in operating frequency band, transmission range and data rates [31]. The main task of the 802.15.4 PHY layer is to provide data transmission and reception service to the 802.15.4 MAC layer, for example, efficient MAC frame (MAC PDU) exchange among WSN nodes. The main tasks performed by the PHY layer are [31]:

- PHY PDU encapsulated MAC PDU transmission and reception
- Channel frequency selection
- Clear Channel Assessment (CCA) signal generation for CSMA/CA MAC layer mechanism
- Link Quality Indicator (LQI) signal generation for received MAC PDUs
- Energy Detection (ED) signal generation for any of the underlying frequency channels
- Activation and deactivation of the radio-transceiver

From the above list, we may find that PHY layer can provide channel assessment functions and generate several PHY signals, such as RSSI, CCA and LQI signals, for MAC layer. Different PHY technologies are investigated as part of different sub-working groups within IEEE 802.15.4 working group. Its latest solutions are defined in IEEE 802.15.4x, while x is c, d or e, which are based on -2003, -2006, -2007 and -2012 version.

#### *2.2.2.3 IEEE 802.15.4 MAC layer*

The two general roles of any MAC methods consist of providing the MAC addresses to WSN nodes and enabling mechanisms for channel access in the situation where multiple nodes should simultaneously share a medium. The IEEE 802.15.4 MAC layer is developed with the target of coordinating access of WSN nodes to the physical medium [30]. It is mainly inspired by the IEEE 802.11 Wireless LAN (WLAN) MAC protocol, but is also introduced additional simplifications wherever possible. A set of tasks handled by the MAC layer in 802.15.4 is listed as following items [31]:

- Generating network Beacons if the device is a coordinator,
- Synchronization to the Beacon,
- Support for PAN association and de-association,
- Support for sensor node security,
- Application of CSMA/CA algorithm for PHY channel access,
- Handling and maintaining Guaranteed Time Slot (GTS) mechanism, and
- Providing a reliable MAC to MAC entity communication between devices.

The above tasks are described in the following text within the process of data communication between network devices using different possible channel access modes and, where applicable, applying CSMA/CA algorithm for random channel access. The IEEE

802.15.4 MAC PDU can be applied to four types of MAC frames: Beacon, data, ACK and MAC command frames. Furthermore, there are two options for device addressing within the network: 64-bit IEEE MAC address and 16-bit Short address.

Beacon enabled and beacon-less modes are the two operating modes in IEEE 802.15.4. These modes offer two different options for how much control is involved in communication process. In the beacon enabled mode, a PAN coordinator takes the role of a central network point which synchronizes and coordinates all the device communications within the network. In the latter beacon-free mode, there is no central control and the control of the channel access is distributed over all devices in the network by application of the celebrated Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm [30].

To sum up, IEEE 802.15.4 proposes a global standard at the MAC and PHY layer but it tries to respond to a wide range of application scenarios of low-power/data-rate/cost sensor and actuator networks. Its presence brings an operational standardized solution that may speed technology development in WSN. Moreover, this basic building block of WSN can be used by other MAC solutions as foundation. For this thesis, we will focus our attention in particular on routing protocol optimized for typically agricultural application scenario, considering the impact of MAC layer. Especially, MAC layer has been thoroughly studied in details over the last decade ( $\geq 100$  distinct proposed solutions), and we will discuss its important optimization designs in after sections, rather than repeat the details of standard.

### 2.2.3 WSN Node upper-layer Protocols

In this sub-section, the two nowadays main specifications for implementing the communication upper layer in WSN will be briefly discussed: ZigBee PRO and 6LoWPAN. Like the lower-layer protocols, these two solutions are also under fast development. Thus, only a basic structural knowledge of them will be mentioned and some elements may not be completely up-to-date. For the routing related issues and more details, we will analyze them more deeply in next two sections.

#### 2.2.3.1 ZigBee PRO

Arguably, ZigBee is the most popular low-cost, low-power consumption wireless networking standard in the current world [29]. The products using this solution have already covered many low-data-rate wireless networks. The below [Figure 2-5](#) depicts its protocol stack. ZigBee alliance defines its networking layer and its framework for the application layer on top of IEEE 802.15.4 MAC standard, so a designed standards-based protocol for interoperability of sensor network is able to be used by its customers.

ZigBee PRO network layer includes the functionalities to ensure the correct operation of the IEEE 802.15.4 MAC layer (single radio in its ad hoc networking) and to provide a set of service interface to the application layer. Moreover, it also can combine a set of routing protocols, such as AODVjr, hierarchical routing algorithm. Due to the routing supports and its improvements, ZigBee PRO network can support star, cluster-tree, and mesh topologies more efficiently.

Based on its specification, ZigBee Application Layer (ZAL) consists of Application Support (APS) sub-layer, ZigBee device objects (ZDO), and chip manufacturer defined application objects, hosting by the application framework. ZigBee devices are interoperable at the application layer according to a protocol specified by ZAL and the ZigBee Cluster Library (ZCL). Further, different typical applications for ZigBee (such as home automation, industry, and agricultural applications) are compliant to a vertical profile approach over the ZAL and

ZCL since they provide the key application protocol functionality in ZigBee, enabling the exchange of commands and data, service discovery, binding and security along with specific profile supports.

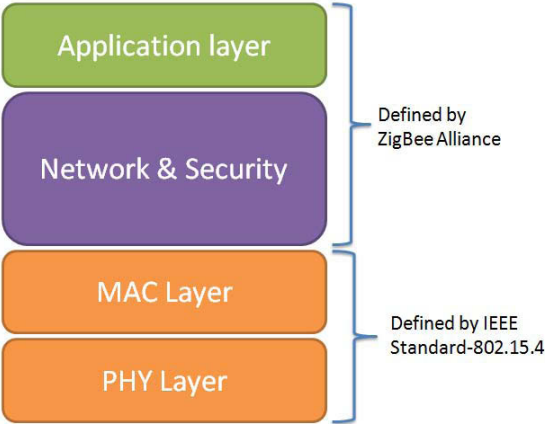


Figure 2-5 ZigBee Protocol Stack

2.2.3.2 6LoWPAN

6LoWPAN is a developing standard of the Internet Engineering Task Force (IETF) 6LoWPAN Working Group [29]. It was designed from the start to be adapted in future IPv6-supported sensor networks.

As stated by Geoff Mulligan (from the 6LoWPAN Working Group) [32], 6LoWPAN comprises a protocol definition to enable IPv6 packets to be carried on top of low data rate, low power, small footprint radio networks (LoWPAN) as typified by the IEEE 802.15.4 radio (see Figure 2-6). Their final goal was to define an adaptation layer to deal with the requirements imposed by IPv6, such as the increased address sizes and the 1280 bytes Maximum Transmission Unit (MTU). The final design took the concepts used in IPv6 to create a set of headers that allow for the efficient encoding of large IPv6 addresses/headers into a smaller compressed header (sometimes as small as 4 bytes), while at the same time allowing for the use of various mesh networks and supporting fragmentation and reassembly where needed.

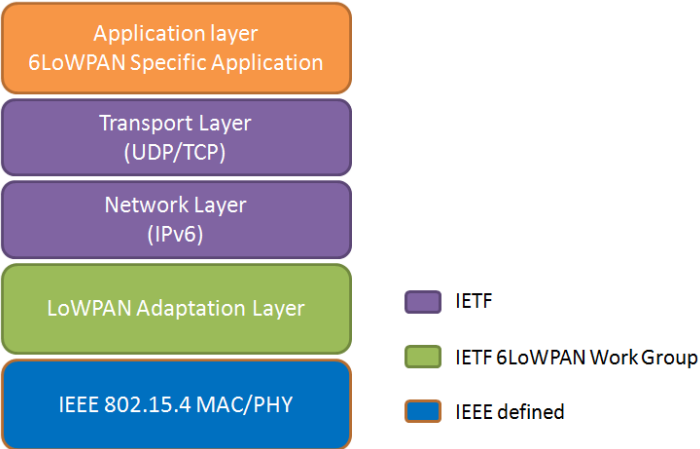


Figure 2-6 6LoWPAN compliant stack

6LoWPAN incorporates a new layer between IPv6 network layer and 802.15.4 MAC layer, called Adaptation Layer, whose main tasks are header compression, packet

fragmentation, and layer-two forwarding. An IPv6 packet is too big regarding to the data payload (127 bytes maximum) size of 802.15.4 standard thus it has to be fragmented. However, breaking up a big packet to number of small fragments and attaching new headers to each fragment may affect the energy level. Moreover, as mentioned in the RFC 4944, this adaptation layer is not only a compliance of IPv6, but also can deal with the packets produced by certain application exchanges (e.g. configuration or provisioning) may require a small number of fragments.

The four basic header types defined in the standard are dispatch header, mesh header, fragmentation header, and HC1/HC6 header. It should be noted that, 6LoWPAN adopts the same stacked headers techniques like IPv6 which means all the devices only need to send the minimum encoding headers. Thus, the cost of using 6LoWPAN is less than or at most equal to other similar protocols, and the overhead (also leads to energy consumption) for the most common packets are much less than other protocols.

However, 6LoWPAN specification does not define the rules of application protocol design since 6LoWPAN stack is dependent on standard internet IPv6 network and transport layers, however, according to [33] statements, application protocols complied with 6LoWPAN adaptation layer still need to have special design and performance requirements according to different scenarios.

#### *2.2.3.3 Application Development*

In most of cases, one WSN system has a special application purpose. The article [33] indicates a number of practical issues, such as commissioning, device role, addressing, mobility, data reliability, security and power limitations, which could be considered as a WSN application. Thus, there are two points of view during its development, one is the domain of application itself and the second point is another domain including the perspectives of hardware, WSN Operating System (OS) and network protocol stack.

Lightweight Operating system (OS) for WSN nodes constitutes the backbone of WSN architecture. Three mainstream types of OS (event driven, multithreading and hybrid paradigms) have been revealed in many previous literatures.

TinyOS is the first open-source OS specifically designed for embedded devices and is considered as the de facto standard OS for building WSN applications. It can combine a thread-programming model with an event-based execution model and its ported versions are able to run on a variety of hardware platforms. During the last ten years, TinyOS is also the main platform for new research development on communication protocols since its TinyOS Berkeley low-power IP stack (BLIP) was one of the first well-known implementation who supports 6LoWPAN solution. There is also a simulator named TOSSIM, which enables more development conveniences for its users.

Contiki is another open-source OS for WSNs and embedded devices. It is based on a multitasking non-preemptive scheduler using the proto-threads abstraction [34]. Similar to TinyOS, Contiki also supports several add-ons and libraries to organize its protocol stack, and its  $\mu$ IPv6 library also provides 6LoWPAN functionality. In the recent years, it has been considered as the second most extended and promising OS for building applications on WSN nodes and the IoT devices orienting the near future.

## 2.2.4 Overview of WSN/WMSN Solutions for precision agriculture

The Wireless Sensor Networks (WSNs) technique has been applied successfully for various environmental monitoring systems. Based on the research and technical development in this domain over decade, many studies have proved that the application of WSN in agricultural environment information monitoring is an alternative way to replace the conventional men force based method, and is also able to improve the convenience, efficiency and performance of traditional applications of Information and Communication Technology (ICT) in agriculture [35]. The underlying concepts of using WSNs in Precision Agriculture (PA) application are mainly related to sensors and their networks.

Advancements of technologies reduced the size of sensors but enhanced the efficiency of collecting information about agricultural environmental attributes. The sensor's accumulated information is valuable context acquisition [36] for improved monitoring and decision making capabilities. However, the recent technical trend indicates that scalar WSNs and their scalar data, such as temperature, soil moisture, air humidity and light intensity, cannot satisfy all the functional requirements of integrating grid computing, ubiquitous computing and context-aware computing into PA applications. Under the background of the emerging Internet of Things (IoT) technologies, the devices supporting video/audio multimedia functions can be easily connected to existing Internet infrastructure. Namely, the study of utilizing Wireless Multimedia Sensor Networks (WMSNs) to provide both scalar data and multimedia data for diverse environmental event detections, such as pest management and plant disease control. [37-40], will become a new research direction of PA domain.

When building a WSN systems or platforms, WSN node hardware devices, operating systems (OS) and energy storage devices are the most concerned as solid foundations. A classification framework that compares the existing OSs according to the core OS is presented in [41]. Architecture, reprogramming, execution model and scheduling are the core OS features that are utilized to constitute this classification framework. Several available energy storage devices are presented in [42], such as battery, fuel cells and ultra-capacitors. The latter two and energy harvesting techniques are emerging promising technologies [25]. Moreover, an exhaustive list of WSN node boards, vendors and their main characteristics are presented in [43].

Environmental monitoring applications are also the basic component in a PA system. The authors of article [44] classify it into wireless terrestrial and underground sensor network. In [45], they are broadly categorized into indoor and outdoor monitoring. A comprehensive review of wireless sensor and networks' applications in agriculture has been done in [46]. In various agricultural services, such as irrigation, fertilization, pesticide or herbicide spraying, animal and pastures monitoring, even horticulture, the researchers have proved the usability and efficiency of WSN in PA through their proposals, and practical systems and platforms.

The systems or platforms described in the above literatures surely represent the tremendous advance of scalar WSN, but the diversity of collected sensing data is still limited by resource-constrained devices. Furthermore, for PA applications, the scalar data such as temperature, soil moisture, air humidity and light intensity are not rich enough to detect all the environmental events including plant diseases and present of insects [40]. After the analysis of the monitoring data, an initial decision can be given by a relevant decision-support model defined in Decision Support System (DSS) of PA. No matter the final analysis is made by farmers or experts, if a PA system could provide more rich information integrating the

sensing data and multimedia detection results, an improved decision from DSS of PA and more precise long-term prediction can be achieved.

The authors of article [38] have discussed the current available WMSN platforms and proposed a robust multi-support and modular WMSN platform that is specifically designed for environmental event detection in PA. In [40], an effective approach of plant disease detection using the MiLive WMSN platform proposed in [38] is presented. Due to the existence of more powerful microprocessor in most of the WMSN platforms, the technologies including image processing, ubiquitous computing, etc. can be utilized in the field of agriculture. Moreover, as the fast development of microelectronics industry and the technology trend introduced in the first section, namely from the perspective of IoT [47], extending scalar WSN to WMSN is an imperative for the PA in the near future [37] and can promote this field to a new advanced stage.

## 2.3 Routing protocols for wireless sensor networks

The essential of routing is to direct the packet forwarding certain decision at each intermediate node from the packet source to its destination. In the majority of WSN scenarios, each WSN may contain a substantial number of nodes that are sensing source of the selected environmental phenomena and could be deployed over a large area. The packet destination is often called sink nodes with centralized collection functionality, and also can support basic packets processing for the end users. In most of the cases, sink nodes are equipped by more powerful hardware so that they can react to the complicated and anticipated events, such as a fire or a housebreaking, even a procedure of produced reactions. Due to the limitation of WSN radio communication range, multi-hop routing has been adopted by various WSN systems since the routing can decide on the succession of intermediate nodes that a packet should traverse to reach a sink node. WSN routing protocol design should follow three important rules: energy efficient, bandwidth saving, and scalability.

Like the traditional Internet and the case of WSN (IoT), it will be very convenient and helpful for retrieving information if each node is attributed a specific address to uniquely identify it, because this address can refer to a specific physical location and also the characteristics of the nodes. Based on our previous investigation, WSN usually adopts an approach called data-centric networking (also called content-based networking). Namely, this network waits for the queries from its end users and provides the answers. Practically, only a subset of WSN nodes is concerned to respond these queries, and the answers could be only provided by the nodes whose sensing data is matched with the requested criteria. Thus, normally, data centric approach and data aggregation are often combined with routing functionality. Moreover, our analysis is focused on the routing issue and its impact on quality of service (QoS) for agricultural WSN application, which are our essential concerns. As several alternative routes between a source and a destination node may exist, each of them could be selected by different QoS properties. In most of cases, a single route cannot be an optimal path to meet all the QoS requirements, thus the route selection should take specific applications into account.

In this section, our investigated WSN routing protocols are going to be introduced. However, due to the variety of current routing approaches and the recommendations from IETF for low-power and lossy networks, we have to focus on the routing required an explicit topology, which leads to the routing algorithm to construct paths for the packet sending and receiving.

*Reactive protocols* are normally suited for the scenarios where the network topology is highly dynamic, traffic is sporadic, and/or burst, and destination may change along the time [48]. Because of no maintained routes, this type of protocol is able to reduce overhead in its similar applied scenarios. The construction of a one-time use path is triggered only when a packet generation happens, followed by packet routing over it. Nevertheless, the reactive protocols do not fit for the periodic traffic since large control overhead may be incurred. The initial time needed to establish a route should not be neglected in the case of time sensitive traffic. This time additionally increases when the network scales to large size (the longer paths). A repair of routing path may be expensive in terms of time and control packets overhead because nodes do not maintain any information about alternative paths.

AODV (Ad hoc On-Demand Distance Vector) [49] is a foundation work, initially built for mobile ad hoc networks (MANET), which inspired reactive protocols for WSN. Lightweight On-demand Ad hoc Distance-vector Routing Protocol (LOAD) and LOADng [50] proposed a set of simplifications to the original AODV protocol to cope with the constraints of LLNs sensor devices also named as the mesh under approach of [51]. LOADng was recently proposed to IETF as a draft specification. Default traffic pattern supported by LOAD(ng) is bi-directional point-to-point traffic. Basic operations of AODV and LOAD(ng) can be resumed as follows. The bi-directional path construction starts on demand by issuing a route-request (RREQ) packet. A RREQ packet eventually reaches the destination after being flooded in the whole network. Upon receiving a RREQ packet, the destination node replies to the originator of the demand with a route-reply (RREP) packet. A RREP packet follows the previously installed reverse route. Reception of the RREP packet at the originator node installs a bi-directional path, making it available for immediate use. When a node detects a broken link on the installed path, a route-repair mechanism would be evoked. Basically a new RREQ/RREP cycle will start to re-discover the destination.

Simulation results [50] showed that LOAD(ng) provides a reasonably high data delivery rates in the networks with up to 1000 nodes randomly distributed on a square. LOAD(ng) achieves a low control data overhead in scenarios of sporadic P2P data packet exchange. Bi-directional path establishment works efficiently and it is invariant to the underlying network topology type. However, the simulation results lack findings on the LOAD(ng) performance for other types of traffic as well for periodic data exchanges.

*Proactive protocols* construct routes towards a set of designated destinations before their use and maintain them afterwards [52]. The routes are immediately available on a packet generation. The proactive approach is particularly suited for converged traffic: a single destination has to be announced in the network. Otherwise, the generated routing overhead increases with the number of routes being created. The incurred path maintenance overhead pays off for the case of periodic traffic from more collecting nodes and/or delay sensitive traffic. When network topology changes are sporadic but not drastic, route inconsistency has to be repaired only locally. A protocol avoids the huge cost of network wide flooding. A proactive protocol is recommended for the LLNs [1] and it will be discussed in next section.

*The hierarchical routing* ensures its data forwarding highly depending on the configured cluster backbone. A subset of nodes is selected to form a network backbone of connected cluster heads. Meanwhile, a cluster head collects packets from the sensors in its cluster and performs data aggregation in order to decrease the number of transmitted packets to the sink. For striving at energy efficient routes and scalable multi-hop operation, the main challenge of this type of routing is how to select the suitable cluster heads in distributed fashion. The authors of LEACH [53] proposed a seminal work. Briefly, the cluster heads are designed to be randomly elected, and announced at each round, then periodically changed to balance the

energy dissipation of nodes. Several improvements of LEACH have been proposed in [54]. Nevertheless, this type of routing protocols is never able to achieve efficient operation in the multi-hop topologies larger than a few hops.

**Multi-path routing protocols** use different manners comparing with the aforementioned routing strategies where a data packet does not follow a single end-to-end path from a source to a destination. Multi-path routing adopts two opposite approaches: a.) Redundancy - a routing protocol sends multiple copies of the same packet on different paths towards the destination. b.) Diversity - a routing protocol forwards packets from a stream of the same source along multiple different paths. In principle, it can be called the primary path and certain number of alternative (or back-up) paths. The main path is usually optimal, while alternative ones are often longer or more energy consuming. Comparing with the other routing methods, Multi-path routing has its own advantages, especially on its QoS provisioning for different applications, increasing network robustness in the dynamic environments, load balancing, low congestion, and effective bandwidth accumulation. Moreover, it has four basic types of multi-path operations fitting for WSN (as Figure 2-7).

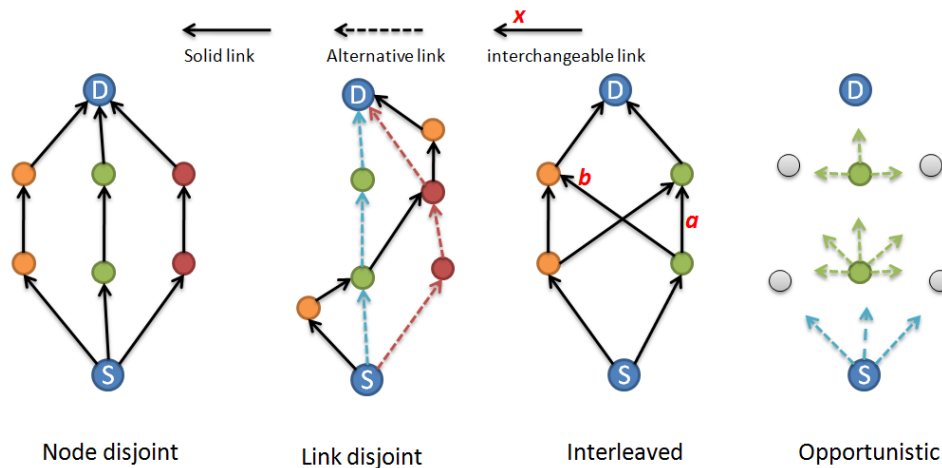


Figure 2-7 Classification of Multi-path operations: node/link disjoint, interleaved, and opportunistic

The differences between the node and link disjoint is obvious. The given multiple paths from the latter approach can share the same nodes but are forbidden to use the repeated links. But the former cannot share the nodes since each path has to go through different nodes. Thus link disjoint is better to be adopted in the WSN as its multiple paths can offer fair level of robustness, low impact of node failures, low complexity and low maintenance cost [55]. Moreover, interleaved approach can enhance the node disjoint further because it uses interchangeable nodes/links to build different paths between a source-destination pair. The literature [56] has discussed to adopt interleaved path considering the QoS reliability requirements of flooding packets. Their proposal can decide how many neighbor nodes need to forward the same packet in each routing step. However, the method proposed by the authors in [57] could explicitly decide on how many paths will be used to send the same packet.

Comparing with the above propositions, opportunistic routing approach has more flexibility and is more simplified because no multi-path structure is built in advance. Only a best-effort type service can be provided and impossible to make hard QoS guaranties. As the routing philosophy becomes to packet basis decisions, the packet holders can choose the most appropriate links and replicate more copies to its neighbors. The nodes with opportunistic routing algorithm use intuitive step-by-step adaptation to mitigate the complexity of building and maintaining multi-path structure but with the cost of degrading their QoS. Thus,



opportunistic method is usually accompanied with other routings, for instance the geographical routing, to achieve higher level of QoS.

Notice that this section is not a comprehensive survey on routing protocols of WSN. The only purpose is to provide an overview of the WSN research in this issue over a decade. Moreover, in next section, we will introduce the exclusive routing standard for IoT, which integrates most of the appropriate strongpoint in the above previous works.

## 2.4 Routing protocols for current Internet of Things (IoT)

### 2.4.1 Based concepts of IPv6 Routing protocol for low power and lossy networks (RPL)

RPL is a standard designed exclusively for routing in LLNs with the expectation of joining thousands of conventional WSN nodes in the network. It supports three basic traffic patterns: multipoint-to-point (MP2P), point-to-multipoint (P2MP) and point-to-point (P2P) (Figure 2-8). The basic idea of RPL is that the high degree of autonomy in the WSN nodes level through building a Destination Oriented DAGs (DODAGs) rooted towards one sink (also called gateway or border router device that is able to connect to IPv4/6 internet).

Table 2-1 Main features of RPL protocol

| <i>Feature</i>                  | <i>Description</i>   |
|---------------------------------|--|
| Network objective               | Application-oriented LLNs (IPv6/6LoWPAN)   |
| Routing methods                 | Source-routing and distance-vector algorithms                                      |
| Traffic flow mode               | MP2P, P2MP and P2P   |
| Basic topology                  | DODAGs-based structure, RPL Instance complianced with defined Version number or ID |
| Control messages                | DIO, DAO, DIS regulated by trickle timer algorithm                                 |
| Neighbor discovery              | IPv6/6LoWPAN neighbor discovery (ND)   |
| Transimission mode              | Uni-cast, Multi-cast, Group-cast   |
| Routing Metrics and constraints | Flexibile and dynamic user defined composition; OFand Rank computing-based         |
| Route info mode                 | Storing and non-storing  |
| Loop avoid methods              | Local/global repair mechanisms   |

In the RPL-based network, it uses three types of control messages. DODAG Information Object (DIO) messages (sent in multicast way) are used to construct and maintain the upwards routes of the DODAG for MP2P traffic pattern. Moreover, the downward routes (for P2MP) are managed by Destination Advertisement Object (DAO) messages that are sent by router node and used for the propagation of routing tables. Another common message is DODAG Information Solicitation (DIS) that can be sent by any node in RPL to solicit DIO messages from its neighborhoods to update routing information. In the RPL specification [1], there are more detail explanation and statement that the reader can find and comprehend. However, only the main features of RPL will be mentioned here to avoid too much content from the standard specification, and a brief summary is presented in Table 2-1.

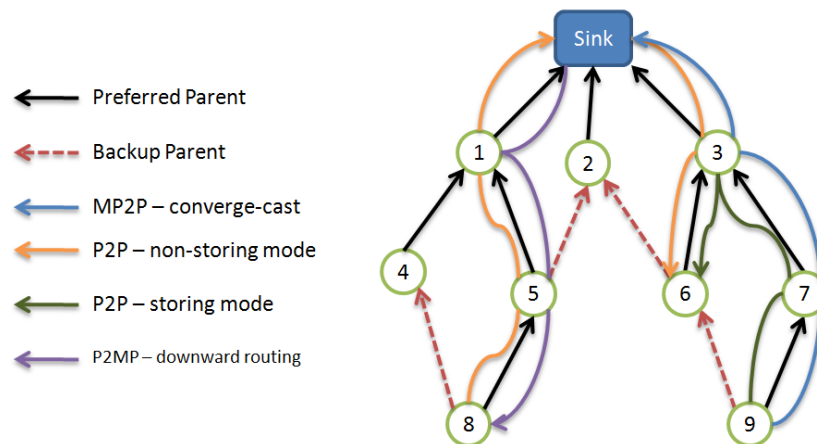


Figure 2-8 RPL DODAG topology and traffic patterns

Furthermore, it will be a desirable way and more attractive to discuss the key concepts of RPL related to Agriculture-LLN (A-LLN) here, rather than utilize extra and redundant paragraphs to repeat the basic mechanism of this elegant routing protocol. A better organized and clarified statement of RPL can be found in [12, 58].

ROLL working group has a deep consideration and long visions for the development of RPL routing protocol. Especially its unique characteristics compared with the conventional routing protocol in the wired or ad-hoc networks described in its specification, this protocol is able to be adapted to a variety of network types through applying specific Objective Functions (OFs). A DODAGs can be optimized according to the specialized OF and identified by an Objective Code Point (OCP), which indicates the dynamic constraints and the metrics (listed in the [Table 2-2](#)), such as hop count, latency, expected transmission count, parents' selection, and residual energy [59].

Table 2-2 A list of routing metric/constraint objects for RPL

| <i>Routing Metric/ Constraint objects</i> | <i>Description</i>  |
|---|---|
| Node state and attribute                  | CPU, Memory, congestion situation   |
| Node Energy                               | Power node, estimated remaining lifetime, our own power metrics               |
| Hop Count                                 | Number of hops  |
| Link Throughput                           | Maximum or minimum value  |
| Link Latency                              | Sum of all latencies, pruning links higher than certain threshold             |
| Link Reliability                          | Packet reception ratio, BER, mean time between failures... LQL; ETX           |
| Link color                                | 10-bit encoded color to links, avoid or attract specific links/ traffic types |

The OFs are belonged to a relative single specification and separated from the core of RPL. This increases the flexibility and scalability of this protocol standard and more important is that RPL is easier to be adapted to meet the requirements of different LLNs and application scenarios. From the OF0 containing single metrics proposed in [59] to a set of ROLL's drafts, numerous contributions have been made for providing Quality-of-Service (QoS) routing in various use cases of LLN. The main idea of ours is to build the OF with a combination of path weight value calculating algorithms with a composite metrics, considering of elementary metrics defined in [59].

## 2.4.2 Modeling and experiments of RPL routing framework

Any routing protocols cannot leave simulation and experimental models. Several works and papers have been proposed for the experiments of RPL and the evaluation of its performance.

The first official simulation model draft is built on OMNET++ [60]. This model can be used for basic performance evaluation study of RPL, such as the MP2P and P2P routing. The authors found that the position of the root node will influence the simulation results. In addition, they demonstrated the efficiency of the trickle timer in controlling the packet overhead and stabilizing the network. In their small-scale network, the simulation shows the significant effect of control packet overhead caused by the global repair procedure.

The authors of [61] tackle the issue of the possible appearance of routing loops which may happen during the procedure of nodes' parents changing and ranks increasing. Their team developed a simulation model of RPL under NS-2 simulator. This model can simulate a large-scale network composed of 1 to 1000 nodes deployed in a large space. In this paper, through the network convergence time and routing messages overhead performance evaluation, the author proved that the majority of the routing loops are resolved in a very short time and just lead to the generation of quite few DIO messages. But in some special cases, when one node carries out the rank increase operation, it may trigger and generate multiple routing loops so the network needs more time to converge to a stable loop-free state. The related node will of course produce a significant number of DIO messages. Thus, the authors found out the default loop avoidance mechanisms are not practical for large-scale RPL networks. This team also presented the RPL P2P routing solution in another paper with the same simulation platform.

The above two simulation models are not open source, thus it is not possible to be used as a good start of this thesis. Thanks to Contiki COOJA [34], the preliminary work is more easily to begin. The author of [62] also adopted this platform to evaluate the network overhead, the throughput and the end-to-end delays for various network sizes. The authors reported the network set-up time, the influence related to the DAO messages and the enhancement of control overhead of RPL, and also pointed out that RPL is still open for further improvements to optimize in facets of convergence time and control overhead in different specific applications.

The simulation models can provide the insights of RPL protocol's behavior. But due to their dependence of emulated channel models, they cannot report the exact performance of RPL, because the simulated environments are different from the real channels, and their hardware emulators are also not dependable. Thus, the real-world testbeds are very important to assess the real protocol behavior and performance.

ContikiRPL is the first implementation of RPL for real-world devices. It is integrated in Contiki OS as a built-in component routing protocol. The platform of Contiki is quite comprehensive including simulation, experimentation, and evaluation of RPL's mechanisms and performance. It provides simple programming interfaces for replacing the old Objective Functions of ContikiRPL. TinyRPL is another real-world implementation of RPL. It is based on TinyOS 2.x and BLIP. In paper [52], the authors evaluated the performance of RPL through real experimentation using TelosB motes and compared with the CTP protocol. These two RPL implementations have a certain level of interoperability, but need more tests since there was still obvious limitation in the evaluation results.

For a better classification of the implementations and simulators incorporating with RPL, two tables (See [Table 2-3](#) and [Table 2-4](#)) are summarized for both of them.

Table 2-3 RPL implementations for real-world devices

| <b>Name</b> | <b>OS platform</b> | <b>Standard version</b> | <b>Note</b>   |
|-------------|--------------------|-------------------------|---|
| ContikiRPL  | Contiki            | RFC6550                 | Official supporting of Tmote sky platform   |
| OpenWSN     | OpenWSN            | RFC6550                 |   |
| TinyRPL     | TinyOS             | Draft-ietf-roll-rpl-17  | -only TelosB and Epic platform supported<br>-only storing mode and single DODAG supported |
| NanoQplus   | NanoQplus          | Draft-ietf-roll-rpl-13  |   |

Table 2-4 RPL enabled simulators

| <b>Name</b>      | <b>Programming method</b>               | <b>Standard version</b> | <b>Note</b>                |
|------------------|---|-------------------------|----------------------------|
| Cooja/Contiki    | C with limited JAVA libs and Javascript | RFC6550                 | Supporting MSPsim emulator |
| OpenSIM/OpenWSN  | C with Python                           | RFC6550                 |                            |
| NS-3             | C++ and Python                          | Draft-ietf-roll-rpl-19  |                            |
| OMNet++/Castalia | C++ with wrapped NED                    | Draft-ietf-roll-rpl-19  |                            |
| J-SIM            | Tcl/Java                                | Draft-ietf-roll-rpl-19  |                            |
| WSNet [63]       | C with XML                              | RFC6550                 |                            |

During the two-year investigation work, we found that RPL is designed to be widely applicable. Thus, many configuration options of it are available. ROLL specification [1] presents a number of design choices and configuration parameters that may lead the developers to build a more efficient RPL implementation and operation. In the IETF RFC document [64], an overview and evaluation profile are given and provides a performance evaluation of RPL with respect to several metrics of interest (two use cases: a small outdoor nodes deployment for building automation and a large-scale smart meter network).

### 2.4.3 Available Internet of Things (IoT) protocol stacks

In last sub-section, the existing RPL routing models which can be utilized for hardware platforms or simulators have been introduced. But in any projects based on RPL protocol, a protocol stack is required as a foundation to enable ultra-low power and highly reliable mesh network that can be fully integrated into the Internet. Thus in this sub-section, four most promising and viable protocol stack solutions for IoT as well as the upcoming Machine-to-Machine revolution will be analyzed.

As the ZigBee communication stack have been discussed in sub-section 2.3.1, it has been proved that it well aims to enlarge the network in a multi-hop fashion and guarantee the device reachability. However, for achieving the sense of IoT, how to manage a potentially very large number of smart wireless devices forming a capillary networking infrastructure that can be connected to the Internet [65] is still a big challenge for ZigBee. Although ZigBee has the supports of IEEE 802.15.4 standards and solid upper layers, it is not easy to connect ZigBee network to IP-based Internet. As a matter of fact, ZigBee alliance released a new stack so called ZigBeeIP stack, as pictured in [Figure 2-9](#). This new work includes three important layers, such as RPL routing, 6LoWPAN adaptation and CoAP application layers, defined by three different IETF working groups. These new protocols can easily work together with IPv6

and UDP. Thus, ZigBeeIP is stated as a stack that supports IPv6 communications in IoT-compliant multi-hop LLNs.

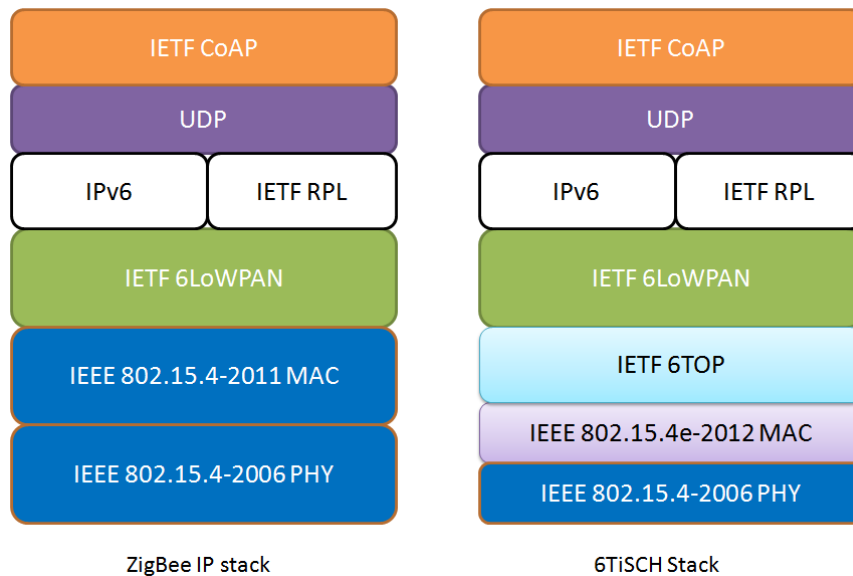


Figure 2-9 ZigBeeIP stack and 6TiSCH stack

Furthermore, the original IEEE 802.15.4 MAC was found that its multi-hop settings are inefficient and unpractical since the use of single channel nature causes its reliability to be unpredictable, and the CSMA/CA method introduces the idle-listening and radio overhearing issues [65]. So in order to cope with large-scale multi-hop resource constrained and IPv6-compliant LLNs, the IEEE standardization integrated the Time Slotted Channel Hopping (TSCH) mechanism into the IEEE 802.15.4e MAC amendment [66]. For utilizing this new powerful MAC within the framework of IPv6-based LLN protocols, “IPv6 over the TSCH mode of IEEE 802.15.4e” (6TiSCH), a new IETF working group was built and have made the efforts, such as to provide the solutions of an optimal distributed scheduling technique and the security mechanisms, especially for industrial LLN applications. Moreover, the 6TiSCH working group has been recently setup to introduce a new intermediate layer, namely the 6TiSCH Operation Sub-layer (6TOP) (See Figure 2-9) [67] in their stack.

Actually, as a commercial software set, ZigBeeIP stack will be similar to its predecessor, and they are not open source. Nevertheless, 6TiSCH stack is still under the period of designing and standardization or at least there is not a prototype of it till this dissertation was started writing. The two following standards-based and pure C protocol stacks, OpenWSN and Contiki uIPv6, are from open-source projects. Furthermore, they can be easily carried out on both off-the-shelf hardware platforms and their specific simulators.

The OpenWSN is not only a protocol stack but also a complete platform with a set of tools developed around this stack. The tools include convenient visualization and debugging software, a simulator, and the whole environment required by Internet connecting. As shown in Figure 2-10, OpenWSN stack is entirely based on IoT standards and similar to the design of 6TiSCH stack using IEEE 802.15.4e TSCH standard to replace the historical MAC protocol. Furthermore, except the aforementioned issues, OpenWSN also makes its efforts on dealing with external interference and multi-path fading issues. According to their evaluation results from GINA platform [68], the memory footprint and energy consumption are quite admissible. Because motes can be synchronized, they are able to wake up only when they need to transmit or receive. And the overhead for keeping the network synchronized, such as the keep-alive message and its ACK, is extremely small (i.e. about 0.02% radio duty cycle for

re-synchronization). On top of IEEE 802.15.4e, OpenWSN implements IoT related standards, such as 6LoWPAN, RPL and CoAP, so their resulting protocol stack can combine ultra-low power, high reliability, Internet connectivity, as well as M2M supporting. This protocol stack is designed to be easily ported to any targeted platforms, and it should be noted that until now, it is also the first and exclusive open-source implementation of the IEEE 802.15.4e standard to the best of our knowledge.

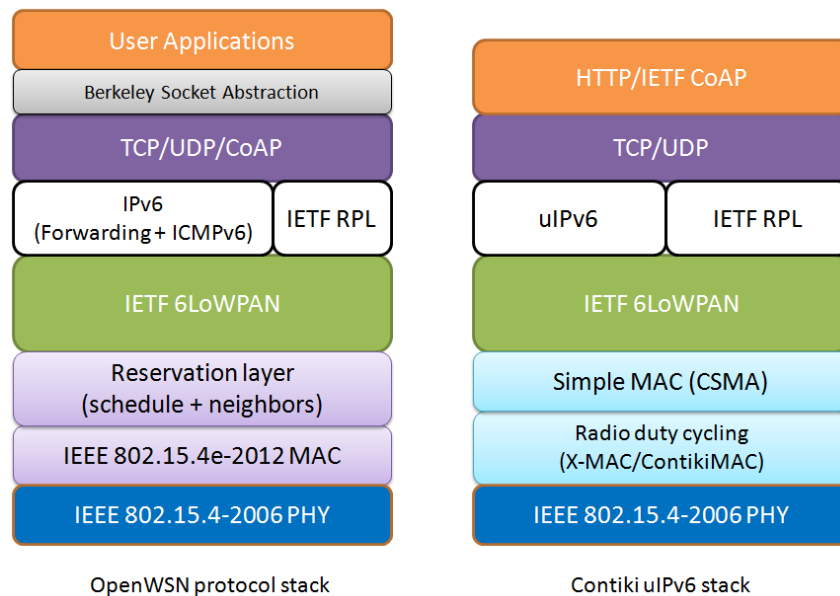


Figure 2-10 Open protocol stack and Contiki uIPv6 stack

Notice that OpenWSN protocol stack and 6TiSCH stack are designated to adopting 802.15.4e MAC standard released by IEEE in 2012. In one latest literature [69], the authors have highlighted the main limitations and deficiencies of the original 802.15.4 standard, especially for the industrial or healthcare applications with special requirements in terms of timeliness, reliability, robustness, and scalability. They also presented some simulation results to show the performance improvements allowed by the new 802.15.4e standard with a set of protocols defined by IETF. The simulation results are used to better reveal how the previous limitations can be overcome by the new protocol integration, which is also a big step towards the IoT.

Moreover, comparing with the belated OpenWSN and ZigBeeIP (released officially in the year of 2013), Contiki uIPv6 stack has already achieved much more progress, including self-contained tools, thorough evaluation, and longer period of debugging and testing since the year of 2010. Thus when this thesis was just beginning, this protocol stack is the only one can be seen as a reference and to be tested. As the first lightweight operating system for IoT, Contiki and the tools around it have passed decade of development. In recent two years, Contiki and its protocol stack have become the most popular platform for the experiment of testing IoT standard protocols. Its OS and software suit were ported on over 30 different commercial hardware and evaluation boards. As the Figure 2-10 depicts, there is a special duty-cycling MAC protocol named ContikiMAC running above the standard-based PHY layer. And the real MAC layer is simplified as a simple CSMA/CA model. But the IoT protocols on top of them follow the specifications released by the IETF working groups and the whole system can be tested by Contiki's COOJA/MSPsim simulator or available hardware devices with the exactly same low-memory-footprint binary code. From the view of its power efficiency, under the case of each node generating a total number of 40 best-effort UDP packets per minute, leaf nodes only cost 0.5-0.8% duty cycle and router nodes have a duty

cycle of 1-3%. Thus after the amount of traffic is adjusted, the average lifetime can achieve to several years with standard AA-size batteries.

## 2.5 Optimization techniques for routing in IPv6 Low-power and Lossy Networks (LLNs)

From the overviews of the aforementioned existing protocol concepts, cases and implementations, we found that using the IPv6 routing standard - RPL is the only choice to cover the agricultural WSN and precision agriculture application in the light of the new IoT paradigm. This is not only because ROLL working group had made their standardization efforts with elaborated specification for RPL over more than seven years, but also because this routing framework standard is based on over decade of WSN research and designed for a comprehensive number of various use cases: home automation, industrial automation, urban environments and commercial building automation [1]. The flexibility of RPL allows us to easily expand its applicability to agricultural WSN, since most of the WSN nodes used in this scenario are battery-powered and deployed in dynamic large-scale fields like most of outdoor environments that may cause lossy link in the multi-hop networks built by the WSN nodes.

As an emerging routing protocol, RPL obtained very fast development in the research field. Currently, its basic mechanism has been thoroughly evaluated through various simulation [58] and real-world protocol stack. Moreover, the ROLL working group also provided numerous RFC documents to describe in details about RPL protocol functioning [70], supported scenarios [21], design guidelines and requirement definitions of the final protocol [14, 71, 72], supported routing metrics [73], energy optimizations and stability mechanisms [74, 75], and preliminary test results [76]. Nevertheless, there are still a lot of spaces left for optimization and improvements of this protocol, especially when the specific mechanisms of RPL and more practical issues in real-world environment are considered. In this section, we mainly summarize the state-of-the-art of RPL's optimization techniques.

### 2.5.1 Energy-efficient metrics and Context-aware objective function

Normally, the routing metrics and Objective Function (OF) in RPL belong to the key component of routing in LLNs because the OF defines how to translate one or more metrics and constraints into a rank [77] which is also similar to gradient-based routing [78]. And OF also specifies the behaviors of how a node selects its parent. Currently, two RFC specifications have presented two OF solution. One of them is basic OF0 defined in [79], and another one MrhOF [77] is more practical so it has been implemented by most of existing RPL models. The routing metrics of RPL are carried by the DIO message option space. OF algorithm is proceeded by each LLN node, and its results will be compared to the calculated weight values hold by the captured DIO to select the preferred parent among its neighboring nodes.

The Expected Transmission Count (ETX) link cost estimation has been often used and verified since it was proposed and elaborated by IETF specification. However, using ETX can bring two obvious drawbacks. The current parent selection mechanism of OF using ETX prefers the parents with the lowest rank. MrhOF won't investigate and evaluate the newly discovered links in high possibility. Namely, the LLN nodes only maintain their parent list

with the currently used link. For the first drawback, the authors in [80] propose a passive probing solution. Their solution will consume more energy when the network starts to converge since their modification force nodes to discover all neighboring nodes as potential parents. The authors also suggest using cache management to solve the problems of rediscovery and re-evaluation. Another drawback is that the router nodes which are near or have good link connection with the sink node will exhaust their batteries in relatively short time, which is also referred as wireless hot spot problem. The reason is apparent because all the other nodes prefer to choose these nodes with smaller additive ETX values based on the selection algorithm. Actually, this phenomenon could influence the network lifetime. If LLN nodes that are closest to the data sink tend to die earlier, parts of the network can be leaving completely unmonitored and causing network partitions. Thus, the authors in [74, 81, 82] propose their work on the considerations of joining multiple conditions (link reliability and energy) to conduct routing in LLNs.

In [82], the authors suggest using an energy-oriented routing decision algorithm which can attempt to reach averaged overall network energy consumption and therefore prolong the lifetime of LLN nodes. Meanwhile, their proposal could help to reduce energy consumption on management and maintenance of the DODAG topology. An ETX plus node residual energy-aware routing algorithm solution is described in this paper.

In article [74], the authors present a new energy-aware and resource oriented enhanced version of RPL, called Resource Oriented and Energy Efficient (ROEE) RPL. They have combined two metrics -- Energy consumption (EC) and Battery Index (BI) to define their energy-aware OF. Moreover, they use resource availability information to refine the rank of each node, and define the binary Resource Availability (RA) parameter in their solution.

In article [83], X.LIU et al. present a new OF and attached routing algorithms to construct a load balanced RPL DODAG. Their new protocol is named as LB-RPL which can achieve balanced workload distribution in the whole network. In addition, they adopt a distributed and non-intrusive fashion to detect the workload imbalance.

Another latest literature [84], which can inspire our work, offers a solution to increase the network lifetime based on a new Energy-aware Objective Function (EAOF) that adopts ETX and remaining energy metrics on each LLN node for routing computation of RPL. The authors focus on the biomedical WSN, especially targeting the domain of healthcare and its applications in the context of E-Health. Their proposed method can increase the network life by 21% and reduce the peaks of energy consumption by 12% comparing with other state-of-the-art solutions (e.g. ContikiRPL). Namely, EAOF could make significant improvements in energy consumption, load balance and network lifetime. Furthermore, with the driving of this new combination of RPL and biomedical wearable sensor networks, the authors' work mitigates the existing problems in the emergent health technologies field (i.e. user' acceptance and wearable system).

### 2.5.2 Routing metrics Composition approach

As stated in [1], OF specifies the rules to select the best parents in the DAG, the number of backup parents, etc. It is decoupled from the defined routing metrics and constraints. Thus, a key algorithm of OF is path calculation that ensures positions (rank) of routers in the DODAG. Normally, the values used by path calculation algorithm are from two types of routing parameters, one of which is routing metrics and another one is routing constraints. Specifically, a routing metrics is an additive and quantitative value which is used to evaluate



the path cost. In RPL, the routing constraints are advertised by the DODAG root. They are used as a “filter” to prune links and nodes that do not satisfy specific properties (e.g. link quality, power-supply methods or a specific user-defined “color” of link characteristic). Contiki does provide a simple approach of single metric (ETX) with no constraint, but it provides extendable interfaces to realize routing constraint in current MrhOF model. To sum up, best path/shortest constrained path should present lowest cost and meets all supplied constraints.

Moreover, the routing metrics can be divided into three categories, such as Link/node metrics type, qualitative/ quantitative type, and dynamic/static type. Notice that, the use of a metric or a constraint is not exclusive. It can be very flexible to use link and node characteristics to meet our routing requirement. For example, the dynamic metrics with necessary multi-threshold: links, nodes’ resources (e.g. residual energy). To be noticed, spurious and unnecessary routing changes may be caused by fine granular metric who updates reflecting each individual change. Thus, different metrics may have different reporting frequency or rates [77].

To the best of our knowledge about traditional WSN, link reliability metric used by a routing protocol means building a DAG with the goal to maximize reliability. The metrics should be ‘Aggregated’ or ‘Recorded’ metrics (e.g. the number of hops, link quality along a path). Moreover, the metrics values of the link (e.g., wireless, wired, PLC) are obtained from MAC layer. Additionally, the node characteristics, for example, a routing constraint of energy powered fashion, such as main-powered or battery-operated, can be adopted to optimize the power consumption for the whole network. More examples are listed below:

- An application requires a quick delivery of packets using a short path and therefore the goal will be to use ETX metric for routing.
- An application may require encrypted communication and therefore the goal will be to avoid non-encrypted links in the path.
- A node may be energy constrained and the objective will be to minimize Energy Consumption by using as many mains connected nodes along the path as possible.

In article [73], the authors present the basic and derived metrics properties and rules. They also discuss about the drawbacks of using single metric, and the possibility and requirements of adopting the composition metrics. As mentioned in this article, generic rules for metrics composition in lexical and additive manners have been defined to achieve convergence, optimality and loop-freeness for RPL. The lexical approach is suitable for any combined two basic or derived metrics but should keep strictly isotonic, for example, Hop Count (HC) and ETX, latency and packet loss percentage. The metric used first is dominating over the second metric since the second one is used only as a tie-break. In the additive manner, multiple additive routing metrics can be composed if they follow the same properties and rules (metric operator, metric order relation). Link or node characteristics can be captured in a more balanced manner. The authors also give a conclusion: the lexical approach is less restrictive. Additive manner is more demanding in mathematical formulation but has more flexibility which can satisfy various QoS requirements according to user demand.

Based on the design guidelines from above literatures, the authors in [73, 85] elaborate how to apply composite RPL routing metrics to satisfy different applications needs and WSNs QoS requirements. They also specify the ways to combine primary RPL routing metrics and prove their proposal by the theoretical framework of routing algebra formalism, and evaluate the achieved performance of their approach quantitatively through the verification in the simulation scenarios.

### 2.5.3 Cross-layer optimization techniques

From the introduction about the available RPL protocol stacks, it can be remarked that the layered approach is often adopted in the WSN research field. Since ROLL and 6LoWPAN working groups pushed WSN into IPv6 vision and the driving IoT technologies, the classical OSI model based layered philosophy is not only used for reducing the complexity, but also make each layer becomes responsible for a limited and well-defined set of tasks. In details of the aforementioned IoT-compliant stacks, MAC layer would take the charge of radio bandwidth sharing, and its upper layer 6LoWPAN will only regard IEEE 802.15.4 for the transmissions. IP layer is utilized for interoperability such as using RPL to make routing decisions.

The stack implementation details are hidden behind the abstract interfaces and each module has their own well defined set of services. This type of design could lead to a simplified protocol stack architecture that should be easily interchanged and replaced. We believe that keeping the standardized layered framework with distinct functionalities and responsibilities of each layer can simplify the protocol design, clarify challenges and speed up the development of IoT [12].

WSN is constituted by WSN nodes which are often battery-operated and have limited resources. The radio duty cycling issue has been discussed in the sub-section 2.4.3. This energy saving mechanism is to keep nodes sleeping in most of the time and wake up periodically to handle communication. A basic trade-off has to be often made between energy, latency, packet deliver ratio (PDR), etc. Thus, the integration of different layers (e.g. routing and MAC) is vital and beneficial, such as reducing memory footprint or energy consumption. As the building block of this thesis is about routing, we especially cannot neglect the influence from the underlying MAC layer, even the upper application layer. The left parts of this sub-section will be mainly focused on the latest literatures using the cross-layer philosophy [86].

In the article [87], the authors improve their previous work of using opportunistic routing to achieve low-latency yet energy efficient data collection in WSN [88]. As the similarities of WSN and LLN discussed in previous sections, the authors decide to adopt opportunistic approach in the LLN context to achieve the requirements of certain LLN nodes, such as individual address and irregular traffic patterns. Their ORPL model relies on any-cast and opportunistic routing. The former is built upon a low-power listening and duty cycling MAC protocol – ContikiMAC. The latter mechanism is based on an enhanced ContikiRPL protocol.

The literature [89] is an extension and more detail work based on the article [87]. Full considerations have been done for the applications which are organized by addressable end points generating traffic with arbitrary patterns. The simple periodic data sources cannot achieve the requirements of the new era of WSN that may require acting as an application-agnostic routing infrastructure. However, their presented ORPL, which is built upon RPL standard and combined with opportunistic routing, enables to support any-to-any and on-demand traffic. Furthermore, two mechanisms, such as bitmaps and Bloom filters, are adopted to meet the targets of space-efficiency, nodes' addressability and networks' scalability.

Their testbed used by above two articles was one experimental platform with 135 nodes named as Indriya testbed [90] and the evaluation results represented that ORPL outperforms the latest solutions, such as standard RPL and CTP models. Latency and duty cycle are conciliating to obtain higher robustness and scalability. Meanwhile, the size of ORPL's routing-table free solution drops down due to using a 64-byte Bloom filter instead of regular routing tables consumed kilobytes' memory for RPL standard. It is very transparent that [91]

didn't choose a common type of cross-layer optimization strategy because they didn't merge adjacent layers, but indeed, they tried to mutually collaborate the entire protocol layers in the flexible Contiki uIPv6 stack. This method is referred as "vertical calibration" in [23] since their proposal strives to find the optimal settings from the global point of view, namely from application level to the MAC level.

[92] adopts conventional cross-layer optimization not like ORPL model. For answering the existing questions in internet draft of the "Multicast Forwarding Using Trickle" (Trickle Multicast) and addressing this domain in RPL's specification, the authors introduce Stateless Multicast RPL Forwarding (SMRF), which is a specific mechanism for RPL networks. SMRF is also extended from Contiki uIPv6 stack. But, configuring SMRF with suitable parameters of duty cycling algorithm, such as channel check interval and forwarding delay, is particularly useful in their case. Thus, the authors also design and create new interfaces between RPL routing layer and duty cycle layer to achieve these requirements.

Except the above literatures, which propose new mechanisms and features for RPL networks with cross-layer optimizations, the researchers in several other latest literatures present their work about RPL optimization dedicating to the interactions between routing layer and IEEE802.15.4 MAC standard [93] [5].

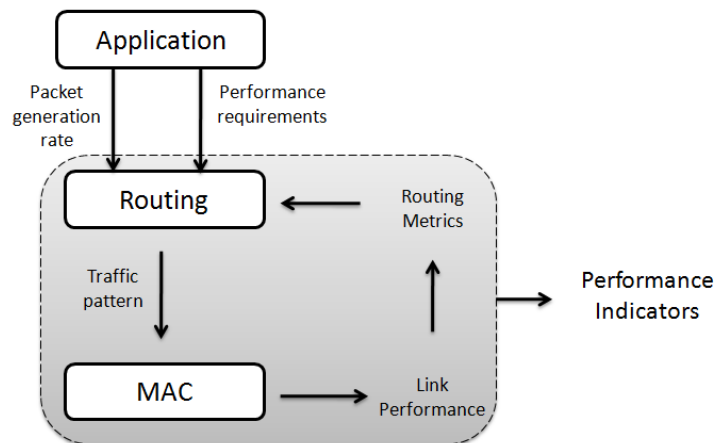


Figure 2-11 The loop diagram of MAC and routing interactions

The authors in the [94] propose novel metrics that may account for the complex interactions between MAC and routing. Their solution enables a protocol selection mechanism to choose the routing option and adapt the MAC parameters (according to the relation between them as shown in Figure 2-11), by given specific performance constraints. They introduce the R-metric that extends the ETX metric at the MAC layer according to RPL specifications. But the proposed R-metric is representative of the probability that a packet is correctly received in each link of the paths and this value is calculated from the maximum number of back-offs and retransmissions at the MAC layer. So R-metric contains the effects of contention to represent link reliability meanwhile it can be estimated faster than ETX since ETX needs to cumulate ACKs. Q-metric is another effort from the authors. It is used to distribute the forwarded traffic to provide load balancing in the network for the objective of network lifetime. Moreover, their novel metrics are based on a proposed mathematical framework for joint optimization of the MAC and the routing layers parameters, namely a depth modeling of the IEEE 802.15.4 MAC and RPL protocol interactions, and consideration of an efficient joint adaptation for them.

Moreover, [5] present their modified IEEE 802.15.4-2006 model fitting for RPL routing protocol. Unlike the aforementioned literatures, the authors tried to solve the problems of

using MAC layer standard in multi-hop network topology, such as single point of failure, single path approach due to adopting a tree structure. A solution is proposed through creating a new topology named as Cluster-Directed Acyclic Graph (Cluster-DAG) modified from the topology of IEEE 802.15.4. This Cluster-DAG structure permits to create alternative path to the sink node depending on the exploitation of redundant topology by RPL. The authors also provide simple greedy scheduling algorithms to adapt this special DAG structure. Their solutions have been evaluated in simulation scenarios and the results demonstrate and prove the efficiency, robustness, low delay and low energy consumption of the algorithms.

#### 2.5.4 Memory-efficient storing mode

As the on-chip memory is valuable resource in the circumstance of WSN, the size of routing table has to be limited so more space can be provided for the other components of WSN system. Thus, in most of the LLN applications, it should be noted that the important tradeoff between memory consumption and network scalability.

The authors in [89] integrate new approaches to enable ORPL scale to large networks of addressable nodes, such as bitmap and bloom filters, and also to construct and manage the routing set for their proposed RPL model instead of traditional routing table. The routing set in a static ORPL network is more compact through using bitmap and its propagation is also opportunistic. In the scenarios where new node may join the network after deployment, bloom filters are needed to represent routing sets since bloom filter is a space-efficient, probabilistic data structure for set insertion, membership query, and merging [87]. However, applying this approach in RPL has bigger complexity and requires SAX (Shift-and-Xor) hash function on the input. Moreover, due to the implied possibility of false positives of applying bloom filter, the authors also defined a set of false positive recovery mechanisms, such as blacklisting and returning, and false exploring.

Comparing with the work in ORPL, MERPL [95] is proposed to have specific pertinence on the storing mode according to the RPL standard specification. A pre-specified number  $N$  is defined to make sure the number of routing table entries stored in a single node not to exceed. This factor  $N$  is broadcasted in DIO message to inform the nodes during the DODAG upward route is constructed. But for the downward route, MERPL has special scheme and not completely like original RPL storing mode because parameter  $N$  is used similar to a finitude to switch the MERPL nodes between storing and non-storing. In its procedures of packet receiving and source route generating, the authors also present the specific rules in their scheme. The simulation results demonstrate their new scheme has lower communication overhead, and can provide enough storage resources for running node program, storing the scalar data, even when the size of network is large.

#### 2.5.5 Other related work

##### *2.5.5.1 Point-to-point traffic*

The routing for P2P communication is essentially based on the available paths between the root and the LLN nodes. These paths are initiated by the communication of DAO-messages to their preferred parent. According to [76], this path setup can lead to congestion on the LLN nodes around the root. In addition, the limitations on packet sizes for constrained devices for non-storing mode introduce the risk of fragmentation for paths with multiple hops. In contrast, for operation in storing mode, the limited memory influences the number of paths a node close to the root can store.

The authors of [96] state that the importance of point-to-point traffic flows in low-power and lossy networks are underestimated. In the paper, a network consisting of about 1,000 nodes that the shortest cost P2P routes performs significantly better than the current RPL standard (using up and down P2P routes) is demonstrated. This illustrates the need of additional point-to-point routing mechanisms. This conclusion is also confirmed by [97]. In this paper a solution is provided, called P2P-RPL, which extends ContikiRPL and performs better in a network of 27 fixed nodes running Contiki with an average node degree of 4.39. While data packets in standard RPL traverse approximately 5 links on average, the links that are traversed when using P2P-RPL are halved for the same network. For even deeper nested DODAG trees, even higher gains are expected. P2P-RPL also decrease the traffic load around the sink: in storing mode with standard RPL 74,53% of the routes traverse the root, while for P2P-RPL this is only 16,03%.

#### *2.5.5.2 Multipoint-to-point traffic*

In many IoT use cases, different LLN nodes send their sensing data to a central sink (also called edge router or boarder router). For this type of traffic, RPL requires very limited control overhead. This overhead can be further reduced by the use of the Trickle timer [98], which decreases the frequency of the sending of DIO messages when the network is stable. Also the responsibility of maintaining routes from leafs to the sink is delegated to each LLN node by only selecting a parent which is closer (according to the OF) to the sink.

#### *2.5.5.3 Multicast*

Possibilities for the usage of RPL routing of multicast messages are stated in Multicast Protocol for Low power and Lossy Networks (MPL) [99]. According to [92] the proposed draft solution has the advantage that it will work without modifications and reliability is increased by the pre-datagram state information maintenance, but it also has a number of drawbacks. The first drawback is that, instead of storing only destination information, for each packet a state has to be stored, which can result in scalability issues. The use of caching of messages, to avoid duplicates, can possibly improve the performance. Other drawbacks are the increase in complexity, susceptibility for out-of-order datagram arrival, and energy and bandwidth inefficiencies due to the forwarding of messages to all parts of the network instead of only two parts with interested nodes (lack of group registration). To solve these issues, [92] introduces an alternative protocol, called SMRF (Stateless Multicast RPL Forwarding).

SMRF is an improved multicast forwarding algorithm and does not define any control messages of its own. It is also stateless so nodes do not need to maintain per-packet information. Compared to Trickle Multicast (TM), SMRF could achieve lower end-to-end delays, better energy efficiency and more reliable design.

#### *2.5.5.4 Any-cast*

Any-cast is a new communication traffic type in set of IPv6 technology. Currently, only one supported research work for any-cast are provided in the domain of RPL routing protocol [89]. It is apparent to see that the use of any-cast in RPL could be very efficient, especially when multiple sinks (destinations) are available in large networks. ORPL brings opportunistic routing to RPL, aiming for low-latency, reliable communication in duty-cycled networks. Furthermore, ORPL supports low-power mesh that provides any-to-any traffic with arbitrary patterns. Briefly, with its cross-layer optimization and memory-efficient techniques, the topology generated by ORPL and its any-to-any routing decision enable first routing upwards to any common ancestor, and then downwards to the destination. The unique combination of

original RPL router topology with any-to-any routing and efficient routing set for forwarding decision are the keys to ORPL's scalability and robustness.

## 2.6 Conclusion

In this chapter, we reviewed the communication protocols that should be referred in the design of a routing protocol dedicated to Precision Agriculture applications, and we also introduced RPL, which is an emerging IPv6 routing standard for WSN, and the latest literatures about its optimization methodologies. Apparently, under the trend of IoT technology and the standardization efforts from IETF in the field of Low-power and lossy networks, the flexible RPL routing framework is our optimal choice and can be the building brick of this thesis. Based on our investigations, Contiki uIPv6 stack is the most practical solution for the future protocol design and experiment because of aforementioned multiple advantages.

Table 2-5 Existing real-world testbeds for the evaluation of RPL protocol

| <i>Reference</i> | <i>Platform name</i>            | <i>Size of network</i> | <i>indoor /outdoor</i> | <i>Hardware platform</i>                | <i>Evaluated RPL model</i> |
|------------------|---------------------------------|------------------------|------------------------|---|----------------------------|
| [87-90]          | Indriya testbed                 | 135 WSN nodes          | indoor                 | TelosB nodes with Arduino               | ContikiRPL--> ORPL         |
| [52]             | SensLAB platform of INRIA Lille | 100 WSN nodes          | indoor                 | WSN430 boards with TI CC2420 radio chip | ContikiRPL                 |
| [152]            | TinyRPL testbed                 | 51 WSN nodes           | indoor                 | TelosB motes                            | TinyRPL and BLIP           |
| [111]            | PLC testbed on INRIA            | 6 PLC nodes            | indoor                 | CC2420                                  | RPL for PLC network        |

Moreover, a set of appropriate designs for the combination of RPL routing metrics and Objective Function (OF) algorithm are very important to this thesis as building stones since these two components are able to adapt RPL to the WSN of agricultural applications and its specific QoS requirements. Additionally, rational optimization techniques have to be carried out based on RPL's topology and its control message. However, having mind of scalability, interoperability, and compatibility for the future IoT, we do not agree with the ideas from the state-of-the-arts that cannot comply with IETF standardization. Thus, the designed flexible and configurable parts, such as OF and Trickle timer algorithms, will be good breakthroughs for our studies.

Last but not least, most of the existing evaluation works for RPL are based on simulation, and only few our investigated literatures mention about testing RPL on testbeds (See [Table 2-5](#)). Namely, as a promising protocol, RPL requires more experiments using real WSN nodes, especially in outdoor environment. We believe that it is the only method to obtain the exact performance results and to improve RPL protocol. As this thesis is mainly built on the proposals from our applied research, setting up a testbed to test them is our obligatory contribution. Notice that the real-world problems are essential concerns for us. All the considerations in this thesis are about how to improve the performance of using RPL in real-life environment.

The requirements and applicability analysis of integrating precision agriculture (environmental data monitoring application) and IPv6 LLNs will be presented in next chapter.

# **3 Integrating Precision Agriculture and IPv6 Low power and Lossy Network (LLN): requirement and applicability analysis**

## **3.1 Introduction**

In this chapter, an analysis of the routing requirements and applicability of Agricultural Low-power and Lossy Networks (A-LLNs) scenario will be presented. The Precision Agriculture (PA) application is considered as the single use-case of common RPL applicability in A-LLN. Namely, A-LLN is dedicated to provide relatively comprehensive descriptions and definitions for the LLNs as well as Wireless Sensor Networks (WSNs) used by general agro-environmental monitoring system. Moreover, the existing RPL use cases and WSNs for agricultural systems can be our research foundation. It is difficult to distinguish original WSNs and A-LLNs on most of the concepts and basic functions since the intrinsic characteristics of WSN is taking into account by the definition of LLN, such as low energy resources, limited bandwidth, unstable wireless links, low computational capability and small memory. However, LLN exclusively uses IPv6 and this is the key component of moving WSN to the next generation of IP network – Internet of Things (IoT). Thus, we believe that our contribution is viable to push WSNs of agricultural systems to IoT and follows IPv6 technology trend. To our best knowledge, the work in this thesis is the first to propose a new LLN type for the above purpose.

In the following sessions, A-LLN will be defined as a proprietary type of LLN and its RPL applicability analysis for extending traditional WSN based on latest IETF drafts [100] will also be presented. Notice that clarifying appropriate QoS and traffic requirements of PA application is still a tricky issue. It is more practical to give this statement specification considering the additional challenges depending on the purpose and application of A-LLN in this thesis. The detail discussions in terms of deploying A-LLN and its routing requirements will be shown in this chapter. Sets of metrics/constraints and other optional RPL parameters for use in agricultural scenarios and its applicability profile will also be analyzed, having mind about the major obstacle to the development of reliable, easy-to-implement routing protocols. For different applications and deployments of A-LLN, a use of different recommended permutations of options, which were obtained from the preliminary results of our testbed experiments, will be given in the end. Notice that more tests on simulator and real-world system for our analysis will be presented in the next two chapters.

## **3.2 A-LLNs infrastructure description**

Thanks to the rapid advance in the domain of WSN and miniaturization of the WSN node boards, PA started emerging as new trends in the agricultural sector in the past few years. PA ICT (Information and Communication Technology) systems concentrate on providing the techniques for observing, assessing and controlling agricultural production process, and have covered a wide range from herd management to field crop production [101]. In most of the use-cases, PA is always referred in the issues of site-specific crop management (one representative application of A-LLN). This includes several different aspects, such as:

- Environmental monitoring (e.g. soil, crop and climate) in a field which is separated by some complete parcels;
- Providing a Decision Support System (DSS) for possible treatments analysis, which can be for field-wide or specific parcel;
- The methods for taking differential actions, for instance, adjusting in real-time and operations, such as fertilizer, lime and pesticide utilization, tillage, irrigation, and sowing rate.

A precision agriculture system is normally composed of various devices which are typically interconnected using wireless technologies with a backbone network providing connectivity to “command-and-control” management software systems (e.g. DSS) at the data processing center of an experimental farm. Because of the well-known constraints, such as the cost of WSN nodes and the difficulties of their deployment, the number of WSN nodes in a single PA system is between 20 ~ 50 which is well supported by the current WSN with ZigBee or Wi-Fi technologies [27, 46, 47, 103].

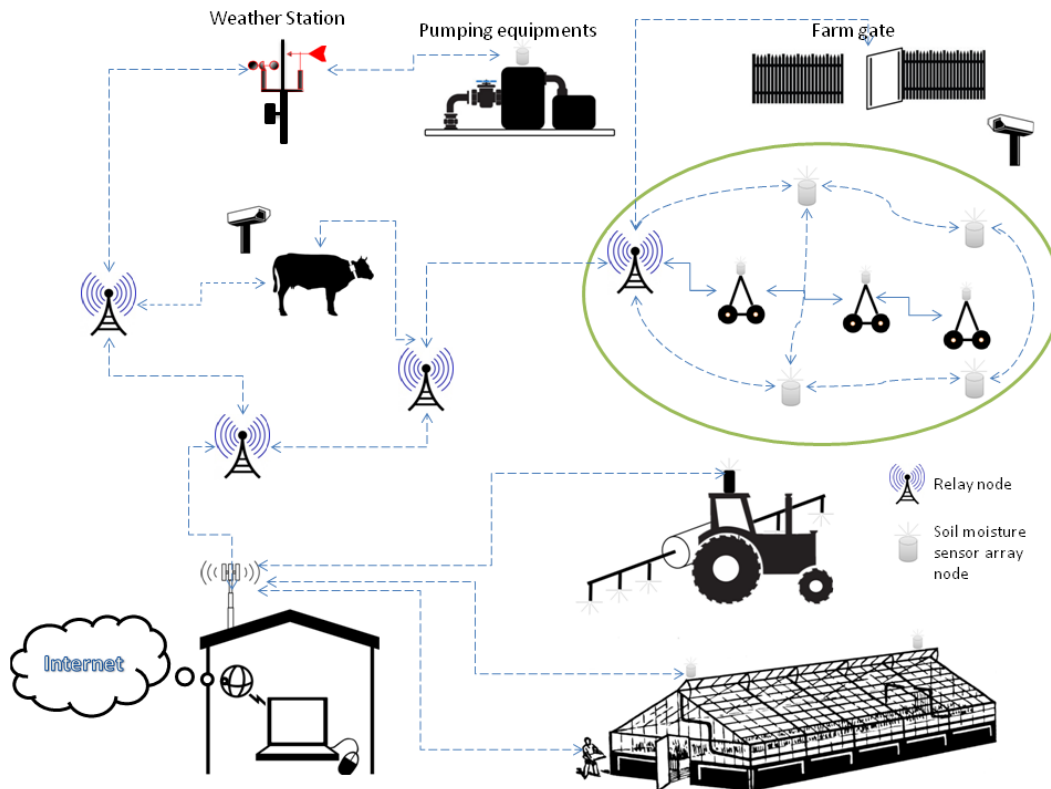


Figure 3-1 Sketch map of a modern precision agriculture system

From the latest literatures about the research of PA system [27] and the white paper from the commercial providers (e.g. Libelium, VALLEY, etc.), the needs of WSN for PA system are transparent, such as the needs of modern agricultural paradigm shift, remote monitoring/control, asset tracking and distance diagnosis (depicted in Figure 3-1). More explanations are listed below:

- In modern farms, their size become larger and they are less contiguous than before. However, fewer people can be hired. The bigger lands with less human resource cause the increasing of difficulties and distances/travel time between fields;
- ICT technologies in Agriculture requires various monitored information, such as data from gauges and sensors (soil moisture, air pressure, environmental, disease, etc), status of farm



gates and building entrance (open/close), irrigation valves, pumping equipment, live video of operations, monitoring of greenhouses, livestock enclosures, and storage facilities, and audible or other alarms;

- To manage a modern farm more efficiently, some basic control functions are needed, such as opening and closing valves and gates; turning on and off lights, pumps, and heaters; and guiding robotic vehicles;
- As the development of agricultural automation technologies, more equipment are used in the different cycles of vegetal growth so these valuable assets, such as center pivot irrigation systems and farm vehicles have to be located or know their relative positions. Moreover, the location of livestock and workers is also needed for their safety or performance;
- Distance diagnosis requires remotely located technicians and specialists and they can access the latest information, monitor and control on-farm assets.

Under the consideration of the needs for wireless connecting and accessing, low-power field WSN nodes in multiple experimental farms, the PA users can collect a significant increasing amount of information and remotely manage a larger number of control points. Thus, the IoT and WoT technologies are urgent to be introduced in the original PA system. The IPv6-based solution, including IEEE802.15.4 PHY and MAC, 6LoWPAN and lightweight IPv6 stack, appears as a core technology in the new PA application and WSN for agricultural system. Following this clue, leveraging a set of open standards for connecting this specific LLN to the Internet is necessary, especially for the selection and optimization of routing path since multi-hop scenario is a base-line for large-scale wireless network needed by the deployment in real-world farm field with above features and functions.

Moreover, according to our discussion in Chapter II, the IETF ROLL working group has defined and analyzed application-specific routing requirements for four domains, such as urban, industrial, home automation, and building automation LLNs. The analysis and guidelines of applicability for Advanced Metering Infrastructure (AMI) (or smart grid), industrial networks and home automation and building control application have been documented and stated more exhaustively [102]. However, because there are still many chances and gaps of research left for adapting RPL routing framework for agricultural ICT systems, we proposed a new LLN type named as A-LLN in [103]. Furthermore, A-LLN is able to be inspired by Urban LLN (U-LLN) [71] since they have more common points on the facets of environmental monitoring, network topology and traffic pattern. But the characteristics of A-LLN cannot be neglected, such as the heterogeneous A-LLN equipments and QoS requirements for the communication of agricultural application.

According to the previous discussion, RPL provides a flexible routing framework that can be adapted to a variety of LLN types through applying specific routing metrics and Objective Functions (OFs). The OFs are separated from the core protocol specification to enable that the RPL can meet different optimization criteria required by a wide range of traffic patterns and applications in agricultural WSN. Thus, RPL is able to accommodate the A-LLN with appropriate adaptations and combining the ingredients of existing WSN for agricultural systems.

Furthermore, 6LoWPAN adaptation technology is another standardized protocol that is viable and efficient for connecting discrete A-LLNs to the external IPv6 network and fulfills the expected more functional applications. One A-LLN is the smallest part in this scenario and it would contain and be equipped with three kinds of key nodes that are described below.

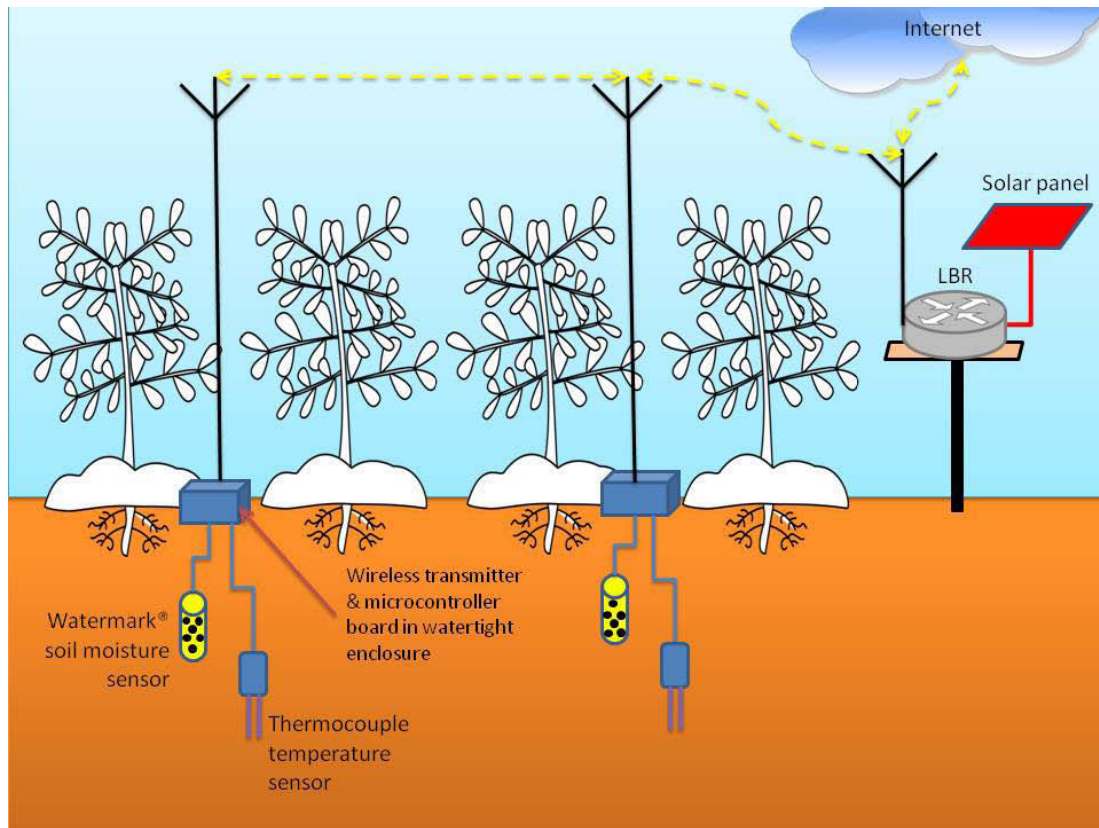


Figure 3-2 Schematic of LBR and smart sensor in A-LLN

Table 3-1 Three types of key nodes in A-LLNs.

| <i>Node name</i>                          | <i>Power Mode</i>  | <i>Network Role</i>         | <i>Static/Mobile</i>  | <i>Functions</i>  | <i>Communication Interface</i>  | <i>Location feature</i>   |
|---|--|-----------------------------|---|---|---|---|
| Edge routers /LBR node                    | Main powered or rechargeable battery powered (e.g. solar panels), always on    | Sinks of A-LLN              | Static generally, but can be installed on the vehicles, robots or Unmanned Aerial Vehicles (UAVs) | Internet accessing, data collecting and processing, and instructions sending  | 3G cellular model, Wi-Fi, Ethernet, and radio module supporting IEEE 802.15.4 | Broad area or the edges of the crop fields  |
| A-LLN sensor node                         | Non-/rechargeable battery or energy scavenger powered, always in sleeping mode | A-LLN routers or leaf nodes | Static  | Sensing ability, e.g. meteorological data and pollution data collections; Data forwarding, relaying, primary processing                               | IEEE 802.15.4 based low-power consuming wireless transmission                 | Normally deployed on the ground like arrays and surrounded by various plants and other obstacles in different heights |
| Actuator nodes/Local Controller (LC) node | Similar to sink node   | A-LLN routers or leaf nodes | Static  | Controlling agricultural equipment, such as the sprinklers of irrigator, switchers of lighting equipment, alarms, valves, and gates; Data forwarding. | IEEE 802.15.4 based low-power consuming wireless transmission                 | Around the agricultural equipments  |

Edge routers/Low-power and Lossy Network Border Routers or LoWPAN Border Routers (LBRs), A-LLN sensor nodes and Actuator nodes/Local Controller (LC) nodes are depicted in Figure 3-2 and their brief descriptions are listed in the Table 3-1. LBRs basically

have more capabilities of processing and memory, and a single A-LLN allows the existence of multiple LBRs since they are able to relay the gathered sensory information to the Internet. Notice that the appellation of A-LLN sensor node is a substitution of WSN nodes. Namely, A-LLN sensor node is defined as a special type of WSN nodes taking account of its functions and applied scenarios. Its main purpose is to provide measurement sensory information, e.g. temperature, light, atmospheric pressure, soil moisture or air humidity, UV intensity, strength and direction of wind, rainfall, gases, pH of dust or rainwater, and heavy metals. Furthermore, a LC node can integrate an A-LLN sensor node to possess low-power transmission.

Due to the characteristics of A-LLN nodes (general designation of the above three types of nodes), each parcel of an experimental field can be deployed 2~5 A-LLN sensor nodes for environmental monitoring. In general scenarios of PA system, these devices are expected to join into the multi-hop mesh networks organized by network aggregation points (i.e. LBRs) and may operate as end-points/routers autonomously in order to increase the cover range as well as to prolong their lifetime. For the actuator nodes, they may rely on alternative sources of energy supply (e.g., solar power or main line power) in many deployment cases. Furthermore, they are often connected to a backhaul network leading to the specific data center through at least one LBR. It should be noticed that our research on A-LLN is dedicated on the environmental monitoring application of precision agriculture. And the infrastructure of our contribution is focused on the light green circle area of [Figure 3-1](#) since most of the low-power devices (A-LLN sensor nodes) are deployed over there.

### 3.3 Deployment scenarios of A-LLNs

One single A-LLN may have around half hundred of A-LLN sensor nodes which are well deployed in a farm. In most of the cases, to localize the nodes needs the assistances of GPS or other practical solutions. The A-LLN nodes will be manually deployed in a monitored field within defined topological constraints. They are low-cost and highly resource constrained, especially for the battery-powered A-LLN sensor nodes, and this presents that the maximal network lifetime is the most important metric object. Thus, the energy-efficient routing manner of RPL is fit for A-LLN system. Nowadays, due to the price of A-LLN sensor nodes and other farm-oriented precision instruments, it is not feasible to deploy large number of them in one experimental field considering the cost saving. Thus, several A-LLNs which are located in different geographical areas even different countries or continents are expected to be combined and the measurement data will converge to the data center systems through the backbone Internet connection.

Except the A-LLN nodes have different powered modes and battery levels, the wireless signals are always influenced by the outdoor deployment environments. The link reliability is very volatile because of the dynamic factors, such as the temporary/permanent link disconnection and the packet errors caused by occupied channel, collisions and signal interferences during the multi-media wireless transmission. The issue will become more serious, for example, when the A-LLN encounters the weathers, such as storm, mist, and snowing. Even for the indoor case of A-LLNs application, the sensor nodes that are deployed in a greenhouse could be covered by leafs or stems of the growing plants. The induced path loss due to signal attenuation may have many differences during the cycles of vegetations. These dynamic environment changes will also cause high failure rate of radio transmission and other issues in the A-LLNs. Therefore, currently, how to manage the malfunctioned or

misbehaved nodes, and to reduce the node failure ratio, are still the huge challenges for the large-scale real-world deployment.

In a typical A-LLN deployment, groups of A-LLN LC nodes and A-LLN sensor nodes within physical parcels of land will form routing domains. Each routing domain is connected to the larger IP infrastructure through one or more LBRs, which is supported by Wide Area Network (WAN) connectivity through various network technologies, e.g., Ethernet, 3G/4G, private WAN. Paths in the mesh network between an A-LLN node and the nearest LBR may be composed of several hops. Normally, LBRs and LC nodes are deployed at the edge of parcel of land and are easy to be powered by the main line or energy-harvesting module (e.g., solar panels), so they have less energy constraints than the A-LLN sensor nodes. In our defined A-LLN scenario, LC nodes can also provide the backbone of network topology while sensor nodes can operate as leaf nodes, and could work as routers only when both of LBRs and LCs are “unreachable”, since the LC devices can afford the additional resources required by routing and forwarding packets.

Deploying large connected IP network infrastructure is always a challenging task. Especially when a long term of system running is expected, a number of trades-offs and considerations are needed in this respect. One of them is managing a larger number of A-LLN sensor nodes per router may lead to increased energy consumption (i.e. the hot spot problem [104]). However, increasing the number of routers in the A-LLN scenario will increase deployment and maintenance costs. Meanwhile, using a sparser routing infrastructure in a large field necessitates the use of higher transmitting power levels of radio frequency chip, which also leads to increase the energy consumption.

Thus, the routing protocol operating in A-LLN deployment with the topology characteristics described above needs to provide good scalability with network size and number of forwarding hops, and have the ability to support energy-aware routing path selection and optimization under the aforementioned specific QoS requirements.

### 3.4 Description of traffic pattern and layer-two applicability

The A-LLNs traffic patterns can be fairly uniform and well-understood. Its traffic is highly asymmetric, where the majority of the traffic volume generated by the A-LLN sensor nodes typically goes through the LBRs, and is directed to the data center servers, in a multipoint-to-point (MP2P) fashion. Moreover, each A-LLN device generates Agricultural Monitoring Data (AMD) traffic according to a schedule (e.g. periodic sensor reads), in response to on-demand queries (e.g. on-demand sensor reads), or in response to some local event (e.g. power outage and other exceptions). This kind of traffic is typically destined to a single data center server. The periodic reports can be aggregated or be sent without requiring a specific query, specially, unsolicited events like alarms and outage notifications.

At the same time, the data center server can also generate Point-to-Multipoint (P2MP) communication traffic through LBRs to configure A-LLN devices or initiate queries, and use unicast and multicast to efficiently communicate with a single A-LLN sensor node or LC node, or groups of these devices. The data center server may send a single small packet at a moment to the A-LLN devices (e.g., a sensor reading request, a small configuration change, and function switch command) or a series of large packets (e.g., a firmware upgrading). However, the latter packets will be rarely used in the testbed but is important for wireless remote updating applications of real-world system.

From the above analysis and description, we found that the traffic generated by the A-LLN nodes and destined to data center server is dominated by periodic sensor reads. Moreover, A-LLN applications normally do not have hard real-time constraints because the change of sensor data is slow and smooth in most of the time. However, noticing that A-LLN sensor nodes are always configured to run sleep&wakeup mode, they are often subject to bounded latency and stringent reliability service level requirements. From the perspective of routing, AMD traffic requires both of efficient MP2P and P2MP communication within the A-LLN nodes. Furthermore, due to the high dynamic environment for A-LLN, the mechanisms, such as timely loop detection or resolution, and broken link repair are required to meet latency requirements. Finally, some availability of redundant routing information, such as backup parents, namely the alternate forwarding paths, are significant to increase the link reliability of A-LLN to meet the specific QoS requirements of its real-world deployment.

Based on the original LLN concepts and RPL specification chartered by ROLL working group, a layered architecture protocol stack is required by A-LLN system. This architecture can be friendly for any link layer, such as the 802.15.4 and 802.11 families. According to the AMD traffic described above and aforementioned available I/WoT protocol stacks, the part of low-power network will be soon dominated by the promising IEEE 802.15.4e MAC layer in the near future. We followed the IETF's recommendation on RPL routing framework to adopt asynchronous contention-based MAC plus IEEE 802.15.4 PHY layer, but keep glancing over the emerging protocols to prepare for the future work. Moreover, if the hardware platform of local controllers and LBRs have Ethernet, 3G cellular network, or ADSL over the Internet, the controlling messages are sure to be transmitted in a more reliable media and in real-time. However, these topics are out of the scope in our current work of this thesis.

### 3.5 Methodology of building a low-cost IoT testbed for A-LLNs

In this section, the methodologies of building a low-cost IoT platform including simulation and hardware testbed for A-LLNs will be discussed. As the first step to forge a reliable protocol into a new scenario, simulation is an indispensable method to test out the improved algorithms and to get the initial results of performance evaluation. Therefore, the RPL and 6LoWPAN simulation and their evaluation tests have been built in COOJA simulator within Contiki. Meanwhile, we also used a set of Atmel evaluation kits (around \$700) as a hardware testbed for more practical experiments. The following two sub-sections will present an overview of the above work.

#### 3.5.1 Description of simulation experiments

Network simulators are extensively used to evaluate and compare the performance of routing protocols for WSN [84]. They are used to enable easy and fast network deployment, controllable and flexible scenarios, and the repeatability of the obtained results. But most of the network simulators still have disadvantages, such as oversimplified channel models and protocol models, which are difficult to represent the real performance comparing with the real-world testbeds. In addition, real-world deployments can avoid these drawbacks but are considerably harder to implement and deploy within low cost. Thus, as our experiment will be executed in both of network simulator and hardware platform, we preferred to use COOJA which is a hybrid approach based cross-level emulation and simulation platform.

### 3.5.1.1 *Contiki/COOJA platform*

Contiki is a lightweight open source OS written in C programming language for WSNs. It follows a modular architecture, and it is built around an event driven kernel. Contiki provides preemptive multitasking at the process level, but to yield the processor to another thread, and the running thread has to invoke the yield function explicitly. In other words, if a running thread continues to run, waiting threads are not scheduled.

The Contiki kernel comprises an event scheduler that dispatches events to the running processes. Process execution is triggered by events dispatched by the kernel to the process or by a polling mechanism. When an event is dispatched to a process, it runs to completion, however, event handlers can use internal mechanisms for preemption (e.g. Multithread library). Contiki maintains a queue of pending events, and events are dispatched to target processes in a First in First out (FIFO) manner. To transmit a data packet, Contiki uses a callback timer. The callback timer takes an expiry time and a pointer to a function that acts as an event handler as arguments. When the timer expires, an event is stored in the event queue and the event handler is called eventually. If there are multiple events pending in an event queue, and events are fired in a FIFO manner, it is possible that the event handler for a callback timer does not execute right away. This phenomenon limits the transmission capability of a node. Furthermore, the communication stack overhead, e.g., copying a message and adding headers to a message, leads to further delay.

Based on our investigation work from the thesis's beginning to the spring of 2014, Contiki&COOJA has become the most popular platform since more than 90% of RPL and IoT related publications of recent two years adopt it or indirectly use it as important related work and citation. Contiki&COOJA is still under developing but it has been proved to be a viable platform to test IoT protocols for LLN nodes with high resource constraints. At the same time, it still has several drawbacks that may bring inconveniences to the researchers and developers. We can list them below:

- Cooja is tightly connected to specific platform emulators. In most of the cases, the limitation of hardware emulators (MSPSim, Avrora and etc.) will bring development difficulties;
- Comparing with the traditional network simulation, Cooja cannot provide the traditional simulation like NS-2, NS-3 or OMNet++, because the protocol simulation in Cooja has more complexity due to its cross level feature. In other words, an abstract protocol model cannot be simulated in Cooja unless its implementation can cooperate with a whole LLN system;
- Currently, Cooja only officially supports the simulation on TelosB-Sky mote platform and ensures its availability.

However, Contiki&Cooja is still a promising platform since many researchers choose it in their research. Most of its open-source components in Contiki repository can be reused and extended for our research and development. Especially, we can build valuable experiments with this platform. COOJA is able to support initial simulation tests of our idea and proposal, but its more attractive characteristics are capable to directly use the same source code and execute the same program on the hardware. Thus, avoiding costing double time to develop the simulation and hardware testbeds is another important reason and motivation for us to adopt COOJA in this thesis.

### 3.5.1.2 *A preliminary simulation of A-LLN using Contiki/COOJA*

In this sub-section, one RPL instance building simulation for A-LLN in Cooja is evaluated. This study is about how the network converged and stabilized using the ContikiRPL with ETX metrics. A network graph and a built DODAG have been depicted in [Figure 3-3](#). The simulation consists of twenty A-LLN sender nodes with radio duty cycle (RDC) control mechanism. The frequency of sending collect packets by each node is set as 60s. One LLN Border Router (LBR) without RDC program processes which are emulated as AVR-Atmega128RFA1 motes and derived from Cooja and uIPv6 modules including UDP, ICMPv6, IPv6, SICSLowPAN, Powertrace, and Rime of the Contiki kernel [34, 61, 105].

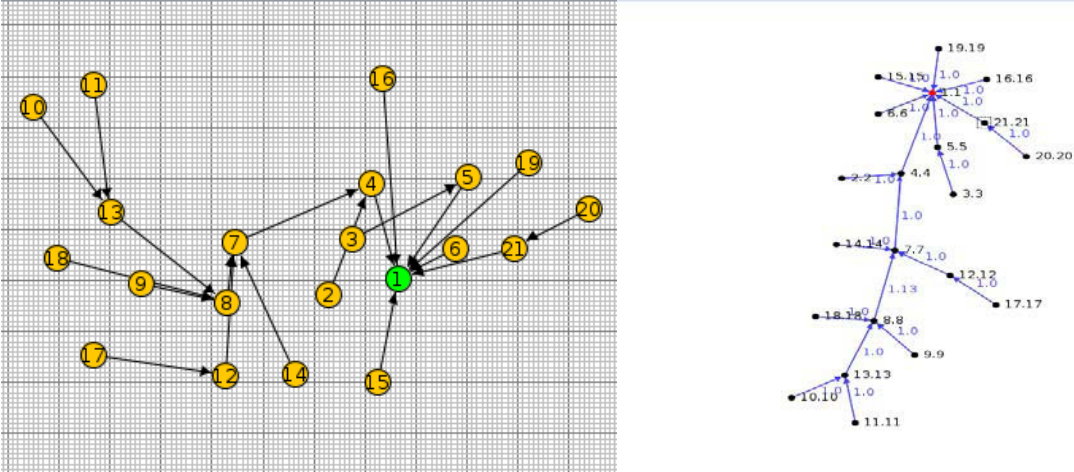


Figure 3-3 Network graph and visualizer on Cooja

Furthermore, with the help of the Collect-View tool and MRM modules [106] provided by Cooja, parts of geographic information of Irstea Montoldre experimental site have been imported into a 1200m×800m static simulation scenario depicted in [Figure 3-4](#). Some metrics could be observed from the GUI of Collect-View tool, such as the measurement data of power consumption, network link quality, and the states of the simulated nodes depicted in [Figure 3-5](#) and [3-6](#).



Figure 3-4 A deployment simulation in COOJA/MRM

Notice that, during this 5-minutes simulation, the average power consumption and RDC of router node 4, 7 and 8 appear much higher than the other nodes. According to our previous experience of real-world WSN systems, without taking appropriate measures, the high transmission power will exhaust the battery of certain nodes in a short time and influence the lifetime of whole network. Thus, a single routing metric ETX is insufficient. Except the





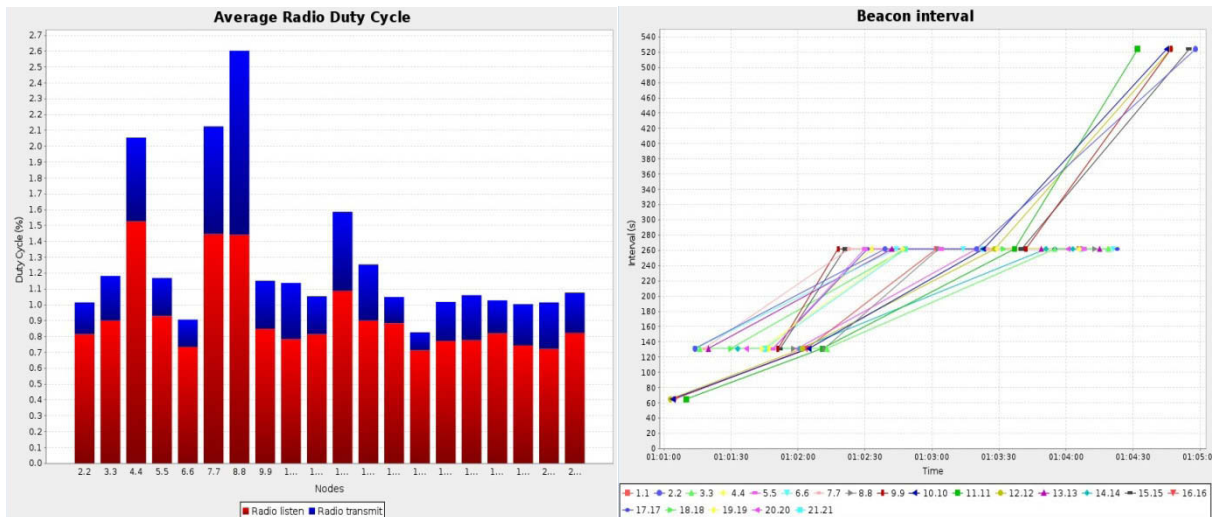


Figure 3-6 Measurement data of average RDC and beacon interval

### 3.5.2 Hardware testbed description

Recalling the found limitations of the simulation in Cooja, testing ContikiRPL in another simulator will have to tackle the unavoidable deflection of simulation results due to different implementations of propagation models, emulators, and other dependent protocol models. Actually, this may cause that the obtained results cannot be comparative. To simplify the solution and present more trustworthy results, evaluating ContikiRPL on a hardware testbed is a more efficient and practical approach. Our work of building a testbed includes porting the necessary components of Contiki to ATMEL Evaluation Kits (cf. Figure 3-7). Namely, this hardware testbed can build a prototype with basic system functions similar to a preliminary A-LLN experimental platform.

Moreover, our work, such as the verification of our routing algorithms and related theoretical proposals (presented in next chapter), will continue to adopt Cooja simulator firstly since it does not need to consider all the layers of complete system (e.g. radio chip or peripherals driver) and with more powerful debugging functions. Nevertheless, it is still the best method to selectively evaluate the proposed protocol model on hardware testbeds, not only because they provide the accurate performance result, but also they can reveal the real-world problems, which are our most concerns.



Figure 3-7 Photos of ATMEGA128RFA1 PCBA, ATMEGA128RFA1 Evaluation Kit and STK 600 with AVR JTAGICE mkII debugging tool

### 3.5.2.1 Experiments of Contiki&COOJA platform on ATMEL Evaluation Kit

Under the precondition of reducing modification and tailoring work from the original Contiki's source code, two experiments using basic “RPL-collect” example of ContikiRPL which are dedicated to test the availability of RPL on ATMEL evaluation kit are conducted . This prototype is easy-to-use and provides Contiki data collection process which can plot abundant network performance results, such as the current RPL DODAG, time-varying network and power profile in detail, by supporting a java-based extendable GUI Collect-view tool. After the adjustments of hardware platform configurations, we have already been able to carry out other components of Contiki/COOJA platform with uIPv6 protocol stack, such as Rpl-border-router, Rpl-udp, SLIP [108] and Erbium CoAP [107], and these modules can remarkably enrich these two experiments on ATMEL evaluation kit.

For an initial test, we adopted default SicslowMAC module without Radio Duty Cycle (RDC) function. Namely, all of the AVR nodes in the network do not have sleeping mode feature and its MAC layer only provides simple channel access management based on CSMA-CA. We deployed four AVR nodes in the ISIMA building (See [Figure 3-8](#)) and observe its routing behaviors like in Cooja simulator. The periodical data-collection was configured as one snapshot per minute, and all the battery-operated kit boards are outage within around 4200s (about 11.5 hours) which is the results obtained after 3-times tests with two new standard AA batteries.



Figure 3-8 Four AVR RPL router nodes deployed in ISIMA building – An indoor environment

### 3.5.2.2 Experiment for an empirical estimation and evaluation of Contiki uIPv6 protocol stack

In another experiment (depicted in [Figure 3-9](#)), ContikiMAC with RDC was installed and configured in our program. A suite of adapted Collect-view (as shown in [Figure 3-10](#)) and Contiki collect-process were used to obtain time-varying network performance and power profile, which will be mainly presented in next section.

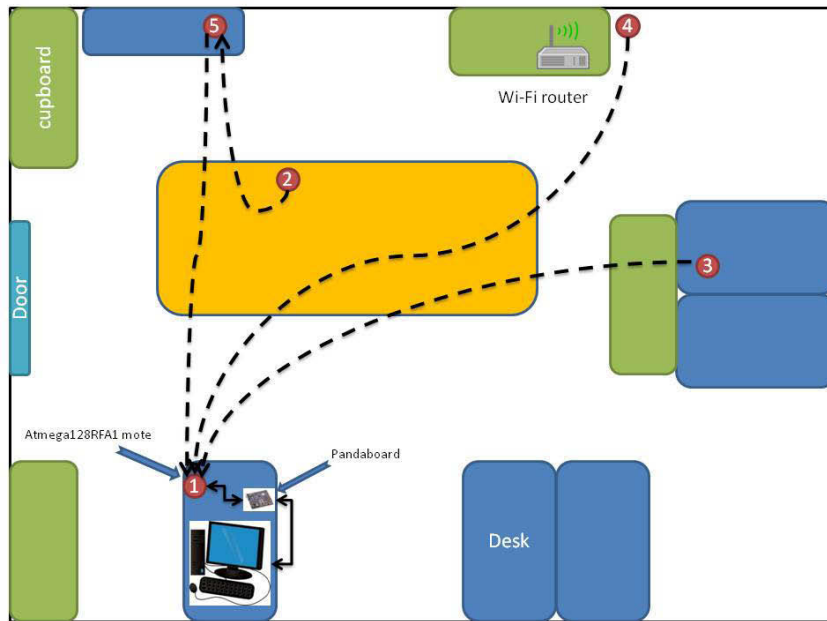


Figure 3-9 Atmel nodes deployed in LIMOS's office – topology snapshot in an indoor environment

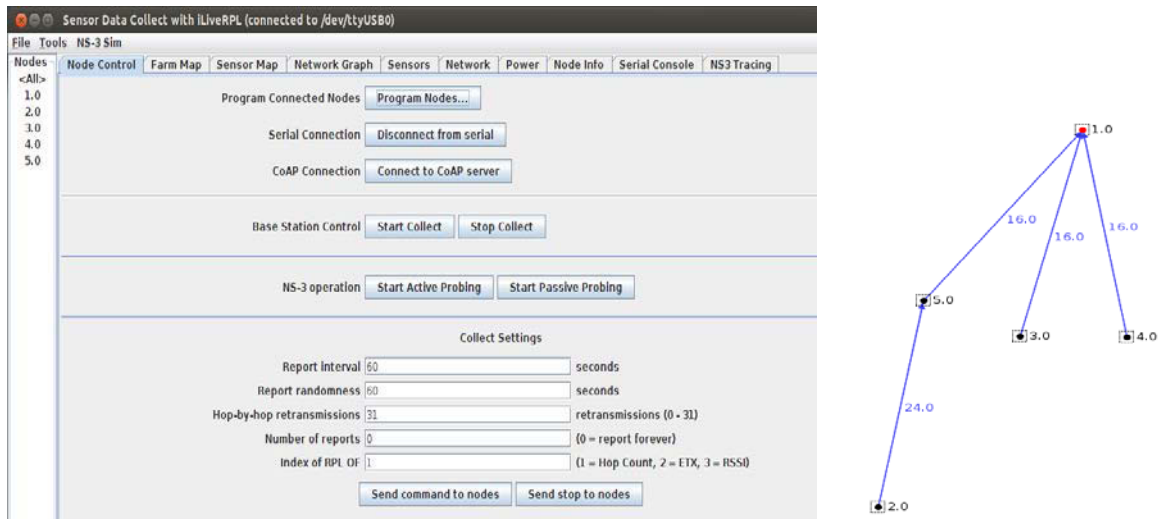


Figure 3-10 Sensor Data Collect tool and one network graph snapshot

### 3.6 Preliminary result analysis of hardware testbed

As the brief descriptions have been given in last section, we will continue to analyze the preliminary result of the second experiment on hardware testbed in this session. It should be noted that we mainly focus on the discussion for the results obtained from the real-world testbed in this chapter, since A-LLN is not fanciness and it can be realized by existing hardware platforms. However, when validation and evaluation of our proposed routing algorithm are needed, the evaluation on both simulator and hardware testbed will be presented and the measured results will be discussed in next two chapters.

#### 3.6.1 Network conditions

To estimate the network conditions of a self-organized network topology in the testbed experiments, we have to consider the exceptions and errors which may exist in the software part and the hardware part. We took off the external antenna of Node 2 to shorten its transmission range, and put node 4 near a Wi-Fi hot spot, and Node 3 and 4 have obstacles between them and the Sink node 1. The test (Figure 3-9) adopts the default RPL routing metric, Objective Function (MrhOF) and a MAC layer with low duty cycling feature, recalling that the current ContikiRPL model uses the estimated number of transmissions (ETX) as the only additive routing metric.

The experiment results of network conditions are shown in Table 3-1. This is a 13 hours test; collection frequency is within two minutes and each node sends monitoring application packets in converge-cast method and wait Acknowledgement (ACK) messages from the Sink node 1.

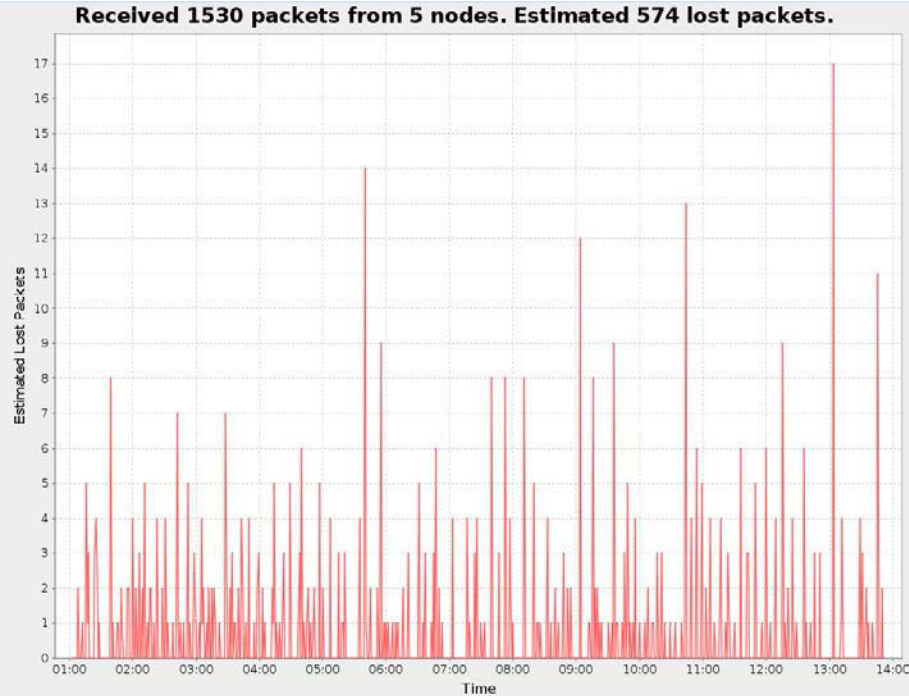
The results we obtained from this experiment prove that the influences due to radio interference and the absence of external antenna are significant with the increased lost packet and network churn count. Therefore we observed the essential differences of the feedback information from node 2 and node 4. Moreover, although the node 3 and node 5 are relatively stable, they still have packet lost in a certain level but with lower possibility. This is compliant with our anticipated results as the sink node periodically triggers rebuilding of RPL DODAG controlled by trickle timer [12], and the interference and dynamic asymmetric radio link leading to frequent activation of RPL repair mechanism.

Table 3-2 AVR-based nodes deployed in LIMOS's office – network conditions

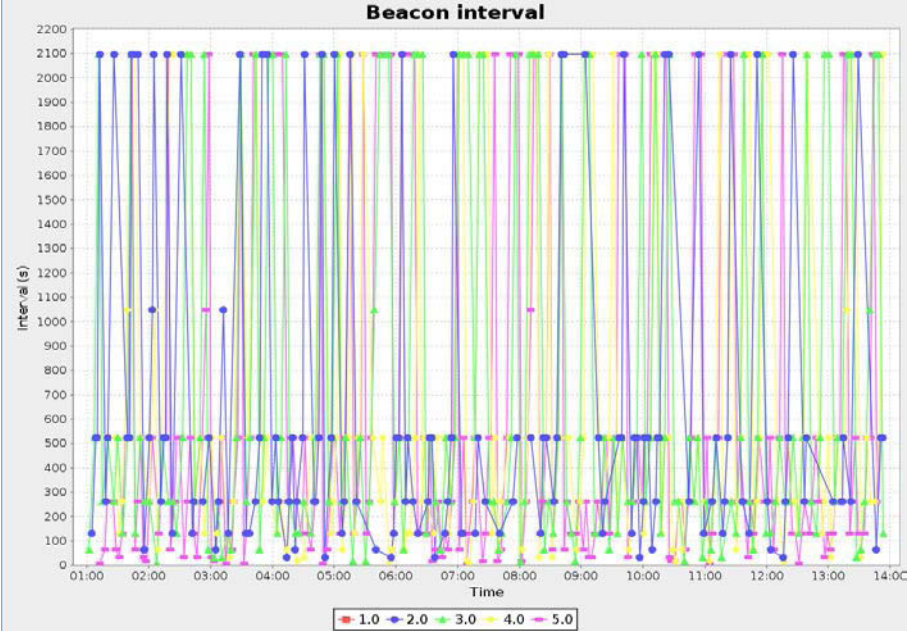
| Node ID | Received | Lost  | Hops  | Routing metric | ETX    | Beacon Interval | Churn |
|---------|----------|-------|-------|----------------|--------|-----------------|-------|
| 2       | 147      | 378   | 2.041 | 780.259        | 25.377 | 11 min, 15 sec  | 25    |
| 3       | 514      | 20    | 1.008 | 390.357        | 16.062 | 12 min, 04 sec  | 6     |
| 4       | 375      | 154   | 1.397 | 528.317        | 19.279 | 12 min, 23 sec  | 34    |
| 5       | 496      | 22    | 1.008 | 391.095        | 16.067 | 11 min, 51 sec  | 8     |
| Avg     | 382.5    | 143.5 | 1.364 | 522.507        | 19.196 | 11 min, 53 sec  | 18.25 |

A substantial increase in measured lost packets can be observed in the Figure 3-11 (a), this plotting shows time-varying packet lost results where we can observe the peak values appearing in a distributed trend since most of the application packets would be undershoot and cannot arrive to their destination -- Node 1. Meanwhile, this network has to tackle the issue of radio conflicts because of DIO message exchanging in broadcast fashion, or the dynamic routing paths which have not been ready due to delay or network churns. Note that the total packet lost ratio is 27.28% after statistic computation. Furthermore, the Figure 3-11 (b) shows the time-varying beacon intervals condition, namely the instantaneous intervals of DIO message managed by the trickle timer of each node. According to the standard RPL

routing behaviors, the DIO beacon interval will drop down to the minimum trickle timer immediately when inconsistencies are found in the current network. The plotting presents that the timer of intervals cannot be stabilized at the maximum value. In other words, the frequent resetting of trickle timer also points out the outcome of varying radio condition and network topology.



(a)



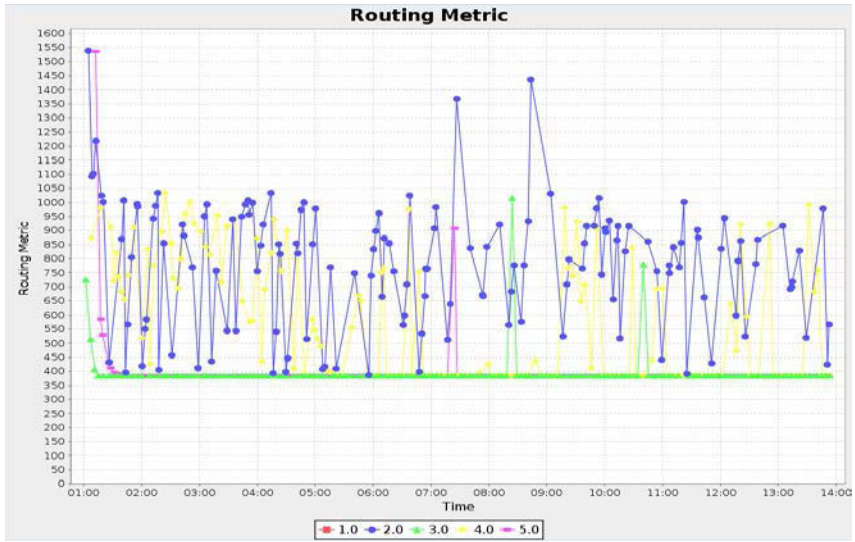
(b)

Figure 3-11 Time-varying network profile of current DODAG: Packet lost and beacon interval

Figure 3-12 (a) and (b) present the stability of each node in the DODAG topology. To estimate this network performance, we recorded the variability of hop count, and routing metric that is used to calculate rank value based on parent selections. Network hop count is a more empirical value to present the stability of a single node. But if the feedback values – ETX from MAC layer impact on the routing metric, essentially, the relative position to the Sink node – rank of DODAG will also change. The data in the routing metric chart shows that the rank of node 3 and 5 can keep stable except when the failure of downward routing and the global repair is triggered. But the node 2 and 4 are apparently very dynamic and sensitive. As under the impact of their located position, they cannot keep their stabilization in this network topology.



(a)



(b)

Figure 3-12 Time-varying network profile: Hops and Routing Metric.

### 3.6.2 Radio duty cycle, power consumption and lifetime

The power profile that is calculated by the cumulative time of radio listen, radio transmission, CPU running and Low Power Mode (LPM) from monitoring application packets are presented in [Table 3-2](#). Like mentioned by many existing literatures, the radio frequency module will consume most of the battery power [109]. In the case of [Figure 3-9](#), the RDC was configured to be active, so this basic energy saving function can also be tested.

Table 3-3 AVR-based nodes deployed in LIMOS's office – power profiles

| Node ID | CPU Power (mw) | LPM Power (mw) | Listen Power (mw) | Transmit Power (mw) | Total Power (mw) | On-time            | Listen Duty Cycle (%) | Transmit Duty Cycle (%) | Avg Inter-packet Time |
|---------|----------------|----------------|-------------------|---------------------|------------------|--------------------|-----------------------|-------------------------|-----------------------|
| 2       | 0.484          | 0.149          | 0.892             | 0.318               | 1.842            | 31 min, 29 sec     | 1.487                 | 0.598                   | 5 min, 13 sec         |
| 3       | 0.482          | 0.149          | 0.979             | 0.213               | 1.822            | 1h, 46 min, 37 sec | 1.631                 | 0.401                   | 1 min, 30 sec         |
| 4       | 0.483          | 0.149          | 0.857             | 0.203               | 1.691            | 1h, 19 min, 22 sec | 1.428                 | 0.382                   | 2 min, 02 sec         |
| 5       | 0.458          | 0.150          | 0.482             | 0.211               | 1.301            | 1h, 43 min, 04 sec | 0.803                 | 0.397                   | 1 min, 32 sec         |
| Avg     | 0.477          | 0.149          | 0.802             | 0.236               | 1.664            | 1h, 20 min, ...    | 1.337                 | 0.444                   | 2 min, 34 sec         |

To estimate the energy profile, it should suppose that two standard AA batteries with 2500 mAh energy are used as power supply, and then this can derive their average theoretical and predicted lifetime which is 4507 hours ( $\approx$  189 days) after calculation from above results. It is also possible to decrease the average RDC even less than one percent through reducing the frequency of monitoring collection or carrying out an experiment in longer time.

We can also observe that the CPU and LPM energy are nearly equal for these four participant nodes (see [Figure 3-13](#)). So if the working hours are similar, the energy consumption can be considered as even level. However, more power consumption and higher average RDC clearly present that node 2 consumes more energy for radio transmission for packet retransmission and routing control messages exchange. The same situations happened in node 3 and node 4 (see [Figure 3-13](#)) but the reasons could be concluded by radio interference and noise leading to a substantial increase of energy consumption for radio listen operation. Since the results of transmission power cost are similar for node 3, 4, 5, Node 5 apparently is not severely affected as the two former nodes and maintains a relative low average power consumption level. [Figure 3-14](#) presents time-varying historical power consumption in this DODAG topology. Although the network is almost a star topology, with a misbehaved node 2 and the anticipated interference source, the recorded data shows a set of periodical peak values. [Figure 3-15](#) presents that average radio duty cycle can also reflect

another profile of power consumption. The different situations (location, device) of each node lead to different RDC results. Lower RDC can insure longer sleeping time and, consequently, save more battery power.

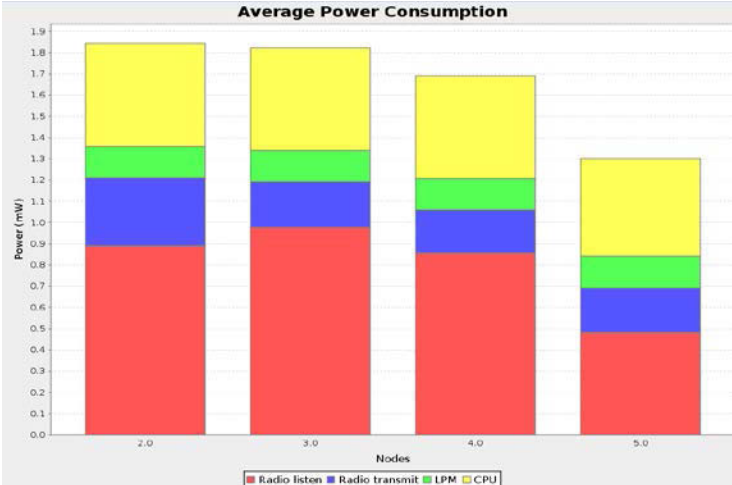


Figure 3-13 Histograms of power consumption profile in our experiment

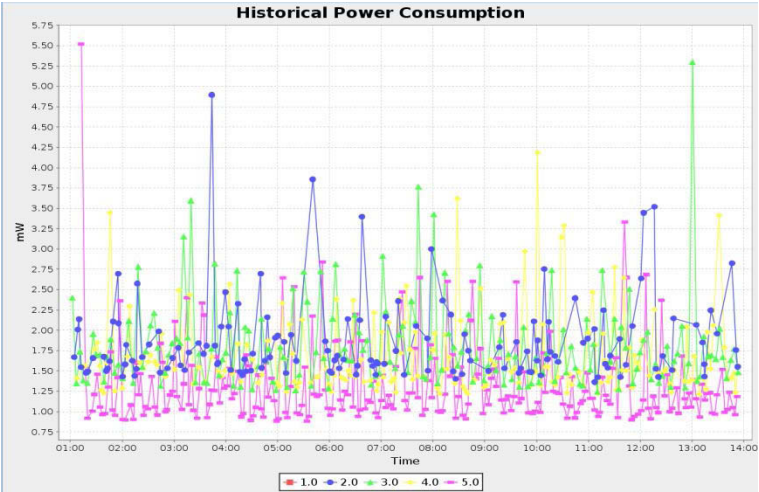


Figure 3-14 Time-varying power consumption profiles of each node in the current DODAG

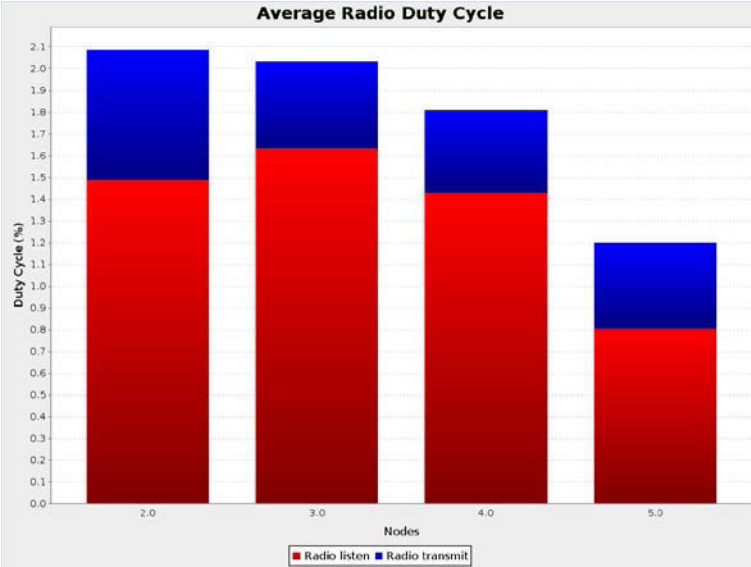


Figure 3-15 Histograms of Radio Duty Cycle profile in our experiment



### 3.6.3 Key lessons

To achieve clarified and credible tests, the best method is to carry out experiments on a hardware testbed. An indoor environment is a relatively simple realistic scenario. In this subsection, we briefly summarize the aforementioned results. Some key items are listed below:

- In this experiment, due to the utilization of default system settings and small number of devices, the multi-hop topology is not well presented. But according to the ContikiRPL's specification, MrhOF and ETX routing metrics are working together to calculate the rank and preferred parent using highest throughput path in these tests. Thus, different configurations and algorithms installed in RPL model can build specific RPL DODAG compliant with required routing strategies to meet various QoS requirements;
- Collecting interval, beacon interval (routing overhead) and network situations (i.e. radio interference and noise) can lead to obvious alteration of power consumption;
- Moreover, the factors, which may influence the power profiles, for example, the performance of antenna, limitations of hardware and the deployed positions, would also directly impact on the result of network lifetime.

According to the results of anticipated theoretical lifetime or network performances, they are very sensitive to the impacts from the characteristics of real-world environment and the performance of testbed. Nevertheless, the objective of these tests is to reveal the capability of RPL in indoor scenario. The above listed factors also imply the complexity of a testbed for RPL evaluation.

Through these experiments, the importance of adapting RPL to the PA application has been presented. Namely, the standard RPL routing framework is urgent to need improvements to achieve its availability in the real-world environment. The dynamic link quality induces frequent oscillations to the DODAG based on ETX path weight value. The results of energy consumption are also higher than our anticipation, and the testbed nodes cannot keep alive in enough long time, even they do not have any measurement sensory missions and actuation functions. Under the harsh outdoor environment, borrowing the observations of these pilot studies, original RPL will provide worse performance in an A-LLN system.

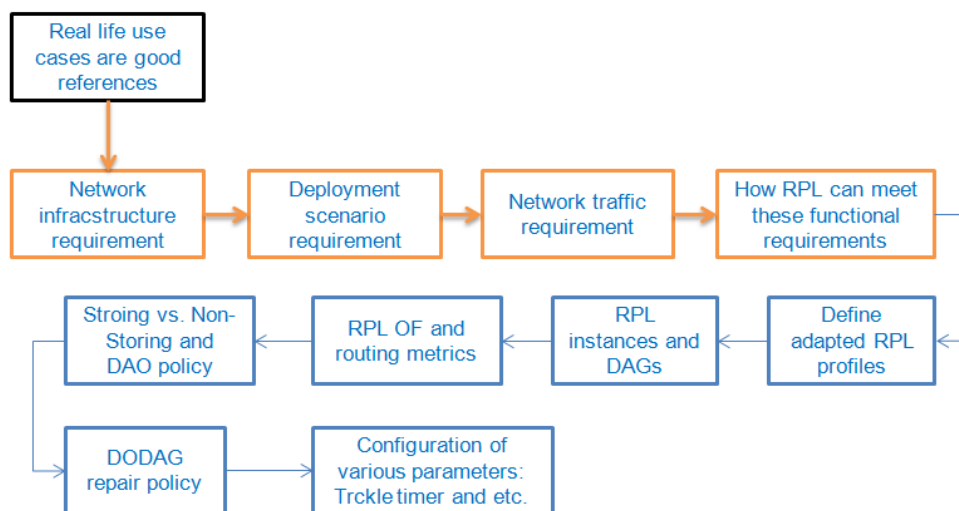


Figure 3-16 A flow chart of adapting RPL routing platform for a specific application

Based on the above analysis, Urban-LLN is referred as a driving use case for the proposed Agriculture-LLN (A-LLN) scenario. Figure 3-16 proposes how to process the

adaptation work step by step. According to A-LLNs infrastructure description, requirements of deployment scenarios and network traffic pattern for A-LLNs (yellow blocks in [Figure 3-16](#)) in previous subsections, the building stones of this thesis are to propose a set of solutions for the RPL framework to meet those requirements. To provide brief descriptions of our preliminary thinking, the main points of this adaptation solution suite, the arisen challenges and our recommendations, will be discussed in next section.

## 3.7 How to adapt RPL profiles to A-LLN: challenges and recommendations

### 3.7.1 RPL instances and multi-DAG

From the view of current existing RPL specifications and implementations, RPL operations are only defined for a single RPL instance. However, multiple RPL instances can be supported in multi-service networks where various applications may use different OF with different routing metrics and constraints, e.g., a network exists both AMD and LC traffic. For a network built by the devices with multi-media functions, this RPL feature will be also very attractive.

### 3.7.2 RPL objective function and routing metrics

- OF of A-LLN:

Based on the design of RPL standard, the objective function (OF) is decoupled from the core RPL mechanisms and also from the metrics used for specific network. RPL relies on an OF which is a flexible and scalable algorithm for selecting parents and computing path costs and rank. Two OFs for RPL have been defined, OF0 and MRHOF, both of which define the selection of a preferred parent and backup parents, and are suitable for most the cases of various applications and deployments. However, neither of the current defined OFs supports multiple metrics that is useful in heterogeneous networks since a combination of metrics could be required by agricultural low power and lossy network (A-LLN) to obtain the optimal selection of routing paths.

- Path metrics of A-LLN:

A-LLN deployments use the link layer technologies exhibiting significant packet loss and required routing metrics should take packet loss into account, so Expected Transmission Count (ETX) metric defined in [59] can be utilized to characterize a path over such lossy link. If some parts of this network do not rely on powered infrastructure, simpler metrics that required less energy to compute would be more appropriate. For most of the cases, a combination of hop count and link quality can satisfy these requirements. To maximum lifetime of whole network, minimizing energy consumption is critical in these networks, so available energy of A-LLN nodes should also be used in conjunction with ETX metrics to achieve energy efficiency and balance. [84] proposed energy-efficient routing requirements for biomedical WSN are similar to A-LLNs since energy is also one of the scarcest resources for A-LLNs scenarios.

### 3.7.3 Storing vs. Non-Storing Mode and DAO sending policy

In most scenarios of A-LLN, LBRs and LC nodes are powered by main line or recoverable power supply so they are not energy-constrained. Instead, these A-LLN nodes may have hardware and communication capacity constraints which are primarily determined by cost, and secondarily by power consumption. In addition, the constraints are the main considerations to outline the requirements of an A-LLN deployment. Thus, the adoption of RPL storing or non-storing mode should be compliant with a deployment specification.

On one hand, RPL non-storing mode should be preferred as a tradeoff when A-LLN devices are memory constrained and cannot adequately store the necessary route tables to support basic hop-by-hop routing. In addition, the use of storing mode may lead to reduced overhead and route repair latency if A-LLN LC nodes are capable of storing such routing tables. In A-LLN scenario, it is belonged to low-density environment, so normally the routing table size will not become challenging. However, this feature still depends on the system complexity. For example, if the devices are required to run an application managed with SNMP, CoAP or HTTP protocol, the A-LLN sensor nodes should perform route aggregation with RPL non-storing mode, but it is alternative feature for LBRs and LC devices.

Two-way or bidirectional communication is a requirement when the local control messages and queries are launched in A-LLN. Thus, A-LLN sensor nodes and LC nodes should send DAO messages to establish downward routing paths from the LBR (root) to them.

### 3.7.4 DODAG repair

The local repair mechanisms in RPL can be used by A-LLNs deployments to effectively handle time-varying link characteristics. Based on the RPL specification, local repair should be triggered by specific broken link detection in low level layer and by loop detection in storing mode. In the first step of this mechanism, a node is detached from its original DODAG and then re-attached to the same or to a different DODAG based on its trickle timers. While in the detached state, if joining the same DODAG, the node advertises an infinite rank value so that its children nodes can select another different parent. This procedure is called poisoning process in the RFC6550's description. After this node finishes sending notifications to its children that it is detached, the node can rejoin the same DODAG but with a higher/lower rank value according to its objective function. From our concerns, this mechanism would be often used by real-world A-LLNs system to cope with the aforementioned highly dynamic environments.

It has little benefit for the A-LLNs deployments to form local sub-DODAGs, except when this group of nodes cannot build any communication to a LBR. But this option could be used for some certain local controller nodes that can provide 3G/4G cellular mobile network or backbone internet connection.

The second DODAG repair mechanism is a global repairing method. In A-LLNs scenario, global repair can update the current DODAG to a new version that is periodically reconstructed to enable a global re-optimization of the graph. This operation should be sparingly employed in order to conserve batteries' energy. But it is also the fastest and most economical technique in the case when the network is extensively damaged. Thus, an A-LLN deployment should equip an efficient autonomous way for detection of large-scale incidents, such as numerous A-LLN nodes lost and disconnect caused by adverse weather (i.e.

snowstorm, thunderstorms, dust storm, heavy rainfall and flooding, etc.) or other unpredictable damages.

### 3.7.5 Analysis of configuration defaults and ranges

- Trickle timer parameter:

Trickle is designed to be adaptive for a wide range of node density. Node densities in A-LLN deployments can vary depending on the development budget and purpose, from nodes having only one or a handful of neighbors to several tens neighbors. Trickle provides a combination of DIO packet suppression and adaptive timers for sending updates. It may cause a short period of congestion when an inconsistency is detected and DIO updates are sent nearly simultaneously by numerous neighboring nodes. These congestions can be avoided by employing specific link layers mechanisms. But when the number of DIO updates reaches to a certain level, it can result in communication latency increasing for other control and data traffic in the A-LLN network. To mitigate this kind of short-term congestion, this preliminary analysis recommend a set of more conservative values for the trickle parameters than those described by [1], and more tests and verifications of simulation and real-world experiments are still needed. Specifically, DIOIntervalMin is set to a larger value to avoid periods of congestion in dense environments, and DIORedundancyConstant is parameterized accordingly as the below explanation. These values should be appropriate for the timely distribution of DIO updates in both sparse and dense scenarios of A-LLN while avoiding the short-term congestion that might arise in the scenarios with more A-LLN sensor nodes or LC nodes.

Because the actual link capacity depends on the particular link technology used within an A-LLN deployment, the Trickle parameters are specified in terms of the link's maximum capacity for conveying link-local multicast messages. If the link can convey 'm' link-local multicast packets per second on average, the expected time it takes to transmit a link-local multicast packet is '1/m seconds'.

DIOIntervalMin: A-LLN nodes should set DIOIntervalMin that is the Trickle  $I_{\min}$  as at least 50 times as long as it takes to convey a link-local multicast packet. This value is larger than that recommended by [1] to avoid congestion in some specific A-LLN deployments. For the extremely energy-constrained A-LLN sensor nodes, DIOIntervalMin is better to be set to a value resulting in a trickle  $I_{\min}$  of several hours (e.g., 2h).

DIOIntervalDoublings: A-LLN nodes should set DIOIntervalDoublings such that the Trickle  $I_{\max}$  is at least TBD (by IANA: Internet Assigned Numbers Authority) minutes or more. For the A-LLN sensor nodes deployments, it can be set to a trickle  $I_{\max}$  value of several days (e.g., 2 days).

DIORedundancyConstant: A-LLN nodes should set DIORedundancyConstant to a value of at least 10. This is due to the larger chosen value for DIOIntervalMin and the proportional relationship between  $I_{\min}$  and k suggested in [71]. Enlarging this parameter is intended to compensate for the increased communication latency of DIO updates caused by the bigger DIOIntervalMin value, though the proportional relationship between  $I_{\min}$  and k suggested in [71] is not preserved. Instead, DIORedundancyConstant is set to a lower value in order to reduce the overhead of DIO if this A-LLN deployment has high density of A-LLN nodes.

- Other parameters:

A-LLNs deployments should set MinHopRankIncrease to 256, resulting in 8-bit of resolution (e.g., for the ETX metric).

To enable local repair, A-LLN deployments should set `MaxRankIncrease` to a value that allows a device to move a small number of hops away from the root. With a `MinHopRankIncrease` of 256, a `MaxRankIncrease` of 1024 would allow a device to move up to 4 hops away.

### 3.7.6 Manageability considerations

RPL enables automatic and consistent configuration of RPL routers through parameters specified by the DODAG root and disseminated through DIO packets. The use of Trickle for scheduling DIO transmissions ensures lightweight yet timely propagation of important network parameter updates, and allows network operators to choose the trade-off points they are comfortable with respect to overhead vs. reliability, and timeliness of network updates.

Along with the Trickle Timer parameters used to control the frequency and redundancy of network updates can be dynamically varied by the roots (LBRs) during the lifetime of the network, all DIO messages should also contain a Metric Container (MC) option for disseminating the metrics and metric values used for DODAG setup. In addition, DIO messages should contain a DODAG Configuration option for disseminating the Trickle Timer parameters throughout the whole A-LLN deployment.

The possibility of dynamically updating of the adopted metrics in the A-LLN as well as the frequency of network updates allows deployment characteristics (e.g., specific applications) to be discovered during network convergence and to be used to tailor network parameters once the network is operational rather than having to rely on precise pre-configuration. This also allows the A-LLN parameters and the overall routing protocol behaviors to be evolved during the lifetime of the network.

RPL specifies a number of variables and events that can be tracked for purposes of network fault detecting and performance monitoring of RPL routers in A-LLN. Depending on the memory and processing capabilities of each A-LLN device, various subsets of these parameters can be employed in the experimental field.

## 3.8 Conclusion

In this chapter, a group of pilot studies have been presented. The aforementioned investigation works mainly serve the proposed A-LLNs definition, including the descriptions of its infrastructure, deployment scenarios, traffic pattern, and layer-two applicability. However, the purpose of this chapter is not only to explain how A-LLNs look like, but also to clarify the methodology of building simulator and hardware testbed for A-LLNs. The testbed are used to evaluate the availability of RPL routing framework, and the lessons from these experiments tell us RPL requires many adaptation and improvement work to be ready for the real-world A-LLNs scenario. Beside, an adaptation procedure is given with the anticipated challenges and our empirical recommendations. From the view of this thesis, due to the revealed complexity of the whole system relied by RPL, we cannot tackle all the issues. Nevertheless, we believe that the network lifetime and sufficient QoS can be the base line of a feasible A-LLN deployment and environmental data collection application of precision agriculture. Thus, in next chapter, another simulation experiment with deeper analysis of energy profile will be carried out to disclose our RPL optimization proposals.

## 4 Modeling, optimization of RPL routing protocol for Precision Agriculture

### 4.1 Optimization and enhancement of RPL routing framework: problem statement

Through the preliminary discussed and elaborated in last chapter, we are able to observe the dynamic environments which have to be faced by the real-world systems. The complexity of after analysis (i.e. unavoidable radio interference, noise, etc.) and unpredictability of system problems (i.e. hardware, protocol stack, OS, etc.) are the main challenges for protocols' design and evaluation. As our main contribution is clarified to be dedicated to the routing protocol of specific precision agriculture application, simulation is needed be adopted due to its simplicity and abundant debugging information. For example, in our experiments using hardware platform (subsection 3.5.2), one big difficulty was to collect evaluated data from each node in wireless way since it is not convenient to connect serial cables to all of them. Thus, one collect process was used to generate monitoring data but this is not a practical approach for real world system since these radio packets would consume extra resources, such as bandwidth and battery power. And tradeoffs have to be made for the transmission of real application packets and monitoring data packet.

The advantages of network simulation have been discussed comprehensively in the literatures of [19, 61, 110, 111]. Network simulator is able to record all the results information, such as network condition, nodes' output and behaviors, which can support the after evaluation very well. However, realistic radio environments are difficult and complicated to be simulated, although there are some path loss models, such as Friis model, log-distance model and power regression model. Nevertheless, the evaluation of a routing protocol model built in a network simulator is still an important step before the real-world deployments are carried out. Thus, we will firstly present one simulation experiment of ContikiRPL model of uIPv6 protocol stack in this section. Some issues would be uncovered more completely than the experiments using hardware platforms. In other words, simulation results could help us to obtain a better understanding of the RPL standard and to clarify the key points (i.e., packet reception ratio, network lifetime and control message overhead) which are mostly related to the performance in the real-world A-LLN communication system. Moreover, we will provide our considerations, ideas and corresponding solutions for these discovered issues respectively.

#### 4.1.1 Simulation and analysis of uIPv6 protocol stack

A basic presentation about our adopted simulation platform has been introduced in subsection 3.5.1 of last chapter. But only a representative simulation of A-LLNs scenario was briefly discussed for exploiting analysis results that is more dedicated to application rather than the lower level protocols. In this section, uIPv6 protocol stack is used as a foundation and experimental target, and our main contribution of adapting RPL routing protocol to A-LLNs will be evaluated and tested in Chapter 5.

##### 4.1.1.1 Simulation setup

As a case study where RPL is adopted to perform environmental data, UDGGM radio medium in Cooja simulator is used to configure radio coverage and distance loss as the fixed parameters. After the RPL routing algorithm setups the network, which needs about 90 seconds, each sensor node in different network size scenarios (holding 20, 30, 40, 50 sensor nodes) starts sending data packet periodically. The purpose of setting fixed traffic interval with different network size is about that the scalability of A-LLN is more important for precision agriculture application according to the discussion in Chapter 3. See [Table 4-1](#) for a detailed description of the network and the simulation configurations. The simulation scripts are organized as a suite of Contiki applications, and the simulation outputs are recorded in raw log files for a further analysis. A set of JAVA programs using JFreeChart library performs for results calculation and plotting functions. For each simulated scenario of different network size, five simulations are applied repeatedly, namely five random topologies per network scenario, and the final results are computed as average values.

Table 4-1 Network Configuration

| <b>Network</b>          |   |
|-------------------------|---|
| Deployment area         | 25 m × 20m  |
| Deployment type         | Random positioned   |
| Number of nodes         | 1 sink with 20, 30, 40, 50 sensor nodes   |
| Radio coverage          | 100 square meters   |
| Distance loss           | 90% RX Ratio  |
| Nodes initial energy    | 0.25mAh = 2700mj; millionth of 2500 mAh estimated by PowerTrace Model [105] with assumed stable 3V voltage                        |
| Network layer protocols | uIPv6   |
| Routing protocol        | RPL routing framework:<br>Trickle timer: k = 10; IntervalMin=12, IntervalMax=8;<br>Routing Metrics: ETX routing metrics and MrhOF |
| Transport layer         | UDP   |
| Data link layer         | CSMA/CA + ContikiMAC + 6LoWPAN  |
| <b>Application</b>      |   |
| Data length             | 20 bytes per packet   |
| Task type               | Time drive  |
| Reporting intervals (s) | 15  |
| <b>Simulation</b>       |   |
| Time                    | 40 mins   |
| Iteration               | 5   |

#### 4.1.1.2 Simulation results

In order to make a quantitative analysis and a future comparison work, we defined the following figures of merit as our best concerns.

**Packet Reception Ratio (PRR):** A-LLNs have to fulfill a certain level of QoS requirements according to the nature of environmental data collection application in precision agriculture. The application-level PRR is one of the most important and common QoS metric in network communication experiment. In this case, the PRR of uIPv6 protocol stack will be evaluated and verified whether it can achieve to the required performance.

**Energy efficiency:** As energy is a constraint in the A-LLN, its efficiency is important to prolong the network lifetime. However, network lifetime is related to network deployment, coverage, availability, connectivity, energy balance, etc., as elaborated in [112], which is not easy to be analyzed comprehensively. Thus, we will discuss more details about the network lifetime issue in next section. The portion of living nodes is used as evaluation metrics here to represent this network performance.

**Controlling message overhead:** As stated in [105], radio activity will strongly influence the level of energy consumption. In this way, the controlling message generated from ContikiRPL model may be seen as a direct impact on the energy consumed by each node. Namely, efficient overhead control at the routing layer means lower power consumption and congestion due to less redundant data transmission.

Table 4-2 Network performance metrics

| Performance metrics  | N = 20   | N = 30   | N = 40  | N = 50   |
|--|----------|----------|---------|----------|
| Packet reception ratio                                     | 62.233 % | 57.481 % | 45.76 % | 68.902 % |
| Portion of living node                                     | 15 %     | 6.66 %   | 7.5 %   | 0 %      |
| Avg. DIO transmission per interval (DIO trickle timer)     | 21.857   | 33.02    | 44.547  | 53.583   |
| Avg. Number of DIO messages per minute (DIO trickle timer) | 15.3     | 42.1     | 59.025  | 80.38    |

The results presented in [Table 4-2](#) are the performance metrics. It should be noted that all the data are average values from five running iterations. From the results of average PRR, they decrease due to the augment of network size (check the PRR values when N=20, 30, 40). It can be observed that as the scalability of RPL standard, a satisfying QoS level cannot be achieved in this case taking into account limited battery power, bandwidth, and radio coverage. In this experiment, part of simulated nodes working as key routers may exhaust their energy in shorter time comparing with the motes working as leaf nodes. However, when there are more redundant routers existing in one scenario (i.e. when N = 50), PRR becomes better as the simulated nodes have enough options after their first best parents stop working. Furthermore, during the change of the node's best parent, some application packets could be lost and sender cannot receive ACK messages from the sink node in this procedure. The portion of living node is a performance metrics to represent the network lifetime. It is obvious that MrhOF using ETX cannot achieve traffic balance and energy efficiency and the consequent hot spot issue might incur a big degradation of the percentage of living node. Apparently, low portion of living node would lead to a directed impact on the average PRR.



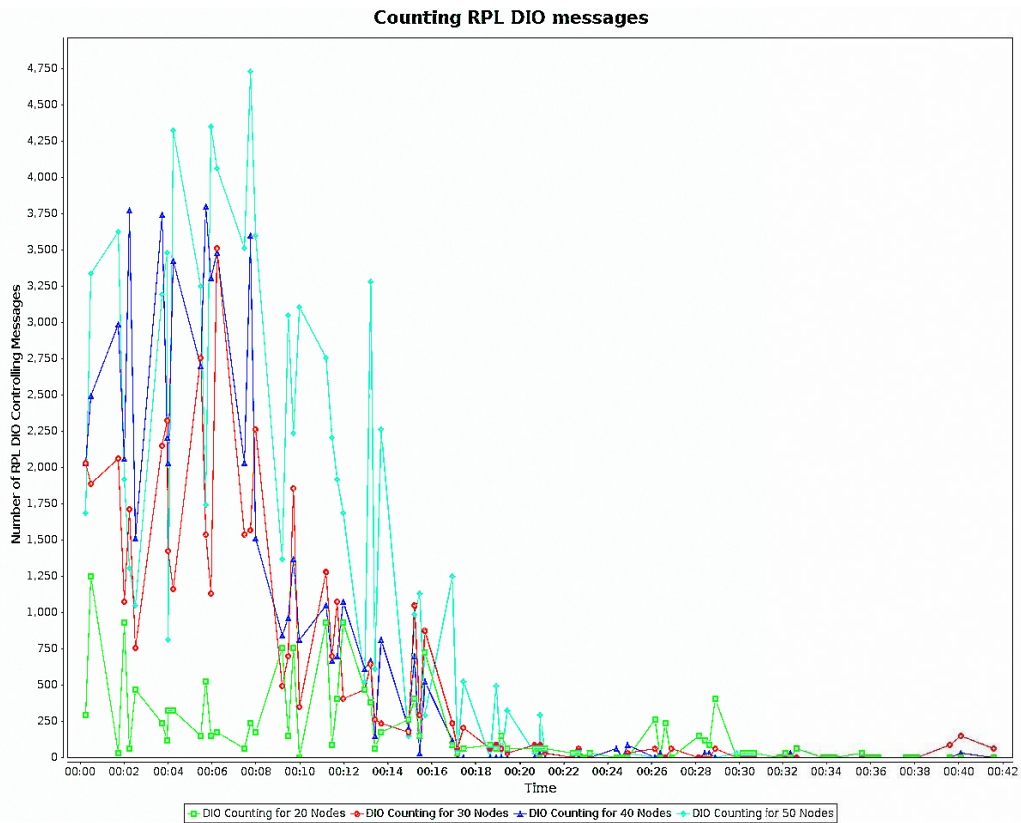


Figure 4-1 Time-varying network profile of uIPv6 protocol stack simulation: Number of DIO overhead

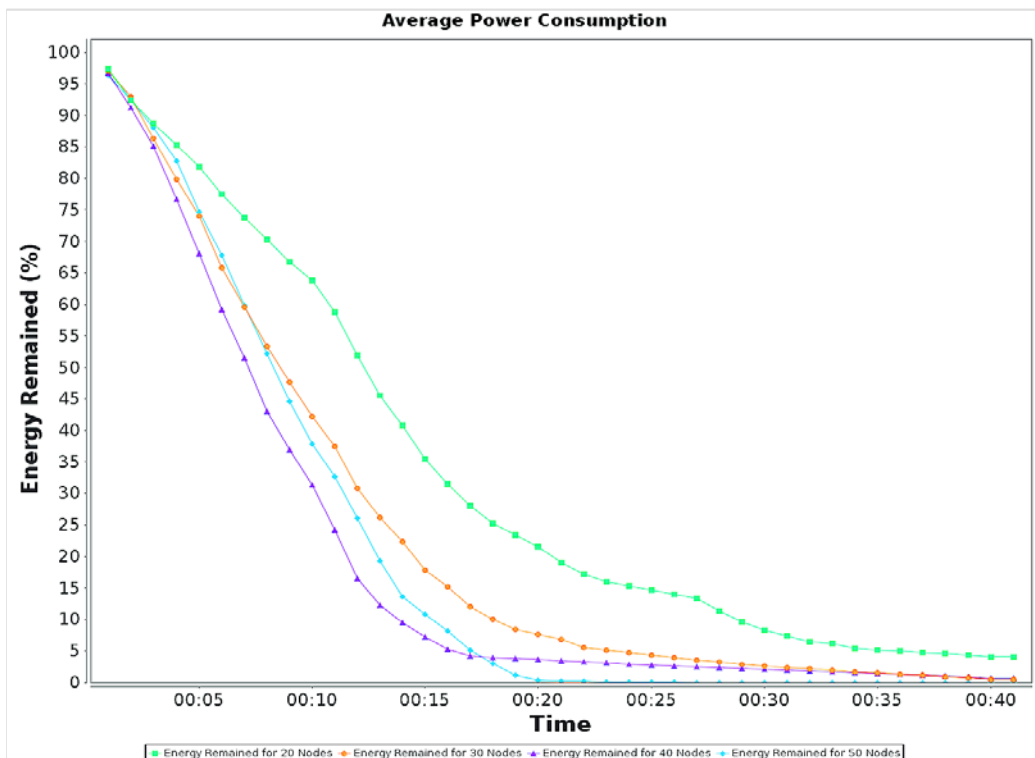


Figure 4-2 Time-varying energy remained profile from uIPv6 protocol stack simulation

The average number of DIO transmission per trickle interval presents to be normal. DIO suppression is actually not very obvious because of two reasons: i. the redundancy constant  $K$  of trickle timer algorithm is configured as 10. But in the radio range of a certain node, it may not cover more than 10 nodes; ii. the impact from MSPsim emulator and Unit Disk Graph

Radio Medium (UDGM) distance loss propagation model might result in lower PRR due to collision, busy channel, died key routers, etc. In addition, the averages of DIO transmission per minute show the overhead generated from RPL protocol in a unit time. The results present the overhead due to DIO message broadcast cannot be ignored since it occupies large proportion of total traffic distribution throughout the network.

Figure 4-1 shows the number of DIO controlling message from the view of the MAC layer. As an asynchronous MAC mechanism ContikiMAC is used in uIPv6 protocol stack, each broadcast packet has to be sent continuously in a complete MAC interval to ensure all the neighbors can receive this packet. This feature directly influence the performance of whole network, especially lead to longer radio activation time, which may cause more energy consumption and collisions. Moreover, we can also clearly observe the operation of trickle timer. Namely, during the setup of the simulated DODAG, a large number DIO messages are required to be broadcasted to achieve consistent state, and then the trickle timer interval would be doubled in an exponential backoff manner until reaching the maximum interval unless inconsistency happens. The curves in Figure 4-1 also show that this mechanism can extremely reduce the overhead of controlling messages when the networks become stable.

From the plotting in Figure 4-2, we can observe the trends of average remained energy in the four scenarios with different network size. These results lead to conclude that the network having bigger size needs the simulated nodes to spend more time in communications and listening, such as application packet relay, control messages in routing layer, and more retransmissions due to congestion or packet lost incurred by collisions or interferences. Thus, this simulation scenario might get big degradation of the remained energy profile. Furthermore, the obtained curves also present to be compliant with the results of portion of living nodes.

#### 4.1.2 Problem statement and contribution highlight

Through the above analysis, we found that there are many points of RPL protocol can be improved and adapted to the A-LLNs of precision agriculture. Essentially, the existing inside mechanisms of RPL is not completely suitable for this application, and certain components in the RPL routing framework need to be redesigned. As large-scale network and centralized structure have been stated as important features of A-LLNs, the multi-hop and dynamically self-organizing routing protocol are pre-requisites. Thus, RPL is the only option to be the building stone of this thesis as well orienting the future Internet. Having mind of RPL's well supporting of IPv6 network layer and 6LoWPAN adaptation layer, it is an expected driving force of moving traditional agricultural WSN to the next generation of IP technology, namely the emerging IoT.

In addition, according to the description of the A-LLN devices in last chapter, they have limited resources, such as low memory capacity, low processor capability and low energy budgets. In the simulated scenarios stated in last subsection, most of issues have been taken into consideration through using the emulator of Cooja and Powertrace model of Contiki. A simple propagation model was adopted, but we believe that the real-world environment would be more dynamic, no matter the indoor (i.e. as discussed in section 3.6) or outdoor (see section 5.3) scenarios. In the current research work of RPL, the literatures about improving and adapting this promising routing framework for a specific real-world application are still scarce. Recalling that only smart grid, industrial automation and E-health areas have been

preliminarily studied, not to mention the agricultural WSN, which also precisely named as agricultural wireless sensor/actuator network (WSAN).

To the best of our knowledge, our research is the first work to extend the traditional WSN technology of ICT in agriculture to the concept of Low-power and Lossy networks (LLNs) [113], which exclusively support IPv6 routing architectural framework and has been claimed as a main part of IoT. Our defined A-LLNs applicability analysis is proposed for this purpose. Moreover, regarding that the sole aim of this thesis is to enhance the applicability, robustness, scalability of RPL for A-LLNs, thereby to adapt RPL to the precision agriculture application, we adopted the following approaches with new designs and evaluations:

- Energy-aware metrics and objective function

This study is about a new energy-aware objective function (OF) algorithm for path selection in order to maximize node and network lifetime in A-LLNs. This OF algorithm can be embedded into RPL routing framework to achieve energy balance and efficiency by choosing the data forwarding route based on remained energy metric and ETX metric.

- Scalable objective function with Hybrid RPL routing metrics

For dealing with the intricacies presented by WSNs, such as limited energy, node and network resources, only one routing metric is often not enough to meet the QoS requirements of a specific application of LLNs. Since the Precision Agriculture (PA) application might need its underlying A-LLNs with respect to a certain level of QoS, for example, delay, reliability, energy consumption and loss, a set of appropriate routing metrics have to be adopted to achieve these requirements. We use RPL routing metric composition approach [73] to combine different primary routing metrics to satisfy the needs of the PA application and A-LLNs' characteristics and limitations. The hybrid routing metrics are designed as an extension of the above energy-aware OF to capture the required effects (e.g. link reliability, remaining energy, system reliability indicator, radio duty cycle, and information resource availability) and achieve the needed QoS requirements.

- Context-aware trickle timer

Regarding to the energy-constrained networks like A-LLNs, we carried out an extensive study of Trickle. As stated in last sub-section, the overhead of routing controlling messages has direct impact on route formation and node power consumption. And our evaluation results show that the original version of Trickle is not efficient enough to control routing update distribution throughout the network. In order to mitigate this issue, we proposed an enhanced version of Trickle algorithm using context-aware technologies, named as CA-Trickle, to guarantee the reliability and the energy-efficiency of A-LLNs. To integrate CA-Trickle into RPL routing framework, the performance of this algorithm will be analyzed, especially on the optimal route formation. Meanwhile, the impact factors of different MAC mechanisms are also studied. But more important work is the utilization of various sensor (e.g., temperature, light, RSSI, etc.) for detecting adverse weather, which may lead to radio intermission. CA-Trickle can provide efficient manner to prevent the regression of Trickle timer to the minimum interval in the special conditions of real-world environment.

- Integrating simulation and real world for mutual optimization

In the history of the WSN, unexpected routing behaviors are always the main issue of the large-scale deployments. Considering the high cost of building a real deployment, network simulators are often used in this domain. In the context of A-LLNs and emerging IoT technologies, we should realize that, in the results from the simulation scenarios and thorough

testing, and the problems, such as unacceptable performance and severe system failures due to sub-optimal routing path, would still happen in the real-world system. For the purpose of providing an answer to this issue, we propose a conceptual structure and a context-aware tool-set design in order to help building the simulated topology which is more close to the real network through mapping a serial routing metrics defined by IETF ROLL working group and the link situations from the actual network. We believe the suggestion of bridging virtual and physical worlds reflected on the proposed tool-set could conduct more precise routing-targeted simulations. Moreover, the knowledge and analyzed simulation results can lead us to optimize the network topology of the future deployed A-LLNs through a close-loop method.

## 4.2 Energy-aware metrics and objective function of IPv6 Routing Protocol for A-LLNs (RPAL)

### 4.2.1 Introduction

This research work is focused on a strategy to extend the A-LLNs' lifetime. As A-LLNs should be able to work without human intervention (e.g. battery replacement or node movement), longer network lifetime is always desirable by most of the wireless applications in real-world experimental fields. We have discussed the energy harvesting technologies which could be promising solutions for the energy related issues in subsection 2.2.1. However, this domain still needs further studies of the availability and practicability in real world. Even if the relevant researches will have progress in the near future, A-LLNs' operational costs will be another issue that might stunt this solution to be applied in most of the miniaturized A-LLNs sensor nodes. Namely, if we want to keep the eyes, ears and nose of the A-LLNs alive for sustainable environmental information collection, it is still essential to use the restricted power under well consideration. Thus, our proposed strategy is designed with three key factors: RPL routing protocol, the multi-hop network topology, and energy efficiency.

This proposal is a solution dedicated to the network lifetime optimization of A-LLNs based on a new Objective Function (OF) of RPL using a set of energy-aware metrics dedicated to environmental data collection in Precision Agriculture (PA) application. This proposed OF adopts the remaining energy metric on each A-LLN node to calculate the optimal paths to route data across the targeted network. This path selection algorithm can help to achieve energy balance by taking into account of the A-LLNs' intrinsic characteristics, such as the heterogeneous radio devices and power supply sources. In order to achieve these purposes, balancing the network lifetime requires the A-LLN nodes to forward data to the highest lifetime path. On the other side, the A-LLN nodes with the low remained energy should select a parent node with good link quality to avoid packet loss and retransmission since this could reduce energy wastage for itself.

This section will present the proposed energy-efficient and lifetime-aware routing mechanisms, which include resource-oriented and energy-aware metrics for extending parent selection algorithm of the original version of RPL. In next section 4.3, a hybrid scheme that uses the work of this section as foundation will be further discussed, so that the ETX metric can be integrated with this energy-aware routing strategy without the suboptimal path selection and routing loops. It should be noted that the feasibility of our proposals have been validated by simulation experiments and real-world testbed, and the results and their analysis will be elaborated in chapter 5.

## 4.2.2 Related work

Since our proposed routing scheme adopts energy-aware as well as resource-oriented metrics, some background knowledge is better to be introduced before we unveil our algorithm design and implementation.

### 4.2.2.1 Energy consumption in theoretical description

Most of the A-LLNs devices are simplified and miniaturized like the traditional WSN nodes. The energy consumption estimation is practical to be described in theoretical way comparing with real measurement using the multimeter. The classical technique for this purpose is summing the energy consumption of all components in a hardware platform. In addition, based on the work of [114], we adopt their proposed finite state machine (FSM) model in our description.

A MCU normally has two main states: active and sleep. Some processors may offer more than one sleep modes to save power. For example, AVR microcontroller (i.e. ATmega128RFA1) of our evaluation testbed could go into idle, sleep, deep-sleep, power-down and power-save modes while the RF transceiver is in SLEEP state, so the whole device can enter the Deep-Sleep mode. Although six sleep modes are defined for the CPU of ATmega128RFA1 MCU, we could simplify them into three main states: active, idle and deep sleep (as depicted in Figure 4-3). According to the datasheet of this AVR MCU [22], each state needs the supports from different peripherals and external trigger intervals. The time spent on these states is an important factor might influence the power consumption since the time is a parameter in the following formula:

$$E = (U * I) * t \quad (4.1)$$

Where U is the voltage and I is the current consumption in the node. This formula could be used to find the energy consumption in joule. And power P is the calculated results from U\*I.

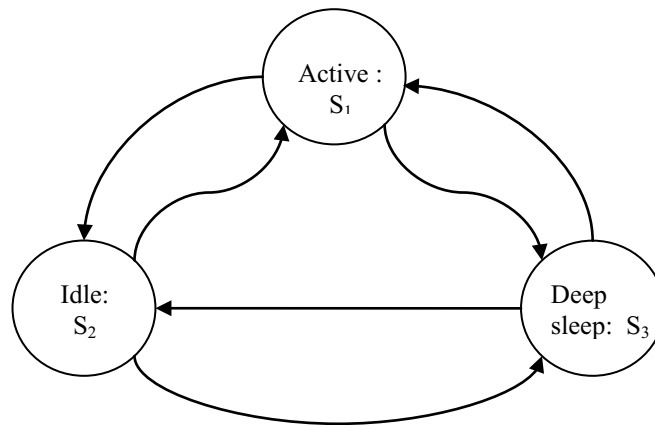


Figure 4-3 Processor States

Thus, the energy consumption for CPU states can be simply defined as:

$$E_{CPU} = \sum_{j=1}^n P_j t_j + \sum_{i,j=1, i \neq j}^n E_{ij} s t_{ij} \quad (4.2)$$

The formula (4.2) based on [114] defines a set of processor states  $S_1, \dots, S_n$ . The energy consumption is given by the sum of the consumption within these states plus the sum of the

energy required by states switching. For example, in a state  $S_j$  can be calculated by the needed power  $P_j$  and total running time  $t_j$ . The energy needed for states switching from state  $S_i$  to  $S_j$  is denoted as  $E_{ij}$ , meanwhile  $st_{ij}$  denotes the total number of switching time.

Moreover, the energy consumption model for RF transmitter is also able to use all its states and transitions. For instance, the low-power 2.4GHz transceiver of ATmega128RFA1 mainly has four basic operating modes and six state transitions, as shown in Figure 4-4.

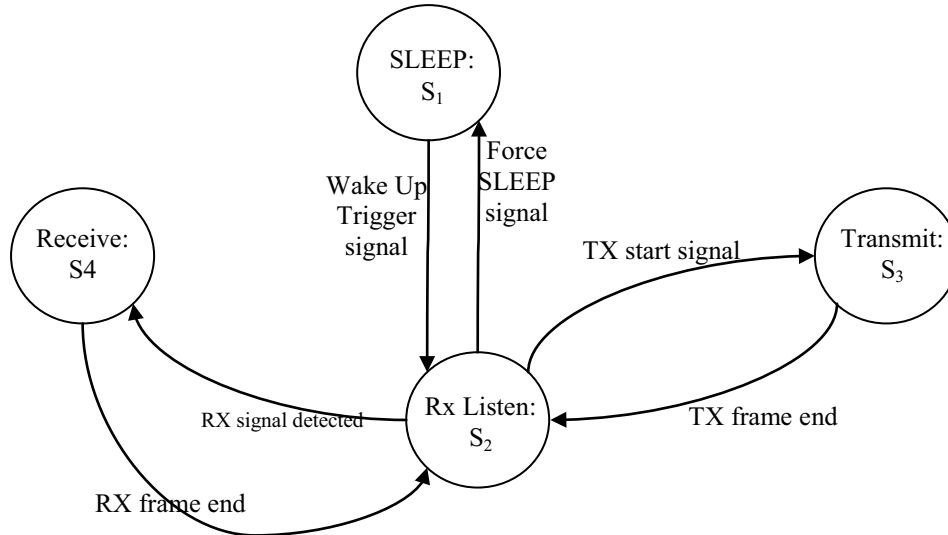


Figure 4-4 Energy Consumption model in FSM of low-power 2.4GHz transceiver of ATmega128RFA1

Except the above two main devices, most of the other devices only have on and off two states. If the energy consumption of RF transceiver and the other peripherals using the similar formula like (4.2), we can know how to calculate the total energy consumption as (4.3):

$$E_{total} = E_{CPU} + E_{RF} + E_{peripheral} \quad (4.3)$$

#### 4.2.2.2 Energy aware techniques

To save more energy for longer time of unattended running, WSN usually uses two categories of energy aware techniques: power management and power control [115].

The working radio transmitter and processor can be considered as the main reason of energy consumption. How to shorten the active time of these two devices is just the issue that power management technique is dedicated to. The straightforward target is to designate them to keep in sleep mode if they have not any activities, in order to minimize energy consumption. The time of being in sleep mode should be as long as possible and the WSN node can wake-up for entering active mode. The mechanisms which provide the mode switch function are always proposed in the MAC layer. As MAC protocols essentially control the communication between each node, it also can ensure that the communicating nodes can be in active mode simultaneously with the necessary clock synchronization (i.e. beacon) for sleep/wake-up schedules.

Moreover, the power control techniques focus on how a WSN node could transmit each data packet with the minimum but appropriate power needed by successful transmission and reception to all its neighbors. One approach of this category called Transmission Power Control (TPC) techniques has been thoroughly studied in the literature [116], which can be

adopted to dynamically adjust the transmission power. The TPC techniques for WSNs have been already proved their efficiencies to significantly reduce energy consumption.

#### 4.2.2.3 *Network lifetime definitions*

The network lifetime basically depends on the survival time of the LLN sensor nodes since they essentially build the network. In other words, the lifetime prediction of the individual nodes can be further used to derive the lifetime of the whole network. Based on our investigation work, the following network lifetime definitions will be introduced, which could be used as a network performance metric in the evaluation and validation of our proposal.

**Network lifetime based on number of alive nodes:** In the literature of [117], the authors give a definition of network lifetime as the time until all nodes have been drained of their energy. Furthermore, the authors of [118] suggest to the time when the first node fails to be the end of the whole network since the key routers would consume their batter power faster. [119] define the network lifetime as the time when the number of failed nodes arrives to a specified percentage ( $k\%$ ). Namely, when  $k = 100$ , their definition is the same as the proposal in [117].

**Network lifetime based on sensor coverage:** [120] introduces the region of interest into the definition of network lifetime. The region of interest is covered by a group of sensor nodes, so the network lifetime is the time when all the nodes are dead in this specific area.

**Network lifetime based on connectivity:** [121] define the network lifetime depending on the percentage of nodes which have an available path to the base station. The connectivity here means the connected node has the ability to transmit data to the base station. [122] explains the network lifetime as the number of packets which could arrive to the base station. This value is also able to be considered as an indicator of connected LLN nodes.

**Network lifetime based on sensor coverage and connectivity:** another type of network lifetime definition is depending on the time when the number of connected nodes in the region of interest drops down below a predefined threshold value. For instance, the A-LLNs lifetime ends when the percentage of connected nodes in a certain coverage area (i.e. a parcel of the experimental farm) is less than a threshold value (i.e. 60%).

On one hand, since many routing protocols can deal with the failed node by topology management and the left alive nodes still can continue to operate. It is not accurate to monitor the performance of this network since the sink node cannot receive any application data for a long time before the last node finally fails. Therefore, the lifetime definition only based on count of LLN nodes alive is not sufficient.

On the other hand, using the network lifetime definitions solely according to the coverage or connectivity of LLN sensor nodes are also not enough. The sensing coverage can only guarantee that the number of alive nodes in this region of interest, but not the transmission between these LLN nodes and the base station. Furthermore, the connectivity is only able to ensure the number of connected nodes but it neglects whether the LLN nodes alive can essentially collect the interesting data. In some application scenarios, the definition of network lifetime based on connectivity is good enough. However, the coverage and the connectivity are all significant factors in A-LLNs and precision agriculture application. Thus, we define that one A-LLN is failed if there are not enough connected nodes (i.e. a predefined connectivity threshold required by specific agricultural application) in specific regions.

### 4.2.3 Energy-aware metrics and objective function of Routing Protocol for A-LLNs (RPAL)

Regarding the routing challenges and design issues in A-LLNs, as presented in Chapter 2, our proposed Energy-Aware Metrics (EAMs) and Objective Function (OF) of routing protocol for A-LLNs (RPAL) are designed with them in mind. To mitigate the effects of packets lost and the electromagnetic interferences in A-LLNs when they are deployed in harsh environments like experimental fields, our EAMs integrate ETX as metric to guarantee that the RPAL router can select the node within enough reliable paths to the DODAG root to be its preferred parent. Therefore, the EAMs pursues the reduction of both the packet error rate (PER) and the end-to-end delay, depending on the retransmission policy implemented by underlying MAC layer protocol. Furthermore, in cases where the nodes have the needs of mobility (i.e. mobile sinks located in tractors, farmers, agribot [123]), the routes are restored based on the stored mode of RPL, while maintaining the criteria of selecting the most reliable paths to the sink. As we have discussed the existing implementations of MRHOF in previous section, OF0 is the simplest OF that only uses hop count as metric without any hysteresis effect. Unlike both of them, our EAMs also integrate the Remained Energy (RE) of each node to introduce energetic considerations when forming DODAG topology to route the data through the A-LLNs. With the help of RE estimated method, RPAL model can be aware of RE in each node to promote the energy balance while still choosing the most reliable and efficient routing paths according to the application's QoS requirements of A-LLN. Our proposal is not only a simple combination of two metrics (ETX and RE). The OF algorithm of RPAL is able to use the ETX and RE metrics efficiently to increase the network lifetime with appropriate tradeoffs.

#### 4.2.3.1 Preferred parents selection of original RPL

A routing metric is a criterion used by the routing protocol model to make routing decisions. As a gradient routing protocol, RPL's path selection is the result of choosing the preferred parent since each of them is the beginning of a path where packets is able to be sent along, and the routing metric disseminated by the parent can achieve to specific requirements (minimized or maximized values). We firstly introduce the preferred parent selection mechanism and the common routing metric in original RPL protocol by modeling methods.

Let  $(A, B)$  denote the link between node A and node B. We assume that nodes are immobile and that link quality is variable. Link quality affects network performance in WSNs using a poor link leading to wasted resources and unreliable service. Hence, the network layer needs to estimate the link quality and to consider it in routing decisions. Link Quality (LQ) estimation can be done by hardware-based methods, such as LQI, RSSI, and Signal to Noise Ratio (SNR); or by software-based methods, such as ETX.

Let  $LQ(A, B)$  denote the link quality estimation for the link  $(A, B)$  where this quality is variable over time.  $LQ(A, B)$  is also called link metric in routing protocols, such as CTP and RPL.

Let  $Attribute(A)$  be the node metric of node A. An example of such attribute would be its remaining energy (RE).

Let  $Nbr(A) = (N_1, N_2 \dots N_k)$  denote the set of nodes which are in the radio range of node A. We call this as the neighbor set of node A.



Let  $R(A)$  denote the set of nodes from which LLN Node A receives a signal.  $Nbr(A)$  and  $R(A)$  are not equal, because nodes can have different radio device (i.e. antenna) or transmission power in the network. So, for example, A may receive a signal from a neighbor B, but B may not be able to receive a transmitted packet from A because of the lower transmission power used by A.

Let  $Rank(A)$  indicates the rank of node A in the DAG.

$PL(A) = (P_1, P_2, \dots, P_i)$  is set to be the parent list of LLN node A. Namely, Node A can receive DIO messages from each  $P \in PL(A)$ . And we also give  $P_{preferred}(A)$  as the best parent of Node A

Based on the above definitions, we could conclude when Node B is a parent of Node A, the following conditions have to be tenable:

$$B \in Nbr(A) \quad (4.4)$$

$$A \in Nbr(B)$$

$$Rank(B) < Rank(A)$$

Moreover, the best parent of Node A denoted by  $P_{preferred}(A)$  can be obtained from the solution of the following calculation.

$$\max/\min \text{Objective\_Function} (LQ(P, A), \text{Attribute}(P)) \quad (4.5)$$

$$\text{Subject to: } P \in PL(A),$$

$$\text{Attribute}(P) > \text{Threshold}_{Attr},$$

$$LQ(P, A) > \text{Threshold}_{LQ}$$

The main part of this calculation is the objective function that needs the link metric and the node attribute metric. Two OF have been suggested for current RPL implementation: OF0 with hop-count and MrhOF with ETX. In OF0, the hop-count property of the node can be used to select parents and paths, independent of the link quality. Based on the above defined notations, we can simply state OF0 as below, where  $hop\_count(P)$  is the number of hops counted for the shortest path from the sink node to the parent node P:

$$\min \text{Objective\_Function} (LQ(P, A), \text{Attribute}(P)) = \text{Objective\_Function}(hop\_count(P)) \quad (4.6)$$

The ETX value indicates how many times of retransmission needed by a successful packet transmission from the sender to a receiver. Note that ETX is an average value and is a receiver-side link estimator to account for lossy links. Namely, the higher ETX values present more lossy the link between two nodes. When MrhOF adopts the ETX metric, the rank of RPL routers are based on their link quality towards the root. Consequently, paths with the highest end-to-end throughput are selected in lossy networks. For introducing a deeper understanding of ETX, we need some more notations to describe its calculation. Since each transmission attempt can be considered as a Bernoulli trial, a packet is received in the first transmission with probability PRP (packet reception probability), and the probability  $PRP \cdot (1 - PRP)$  in second transmission and so on (Note that the time of retransmission is usually controlled by MAC/PHY layer). Thus, ETX can be denoted from the perspective of the receiver side as:

$$\begin{aligned} ETX &= 1 \times PRP + 2 \times PRP(1 - PRP) + 3 \times PRP(1 - PRP)^2 + \dots \\ &= \sum_{t=0}^{\infty} (t + 1) \times PRP(1 - PRP)^t \end{aligned} \quad (4.7)$$

As the asymmetric link issues stated in [124], the existing of this challenge may bring more complexities into the design of routing protocols because two link directions might have different packet reception ratios (PRR). Besides, ETX metric is used as a cumulative link metric (also called additive metric), therefore it is an average value and not an integer, which can be computed on all the links previously used by the targeted node. Namely, when a node uses ETX as routing metric, the RPL model requires the sum of ETX values on each link along the path. Moreover, the aforementioned PRP can be denoted by another two parameters which should be taken into account during the ETX calculation: 1)  $Prob_{Data-S}$ : it represents the probability that a “data” packet is successfully delivered to the receiver, 2)  $Prob_{ACK-s}$ : it is the measured probability that the “acknowledgement” packet is successfully received. So ETX can be described according to the specific formula:

$$Link\ ETX == \frac{1}{Prob_{Data_S} \times Prob_{ACK_S}} \quad (4.8)$$

It should be noted that this equation assumes the two probabilities as constant values for a given link or at least as constant values for the duration of link measurements. So its results are also approximated values. For the implementation of ETX metric, it is common to represent the link quality in current existing energy and lifetime-aware routing protocol for real-world WSNs, such as CTP [125], RLQ [126], RPL [1], ELQR [127], and ELR [128].

#### 4.2.3.2 OF algorithm design of RPAL

The design of the proposed OF algorithm for RPAL is going to be described in this subsection. Let us consider an A-LLN with seven sensor nodes and one sink (Figure 4-5) where the A-LLN nodes equipped with agricultural sensors periodically send monitoring data to the sink. We firstly assume that only SN1, SN2 and SN3 are in the radio range of sink and they have to forward the messages from other four nodes. Each node has three attributes: Rank, link ETX, and RE. If we use MRHOF and ETX metric to build routing paths to the sink, SN4, SN6 and SN7 will choose SN2 as their best parent since it is the one close to the sink with the lowest ETX. Consequently, SN2 will deplete its energy faster and become inactive, and the network cannot respond properly to subsequent messages. To overcome this issue, our proposed OF algorithm takes into account not only the ETX metric but also the available energy of each node. Namely, two routing metrics, the link ETX and the RE of each node are used to compute the best path to the sink. Here is the principle of preferred parents' selection: each node chooses from its neighbors which have more reliable links (under an ETX threshold) to the sink. Then from this subset, the node within the routing path having maximum RE is selected to become the best parent of this node.

Two methods of the maximum RE calculation: i. RE of next hop; ii. RE of the path. The residual energy of the neighbor nodes has been studied deeply and said this information is not sufficient for lifetime balancing among forwarding nodes. Thus, we adopt path residual energy like ELR and MMBCR [129], but this method is not compliant with the RPL specification. Essentially, this metric tries to avoid the routes traversing the nodes who have the least battery capacity among all possible routes [130]. In this way, as will be demonstrated, the energy of the network will get more balanced and fair, and the network lifetime will correspondingly increase.

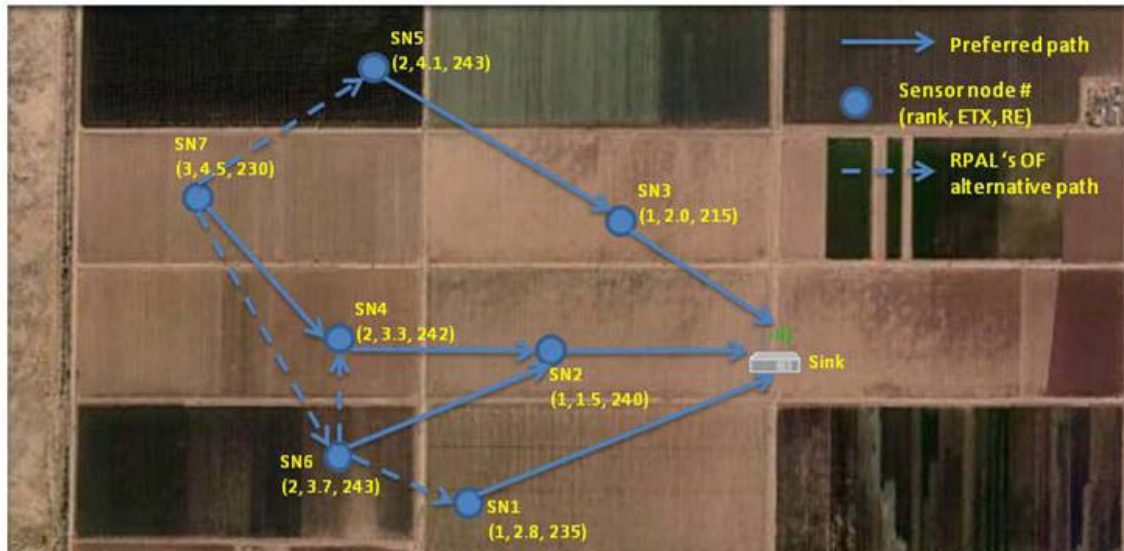


Figure 4-5 A-LLN with seven sensor nodes and one sink. SN2 has to forward the messages from SN4, SN6, and SN7 to the sink. Consequently, it will become inactive due to the energy depletion.

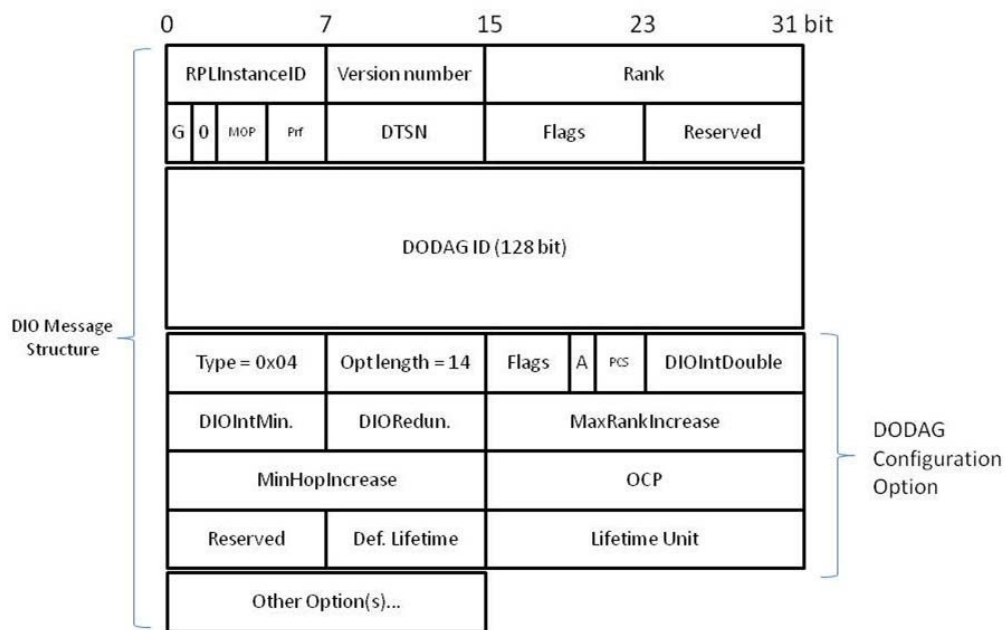


Figure 4-6 The structure of DODAG Information Object control packet

DODAG Information Object (DIO) control packet (Figure 4-6) is the carrier of ETX and RE information. ETX value is measured by the link layer. ETX of sink node (SN1 in Figure 4-5) is 0 since it does not have any parent node. And the energy of sink node is constant to be 100%. The residual energy value is represented in percentage rather than in joules value. Only one byte is required. ETX and RE are contained in the metric containers (as shown in Figure 4-7) defined by RPL standard and embedded in the options part of the DIO format. Furthermore, sink node broadcast the first DIO message to its neighbor nodes. And then the RPL routers would extract this received DIO and continue to disseminate the basic routing information with their own routing metrics. Each RPL router has a maintained parent list to manage the upward tree topology. If a DIO is received, this router will check the entry of sender node in its parent list, and decide whether to update the entry or add a new entry for the sender node. Then the RPL router will broadcast its own DIO to its neighbors after the

estimation of new RE and ETX values. In Figure 4-8, we present a flow chart that can show upon reception of DIO control packet and its continued broadcast (i.e. SN2 in Figure 4-5).

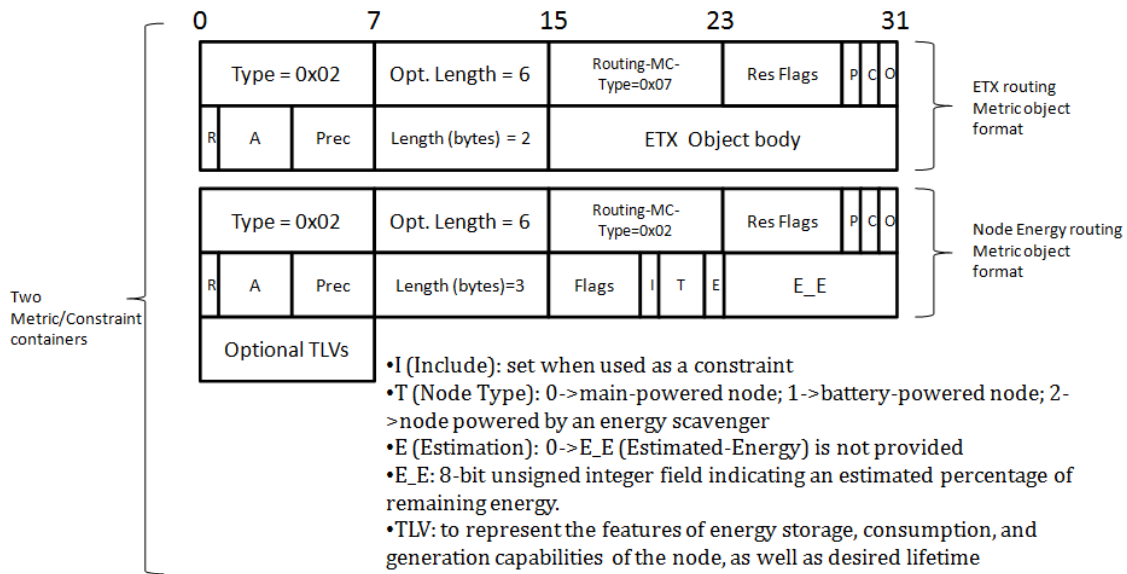


Figure 4-7 The formats of three adopted metric/constraint containers

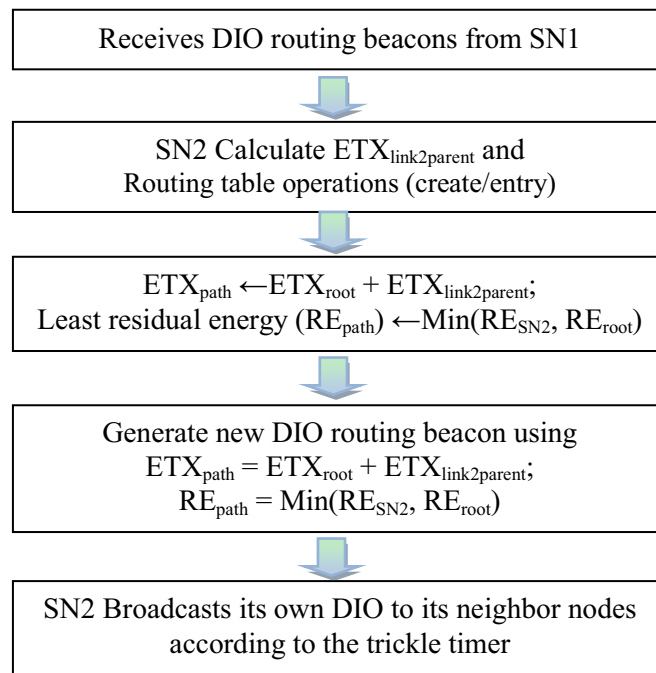


Figure 4-8 An example of DIO control packet broadcast by a RPL routing: SN2

Figure 4-9 shows the proposed OF algorithm in the RPAL model in detail and it assumes there are at least two neighbors/parent candidates for this RPAL router/leaf node. The parameters ETX\_Threshold and RE\_Threshold are re-configurable and dependent on A-LLN's application. The ETX\_Threshold represents the maximum ETX value that each neighbor can reach in order to be considered as a best parent candidate. It is related with the packets End-to-End Delay (E2ED), and depends on the application's QoS requirements. The RE\_Threshold is the minimum difference of RE for a node to switch its best parent. These two values can introduce a configurable level of hysteresis in order to control how often the

preferred parents should be reconfigured. It is used to improve the links stability thereby increasing the network performance. The algorithm can search for the node with the highest least energy node route among all the routes with minimum ETX. Finally, to avoid loops, each node rules out the neighbors with greater rank from being its optional parents.

Algorithm: selection of preferred parent using energy-aware metrics and OF in RPAL

```

1 :   Let P1 ← one available item of NeighborList []
2 :   Let P2 ← another item next to P1 in NeighborList []
3 :   If ( P1.ETX ≤ ETX_Threshold ) & ( P2.ETX ≤ ETX_Threshold )
4 :     If ( P1.RANK ≤ RANK_Self ) & ( P2.RANK ≤ RANK_Self )
5 :       Preferred_Parent = P1.RE > P2.RE ? P1 : P2;
6 :     Else
7 :       If ( P1.RANK ≤ RANK_Self ) || ( P2.RANK ≤ RANK_Self )
8 :         Preferred_Parent = P1.RANK < P2.RANK ? P1 : P2;
9 :       Else
10 :        Preferred_Parent = NULL;
11 :     Else
12 :       If ( P1.ETX ≤ ETX_Threshold ) || ( P2.ETX ≤ ETX_Threshold )
13 :         Preferred_Parent = P1.ETX ≤ P2.ETX ? P1 : P2;
14 :       Else
15 :         Preferred_Parent = NULL;
16 :     Return Preferred_Parent

```

Figure 4-9 RPAL OF selects the neighbor with the viable ETX and the highest RE to be the preferred parent

The OF algorithm of RPAL configuration depends on the A-LLNs' application and its QoS requirements. Using the ETX\_Threshold and RE\_Threshold parameters, our OF could be configurable to meet the specific requirements of precision agriculture application. This simplified solution adopts the RPL framework and its mechanisms to identify and mitigate the energy hole problem. In other words, this proposal is able to avoid congestion or overuse of route leading to the premature death of A-LLN nodes. And this algorithm based on two metric, namely ETX and residual energy, which are organized in lexicographic manner [73], could select the preferred parent more efficiently.

#### 4.2.3.3 Implementation choices

The RPAL model is implemented on Contiki platform. The low value of RE\_Threshold might lead to an increase of the energy consumption since DIO will be exchanged more frequently due to frequent new parents' selection. For the value ETX\_Threshold, if it  $\geq 1$ , it may lead to an increase of the packet delay due to the increase of the hop count. In this study, we followed the "DIVISOR" of rank calculation defined in ContikiRPL model to control the preferred parent switch. Namely, only when the rank result differs more than parent switch threshold (i.e. 2), the hysteresis will be deactivated then the stability of the preferred parent is not maintained anymore. Moreover, two entries, RE and ETX, are added in the parent data structure like a stack list. Adding a RE entry (2 bytes) can be easily done in the RPL routing framework by assigning the option length in the DIO control message option to 6 and length field in the routing metric object as 3 (Figure 4-7). For avoiding the size of DIO is larger than the biggest 6LoWPAN packet, we tried to compress the prefix information option of DIO into 4 bytes rather than the original 16 bytes (Figure 4-10) since A-LLNs are not a dense network circumstance. Moreover, reducing the number of IPv6 prefix could help to mitigate the side effects brought by fragmentation of 6LoWPAN adaptation layer, such as higher packet lost and bit errors, and longer E2ED.

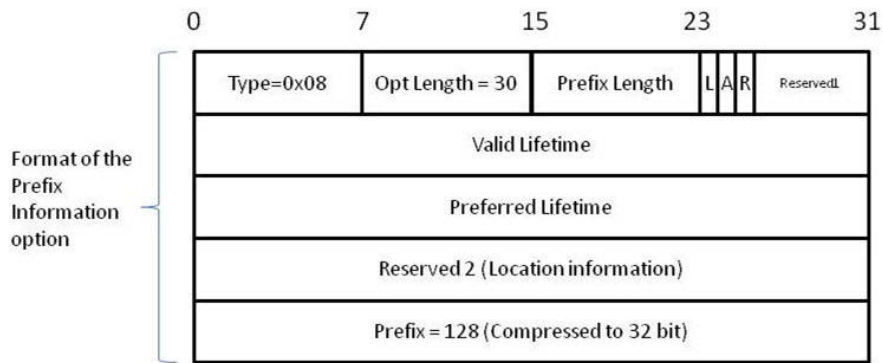


Figure 4-10 The compressed format of the prefix information option

When comparing the Contiki OS implementations of both OF0 and MrhOF with RPAL OF algorithm, the computational requisites of these three OFs are similar because they perform the same algebraic operations. Regarding the extra bandwidth required to broadcast the metrics across the network, 9 more bytes are added to the DAG Metric Container used to report metrics throughout the DODAG. To sum up, both the additional costs of traffic and the computational complexity introduced by RPAL model are acceptable.

### 4.3 Scalable Context-Aware Objective Function (SCAOF) with Hybrid RPAL routing metrics

As the third chapter of this thesis has presented our considerations about how to adapt RPL to Precision agriculture (PA) application, namely, we gave a novel conceptual definition of A-LLNs to introduce the RPL routing framework to the generalized WSN, which is able to support environmental monitoring and remote control functions needed by the agricultural applications. After the aforementioned studies including tests on the simulator and experimental hardware platforms, we then focus on a proposal of designing a Scalable Context-aware Objective Function (SCAOF) with a set of appropriate metrics for the RPAL model. In the previous section, we provide a simplified parent selection algorithm to composite two routing metrics ETX and RE to satisfy the needs of A-LLNs, such as reliable transmission and energy consumption balance at the same time. In this section, we make further efforts for an investigation about the routing metric combination and proving the efficiency of this approach (i.e. loop-free, optimality and convergence).

Apparently, using the composition of the primary routing metrics ETX and RE are not sufficient to mitigate the intricacies of the real-world A-LLNs. For example, an environmental monitoring application in experimental field is loss and delay tolerant. Thus, a tradeoff might be made within these two metrics. Namely, ETX routing metric can have a higher threshold taking the retransmission mechanism into account. If A-LLN sensor nodes are required to support responding for the sensing data queries or remote control actuators in a parcel of field, the communication reliability are more important than any other performance perspectives including energy consumption, recalling that A-LLN devices are always equipped with large capacity battery, even energy scavenger. It is a tricky question left for LLN designer to decide which primary routing metric is needed depending on their applications/devices at hand, and how to combine routing metrics in a flexible manner, more important, to ensure the availability of routing protocol model. SCAOF in RPAL is a specific algorithm based on routing algebra and routing metrics composition approach for real-world A-LLNs. Moreover,

the additional resource-aware metrics are combined into RPAL model through SCAOF, which can provide more practical upward routing paths after integrating context-aware resources into the best parent selecting decisions.

#### 4.3.1 Related work

As stated in [77], OF specifies the rules to select the best parents, the number of backup parents, and the relations with multiple candidate neighbors in the DAG. It is decoupled from the definition of routing metrics and constraints. Thus, the key function of OF algorithm is path calculation to give relative positions (rank) of routers in the DODAG. Moreover, an OF is also the key of how the RPL DODAG tree is constructed initially and updated occasionally. Normally, the values used by path calculation algorithm are from two kinds of routing parameters, one is routing metrics and another one is routing constraints. Specifically, a routing metrics is an additive and quantitative value which is used to evaluate the path cost. In RPL, the routing constraints are also advertised by the DODAG root. They are used as a “filter” to prune links and nodes that do not satisfy specific properties (e.g. link quality, power-supply methods or a specific user-defined “color” of link characteristic) defined by the applications. ContikiRPL model provides an approach of using single metric (i.e. ETX) without supporting of routing constraint. To sum up, best path/shortest constrained path should present lowest path cost and meets all supplied constraints.

Moreover, the routing metrics can be divided into three categories, such as Link/node metric type, qualitative/ quantitative type, and dynamic/static type. Furthermore, the use of a metric or a constraint is not exclusive. It is very flexible to use link and node characteristics to meet our routing requirements. For example, the dynamic metrics with necessary multi-threshold: links, nodes’ resources (e.g. residual energy) have been used in our first proposal. To be noticed, spurious and unnecessary routing changes may be caused by fine granular metric who updates the impact of each individual change. Thus, different metrics may have different reporting frequency or rates [77]. In traditional WSN, link reliability metric used by a routing protocol means building a topology with the goal to maximize reliability. The metric should be aggregated or recorded (e.g. the number of hops, link quality along a path). Moreover, the link (e.g., wireless, wired, PLC) metrics values can be obtained from lower layer. The use of node characteristic in the perspective of energy constraint, such as mains-powered and battery-operated, means optimizing the power utilization of the whole network.

Since we have discussed the routing metrics composition approach in Chapter 2, we decide to adopt this method for the hybrid RPAL routing metrics, which is also the key element and foundation for the extendibility of SCAOF. In article [131], the research group provides more detail theoretical background knowledge (i.e. the principles and basic theorems of the adopted routing algebra), and the methods to prove and to evaluate their designed composite metric. However, executing a modified RPL model in JSIM network simulation [73] could only show the performance of the combining primary in a limited level. Therefore, our defined RPAL routing metrics and SCAOF will be evaluated in a more versatile simulator Cooja with emulator and in hardware testbed, because both of them can introduce more precise necessary properties from realistic WSN scenarios to the adopted metrics. Moreover, this is also helpful to generalize the composite metric method to be applied in real-world low-power and lossy network system.

This hybrid routing metric solution follows the routing algebra stated in [132]. A RPL routing metric can be formally represented as a quadruplet  $(S, \oplus, \omega, \lesssim)$  path weight structure,

where  $S$  is the set of paths,  $\omega$  is the objective function that maps a path or a link to a weight value,  $\preceq$  is a special order relation and  $\oplus$  is the path concatenation operation. For example, where  $\omega(\alpha) \preceq \omega(\beta)$  means "path  $\alpha$  is lighter (better) than or equal to path  $\beta$ ",  $\preceq$  provides a total order of weights and it can cooperate with  $\omega(\cdot)$  to capture different path and node characteristics (i.e. delay, bandwidth, hop count, link reliability and energy consumption). The essential purpose of this routing algebra is to use the appropriate metrics for routing the packets along the lightest/optimal path according to the decisions based on an ordered path set. Furthermore, this routing algebra also introduces two primitive properties of routing metrics composition: monotonicity and isotonicity.

Briefly speaking, if one selected metric is monotonic, then the network topology made by this metric can be free of loops. In other words, the monotonic property could ensure the convergence of a routing algorithm. The isotonicity property essentially affects the order of the path weights and could ensure their convergence is optimal for distance vector protocols like RPL. Based on the previous research of Yang et al. in [132, 133], the primary routing metrics (i.e. hop-count, ETX and expected transmission time) have been investigated and proved their monotonicity and strict isotonicity, which can guarantee the optimality, consistency and loop-freeness of any routing protocol type. Meanwhile, some other routing metric have to be testified carefully.

Gouda et al. are the first to define the lexicographic and additive routing metric compositions in [134]. The lexical metric composition of two routing metrics  $(S, \oplus, \omega_1, \preceq_1)$  and  $(S, \oplus, \omega_2, \preceq_2)$  can be considered as the lexicographic composition relation  $\preceq_{lex}$  over the ordered pair  $(\preceq_1, \preceq_2)$ . If and only if, for every link pair  $(\alpha, \beta)$  in  $S$ , they can satisfy the mapping of weight pairs  $(\omega_1(\alpha), \omega_2(\alpha))$  and  $(\omega_1(\beta), \omega_2(\beta))$  in the Cartesian product of the weight value sets for these two routing metrics  $W_1 \times W_2$ . The additive composition relation  $\preceq_{add}$  over the set  $W_1 \times W_2$  can be simply defined as:  $(\omega_1(\alpha), \omega_2(\alpha)) \preceq_{add} (\omega_1(\beta), \omega_2(\beta)) \Leftrightarrow \omega_1(\alpha) + \omega_2(\alpha) \leq \omega_1(\beta) + \omega_2(\beta)$ .

#### 4.3.2 An hybrid solution of resource-aware and energy-aware routing metrics composition

Our aim is to give a design of routing metrics containing the information from A-LLN router/leaf nodes and network characteristics in the DIO carriers. More important, the selected composite metrics of this proposed hybrid solution should be suitable to meet the A-LLNs' requirements as well as the monotonicity and strict isotonicity so that the RPAL protocol can converge to optimal paths in a loop-free manner.

We have discussed the use of ETX in subsection 4.2.3. Furthermore, according to [77, 133], ETX has been proved to be strictly isotonic and monotonic. As we have already considered energy-aware routing metrics with ETX and Residual Energy (RE), the aforementioned routing metrics have the ability to achieve the initial targets of increasing the energy efficiency. In fact, if we put ETX as the first metric, then it will dominate the path selection regardless of the path weights of the rest metrics. Namely, the composite metrics proposed in section 4.2.3 will take the second metric RE into account only if more than one paths mapping to equal/less than the weights of the first metric ETX. In this way, it essentially considers the energy cost of retransmission (through ETX) firstly. But if only few paths are available based on the defined threshold, these paths could have more traffic load than others. Besides, the nodes closer to the sink are more likely to meet premature energy depletion



because the selected paths have to relay more packets. In other words, a combination of ETX and RE in lexicographic manner cannot solve the hot spot problem, and only can mitigate the consequential network disconnection issue.

The basic purpose of energy-aware routing is the elongation of the network lifetime [135]. As we have discussed four criterions to consider whether a wireless network is alive in subsection 4.2.2, it is easy to conclude that our adopted RE metric is not strictly isotonic and cannot be used in the routing metric additive manner. The aforementioned RE indicates the lowest energy level in the path which is concave and should be a max-min criterion. If we define  $\omega(\alpha)$  to reflect the RE of a link  $\alpha$ , and  $\mathcal{H}$  is the node set that constructs link  $\alpha$ , and  $i$  is an end node of this link, we can assume that  $\omega(\alpha) = \min\{RE^i | i \in \mathcal{H}\}$  and  $RE^i = \frac{C_{now}^i}{C_{max}^i} \leq 1$ . If one node tries to select a forwarding path between  $\alpha$  and  $\beta$ , the order relation  $\lesssim$  is  $\max\{\omega(\alpha), \omega(\beta)\}$ , namely the "more than or equal" relation over real numbers. Thus, assuming  $\omega(\alpha) < \omega(\beta)$  it may happen that  $\omega(\alpha) < \omega(\beta) \leq \omega(\gamma)$  in which special case:  $\omega(\alpha \oplus \gamma) = \max\{\omega(\alpha), \omega(\gamma)\} = \omega(\gamma) = \max\{\omega(\beta), \omega(\gamma)\} = \omega(\beta \oplus \gamma)$ .

Therefore, although the RE of path metric can achieve good performance on the evaluations dedicated to keeping all nodes are alive as long as possible through avoiding the most fragile routing path, it is not good enough when A-LLNs connectivity and coverage are considered [73]. Especially, when RPAL model cannot capture sufficient and opportune energy-related attributes of all the routing paths, the parent selection may not be optimal due to the loss and delay of DIO control messages. Furthermore, as the aggregation rule of this RE is concave (min.), it only can be used in the manner of lexicographic combination and this limits the scalability of RPAL OF algorithm.

#### 4.3.2.1 Designing combinable resource-aware and energy-aware routing metrics

Based on the above discussions, we decided to adapt RE to an additive routing metric then it could be strictly monotonic and isotonic to satisfy all the assumptions of theorems proposed in [73]. The opted additive RE metric is based on summated metric values of the links in the routing path. For example, we assume one path  $\alpha$  and its length is  $n$  hops, then the weight of path  $\alpha$  indicates the energy on average for all traversing nodes:

$$\omega(\alpha) = \frac{\sum_1^n \frac{1}{Rem. Energy^i}}{n} \quad (4.9)$$

Table 4-3 Descriptions of the adopted routing metrics

| <i>Adopted metrics</i> | <i>Domain</i> | <i>Aggregation rule</i> | <i>Order relation</i>                   |
|------------------------|---------------|-------------------------|---|
| ETX                    | [1, 512]*128  | Additive                | (<) $\rightarrow$ ([1, 512], '+', '<')  |
| Rem.Energy (%)         | [0, 1]        | Concave (min.)          | (>) $\rightarrow$ ([0, 1], 'min.', '>') |
| 1/Rem.Energy           | [1, 255]      | Additive                | (<) $\rightarrow$ ([1, 255], '+', '<')  |

Note that the previous RE needs to be transformed to (1/RE), and (1/RE) can have the same metric range in the required granularization, order relation, metric operator with ETX. As the guideline provided by [73], Table 4-3 depicts two adopted metrics and one derived form of RE in our solutions. Moreover, this routing metric cannot work alone since it also needs the hop count information, and to clarify the rules: (1) If two paths  $\alpha$  and  $\beta$  have same length  $n$  and all the traversing routers are battery powered without the effects of energy

harvesting devices, the path with higher average energy will be preferred. (2) If  $\alpha$  and  $\beta$  have the same average energy value, then the path with the lowest length (or number of involved nodes) will be preferred. (3) If  $\alpha$  and  $\beta$  have different average energy values and path lengths, then the routing decision should be made with the cooperation of ETX metrics.

Moreover, we also considered the node powered mode types and attempted to add this element to this proposal. We have two bits as "T" flags to represent the node type in the RE metric container (see Figure 4-7), and each DIO message could carry this information from its sender (an end-point of path), so the receiver nodes could judge whether to select this optional routing path since an appropriate routing strategy is to avoid using the battery-powered node. Moreover, the optional Type-Length-Value (TLVs) can be used to record the count of these three types of nodes. For example, the count of battery-powered node is able to be described as an appended routing metric which is organized by additive aggregation rule and '<' as its order relation. Namely, a routing path with fewer battery-power nodes is preferred. On the other side, the counts of main-powered node or energy scavenger powered node can be also considered in this method and be carried in the TLVs. However, the domain of this metric is not compatible with the ETX and (1/RE), so it only can be used in lexicographic manner based on the theorems of [73].

In addition to the energy-aware metric for estimating energy consumption and the power source type, the other resources of A-LLNs device, which can be defined as affordable workload, hardware robustness and availability information, should also be considered. These three new routing metrics will be carried in the link color object container of DIO message in the RPAL model.

- The definition of affordable workload is inspired by the battery index [82] that represents how much prone a node is to consume energy. In most of the cases, this metric will be highly depending on the deployed location of this node, but it also can be generalized to use four operating states of radio transceiver for its computation: Transmission (TX), Reception (RX), idle and sleep. In other words, the affordable workload is an hierarchical Radio Duty Cycle (RDC) since almost all the discrepant energy consumption is associated with the radio operations;
- The hardware robustness in our proposal is presented as a hardware restart count since the system starts working (i.e. the record provided by NanoRisc of Ext\_Milive board [37]);
- The availability information is another resource which means particular RPAL DODAG paths are associated with a certain application data (i.e. sensing environmental data or event detection) requested by the monitoring application of precision agriculture. Namely, this metric can represent the features of the nodes in this path, particularly the role that can monitor the important retrievable resource information (i.e. soil moisture, temperature, etc.).

It should be noted that we assume most of the MCU of A-LLN devices are highly efficient and low power consuming so its energy consumption can be ignored. Moreover, as most of the nodes of A-LLNs have similar workload of environmental sensing mission, we consider the RDC value as the most influential factor for the affordable workload metric and it will only be taken into account when the DODAG meets routing oscillations when the weight value change of ETX and RE composite routing metric is bigger than an hysteresis threshold. Meanwhile, since the RDC result is normally calculated from the ratio between the Active Time and the sum of the active and the inactive time of a node, the time value is cumulative which leads to the obtained RDC results are average values and are available after the radio transceiver has been working for a period of time.

Therefore, the workload metric is going to cooperate with the hardware robustness metric in our design. Since in most of the cases in LLNs, the restarting is the most usual and simple operation when a system meets faults or exceptions in software or hardware. A special component like NanoRisc proposed in [37] is able to provide this valuable information. Its recorded data can be collected by RPAL model and set to clear periodically (i.e. one hour as collecting frequency). As the count of restarting is also a time-varying cumulative value, it will be updated to the RPAL model with the workload metric in the same frequency.

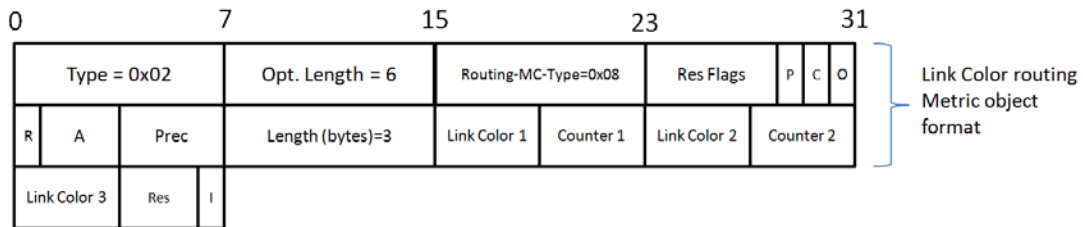


Figure 4-11 Our proposed link color metric container format -- first solution

Table 4-4 Utilization of the three link color elements -- first solution

| <i>Link color</i>        | <i>Carried data</i>               | <i>Utilization</i>  |
|--------------------------|-----------------------------------|---|
| Link color 1 + Counter 1 | Affordable workload               | If the targeted node is battery powered, the 4-bit <i>link color 1</i> flags will be used to represent the RDC level of this node. Setting low bit means RF workload is low and setting high bit for high RDC level.<br><i>Counter 1</i> is used for counting the number of nodes that are too busy in this optional path.  |
| Link color 2 + Counter 2 | Hardware robustness               | The 4 bits of <i>link color 2</i> flags are used to present the four robustness level of the targeted node. If the restart count is low, the low bit will be set. If the node fail is frequent in a certain period, the high bit will be set.<br><i>Counter 2</i> is used for recording the number of nodes which are too fragile in this optional path.  |
| Link color 3 + I flag    | Availability information resource | The 4 bits of <i>link color 3</i> flags are used to present four availability information resource (sensing capability) levels. Namely, if this level is high, this targeted node has more monitored info to forward and even need to respond to the queries from sink node.<br><i>I flag</i> is set when that links with the specified color must be included. When cleared, it means this color must be excluded. |

In particular, the research about link color routing metric is quite scarce before the drafting of this dissertation. However, it is an efficient metric to disseminate the link quality information. As we have already adopted ETX metric to present link quality, we propose to use link color metric container to give the three new defined routing metrics a piggyback. In the [Figure 4-11](#), the format of this container using cumulative color counters is defined, and the utilization of our first solution and the meanings of each Link Color flag field are depicted in [Table 4-4](#). Two counters are designated to record the number of the nodes which are too busy and too vulnerable. Additionally, the “I” flag of link color 3 could also determine whether to exclude the links with the specified color. Namely, the nodes, which have important monitoring missions or should respond for the queries in a short time, are able to avoid being as routers or joining a long routing path. These three link colors present the

conditions of the nodes in an optional link path so that some dangerous path can be pruned, but the counters would induce more complexity into RPAL routing algorithm, thereby this might bring more overburden of the MCU and the computing resource is also limited for the A-LLN devices. Essentially, we use Link Color as a heterogeneous constraint rather than a scalar metric like ETX and RE. Thus, we propose a simplified idea to consider the conditions of the end point rather than the whole link path (shown in Figure 4-12).

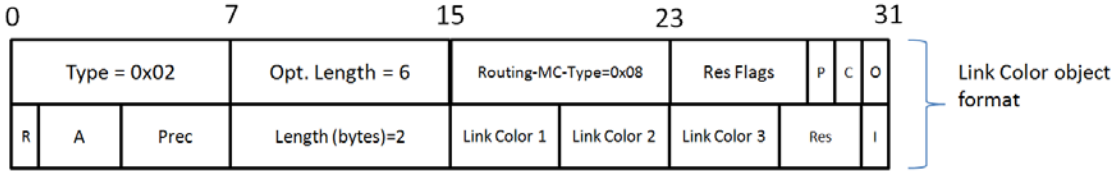


Figure 4-12 Our proposed link color container and routing constraint object format -- second solution

The second routing constraint object format carries three condition information of a sender, and its neighbor will judge whether to join this node as next hop. The “I” flag will be used like the first solution but it is also a more straightforward answer to inform the other nodes that this node is not appropriate to be a router due to its current conditions. This leads to a shorter message format (one byte less) and reduce the workload of MCU. Furthermore, it should be noted that the trade-offs made by this solution might cause suboptimal routing decision in a case of large-scale multi-hop deployment. Because when one node would join in this network topology, it only knows the conditions of its neighbors rather than its optional routing paths with a global view.

To sum up, the purpose of our composite routing metric proposal is to take context awareness into account in RPAL DODAG construction (by adding 17 bytes to the original MrhOF DIO message), with a view to make RPAL model more flexible and scalable for node failures and to operate more efficiently with context changes. The dynamic context requires routing metrics or constraints to describe and disseminate them for making optimal routing decisions, so that the A-LLNs can deal with the real-world environment more wisely with limited resources and more suitable for precision agricultural applications.

4.3.2.2 Designing context-aware objective function

RPAL model can capture the targeted attributes of node state, link quality, and indications incurring connectivity intermittence in A-LLN scenario. Essentially, SCAOF gives a rule constitutor that defines how to use context-aware information to calculate rank and preferred parent selection. Thus, SCAOF can manage the initial construction and occasional updating of RPAL DODAG tree. It is particularly designed by composite routing metric/constraint and this is a highly scalable and flexible approach. Meanwhile, SCAOF is able to employ standardized MrhOF in more context-aware manner. A routing topology is expected by assigning a more important role to the nodes that can positively reply to the requests from an A-LLN application, through avoiding the dangerous nodes to forward sensor data, and improving energy balance in network using link-quality-aware and energy-aware metrics.

SCAOF adopts accumulation, estimation, and prediction techniques over the context of the A-LLN sensor node to calculate the Instantaneous Suitability  $IS_i$  of a node  $i$  and choose whether to let this node be a parent based on its survivability in the current RPAL DODAG topology. This survivability is represented by the residual energy, link quality, connectivity (duty-cycle), robustness and available information resource of this optional parent. Meanwhile, to fulfill the supports of the functions and requirements of wireless multi-media

sensor network [73, 131] (WMSN), we propose to use lexical approach which contains two lexical elements, but the second one is an additive metric composition function, to express the combination of these metrics/constraints:

$$\text{(Link Color Object, } \langle (a1 * ETX) + (a2 * RE) \rangle)$$

This expression only presents IEEE 802.15.4 low-power communication medium. The proposed SCAOF of RPAL will select the nodes with appropriate link color object, and then, the basic routing metrics ETX and RE (Remaining Energy) will work in the additive manner, for ensuring the QoS and network lifetime requirements. A-LLN Nodes calculate their attributes locally and exchange them via DIOs. Each node then computes the suitability values of its neighbors respectively, and decides which one can be the preferred parent.

We have defined two rules for Link Color Object (LCO): to be used as a constraint or as a recorded metric like the two solutions have been explained in last sub-section. LCO will bring the flexibility for this metric/constraint composition function. We use it to mark whether an endpoint is capable to be a parent or a path is appropriate to forward data packets. As the first lexical elements, when a node receives the DIO carrying a LCO, it will firstly inspect its content. A viable solution for this inspection is to check if the suitability values are within the tolerated difference rather than beyond the defined thresholds between two optional nodes or paths. Thus, the first part of the  $IS_i$  result is based on the metric/constraint indicated by the counters or 'I' flag in LCO.

For the second lexical metric, its suitability equation is similar to the aggregation rule of the additive routing metrics and the results are corresponding to their weights, which are also the main factor to the rank calculation of the SCAOF. To some extent, Precision Agriculture (PA) applications require prolonging network lifetime more than keeping the link reliability according to the applicability analysis. Thus, the parameters  $a1$  and  $a2$  here are (0.4, 0.6) or (0.3, 0.7) which will be more fit for PA application and present the A-LLNs nodes tend to choose their parents with more residual energy. A generalized method of RPAL rank calculation is depicted in [Formula 4.10](#).

$$p_{pref}(n) = p \in P_n | \min [rank(n, p)]$$

$$rank(n, p) = rank(p, p_{pref}(p)) + \alpha_1 ETX(n, p) + \alpha_2 RE(n) \quad (4.10)$$

To be noticed, different PA applications have various QoS or constraint requirements. However, there is no perfect solution, but it should be adaptable. Our proposed structure can be used in most of the generalized cases. Therefore, based on our applicability analysis in Chapter 3 and our methodologies, we will use Cooja simulation platform to evaluate and verify our above proposals (See [Chapter 5](#)). Furthermore, according to the RPL specification, the downward routing is built upon the existing DODAG topology for upward routing. This is the reason why the above proposals are focused on DIO message format and upward routing decisions. On one hand, environmental data collection requires stable converged topology and it is the basic purpose of A-LLN. On the other hand, if the topology for data collection is well optimized, a bi-directional communication will be easily achieved.

## 4.4 The context-aware trickle algorithm

### 4.4.1 Introduction

In this section, an extensive study of trickle algorithm that is used to control routing update distribution across the A-LLNs will be carried out. As this algorithm is one main mechanism of RPL (also RPAL), its performance study and experiment are necessary for this thesis especially when the proposed context-aware objective function and hybrid routing metrics have been introduced. The new route formation mechanism needs energy efficient DIO broadcasting method since DIO takes the entire metric/constraint object containers. Furthermore, the original trickle algorithm might result different impact on power consumption, propagation efficiency and broadcast fairness, because it is never verified in a dynamic environment scenarios. Many related literatures [50, 76, 136] which studied the behaviors of the original algorithm have pointed out that the non-deterministic nature of Trickle can lead to sub-optimal routing formation, unfair broadcast and suppression, and less efficiency in multi-hop unsynchronized LLNs.

Nevertheless, Trickle is a built-in energy-saving mechanism included in RPL. It particularly aims at minimizing the amount of route updates dissemination but still enough for topology maintenance. Namely, the target of this algorithm is to conserve power and reduce network congestion through keeping the frequency of control traffic as low as possible. The essential methods for efficient routing are: a) Rate adaptation for different situations of current network, b) Suppression of avoiding sending redundant information. The control traffic of RPL is one type of routing beacons with path weights (scalar metrics values or constraint flags). It is normally sent in broadcast manner to achieve the messages reaching at all neighbors. However, in the LLNs' circumstances, broadcast is a highly power consuming transmission and an expensive method, and requires more bandwidth, due to the sleep/wake-up mechanism of duty cycled low-power WSN. In particular, the efficiency of Trickle depends on a fundamental trade-off: increasing the quality of the routing graph with more control traffic or increasing network lifetime with less control traffic, namely route quality vs. energy consumption.

A simple solution used by RPL is to provide a time schedule function for regulating DIO control messages broadcast transmission: adapting to a lower interval when the path cost change little or the network is stable; suppressing their transmission when the same message has been heard enough times. And in our opinion, the studies from the RPL specifications are not clear and sufficient to be guidelines for the design of RPAL model. The complexity is difficult to predict since the problems are impossible to be fully modeled and analyzed due to the intricate interactions within the behaviors of duty-cycling mechanisms in MAC layer, traffic control in network layer, and data traffic in application layer. For example, rapid dissemination of large number of control packets can lead to better maintained routing paths and topology, but this operation will cause severe congestion in the low level layers of network stack, which will induce interferes to the data traffic and the low performance of application layer.

In this work, we firstly introduce the related work about the performance studies of Trickle algorithm and about its optimization approaches that can be used in the RPAL model. We will discuss the possibility of combining the selected possible solutions that are expected to address the urgent problems with particular focus on Trickle, such as its fair broadcast, resynchronization, and efficiency. Moreover, we expect that our work could improve and

optimize network formation time, route quality and energy consumption in real-world A-LLNs.

#### 4.4.2 Related work

The Trickle [137] algorithm is originally designed for polite gossiping in multi-hop wireless networks. In particular, its main purpose is data dissemination, such as software version, or similar slow-changing data. Trickle disseminates new information fast, but sends very little information when there is no new information available for dissemination, and does load balancing between the nodes [138]. Thus, Trickle has two core mechanisms: one is to provide network maintenance by a consistency model and another one is to provide propagation through a redundant message suppression mechanism.

According to our investigation, the authors of articles [139] and [136, 140] have studied this algorithm theoretically from building analytical models for the estimation of message count and algorithm's behavior, especially the required time to achieve consistency. It should be noted that their proposed models are designed for general applicability and their evaluations are only performed at the steady state. The model of [139] is built for Trickle's behavior for the delay of consistency as well as the number of packets broadcast. And the model in [140] is presented to be only used to predict the number of transmitted messages but taking the redundancy constant and the average node degree into account.

For the Trickle of RPL, Trickle algorithm is adopted as a built-in energy-saving mechanism in the route processing, which is aiming to particularly minimizing the amount of route updates broadcast while keeping low route convergence times [98]. Because the research about the exclusive Trickle of RPL is scarce, and also because of the LLNs' features, the original Trickle will easily lead the RPL DODAG to long convergence periods or sub-optimal routes due to link quality variations and message losses. The authors of [64, 76, 141, 142] have observed that ill-considered Trickle parameters may also cause extra overheads in the RPL data traffic flows. Bigger overhead and more bandwidth usage will bring more collisions. However, the energy overhead will drain the RPL routers' power. Fortunately, the authors of one recent literature [143] presented an available solution, which is an enhanced version of this algorithm named as Trickle-F, dedicating to the sub-optimal route formation problem caused by high message suppression. Trickle-F could mitigate this issue and guarantee fair broadcast suppression with considering the different Trickle's parameter settings and studying their overall dynamics influences for LLNs system. Meanwhile, the authors proposed a set of guidelines to optimize the configuration of this algorithm and their simulation experiments validated that a set of modifications to the original algorithm is necessary and could increase the spatial fairness in message transmission and facilitate the discovery of all the routes in the network.

However, from the view points of using RPL in a real-world system, the proposal in [143] has two limitations: 1) Resynchronization is not concerned in their work, and the evaluation is performed at an assumed synchronous network. 2) The proposed mechanism is still not robust enough to deal with the real dynamic environment. The former issue has been discussed in [138] and a specific modified Trickle was proposed to synchronize the schedules of the nodes across the network. Furthermore, to the best of our knowledge, the research about the latter issue is very scarce and building models for this distributed algorithm are impossible to describe all the factors and inherent complexity. Thus, under the considerations in the last chapter and the aforementioned context-aware characteristics, we decide to further extend this algorithm and apply its new features in RPAL model. The proposed new context-aware Trickle is also dedicated to the A-LLNs scenario. As a main part contribution in our work

except the previous SCAOF design, this proposal is expected to guarantee longer network lifetime through the resistance of Trickle phase shift, disruption caused by adverse weather and other highly dynamic environments, and the supporting of fair broadcast.

#### 4.4.2.1 Overview of Trickle algorithm description

Trickle operates based on three parameters, three variables and six main rules [137]. This algorithm is a simple, yet elegant and powerful algorithm.

The three parameters used to configure the trickle algorithm are:

- $I_{min}$ : the minimum interval size
- $I_{max}$ : the maximum interval size
- $k$ : the redundancy constant

The three variables required by trickle algorithm to track the current status are:

- $I$ : the current interval size
- $t$ : the tentative transmission time within the current interval
- $c$ : the number of heard messages within the current interval.

Trickle operates according to the following rules, which can be clarified as two transmission rules (without the problem of broadcast storms) and two reception rules:

- Initially, Trickle sets  $I$  to a value in the range  $[I_{min}, I_{max}]$ .
- At the beginning of each interval, Trickle resets  $c$  to 0 and sets  $t$  to a random instant within the range  $[I/2, I]$ .
- If a node hears a consistent transmission, Trickle increments its counter  $c$ .
- At the time  $t$ , if the counter  $c$  is smaller than the redundancy constant,  $k$ , Trickle allows the message transmission; otherwise, the transmission is suppressed.
- On expiry of the interval  $I$ , Trickle doubles the interval length. If the new interval length is greater than  $I_{max}$ , Trickle sets the new interval length to  $I_{max}$  and executes step 2
- If Trickle hears an inconsistent transmission, it resets  $I$  to  $I_{min}$  and executes step 2.

With the few parameters, variables, and basic rules, Trickle has the abilities to adapt the communication well to different network densities and consistency churns [140]. For instances, when the density of nodes is low, Trickle will regulate the nodes' sending rate to high frequency; when the density is high, nodes send rarely. For the cases of a lot of inconsistency churns happening, Trickle will try to propagate the information fast with a high rate, but use exponential back-off manner to achieve a lower rate when the nodes are detected to be consistent later. We use a data flow chart [Figure 4-13](#) to explain the above rules and the utilizations for the parameters and variables.



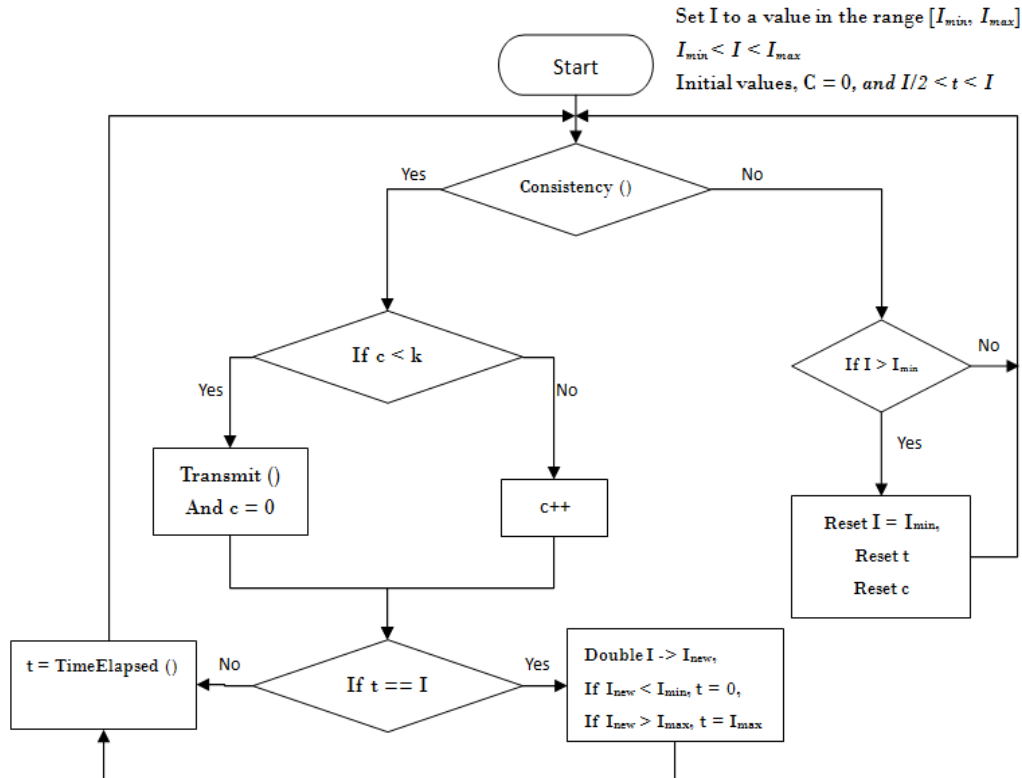


Figure 4-13 Data flow chart of original Trickle dissemination algorithm

#### 4.4.2.2 The Trickle in RPL routing framework

With the similar approach, in LLNs organized by RPL-based routing protocol, the gossip of original Trickle algorithm becomes DIO broadcast transmission. The Trickle in RPL regulates this important routing control traffic message to reduce nodes' energy consumption.

Comparing with the DIO broadcast transmission on a periodic basis, a node in LLNs can suppress the transmission in a given period if enough DIO packets have been heard or even overheard from its neighbors. This given period is also presented as dynamically adapted interval depending on the received RPL routing control messages (i.e. DIO, DIS and DAO). If the carried information is consistent with current route conditions after their processing, the interval length will be exponentially increased. Otherwise, the interval is reset to the minimum length to boost spreading the updated information (see Figure 4-14). Based on our observation, the utilization of Trickle in RPL has the same logic as the original one except how it specifies the conditions determining inconsistent event or receiving packets which cause the reset of the Trickle timer. In particular, the reset policies defined by RPL specification have two kinds: mandatory reset and implementation dependent reset. As these policies are related to one of our proposals, the discussion of their impact on the network topology is left in subsection 4.4.2.3. Here, only the Trickle settings based on the results of our previous ContikiRPL experiments (subsection 4.1) will be highlighted.

---

Trickle Algorithm Pseudo-code

---

```

Function Initialization()
     $I \leftarrow I_{min}$ 
Function IntervalBeginS()
     $c \leftarrow 0$ 

     $t \leftarrow \text{random}(\frac{1}{2}, I)$ 

Function ConsistentTransmissionReceived()
     $c \leftarrow c+1$ 
Function TimerExpires()
    If  $k \geq c$  then
        Transmit DIO
    else
        Suppress DIO
    end if
Function IntervalEnds()
     $c \leftarrow 0$ 
    if InconsistentTransmissionReceived then
         $I \leftarrow I_{min}$ 
    else
         $I \leftarrow I \times 2$ 
        if  $I_{max} \leq I$  then
             $I \leftarrow I_{max}$ 
        end if
    end if
end if

```

---

Figure 4-14 Pseudo-code of Trickle algorithm used in RPL routing framework

As a model according to the RPL specification, we can modify three main parameters of the Trickle timer in ContikiRPL [18]:

- $I_{min}$ : the minimum interval size;
- $I_{max}$ : the maximum interval size;
- $k$ : the redundancy constant

For the first built DODAG, a tradeoff between formation time and route quality has to be considered.

- Low  $I_{min}$ : the creation of the first DODAG will be within a short space of time, but these routes are suboptimal and need extra interval time to be refined as most of the routing metrics are additional and accumulative;
- High  $I_{min}$ : opposite observations.

Based on RFC6550, ContikiRPL implements a mechanism called lollipop counter fashion to increment the DODAGVersionNumber periodically when the root decides to form a new version of the DODAG in order to revalidate the integrity and allow a global repair to occur. Thus, we can define  $T_{reset}$  as the period between two DODAG resets, which is controlled by the parameters of lollipop counter. The  $I_{min}$  of Trickle should be adapted to the  $T_{reset}$ .

- Low  $T_{reset}$ : Frequent DODAG resets. The formation time will be the priority;
- High  $T_{reset}$ : A trade-off can be made between the formation time and energy consumption.

For the redundancy threshold  $k$ , it essentially controls the trade-off between energy consumption and route quality, so we can observe the below results:

- Low k values: reduce the energy consumption of each node, but routes maybe suboptimal because of insufficient routing information exchanges;
- High k values: opposite observations.

#### 4.4.2.3 Overview of Kermajani's Trickle model for counting message transmissions in steady state

In this sub-section, we briefly introduce an analytical model presented in [139] that is built for Trickle's behavior for the delay of consistency as well as the number of packets broadcast in a WSN. This model is initially designed for CTP protocol [125]. For simplicity, it needs to assume that its studied network is a static network where the state is steady, and the current Trickle interval size of all the nodes is the same and is equal to  $I_{max}$ . Namely, this assumption can be explained as the entire link characteristic in the WSN deployment is very stable and Trickle is in the synchronous mode. But for more dynamic WSNs, this model can also provide a lower bound results for the number of message transmissions.

The authors firstly gave the following definitions:

- A: a size of uniformly random spatial distribution for the nodes on a two-dimensional area
- N: total number of nodes
- a: the area defined by the coverage range of a single node

The probability that a node will be a neighbor of a given node, 'q', could be calculated as [Formula \(4.11\)](#).

$$q = \frac{a}{A} \quad (4.11)$$

The average probability  $P(tx)$  that denotes a node 'x' in this network, which will send a message in a given (current) interval 't'. Meanwhile, 'k' is the same definition as the Trickle redundancy constant. For the simplicity of this model, the authors only considered two possible situations: i. Node 'x' has fewer than k neighbors; ii. Node 'x' has more than k neighbors.

In the first case, assume that the number of neighbors around node 'x' is 'y'. Also assume that  $P(y < k)$  is the probability that the number of neighbors of node 'x' will be smaller than 'k', and  $P(tx|y < k)$  is the probability that node 'x' will send a message in the current interval when the number of its neighbors is fewer than 'k'.

In the second case, the definition of the relevant probability could be  $P(y \geq k)$  and  $P(tx|y \geq k)$  similar to the first case.

Thus, the results of  $P(tx)$ , namely the average probability that a node will send a message in a given interval can be presented as [Formula \(4.12\)](#).

$$P(tx) = P(tx|y < k) \cdot P(y < k) + P(tx|y \geq k) \cdot P(y \geq k) \quad (4.12)$$

It is easy to make sure of that the result of  $P(tx|y < k)$  is 1 (100%). But how to calculate  $P(y < k)$  needs a new parameter 'N' which is defined as total number of nodes. Note that each node can have at most 'N-1' neighbors as an extreme case. So this possibility requires using the binomial coefficient to represent the combination computation. Then, the probability that node 'x' will have fewer than 'k' neighbors ( $P(y < k)$ ), and at least have 'k' neighbors ( $P(y \geq k)$ ), can be obtained from the calculations of [Formula \(4.13\)](#) and [\(4.14\)](#).

$$P(y < k) = \sum_{i=0}^{k-1} \left( \binom{N-1}{i} \cdot q^i \cdot (1-q)^{N-1-i} \right) \quad (4.13)$$

$$P(y \geq k) = \sum_{i=k}^{N-1} \left( \binom{N-1}{i} \cdot q^i \cdot (1-q)^{N-1-i} \right) \quad (4.14)$$

For calculating  $P(\text{tx}|y \geq k)$  that is the last part of equation (4.12), the authors proposed to consider the two following possible cases:

- The time selected by node 'x' for the transmission of its message is one of the first 'k' transmission times selected by its neighbors and by itself
- The time selected by node 'x' is not one of those first 'k' transmission times

Then, in the first case, the probability of selecting one of the first 'k' transmission times, denoted by 'P(i)', can be obtained from Equation (4.15).

$$P(i) = \frac{k}{y+1} \quad (4.15)$$

In the second case, node 'x' can send its message if, at time 't', at most 'k-1' of the subset of neighbors that have selected smaller transmission times than that of node 'x' actually transmit their messages. The remaining neighbors suppress their transmissions due to their cumulative message counter is bigger than redundant constant 'k'. The probability that node x will select any of the last 'y+1-k' times, denoted by P(ii) Equation (4.16).

$$P(ii) = 1 - \frac{k}{y+1} \quad (4.16)$$

The probability that, in the case of P(ii), at most 'k-1' nodes will transmit before node 'x', denoted 'Γ', which can be expressed as Equation (4.17)

$$\Gamma = \sum_{j=0}^{k-1} \left( \binom{n-1}{j} \cdot (P(\text{tx}))^j \cdot (1-P(\text{tx}))^{n-1-j} \right) \quad (4.17)$$

Where 'n' is the positive integer that denotes the position of node 'x' transmission time in the set of increasingly ordered transmission times selected by node 'x' and by its neighbors. Note that there are 'n-1' nodes with smaller selected transmission time than the one chosen by node 'x', and meanwhile meets the situation of 'n > k'.

Based on the above calculations and assumptions, the authors proposed a final expression for 'P(tx)', which is the average probability of sending a message for Node 'x' during a given time interval 't' by insert (4.11) and (4.13)-(4.17) into (4.12).

$$P(\text{tx}) = \sum_{i=0}^{k-1} \left( \binom{N-1}{i} \cdot \left(\frac{a}{A}\right)^i \cdot \left(1 - \frac{a}{A}\right)^{N-1-i} \right) + \sum_{i=k}^{N-1} \left( \left(\frac{k}{i+1}\right) \cdot \left( \binom{N-1}{i} \cdot \left(\frac{a}{A}\right)^i \cdot \left(1 - \frac{a}{A}\right)^{N-1-i} \right) \right) + \sum_{i=k}^{N-1} \left[ \left(1 - \frac{k}{i+1}\right) \cdot \left( \binom{N-1}{i} \cdot \left(\frac{a}{A}\right)^i \cdot \left(1 - \frac{a}{A}\right)^{N-1-i} \right) \cdot \sum_{j=0}^{k-1} \left( \binom{i}{j} \cdot (P(\text{tx}))^j \cdot (1-P(\text{tx}))^{i-j} \right) \right] \quad (4.18)$$

From (4.18), we can derive to the average number of transmissions in a static network composed of 'N' nodes in a given time interval 't', denoted as  $N_{Tx}$ .

$$N_{Tx} = P(\text{tx}) \cdot N \quad (4.19)$$

### 4.4.3 A joint analytical Trickle model for RPL controlling messages dissemination

#### 4.4.3.1 Description of the joint analytical model

For the record, the analytical Trickle model in [139] is designed for original Trickle algorithm. As we prefer to measure the performance of the Trickle behaviors in RPL routing framework, calculating the bandwidth usage of RPL main controlling messages DIO, DAO in LLN routing is more valuable. Since the average size of DIO in the ContikiRPL is 97 bytes and the highest data rate for 802.15.4 network is 250 kbit/s for 2.4GHz band, the average number of its broadcast can heavily influence the conditions of this LLN. So we decide to extend the previously described analytical Trickle model and denote Bandwidth Usage (BWU) of DIO as [Formula \(4.20\)](#), note that the 'T' here is still a specific given time interval, CCA means the attempt times and the number of symbols cost for clear channel assessment operation.

$$BWU_{DIO} = \frac{N_{Tx} \cdot [Packet\_size + CCA\_Operation]}{Data\_rate\_of\_2.4GHz\_band \cdot T} \quad (4.20)$$

For a better usage of the result in [\(4.20\)](#), we can extend the definition of 'T'. As we know, the first interval 'T' of DIO for root node is  $I_{min}$ . The DODAG building procedure is organized by a set of intervals. Since each node will have its own consecutive intervals, for the simplicity of our calculation, we could assume all the nodes will keep doubling its first "T" until they achieve to DODAG consistency. Namely, all nodes in this LLN arrive to  $I_{max}$  interval at the same time and keep uniform DIO version number, which also indicates the steady state of the DODAG network topology.

We propose to define a parameter SET(I), and it is corresponding to how many intervals (i.e., DIO cycles) existing in this set. It is obvious that the variables from [Equation \(4.19\)](#), such as 'N', 'a', 'A', and 'k', can still leave in the [Equation \(4.20\)](#).

In the article [140], the authors build a model for the Probability Density Function (PDF) of the time to consistent scenario. This PDF model can indicate an estimated network consistency delay which indicates the period of time from the initialization of DODAG to its stable status. However, as this analytical model is still needed further studies, it lacks the regards of the impacts brought by the parameters of trickle timer. Thus, it is not completely ready to adopt in our research work. Nevertheless, it still reminds us that the analytical model proposed by [139] only takes one Trickle interval into account and this limits the further study on Trickle's performance evaluation for RPL routing protocol.

We could continue to extend the PDF model and combine it with the function of the redundancy constant and the average node degree proposed in [139], but we also can continue our work based on the [Formula \(4.20\)](#) in a simple manner with one more assumption to obtain the results of SET(I).

Trickle will increase the current interval exponentially from  $I_{min}$  to  $I_{max}$ . For example, in ContikiRPL's configurations,  $I_{min}=2^{IntervalMin}$  (ms),  $I_{max} =2^{(IntervalMin+IntervalMax)}$  (ms), Namely, the first trickle interval of all the nodes is  $I_{min}=2^{12}$  ms=4096 ms≈4 s, and when nodes achieve theoretical consistency, its DIO cycle is constant as  $I_{max} =2^{(12+8)}$  ms ≈17.48 min.

Thus, SET(I) can be coped with a geometric series that computes the sum of time for all the Trickle intervals as [Equations \(4.21\)](#):

$$\begin{aligned}
SET(I) &= 2^{(IntervalMin+IntervalMax+1)} - 2^{IntervalMin} \quad (\text{ms}) \\
SET(I) &= \frac{2^{(IntervalMin+IntervalMax+1)} - 2^{IntervalMin}}{1000} \quad (\text{s})
\end{aligned} \tag{4.21}$$

Insert  $SET(I)$  as well as the other values of the already known parameters (e.g. The count of CCA attempts in ContikiMAC is 6 and one CCA attempt costs 2 symbols, namely around 4-bit length) into [Formula \(4.20\)](#), then we can get [Equations \(4.22\)](#).

$$\begin{aligned}
BWU_{DIO} &= \frac{N_{Tx} \cdot [(97 \cdot 8) + CCA \cdot 4] \cdot IntervalMax}{250 \cdot 1024 \cdot SET(I)} \\
BWU_{DIO} &= \frac{N_{Tx} \cdot [(97 \cdot 8) + CCA \cdot 4] \cdot IntervalMax \cdot 1000}{250 \cdot 1024 \cdot [2^{(IntervalMin+IntervalMax+1)} - 2^{IntervalMin}]}
\end{aligned} \tag{4.22}$$

The [\(4.22\)](#) is similar to [\(4.20\)](#), and its numerator of the right side fractional expression indicates the estimated total bit data flow of DIO transmission from the time of first cycle to the first constant cycle of consistency status. The exact uniformed unit should use bit not symbol. Its denominator is the approximate maximum network bit data flow (i.e. 250kbps) under 2.4GHz network's bandwidth.

Thus, the result of [Equations \(4.22\)](#) indicates the percentage of bandwidth usage for DIO messages during the building of a DODAG, and not limited in a single given trickle interval like the original analytical model. However, it introduces more assumptions: during the DIO transmission, Packet Receive Ratio (PRR) is 100% within radio range; no inconsistency happens and all the nodes are in synchronous mode.

#### 4.4.3.2 Evaluation of the joint analytical model

From the above model description, extending the original trickle analytical model and adapting it for RPL DIO broadcasting analysis is not complex. All we need is to know the broadcasting mechanisms in the MAC layer. We still use Contiki system as our research target, and this requires evaluating the number of total strobes and CCA operation in each ContikiMAC broadcast interval. Thus the [Formula \(4.20\)](#) can be changed to [Formula \(4.20'\)](#).

$$BWU_{DIO} = \frac{N_{Tx} \cdot [Packet\_size \cdot Broadcast\_strobe\_times + CCA\_Operation]}{Data\_rate\_of\_2.4Ghz\_band \cdot T} \tag{4.20'}$$

$$BWU_{DIO} = \frac{N_{Tx} \cdot [(97 \cdot 8 \cdot 29) + CCA \cdot 4] \cdot IntervalMax \cdot 1000}{250 \cdot 1024 \cdot [2^{(IntervalMin+IntervalMax+1)} - 2^{IntervalMin}]} \tag{4.22'}$$

Through many related studies on the mechanisms of ContikiMAC [144], it has been proved as an efficient asynchronous radio duty cycled MAC protocol. Under the default configuration and the defined rules of ContikiMAC broadcast transmission [145], each broadcast packets requires 29 strobes, so we can extend the [Formula \(4.22\)](#) to [Formula \(4.22'\)](#). ContikiMAC will force a node to wake up and transmit continuous broadcast packets to all the neighbors in a full fixed wake-up interval. This approach is similar to the beaconless mode of IEEE 802.15.4 standard (asynchronous mode and no acknowledgement answers), and it can ensure all the neighbors can hear at least one broadcasted message no matter when their wake-up intervals start. The rationale behind proposing ContikiMAC as an example is that most of the literatures point out the synchronous MAC protocols would consume more memory, energy, computation resources, and bandwidth [146, 147] in multi-hop WSN

because of their underlying synchronization mechanisms, so they are not suitable for the constraint resources and scenarios of low power and lossy networks, not to mention our defined A-LLNs.

We implement a root-finding algorithm in JAVA for the Equation (4.18) since it is a polynomial in  $P(tx)$  and also including a set of programs for plotting the results by JFreeChart library (as shown in Figure 4.15). Meanwhile, we assigned 100 nodes in a network. The nodes are placed on a square scenario of area  $150m \times 150m$  with  $100 m^2$  coverage range. The parameters of IntervalMin and IntervalMax are given by 12 and 8 respectively.

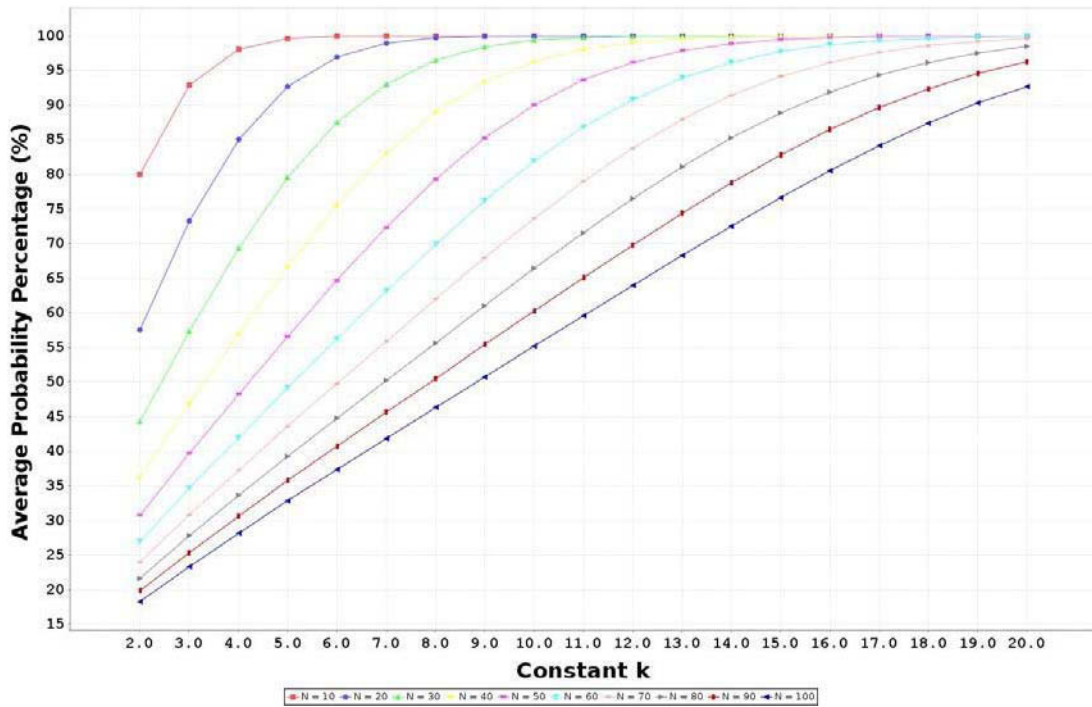


Figure 4-15 Find the roots for equation (4.18) -- average probability of sending a message in a given interval

The Figure 4-16 depicts the results of Equation (4.22') that indicates the percentage of bandwidth usage for total DIO messages broadcast during the building procedure of a DODAG. In particular, the lines with different colors indicate the size of DODAG, so this result plotting presents the effects due to the average node degree and redundant constant 'k'. As shown in Figure 4-16, we may find that the DODAG will yield greater number of DIO transmissions for higher values of 'k' in comparison with the network size. Moreover, we can also observe that the results of BWU(DIO) is very low as the long period of waiting the Trickle to arrive  $I_{max}$ .

For presenting the change of bandwidth usage caused by DIO broadcast in each interval, as shown in Figure 4-17 and Figure 4-18, we use Equation (4.20') to calculate the results of  $BWU_I(DIO)$  according to consecutive Trickle interval. Namely, the X axis is regulated as the adjacent interval and the results of  $BWU_I(DIO)$  is the corresponding bandwidth usage in a certain period of Trickle running time. In Figure 4-17, with increasing the network size and a fixed 'k' value (10, recommended by RPL specification), it denotes that the bandwidth usage is overwhelming when average node degree arrives to a certain level. Apparently, the influence of broadcast storm is severe when the DODAG is starting to be built, especially for the first five intervals. However, it also has another profile that can present the efficiency of exponential back-off mechanism in Trickle since the results of  $BWU_I(DIO)$  reduce sharply for the dense network after awhile (less than two minutes). In Figure 4-18, we assign a fixed

network size as 50, so we can validate the trends of BWU\_I(DIO) corresponding to different constant 'k' values.

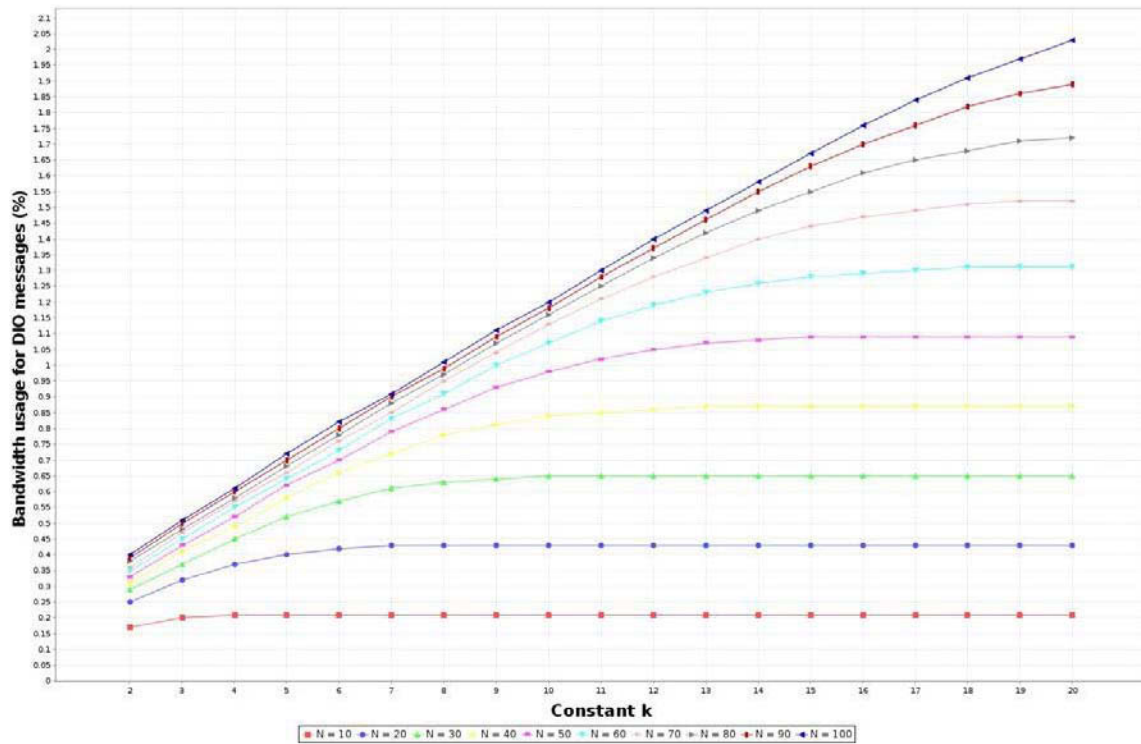


Figure 4-16 Percentage of bandwidth usage for DIO messages during the building of a stable DODAG (Joint analytical model, BWU(DIO))

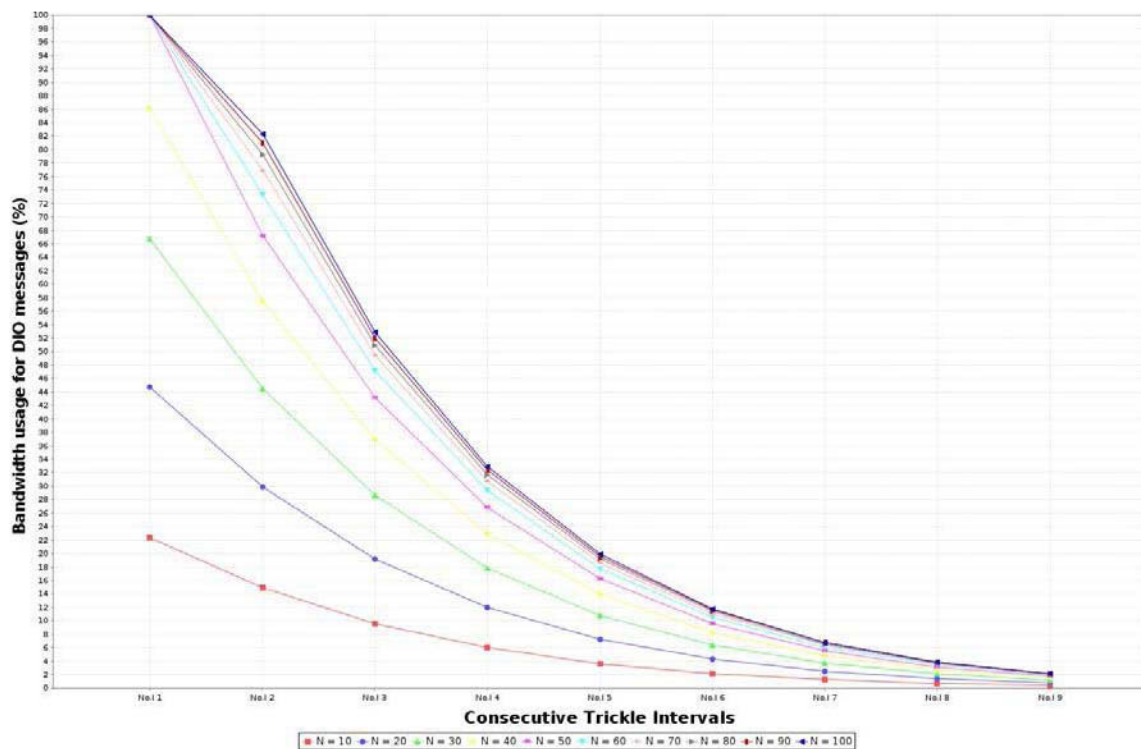


Figure 4-17 Percentage of bandwidth usage for DIO messages in consecutive trickle intervals (Joint analytical model, BWU\_I(DIO), k=10)



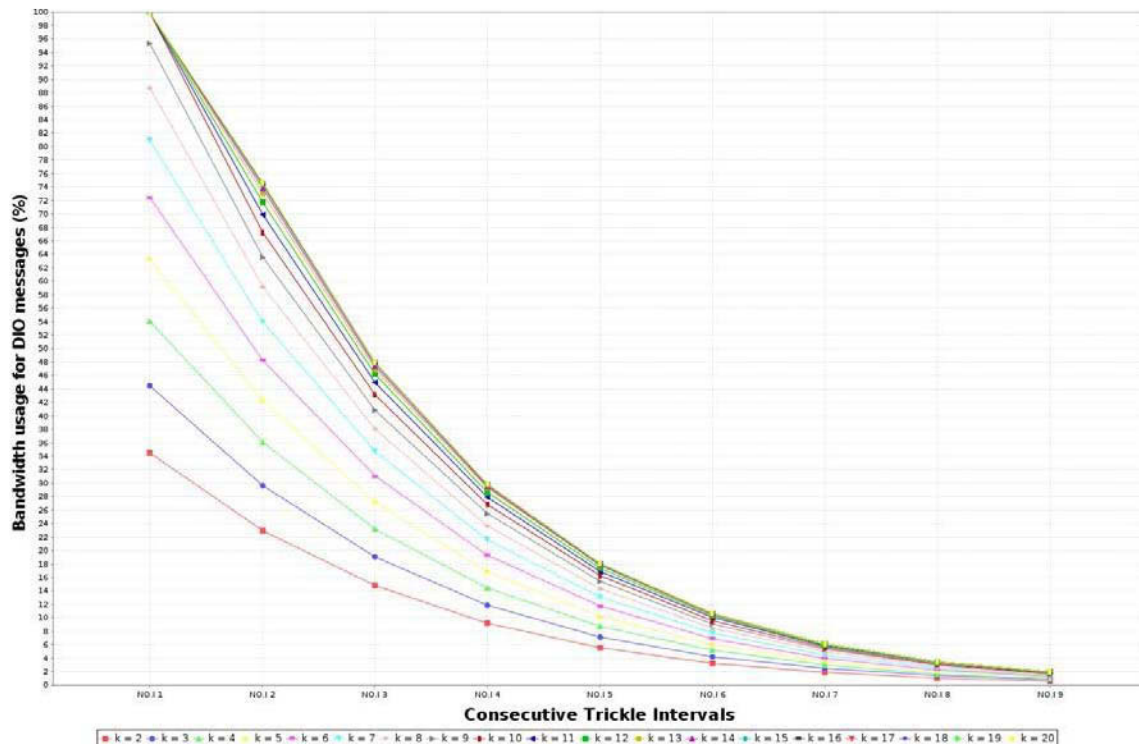


Figure 4-18 Percentage of bandwidth usage for DIO messages in consecutive trickle intervals (Analytical model, BWU\_I(DIO), N=50)

#### 4.4.4 The Context-aware Trickle algorithm for A-LLNs: CA-Trickle

Through our investigation, due to the influence of the parameters  $I_{min}$ , 'k' and the random tentative transmission timer 't', some researchers have observed that there is a certain probability that some nodes are always kept in suppression of their messages due to the non-deterministic nature of Trickle [143]. From the perspectives of power consumption and overhead, this phenomenon is reasonable, but its potential impact is the better route paths may never be discovered. Since a part of routes are sub-optimal, the probability of inconsistency and packets loss ratio is relatively high for these hapless nodes.

Moreover, our joint analytical model has highlighted the heavy overhead caused by DIO dissemination according to the original Trickle algorithm in RPL. Meanwhile, another routing control packet DAO that is used for maintaining downward routes can also be controlled by Trickle. Although DAO is transmitted in unicast manner, undoubtedly, this will further aggravate the utilization of the limited bandwidth resource. This will lead to more congestions and collisions. But we concern more about whether using the Trickle of original RPL framework in our RPAL model will cause more failures in environmental data collection application or shorten the lifetime of A-LLNs.

Recalling the related work in subsection 4.4.2, one research direction is to study the impacts on Trickle's performance corresponding to different configured parameters. However, these related works are more often involved the modeling to discover efficient settings of the Trickle algorithm, and this approach cannot be practical enough to our studies on A-LLNs and on precision agriculture applications. Furthermore, ROLL WG has recommended the most suitable parameters for various application areas. Another direction is to propose

enhanced versions of Trickle protocol. Namely, the researchers integrate new mechanisms into the original algorithm to achieve the augments of its efficiency and performance, such as reducing the time to consistency, topology formation time, and average energy consumption. Apparently, this perspective is more flexible for us to adapt RPL to a specific application. Thus, we decide to merge more context-aware features into the Trickle to expand the second study direction.

#### *4.4.4.1 Fair and synchronized routing control message dissemination mechanism in RPAL model*

The theoretical estimated results in the subsection 4.4.3.2 present that the possibility of each router sending a control message is not optimal in a medium size network, even though under the recommended parameters from RPL specification. However, we also can observe the efficiency of Trickle's rate adaptation and suppression mechanisms from the results of the joint model (see [Figure 4-16 - 4-18](#)), and their initial purposes are to conserve power and reduce network congestion, and keeping the control traffic frequency as low as possible when the network is stable or needs avoiding redundancies. Thus, we believe that the Trickle has the basic ability to prevent sending excessive control traffic and it can maintain the quality of DODAG in an acceptable level. Nevertheless, the efficiency and performance of Trickle still need to improve. Especially, the literatures discussing about RPL's Trickle in the real-world environments and the studies about adapting it to a specific application are still very scarce, not to mention the considerations for the intricate interactions in the behaviors of the radio medium, duty cycling mechanisms, control traffic rate, and data traffic.

In our main contributions, we tried to introduce context information into RPL framework to adapt it to A-LLNs. A new enhanced version of Trickle is also proposed and following this logic as well as keeping its highly autonomous principles. In this sub-section, we mainly consider the context generated by the low-level layers of LLNs. A further discussion about using the contexts from the application level in Trickle is left in next sub-section.

Recalling the results in [Figure 4-15](#) and [Equation \(4.18\)](#) which are built by summation of various probabilities, we assumed that each node have the same possibility to broadcast its own routing control message in each interval. However, the similarity is only because of our assumptions. For instance, all nodes are in steady state and have stable links. If the network dynamics increases like real-world LLNs, the results could be different due to busy channel, occasions of sleep and wake-up (i.e., synchronization in MAC layer), the deployed position of a multi-hop topology, etc. Namely, some nodes can get higher possibility to broadcast their control messages all the time but the others may always have lower possibility. This phenomenon should be more noticeable when average node degree is much higher than the Trickle's parameter 'k', which indicates more messages will be suppressed in each neighborhood. Although the average broadcast transmission probability is nearly equal in a long period of time, it does not mean that the original Trickle gives the same opportunity to the routers to share routing information in a short time scale.

For instance, if one router node has a better link quality path to the root but it is not good enough to change its 'rank', this is not an inconsistency to trigger the Trickle reset and the periods of interval will keep in normal state. Thus, if this router node has been suppressed in multiple intervals and not allowed to send any DIO messages for a long time, the routes traversing this node may remain undiscovered and therefore unused for such time even though they are better than those current active ones in the DODAG ([Figure 4-19](#)). These conditions often introduce sub-optimal routes and impact the required discovering time of all

the available routes [143]. In other words, the Trickle needs an additional mechanism to cope with this issue, especially to guarantee a spatially fair broadcast suppression in short-term. This new principle should facilitate the rapid discovery of all available paths among the router nodes around their neighborhoods. Meanwhile, it could also improve the energy balance because it avoids some router nodes always getting the chance to broadcast DIO and exhausting their battery power.

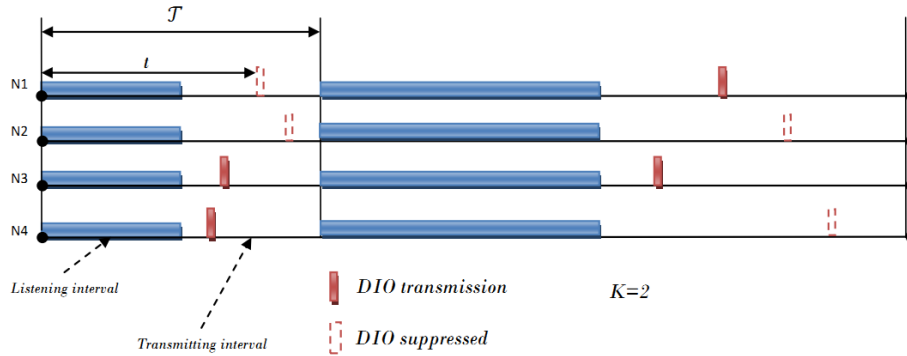


Figure 4-19 Observation: Node 2 has been suppressed for two DIO cycles

Therefore, we introduce the number of consecutive suppressions for the targeted node as the first context information into the original Trickle algorithm, to achieve fair DIO multicast within the same level of overhead and power consumption, but with smaller probability of suboptimal routes. This context can help CA-Trickle to prioritize the A-LLN nodes in a DODAG based on this following rule: a router node that has transmitted its DIO in consecutive intervals is assigned with higher '*Context\_coefficient*'; the smaller the value of '*Context\_coefficient*', the higher the transmission priority of this router node in next interval.

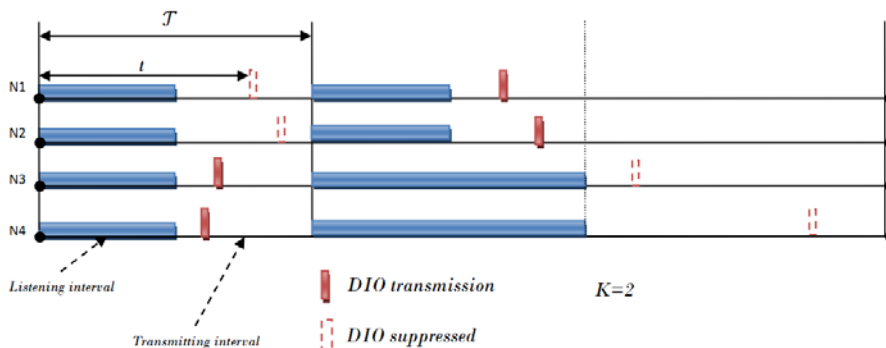


Figure 4-20 The modification of original Trickle proposed in Trickle-F

In order to achieve the same principles, the authors in [143] proposed to modify the computation of the start time and length of the next transmission period. However, their modification to the original Trickle algorithm did not consider the impact of time drift. Namely, when the LLN nodes start to lose their synchronization of Trickle intervals, time drift will often emerge. Moreover, their modification would lead to more failures of load balancing for the DODAG with interval phase shift according to the simulation results presented in [138, 139]. In detail, the approach adopted by the authors in [143] is to locate the transmission instant timer at the second half of the node's original "listen-only" period and then shorten the original "listen-only" period into half (see Figure 4-20). Thus, this modification will lead to doubled possibility of short listen problem. This issue is the main reason of generating wasteful additional transmissions [98] in the network with interval skews.

Nevertheless, shifting the transmission timer to earlier time is not helpful to achieve fair broadcast suppression among the nodes in asynchronous Trickle state. Thus, we introduce the

synchronizing condition of the targeted nodes' Trickle interval denoted by  $\delta_{synchro}$  as the second context information. This context can work with the first one to tackle the pathologies of using Trickle in real low-power and lossy network. For instance, if a new node tries to join in a large DODAG built by nodes with synchronized Trickle intervals, it waits the first received beacon with configuration information and it can start its Trickle. Then, this new DODAG member will become a troublemaker to invalidate the existing suppression mechanism. Another case where load balancing often fails is when the average node degree is small. As a multi-hop topology, it could partially have this case inside a DODAG, since the DIO information propagation is slow within a bottleneck LLN topology where desynchronized Trickle timer or interval skews would happen. Namely, in these cases, some nodes without synchronized timer may end up sending packets almost every interval or do not perform any transmission because the DIO message wavelet can be blocked by a potential network bottleneck.

The solution of CA-Trickle introduces two parameters '*Context coefficient*' and  $\delta_{synchro}$  into original Trickle algorithm. They can achieve our requisite probability changes for fair DIO broadcast suppression as well as asymptotically resynchronized intervals.

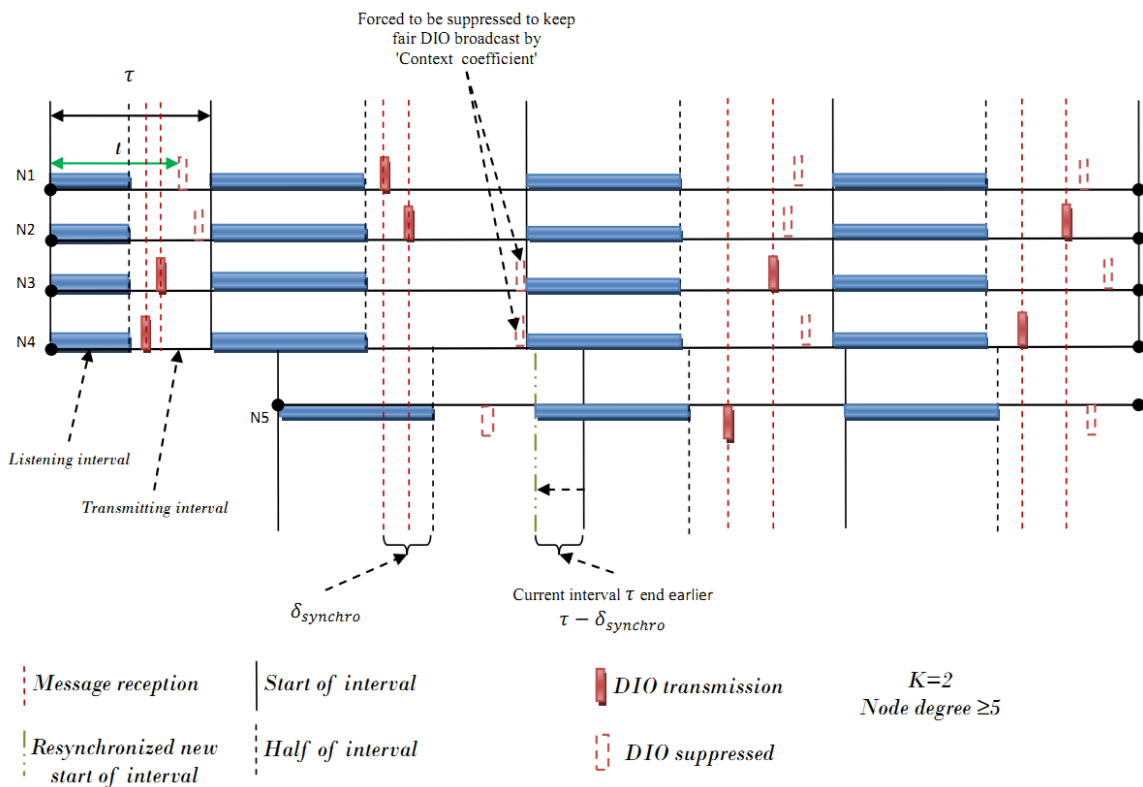


Figure 4-21 Example of CA-Trickle operation with four synchronized nodes and one new joint node

To achieve the above purposes, we adopt a simple method of using '*Context coefficient*' to record how many cycles a node keeps transmitting its DIO message. Not similar to the Trickle-F, we propose to force the garrulous nodes to choose their transmission timers 't' near to the end of current Trickle interval  $\mathcal{T}$  rather than locating them in the Trickle's "listen-only" period. As shown in Figure 4-21, the node 3 and node 4 are forced to suppress their DIO at their second interval. Meanwhile, we use another context parameter  $\delta_{synchro}$  to help node 5 to catch up the other nodes without Trickle interval skews.

The basic idea of introducing  $\delta_{synchro}$  into the Trickle algorithm is similar to the manners in [19, 142], which is to start the next interval earlier if this node got a DIO message in its second half of its "listen-only" period. The utilization of  $\delta_{synchro}$  can be refined, especially on selecting the maximum value from the collected  $\delta_{synchro}$  in a recovery cycle. This way can reduce the time of rescheduling and also improve the efficiency and remove the wasteful traffic load appearing in the DODAG. Furthermore, we also defined extra rules to prevent the nodes in asynchronous Trickle state making chaos in the stable DODAG topology. Due to the propagation wavelets existing in multi-hop network, hop count will incur the phase shift of Trickle intervals. Meanwhile, the time drifts in a certain level (around 50% phase shift) should be asymptotically rescheduled to approach "perfect" but this procedure has potential dangers to lead complete failure of Trickle synchronization. However, even in the worse case, the CA-Trickle still have the same efficiency like original Trickle. Since there is no modification on the length of listen-only period, the basic mechanism of solving short listen problem in asynchronous Trickle schedule is kept, except the interval is turned to  $\mathcal{T} - \delta_{synchro}$ .

---

CA-Trickle Algorithm Pseudo-code

---

```

Function Initialization()
     $\mathcal{T} \leftarrow I_{min}$ 
    Context_coefficient  $\leftarrow 0$ 
Function Interval_Begins()
     $c \leftarrow 0$ 
     $t \leftarrow \text{random}((\mathcal{T} - \delta_{synchro}) * \frac{\text{Context\_coefficient}}{\text{Context\_coefficient}+1}, (\mathcal{T} - \delta_{synchro}))$ 
    If Context_coefficient  $\geq$  [should keep silence in this cycle] then
         $t \leftarrow (\mathcal{T} - \delta_{synchro})$ 
    end if
     $\delta_{synchro} \leftarrow 0$ 
Function Consistent_Transmission_Received()
     $c \leftarrow c+1$ 
    if Context_CurrentTimer  $\in (\mathcal{T}/4, \mathcal{T}/2)$ 
         $\delta_{synchro} = \omega_{synchro} * (\text{Context\_CurrentTimer} - \frac{\mathcal{T}}{2})$ 
    end if
Function Inconsistent_Transmission_Received()
     $\mathcal{T} \leftarrow I_{min}$ 
    Context_coefficient  $\leftarrow 1$ 
Function Transmission_Timer_t_Expires()
    If  $k \geq c$  then
        Transmit DIO
        Context_coefficient  $\leftarrow ++$ 
    else
        suppress DIO
        Context_coefficient  $\leftarrow 1$ 
    end if
Function Interval_ $\mathcal{T}_{synchro}$ _Ends()
     $c \leftarrow 0$ 
     $\mathcal{T} \leftarrow \mathcal{T} \times 2$ 
    if  $I_{max} \leq \mathcal{T}$  then
         $\mathcal{T} \leftarrow I_{max}$ 
    end if
     $\mathcal{T}_{synchro} \leftarrow \mathcal{T} - \delta_{synchro}$ 

```

---

Figure 4-22 Pseudo-code of CA-Trickle algorithm

From the algorithm description in [Figure 4-22](#), the worst case due to interval skews (i.e., equal to  $\frac{T}{2}$ ) will still keep the same performance when the cycle length is  $T - \omega_{synchro} * (0)$ . In order to achieve DIO broadcast fairness, each node tracks the parameter '*Context\_coefficient*' that indicates the number of continuous communication intervals where this node gets the chance to send its DIO. If a DIO is suppressed, '*Context\_coefficient*' will be reset; otherwise, this counter is incremented. Namely, contrary to the idea of Trickle-F, we use this context information to ensure that each node gets a proportional suppression priority to the value of '*Context\_coefficient*' counter. Meanwhile, our modifications do not enforce variational length of the listening and transmitting periods so CA-Trickle can keep the same ability of avoiding short-listen problem like the original Trickle. But CA-Trickle can achieve DIO broadcast fairness through fair suppression settings.

In detail, our manner is to postpone the transmission instant '*t*' in a selected sub-period depending on '*Context\_coefficient*' as follow:  $[(T - \delta_{synchro}) * \frac{Context\_coefficient}{Context\_coefficient+1}, (T - \delta_{synchro})]$ . This ensures the sub-period for the nodes that send more DIO message are more near to the end of next interval. In other words, nodes which have sent consecutive DIO messages get lower transmission probability, so nodes that have been waited for long time or suppressed one time will have more chance for their DIO transmission ([Figure 4-20](#)). It is significant to highlight that the constant of [*Should keep silence in this cycle*] solves the issue when the accumulative counter of '*Context\_coefficient*', so this threshold value can force a node to keep silent in a cycle.

Moreover, the utilization of  $\delta_{synchro}$  is depending on the '*Context\_CurrentTimer*', which is a dynamic value to record the time stamp of certain DIO message receptions. Through this variable, the interval skew level can be obtained. If the condition could reduce the efficiency of Trickle, CA-Trickle will cut down the length of the in progress interval and start the next interval earlier to compensate for phase drift. The context information about synchronizing condition  $\delta_{synchro}$  will be reset in every interval and be checked as long as one consistent DIO is received when  $I_{max}$  has been achieved.

To sum up, we have explained how to merge the context of suppression condition and synchronizing condition into Trickle algorithm. Some modifications are made for enabling the fairness of DIO broadcast and asymptotic resynchronization. However, the target of this proposal is essentially to improve Trickle's efficiency and to achieve better load balance which could increase the propagation speed and reduce the delay of searching optimal routes, and more important is to make the DODAG of A-LLNs more energy efficient.

Since we have introduced context features into Trickle, the mitigation of the aforementioned issues will be presented in [Chapter 5](#). However, the new CA-Trickle only improves the performance of network topology in steady state. For the dynamic environments in A-LLNs scenario, Trickle has to cope with many inconsistencies that may induce reset operation and various resulted situations afterwards. Thus, we will discuss this real-world issue about Trickle's reset in next sub-section and provide a specific solution to further adapt RPL framework to the routing in A-LLNs (RPAL) and meet the requirements of precision agriculture application.

#### 4.4.4.2 *Weather disruption-tolerant trickle algorithm: coagulable trickle timer*

In the RPL standardized specification, Trickle is mentioned in the sections that describe how RPL discovers and maintains upward routes and how RPL nodes operate DIO transmission. Trickle controls the DIO control message transmission. Essentially, it is also a sub-mechanism inside the discovery and maintenance of upward routes, which allows a node to join in a DODAG by discovering neighbors and identifying a set of parents. Moreover, the DODAG root will firstly advertise DIO messages and the operation of Trickle are determined by a set of configurable parameters. At the beginning of building a DODAG, only root node has this information to configure its local RPL routers. With the defined Trickle timers in routers, they can use this timer and DIO messages to advertise these parameters throughout the DODAG. In other words, router nodes have to wait to be informed how they can manage the DIO dissemination of their routing state by root node. The advertised DIO under the control of configured Trickle timers will have two jobs: upward route discovery for DODAG building and the configuration router nodes which are not in the radio range of root node. So Trickle is a basic mechanism of RPL, since it impacts on the consequence of DODAG's building and maintenance. Meanwhile, it is worth more studies of its optimization methods in real world.

Furthermore, as a simplified solution of rapid propagation for certain exceptional conditions, Trickle can also reset its timer in response to external "events" and receiving packets. According to the RPL specification, the considered inconsistencies with respect to the Trickle timer resetting are:

- The inconsistencies detected when forwarding a packet, such as loops.
- Receiving a multicast DIS message or an inconsistent DIO messages.
- Joining a new DODAG version (e.g. DODAG root updates DODAGVersionNumber).

In the design of RPAL model, we take the effects of the A-LLNs environment into account. Although the above rules are suitable for most of the application cases, an implementation based on standardized RPL still needs to consider other messages or events as inconsistencies. For example, the second inconsistent case normally happens when a new node starts to join in an existing DODAG. Its neighbors will reset their Trickle timers to help this new node catch up the progress of DODAG building, or advertise enough information of the current DODAG to this new node as soon as possible. The third rule is used when root node allows a global repair or revalidation of the DODAG integrity to occur according to 'lollipop' fashion [148]. These two rules with simple conditions are also required by the RPAL model.

The inconsistencies due to routing loops may have multiple reasons, such as control packet loss. RPL includes a reactive loop detection technique that can protect DODAG from meltdown and triggers repair mechanism for broken paths. This approach is based on the detection of the source node operation and router operation. In particular, instance forwarding, DAG inconsistency loop detection and DAO inconsistency detection are the main mechanisms to process this issue. For example, if the direction of a packet does not match the rank relationship in upward route, the receivers will detect this inconsistency in current DODAG. Additionally, DAO inconsistency will be detected when a router has a downward route that was previously heard from a child node. But this downward route is not available anymore due to obsolete DAO states, and this leads to a packet that should go down tries to go up a gain. To sum up, the general manner of loop detection and recovery is to check whether there is forwarding direction errors happening in the current DODAG.

As our A-LLNs are designated to work in highly dynamic environments, as well as considering the application of environmental data collection, the influences from weather, human, farm machinery, the growth of plants' stems and leaves, and the diversity of devices, will be honestly mapped to the state of network topology. We believe that our proposed SCAOF and hybrid routing metrics design are able to minimize the network churn and efficiently manage rank assignment. And for the common cases, the inherent mechanisms of RPL has been proved and validated [149]. Thus, some extreme weather conditions attract our concerns, especially in the exceptional cases where an A-LLNs deployment is exposed in severe weather, such as heavy snow or ice, heavy accumulations, or in extremely bad weather – unusually large accumulations of snow, ice, and sleet. Moreover, the large-scale experimental fields are the primary applying areas of A-LLNs, and its expected lifetime can be maximized to over two years without human intervention. Thus, the possibility of meeting regional and seasonal severe weather phenomena, such as blizzards, snowstorms, ice storms, and dust storms, should be paid attention in this autonomous system.

From the viewpoint of application layer design of a real-world A-LLNs system, the collected environmental monitoring data is always out of normal range in the exceptional situations, so an advisable manner is to carry out a specific data aggregation method to suppress the application packets until sensor data recovers to normality for reducing energy consumption. We have defined that CA-Trickle of RPAL model can obtain the contexts of broadcast fairness and phase shift. But the Trickle used in real world is impossible to be guaranteed as steady state all the time. Furthermore, the Trickle resetting mechanism requires more considerations since increasing control traffic frequency might heavily impact the lifetime [150]. Through the inspiration from the cross-layer design, we propose to further extend the context of sensing data from application layer to CA-Trickle model and design a novel mechanism called '*coagulable Trickle timer*'.

The new proposed timer approach is inspired by a natural phenomenon that causes transformation of a liquid (Trickle in normal state) into or as if into solid mass (frozen Trickle). Trickle works like a streamlet which is represented by time-varying control traffic frequency and time base of a router node. When a network gradually becomes stable, control traffic will be under suppression state similar to water stream flowing slower and slower. The Trickle reset behavior could speed up the water stream of the source node that is triggered by hearing certain packets or 'events'. Thus, an issue emerges because some resetting actions do not have to be carried out, but they cannot be avoided according to the current defined rules of RPL standard. In other words, for saving more energy on battery-powered nodes as well as reducing the waste of water volume of this streamlet, the timer in original Trickle needs to be stopped or frozen in certain cases.

This novel mechanism is used to prevent the current Trickle timer from backing to the minimum interval through the awareness of the sensing data context. It can deal with the route loop issues happened in the adverse weather conditions, especially for its effects on the radio coverage, signal strength interference and link quality (i.e. ETX value). In particular, for maintaining the neighbors and parents within a DODAG, Neighbor Unreachability Detection (NUD) [151] is often used to determine whether a neighbor is no longer reachable. Combining the neighbor discovery mechanism of link layer, this will impact the ETX value, neighbor list and routing table of the RPL. Namely, in the special conditions, some nodes in the DODAG might become islets or sub-DODAG (also called floating DAG) due to disconnected links and rank relationship churns in current topology. The original loop detection and recovery mechanism is competent for the small scale of disruption [152]. But for the case of temporary large-scale connectivity failure, according to the RPL specification [1], one router node will reset its Trickle timer of routing control traffic continuously and try



to recover the topology or rejoin a new DODAG, until the lifetime of all its neighbor information and routing entries are expired. Furthermore, a sink node will frequently trigger its DODAG's global repair due to DAO inconsistencies. Apparently, this set of repairing procedures of upward and downward route would waste large volume of battery energy. And as the previous explained, repairing the DODAG topology without application packet transmission has less value for delay-tolerant A-LLNs.

Since the weather could be getting better, the accumulation of raining and snow would be cleaned by various runoff or evaporation, and this procedure might need couple of hours, even days. When the monitoring sensor data returns to routine state, the frozen Trickle timer is also going to melt as flowing streamlet, then router nodes commence the traffic control based on the configuration of previous parameters, and the backup of parent list and routing table. In detail, we recommend that the A-LLN nodes can backup the following information in non-volatile memory (e.g. EEPROM) before they activate the coagulable Trickle timer.

- The current DODAG version uniquely defined by tuple (RPLInstancenID, DODAGID, DODAGVersionNumber);
- The fields of 'Grounded', 'Mode of Operation', and 'DAGPreference';
- The DODAG configuration option: 'DIOIntervalDoublings', 'DIOIntervalMin', 'DIORedundancyConstant';
- Rank and DAO Trigger Sequence Number (DTSN);
- List of neighbors, preferred parent and backup parents, list of siblings, and downward routing table.

This procedure can be briefly depicted in Figure 4-23, and the aforementioned resynchronization is not presented for simplifying the diagram. Meanwhile, if root node still detects DAO inconsistencies after an environmental monitoring cycle, it will decide to revalidate the whole DODAG by update DODAG number for pruning the routers which cannot leave frozen state.

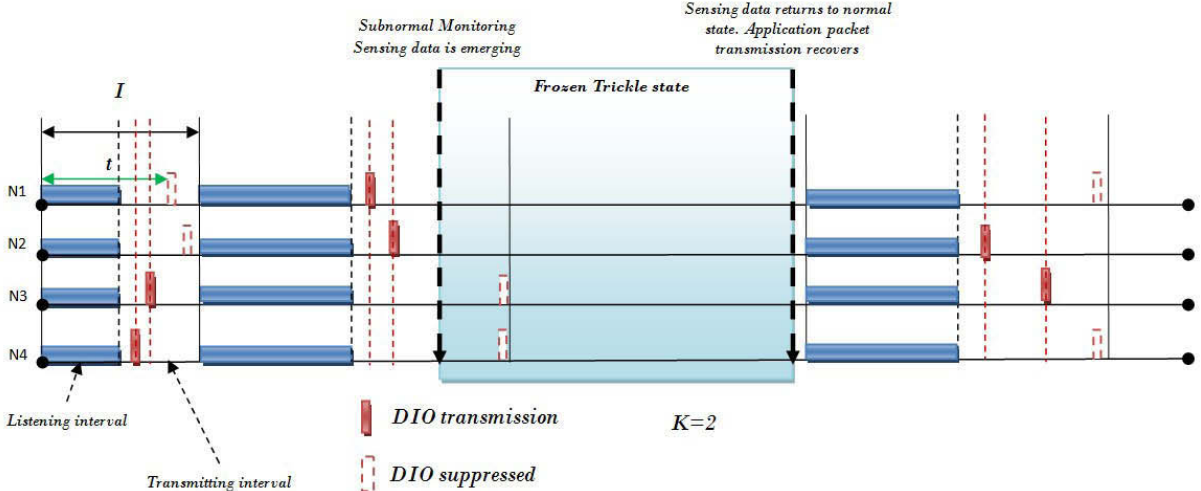


Figure 4-23 Schematic diagram of the start and the end the coagulable Trickle timer

Based on the above descriptions, we propose a novel mechanism for the Trickle algorithm, which enables to perceive more contexts and what has happened around the natural world, so it can aim at guaranteeing intelligent resetting decision among A-LLN nodes and then augmenting their survival rate in adverse weather conditions. The RPAL model is a routing protocol model dedicated to real-world environments with simplified improvements of original RPL framework. Thus, the rationale behind the coagulable Trickle timer is that its

complexity is limited since it only introduces a backup operation and a predefined judgment for Trickle resetting action. The latter one is strictly depending on the monitored sensing data from the application layer (i.e. temperature, humidity, soil moisture and rainfall sensors, anemometer, etc), which is able to remind the Trickle timer of RPAL model to perceive the current context. Of course, these modifications may introduce more MCU workload to some extent but it can efficiently prevent the energy waste on radio transmitter as the unnecessary actions of increasing control traffic frequency are avoided by entering frozen Trickle state.

It should be remarked that coagulable Trickle timer mechanism also can be used for saving more battery energy but it still requires the expensive global repair. For example, when battery level is lower than a designated threshold, DAO delay timer could be adapted to frozen state too. This action will invalidate the downward routing but it can certainly prolong the A-LLNs' lifetime. Since the basic function in the precision agriculture application is data collection, keeping the upward routing alive as long as possible is more valuable.

In addition, the applied areas of this proposal are not limited in the routing in LLNs (RPL). It can be widely utilized in more domains and generalized to CTP, and other application layer protocols, which adopt Trickle algorithm.

## 4.5 Integrating simulation and real world for mutual optimization: Closed Loop of Application-Simulation (CLAS)

In the history of the WSN, unexpected routing behaviors are always main issues of large scale WSN deployments. Considering the high cost of building a real deployment, network simulators are often used in this domain. However, the original problem is still not solved although the era of IoT has been coming. A new concept of LLN is emerging. We realize that, no matter how wonderful the results from the simulation scenarios and thorough testing, the problems, such as bad performance or even severe system failures due to suboptimal routing path, would still happen in the real-world system. A context-aware tool-set can help to build the simulation topology which is more close to the real network through mapping a serial routing metrics defined by IETF ROLL WG and the link situation of the actual network. We believe that bridging virtual and physical worlds reflected on the proposed tool-set could conduct more precise routing-targeted simulations. Moreover, by close-loop method, the knowledge and analyzed simulation results can lead to improve the network topology of the deployed LLNs.

### 4.5.1 Introduction

For a long period of time, the researchers and developers have to suffer the routing issues of Wireless Sensor Networks (WSNs). Although this domain has been continued to research for more than a decade, deploying sensor nodes is surely not an easy take as expected because the wireless communication may cause lots of unpredicted problems. Especially for the distribution of nodes in the wild, the troubles of routing will become more due to environmental condition changes and often mentioned remote firmware updates [153]. As we know, it is not enough to keep using a star topology or single-hop network for most of larger WSNs deployments since the radio range is limited and the area to cover is large. Thus, a well optimized and configured routing path searching strategy will bring significant effects on such multi-hop wireless-mesh based network.

As the coming of Internet of things (IoT) technologies, we have numerous reasons to believe that the quantity of sensor nodes will grow rapidly to huge number in the near future [12]. Unfortunately, the important problem, which is how to provide proper routing functions, is still not settled down. Thanks to the emerging concept of low power and lossy network (LLN) [1] and its routing framework of the IPv6 Routing Protocol for LLN (RPL) proposed by the IETF ROLL working group, the standardization effort has been made for the nodes which are typically operated with constraints on processing power, memory, power consumption, and lifetime. Furthermore, communication links of LLN are characterized by high loss rate, low data rate, low transmission power, and short communication range. These features are similar to traditional WSN so the LLN can be seen as an extension. Based on the reasons chartered by ROLL working group, the conventional routing protocols in mobile ad-hoc networks, such as AODV, OSPF, OLSR and DSR, are not suitable for routing in LLNs because of high routing overhead [1].

RPL has been designed to operate in low power and lossy networks with thousands of nodes. Its applicability in the Advanced Metering Infrastructures (AMIs), home automation, building control and industrial networks has been proposed and recognized. RFC 6550 has been published in March 2012, and most of the structure and parameters of RPL were clearly defined. Destination Oriented Directed Acyclic Graph (DODAG) is basic logic structure in RPL. DAG topology is used to establish bidirectional routes for LLNs. RPL routes are optimized for various most common traffics, such as multipoint-to-point (MP2P), point-to-multipoint (P2MP) and point-to-point (P2P), based on the measurements of routing metrics and constraints, the rank calculation and preferred parent selection strategy defined by Objective Function (OF).

Currently, the researchers and developers find that it is a big challenge to adapt RPL framework for their deployments because of its complexity and flexibility. For example, in most of cases, energy consumption is a critical factor related to the expected lifetime of an LLN system, and RPL should be able to provide a set of corresponding routing mechanisms in order to minimize energy use and prolong system lifetime by defining a number of energy-aware routing metrics and assigning suitable parameters of built-in energy-saving mechanisms like trickle algorithm [98]. However, a deployment may have various specific requirements on different aspects such as Quality of Service (QoS), Therefore, simulating and testing our defined A-LLNs scenario are necessary before its deployment in the real world.

Apparently, a good way of testing is to set up a testbed network in an indoor environment. However, toggling LED cannot reflect enough information on what is going on in our RPL model. So if each node in the network can run a probe thread and export the data can map to the changes of nodes routing behaviors, the testing can be more reliable. Unfortunately, it is not easy to execute any debugging on the testbed hardware. A WSN-simulator can be helpful not only on the network debugging, but also on setting up arbitrary network topologies in different scripted scenarios or test cases to optimize the WSN lifetime.

#### 4.5.2 Problem statement

Testbed and simulation are the most common used methods to test protocol models even a whole system before real deployment. As we have discussed in the previous section, unpredicted routing issue is a significant factor for the WSN deployment. Numerous routing protocol models have been built in various WSN-simulators. However, in the real WSN system, the routing algorithm seldom shows the same behavior as in the tests. One main

reason is that neither testbed nor simulation can be tuned exactly to the real deployment environment, because the radio frequency propagation model is environment dependent. Therefore we suggest adopting a context-aware tool which allows a routing-targeted LLN development. As there is no alternative candidate of routing protocol, adjusting parameters and OF code of RPL for specific deployment requirements are our final target.

A context-aware tool-set can provide more correct and accurate configurations for a WSN-simulator, so it can rebuild a more reasonable good resemblance of a hardware testbed even a real deployment in the simulated environment. Most of the current WSN simulators are able to support these complex network configurations. Using such well configured simulated scenario, it can help us to understand why the algorithms of RPL framework behave in the unexpected way, and allows detecting the exceptional issues of RPL routers, such as resource insufficiency, congestion, and cycle paths. We hope that our solution is possible to provide the automated optimization and configuration on a whole LLN network. But, it is not a good idea to start from the consideration of all the components and network layers in the LLNs, like Operating System (OS), services application, MAC layer and other working consequence algorithms. As an initial work of exhaustive iLive-CLAS system, this context-aware tool-set is only functional for providing the means to configure a WSN-simulator and RPL protocol model. However, the essential concept of iLive-CLAS system, based on a continuous close-loop method which enables to map bi-directionally the simulation results and the real-world ones, will be tested in this tool-set.

As we have discussed, a simulator solo cannot make accurate assumptions about the network topology [154]. Thus, the detailed context knowledge about the deployed LLN is the core information in this approach. But to simplify the current implementation, it is more practical to limit the selected mapping data because the redundant data will surely make increase the system complexity. It should contain the description of the adjustments (i.e. RSSI or LQI) for a radio medium model of WSN-simulator to get reasonable predictions. Furthermore, information about RPL routing metrics is necessary for this simulator-supported routing targeted LLN development. After the simulator has been configured accordingly, the extracted information is expected to improve the RPL routing behaviors of the deployed LLNs. This procedure opens three main problems for this research work: First, how to automatically and efficiently map the real network to the simulator? Second, how the simulation results can be used efficiently to the targeted LLN? The third problem is how to measure the quality and performance of the new updated LLN topologies, namely the continuing evolutions of RPL DODAG, after the context-aware tool-set provides the feedbacks of simulation to the real-world LLN system.

#### 4.5.3 MAP4LLNSIM/LLNRUN4NS tool-set architecture design

We designed a tool-set that enables to tackle the questions stated in the previous section. This context-aware tool-set includes:

- 1) Map4LLNSim: A tool for real-time mapping Real/Physical world (i.e. RPL nodes metrics information, parameters and network connectivity situations) into simulation scenarios.

- 2) LLNRun4NS: A tool for using the information from Map4LLNSim to configure our RPL model in simulator and help to analyze, visualize and at last optimize the targeted LLN

deployment by the conclusions drawn from the simulation results to improve RPL OF algorithm and trickle timer configurations in this physical LLN system (Figure 4-24).

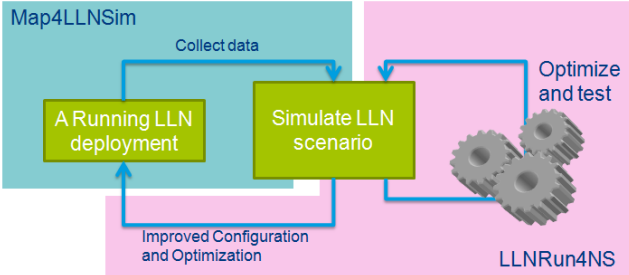


Figure 4-24 MAP4LLNSim/ LLNRun4NS TOOL-SET ARCHITECTURE

MAP4LLNSim is divided into an application running on the RPL routers that transmit relevant information through upward routing path of RPL, a corresponding application running on the RPL sink node that collect these information, and a program with support of SLIP [108] on a PC that can connect the RPL sink node, collect the data periodically and translate it into a script that can configure the targeted simulator. LLNRun4NS is a set of programs that is able to use the well configured simulator by MAP4LLNSim to draw improvement instructions and recommended parameter settings. These tools can be adopted by different tests, such as non-functional properties, parameters and visualized prediction of RPL routing behaviors.

As already illustrated, it is difficult to make accurate predictions about the connectivity of a LLN. But with the actual measurements from MAP4LLNSim, this main factor that influences node’s behavior can be analyzed and processed by a specific propagation model in the simulation. As the first-phase work, only the static LLN is considered and thus the low rate change can allow to make reasonable predictions or to track the changes with small overhead for RPL routers. If captured data can be recorded over a sufficient amount of time, most of the temporary disturbances in connectivity of targeted LLN are considered representative in the simulator. MAP4LLNSim is also capable to log the unexpected events in OS level or hardware level, such as system reboots, sudden failures, and errors derived from our experimental LLN deployment.

Table 4-5 RPL ROUTING METRIC AND CONSTRAINT OBJECTS

| Routing Metric /Constraint objects | Description   |
|------------------------------------|---|
| Node state and attribute           | CPU, Memory, congestion situation   |
| Node Energy                        | Power node, estimated remaining lifetime and, self-built power metrics          |
| Hop Count                          | Number of hops  |
| Link Throughput                    | (M&C) Maximum or minimum value  |
| Link Latency                       | (M&C) sum of all latencies, pruning links higher than certain threshold         |
| Link Reliability                   | Packet reception ratio, BER, mean time between failures... LQL; ETX             |
| Link color                         | 10-bit encoded color to links, avoid or attract specific links -> traffic types |

When our proposal commenced to be implemented, the function of mapping the link quality between the different nodes is in our first phase plan. The link quality is often used for routing protocol to organize the network topology dynamically. Furthermore, in RPL routing

framework, the IETF ROLL WG defined its usage as RPL routing Metrics (M) or Constraints (C) [59] which are shown in [Table 4-5](#).

It will be a pity to spurn these well defined metrics. Especially, the Link Quality Level (LQL) can be deduced by Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI). The packet reception ratio can be got from packet loss. Thus, this set of information will be sufficient for both of our propagation model and RPL model in simulation. Moreover, MAP4LLNSim adopts a hybrid solution including passive probing and active probing data packets sending. The target is, to provide a default periodic data collection, and an automatic probing mechanism to cope with temporary changes in the RPL DODAG. In the latter case, the OF of RPL or a data link layer model can active a suspended sub-thread of MAP4LLNSim in a deployed LLN system. But, the changes of routing metrics used by OF are more preferable because the information from the received DIO messages can also estimate and reflect disturbances very efficiently [1]. Except the above mentions, MAP4LLNSim will also support an evaluation method to eliminate redundant acquiring properties for reducing transmission overhead from RPL routers and sink node. This mechanism is efficient for data management when MAP4LLNSim continues to conduct the simulated DODAG evolutions in an infinite close loop method.

LLNRun4NS is based on the common graphical interfaces of the simulator. The gathered information about DODAG topology from MAP4LLNSim can be easily visualized. The Collect-View tool of COOJA [19] can show the connection quality in a DODAG by using spring graph layout and locating the nodes manually on a map. Namely, the distance between two nodes indicates the path weight/cost calculated from collected data. Once the simulation scenario is well configured and it is visualized similarly to the real DODAG, the simulation is called to start running. LLNRun4NS will acquire the data from simulator and analyze them. However, too much simulation tracing log will not be beneficial for executing simulation. LLNRun4NS can intercept the data acquisition to select and preprocess the tracing log for further analysis. As this designed tool-set targeting RPL routing, the preprocessing and the analyzing results are strongly concentrated on the requirements of configurations and optimizations for RPL's behaviors. Furthermore, LLNRun4NS can control the RPL simulation model to have a thorough test using different trickle timer configurations, routing metrics compositions [131], and even debugging or plotting the data from simulator can be helpful to detect the unexpected RPL routing behaviors.

How to find the best settings of RPL routing protocol with optimal path is always a problem that should be considered when planning a LLN deployment. In this tool-set, only the routing layer will be tuned based on RPL framework, in particular the RPL routers possess enough context-aware features. For the other network layers like MAC layer [93] or application layer, in-depth knowledge is required to provide reasonable tunings because the nodes might need different configured strategy depending on their location or function within the LLN. The current LLNRun4NS therefore only provides a parameter list defined in RPL framework, and supports finding an optimized configuration for each RPL router in the deployed DODAG. At the same time, LLNRun4NS also helps the maintenance of the LLN especially when MAP4LLNSim detects the changes in the RPL DODAG and maps them to the simulator.

After the analyzing a simulation run of the current DODAG and comparing it with the previous run, LLNRun4NS should detect the explicit problems and what is going on in the RPL layer of the running RPL routers and sink node. It is not easy to affirm that one revision test against the reference-run can help to detect all the causes of regression or improvement. Thus, we suggest that LLNRun4NS needs to run a several recursive tests to give the exact

reasons of changes and misbehaviors. Moreover, one cycle of executing means one time evolution for both of the virtual and physical world. To achieve the better results, the closed loop needs to be performed continuously. Of course, we also recommend that the drawn results from this tool-set are only applied to the distinct LLN deployment tests because the same parameters may cause unpredictable impacts on the behaviors of another deployment.

#### 4.5.4 Related work

Based on our investigations, the classic network simulators like NS-2, NS-3 or OMNet++ have been extended to the WSN domain [110, 155, 156]. They all can meet the needs of our tool-set, but the code must be ported and recompiled to run in both of the simulator and hardware. Thus, it is difficult to keep the coherence of the programs for the two sides especially when the limited resources of the real sensor nodes are considered. Due to the choice we have made for the first phase, the programs implemented for RPL's logic can be same but the delays or bottlenecks caused by the hardware peripherals still cannot be neglected. The COOJA simulator [19] targets exclusively the WSN and IoT relevant simulations. It can connect various plug-in including the emulators like MSPsim or Avrora for working together with different network models.

Our context-aware tool-set is inspired by the RealSim and Dryrun architecture [154] designed for COOJA simulator. These tools can be used by universal WSN deployment and provide a suite kit of deployment-targeted development mainly on the respective, such as system debugging and deployment optimization. Their work and the authors of [6] also present the concept of mapping a real deployment to a simulator. The latter focuses on moving the information about the state of real sensor nodes to and from the simulator, and former's interests is the common network topology. But none of them tries their optimizing strategy for a tuning of routing layer, not even mention to the promising IoT compatible RPL routing framework.

#### 4.5.5 Current progress and challenges of CLAS

In the current progress of this designed context-aware tool-set, MAP4LLNSim is the core component to provide the context sensing and mapping functions. It supports automatic detection of RPL routing metrics and link situation through active probing. This scripted information can be automatically used to tune a simulator. In its implementation, the data about link quality can represent the links configured by COOJA's Directed Graph Radio Medium (DGRM) and the propagation model designed for the WPAN model in NS-3 [155]. While LLNRun4NS is a JAVA program based on Collect-view tool for TelosB node, we added necessary additional interfaces to control the simulations in COOJA or NS-3. A plug-in of COOJA named Cooja-dbus is used to control the simulation process from an external program. But in NS-3, LLNRun4NS is able to modify or reorganize its main simulation scripts. Currently, we still use the file input and output operations to access and analyze as much tracing log as possible, but we are planning to adopt an efficient approach to do this task and save all the helpful data to a database. Our current design with Cooja and NS-3 [110] is shown in [Figure 4-25](#).

1) Real-world link quality properties and RPL routing metrics probing are exported in a new cycle: A hybrid solution for link quality monitoring: Passive probing (by default or

manually) and Active probing (automatically); Sensor reading is a part of acquiring properties; the data will be exported to the MAP4LLNSim through a RPL sink node in a formatted log.

2) Saving, acquiring and preprocessing the data message in a script for analysis: The data will be saved and acquired in structures based on different requirements; LLNRun4NS will provide a GUI analysis module for graphing the network topology and data display.

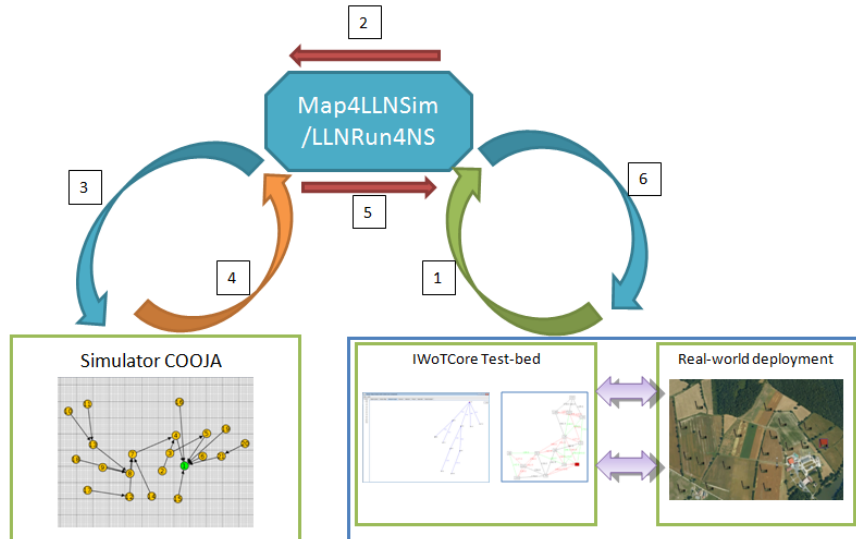


Figure 4-25 Schematic flow diagram of MAP4LLNSim/LLNRun4NS tool-set

3) Generating, importing acquired data to a simulator: LLNRun4NS will execute a simulation process in the background after the simulator script has been configured to resemble the real RPL network; the real-world data will be imported into the simulation and then the tracing file of all the simulated RPL nodes can be output.

4) Validation of simulation tracing files and transferring them to LLNRun4NS: Pcap tracing files generated by Cooja or NS-3 can be tested and analyzed in the Wireshark tool; the tracing file is organized to store the important information of the entire simulated network behaviors.

5) Processing tracing files in the LLNRun4NS: LLNRun4NS GUI is able to show the simulation results; to predict the network condition (i.e. RPL DODAG changes) and to provide the configured parameters (OF, routing metrics and Trickle timer) for each RPL router.

6) Transmitting the feed-back configuration to the real-world LLN and waiting for the next cycle: First phase of this project is to test the tool-set on a testbed: i. Emulator-based; ii. Development suite-based; Next step is in the real LLN deployment of an experimental field.

MAP4LLNSim/ LLNRun4NS tool-set is dedicated to a single LLN built by recourse-constrained hardware installed with I/WoT protocol stack. Its context-aware features, including routing metrics, DODAG structure and link quality, will help to monitor the behaviors of RPL routing protocol, to assist avoiding and addressing problems caused by suboptimal routing path (high packet loss ratio or unexpected battery energy dissipation) in advance. Hopefully, considering the effects of plant growth cycle, a too-set prototype can also provide the estimation, optimization (i.e. cooperating with CA-Trickle to control DIO broadcast) and forecast functions for A-LLNs through centralized manner in the future work.



Our current progress is focusing on the reconfiguration of the factors in SCAOF (i.e.,  $a1$  and  $a2$  of [Formula 4.10](#)), as well as preliminary lifetime estimation. Unfortunately, the current implementation of CLAS is still not complete and some components have defects. The high energy consuming data exchange is a big challenge. Because no matter passive probing or active probing, MAP4LLNSim has to rely on the already built DODAG for probing and acknowledgement messages transmission. Sending reduplicate unicast packets and waiting their ACK are ineffective and induce heavy overhead. This will surely deteriorate the constrained resources of LLNs. Meanwhile, we need deeper considerations on the impacts of the prediction and the feed-back configuration from LLNRun4NS to the network topology in real world.

First of all, the synchronization and time schedule issues for MAP4LLNSim and LLNRun4NS have to be clarified and well defined. The simulation process should be awaked by LLNRun4NS only when MAP4LLNSim has found the current DODAG requires external intervention, for instance, the configuration of inherent distributed mechanism (i.e. SCAOF or Trickle timer) is not practical enough to achieve the expected QoS requirements. Secondly, notice that MAP4LLNSim only can map instant link quality information to the simulation. For example, the low sample rate of MAP4LLNSim is impossible to maintain the entire link mapping information in fresh state. Moreover, LLNRun4NS has to execute recursive tests and extract one optimizing configuration from a set of consecutive cycles. Thirdly, since the availability of this tool-set is highly related to whether the new configured parameters from LLNRun4NS can essentially improve the current QoS, the research about fuzzy logic [157] and machine learning [158, 159] theories can surely provide more inspirations to our future work.

To sum up, although currently we cannot prove the efficiency of CLAS due to the above challenges, it is not to assert that the approach in CLAS cannot be adapted to LLNs scenarios. We have proposed this brief design of MAP4LLNSim/ LLNRun4NS tool-set with the idea of CLAS in the NICST 2014 workshop. Our contributions, which are designing an assistant tool-set for RPL framework and providing the considerations of theoretical background, challenges and potential issues based on the current implementation progress, have been highlighted in this section.

# 5 Performance evaluation of routing protocol for Agriculture-LLNs: RPAL

## 5.1 Adaptation and improvement of simulator, protocol stack and application

As the evaluation work mainly relies on simulation platform at the beginning, the COOJA cross-level simulator platform is adopted to test the above proposals. Thanks to the existing emulator model of TI MSP430x MCU and TI CC2520 radio model, it could install a full version of the uIPv6 protocol stack with RPAL model and hold evaluating experiments. Moreover, in IRSTEAs, we also had a master internship project [39] about the emulations of AVR-Zigbit hardware platform (ATmega128 MCU plus Atmel AT86RF230 radio transceiver) and Atmel Atmega128RFA1 single-chip solution hardware platform (An integrated system on chip). The basic idea of this project is building a cross-level debugging system for IWoTCore boards [37] and MiLive WMSN platform [20]. However, since some program components are needed further validation and bug elimination, we consider them as a future work in next chapter.

In the physical layer, we have tested IEEE 802.11 c/d/g in the Pandaboard as a small project but we found it is difficult to manage the energy consumption issue. Moreover, ZigBee PRO is not easy to be modified since the users are only able to change its application layer and device drivers through its designated APIs. Moreover, IEEE 802.15.4 PHY layer is the foundation of the IoT network stack recommended by the ROLL WG [28]. This standard is the most available choice before the standards of low-power Wi-Fi, Bluetooth and Power Line Communication (PLC) are completely ready and released. ROLL WG also had a clear statement about IEEE 802.15.4 MAC layer, especially its cluster topology and beacon-enable mode, which are not well suitable for LLNs because these two mechanisms are extremely power consuming due to their management and resynchronization procedures. This is the main reason why most of the related work adopt IEEE 802.15.4 beacon-less mode. But this mode does not have radio duty control mechanism so the radio transceiver is always switched on during its working time.

From the perspective of low-power networks, the radio transceiver must be switched off as long as possible to save energy. So we choose an open source MAC layer solution in Contiki, which has been adopted and validated by RIME stack [160] and IoT-compatible uIPv6 stack. In fact, in Contiki, it has two models to realize the MAC-level processing. One model only contains basic CSMA (Carrier Sense Multiple Access) mechanism that is responsible for avoiding collisions at the radio medium and retransmitting packets if there were a collision. Another one ContikiMAC provides an efficient Radio Duty Cycling (RDC) layer. It should be pointed out that this protocol suite can be used like standard IEEE 802.15.4 MAC in beacon-less mode if no RDC layer is added. We used the ContikiMAC RDC layer since it provides both low-power listening and low-power probing mechanisms. Moreover, RDC and MAC protocols are important parts of Contiki netstack as they ultimately determine the power consumption of the LLN nodes and their behaviors when the network is congested.

As the main target of this thesis is to provide RPAL routing protocol dedicated to the agricultural application, we also need 6LoWPAN to qualify IPv6-based functions to A-LLNs. Meanwhile, a compatible application protocol is required to equip A-LLNs with Web of

Things technologies. More important, the affiliation of CoAP, RPL, IPv6 and 6LoWPAN can prove their adaptations to the resource-constrained environment of A-LLNs. As 6LoWPAN adaptation layer has been discussed in Chapter 2, only a few points related to our evaluation work will be complemented here. Except a flexible and adaptive PHY/MAC layer, the open-source 6LoWPAN architecture is also required to achieve our purposes. The functional division of this adaptation layer is basically built by header compression, fragmentation and addressing. SICSlowpan is the first 6LoWPAN implementation based on the uIPv6 which is developed by Cisco, Atmel, and SICS. Its more detail information can be found from the recommendation draft document of 6LoWPAN WG about adopting the uIPv6 protocol stack in the year of 2008.

As precision agriculture application can be divided into various services, CoAP which is designed for low-power embedded networks and considered the energy, memory and processing constraints of wireless embedded devices (RFC 6690), can be adopted as a RESTful application layer. Our evaluation work will also present this specific application as a use case of Web of Things but only from the perspective of network protocol rather than using CoAP resource for modeling agricultural sensing application. Since CoAP can prove whether a protocol stack is available to support efficient communication for a real application, the essential targets of its adaptation are different with the current research on CoAP which includes the topics comprising its performance evaluation, comparison with HTTP and SoAP based approaches, its scalability and friendly usage, auto configuration capabilities, and the study of its applicability for various applications [8]. We chose the following CoAP open source implementations and test them on both simulation and hardware testbed.

- Contiki OS CoAP, Contiki C# platform, supports CoAP-03/08, observer model, block-wise transfers and resource discovery [107];
- Copper CoAP browser plug-in, running on Firefox, supports fully functional CoAP client side and remote test server for debug, matching the REST engine of Contiki;
- jCoAP, JAVA SE and Android platform, contains most of the basic features in its latest version, has been ported to Pandaboard as a CoAP client and proxy in a project during the thesis;
- Nodes Android application, Android Market, HTTP-CoAP bridge and browser for a given Android device and SDK. Our testbed system (i.e. tablet) partially refers to its GUI design.

In sum, the accessions of 6LoWPAN and CoAP enable a better evaluation for the RPAL model and previous proposed inner mechanisms since an incomplete netstack without low level layers (i.e. IEEE 802.15.4 PHY/MAC and RDC protocol) is not available to support running the RPAL model, and the testbeds without high level layers (i.e. 6LoWPAN, IPv6 and CoAP) cannot represent that the RPAL model is dedicated to a specific application orienting to IoT technology. Thus, to achieve the above purposes, we adopt a complete netstack as shown in [Figure 5-1](#). Namely, we integrate the aforementioned components including protocols or mechanisms into this netstack. It should be noticed that the experimental results might be influenced by numerous factors, such as configured parameters in different network layers, emulator, and simulation scenarios or hardware testbed deployments, but this is the only manner to test whether our proposals are close to be ready for the real-world system. Furthermore, the RPAL model could not only guarantee a better performance on its adaptation for A-LLNs scenarios comparing with the original RPL framework. It also needs to be well cooperated with other emerging protocols and models which are driving forces of pushing traditional WSN technologies to the era of IoT in the agricultural domain.

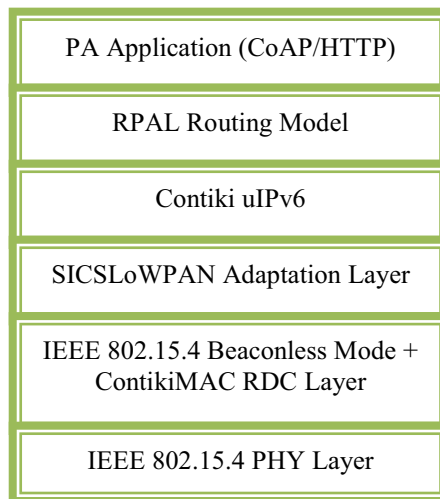


Figure 5-1 Protocol stack for evaluate RPAL Routing Model

## 5.2 Performance evaluation in simulation scenarios

In this section, two main proposed algorithms of RPAL model will be evaluated in simulation scenarios. The configuration of COOJA simulator, MSPsim emulator and wireless channel model will be firstly presented. Then, the preliminary proposal validation of energy-aware metrics and SCAOF will be presented in a small-size network firstly, so the changes of data forwarding routes can be observed. The performance evaluation of these proposals will take into account different network topologies and different node types. Furthermore, both of the CA-Trickle and SCAOF algorithms will be tested under enhanced simulation scenario scripts which can enable runtime adjustments of radio medium, node state and behavior.

### 5.2.1 Simulation setup and designated scenarios

Environmental data collection is one of the key applications of A-LLNs in the envisioned IoT. As some nature situations could be very harsh or difficult to obtain frequent human interferences, A-LLNs normally adopt wireless medium. Most of the A-LLN nodes are typical highly constrained devices. In addition, the heterogeneous monitoring sensors and remote control units extremely enrich the functionalities of the A-LLN application which are indispensable for Precision Agriculture. Since we had a discussion about Agricultural low-power and lossy network (A-LLN) in Chapter 3, only some key points are needed to be noticed, which especially impact the simulation scenarios.

When network architecture is considered, two approaches are generally used: centralized and distributed architectures. The majority of existing WSN deployment in experimental field uses the centralized method (e.g. a coordinator node as a central node in ZigBee PRO network). Although the distributed fashion can achieve lower latency, we still consider it as an assistant to the former one since a single A-LLN can be seen as a centralized architecture but it is also able to be divided into several parts or extended with other A-LLNs through proper IoT technologies. Thus, A-LLNs are expected to be a part of the smart agriculture's infrastructure in futuristic scenario, and there should be a central unit (i.e. an A-LLN border router or edge router) that is playing the role of a network coordinator among the A-LLN sensor motes and the external "things". Furthermore, our study is focusing on the routing

optimization in a single A-LLN so the simulation will be dedicated to centralized architecture like the settings of aforementioned empirical experiments and simulation tests.

#### 5.2.1.1 Topology

For the simulation settings, we still keep most of the parameters which have been configured in subsection 4.1.1. But considering the topology issue, a common simplification similar to other literatures, which adopt the assumptions of a grid-like network topology as well as a tree-like network topology, has been actualized. In some cases, these two types of topologies could be equal for DODAGs organization as the decisions made by RPL framework. The difference of them is that the main consequence of the former is a near-uniform distribution of the number of node degree (neighbors' count). Although both of them are easily built in simulator, they cannot reflect common deployment scenarios for environmental data collection in precision agriculture. Moreover, the simplification would strongly impact the performance evaluation results.

On one hand, when we explained the first Contiki/Cooja simulation for A-LLNs scenarios in subsection 3.5.1, a virtual 1200m\*800m crop field map and developed a realistic topology by using the Multi-path Ray-tracer Medium (MRM) model and its radio signal propagation model. On the other hand, Distance Loss Unit Disk Graph Medium (UDGM) is used to build the simplified scenario in subsection 4.1.1. Apparently, to obtain realistic results, MRM is more preferable since it adopts more powerful analytical approach with dynamic received power calculation by Friis formula [161], and the range calculations of transmitter signal based on the attenuation, refraction, reflection and diffraction of obstacles. However, this set of models will extremely drag down the whole system when a large number of nodes are simulating. And the deployment of A-LLNs is not included in this thesis. So we decided to adopt UDGM and to evaluate our routing model in the basic topologies described in the related literatures [73, 74, 143, 162] and to consider the deployment issue including the location of various obstacles as future work.

Since the realistic crop fields are mostly organized in some regular parcels, the shapes of them could be rectangle or quadrangle (see [Figure 3-4](#) or [Figure 4-5](#)), so they can be simplified as grid topology. In current circumstances, a WSN with around 20 nodes are quite common for most of the LLN use cases, and a single A-LLN has the same size. However, this number is depending on numerous factors, such as the size of the targeted experimental field, device cost, budget, and the specific functionality. For example, a sparse network is enough for smart irrigation that is one of cases in precision agriculture, but it is not enough for a farm who also needs livestock management. Thus, we decided to further simplify the definitions of simulation scenarios and limit them into the crop fields' scenario in a fixed size area.

Considering the network scalability as well as the low density of the A-LLN, we define the number of sensor nodes as 10, 20, and 30 for the energy-aware metrics and SCAOF evaluation. And the topologies are designed under the following assumptions:

- The generated topology of 10 nodes is only used for the preliminary validation of RPAL model. The Java-based GUI plug-in of Cooja simulator is able to faithfully present the topology construction of this scenario. The nodes are manually located in a fixed size area;
- The generated topologies of 20 and 30 nodes are used for further performance evaluations of RPAL model, such as the average packet delay, packet loss rate, hop distance, routing table size, overhead, average remaining energy and network lifetime. Since we have two proposals about improving the routing metrics and objective functions of standard RPL

framework, the energy-aware routing metric and SCAOF of RPAL model will be evaluated and their performance will compare with the original mechanisms;

- The nodes count is a basic metric to classify the different simulation scenarios, but we also can assign different roles and states to a certain proportion of nodes for organizing more complex scenarios;
- Those small groups of 20 and 30 nodes are simulated in a grid topology and their locations could be the junctions of the edges of adjacent grids or the centers of the grids. Namely, the sensor nodes are uniformly distributed around but the sink is placed at the boundary of this topology.

The networks with 50 and 100 nodes are normally too large for a single A-LLN since this is not an efficient fashion of network organization. If a realistic large-scale field is difficult to be covered by the small groups of A-LLN nodes following the above assumptions, multiple sink will be needed to divide the network into several dissociative topologies and all of them are still compliant with the aforementioned assumptions. For the simulation scenarios of 50 and 100 nodes, which are also organized in the more subdivided grid manner and are still located in the uniformly distributed positions, they are only adopted for testing our CA-Trickle algorithm comparing with the original Trickle. But the approach of using multiple sink is out of our current research.

#### 5.2.1.2 Traffic pattern

Essentially, the A-LLN nodes still adopt UDP as the transport layer protocol and their application process includes best effort transmission and acknowledges. Therefore, the traffic in a single A-LLN is distributed evenly between point-to-multipoint (i.e. DIO and DIS broadcast and IPv6 Neighbor Discovery mechanisms) and multipoint-to-point (i.e. application packets and DAO transmission). It is important to note that we have adopted CoAP application layer protocol to carry out the queries of available information resource in the unicast method. In particularly, the traffic pattern of each A-LLN node depends on its defined logical role (as depicted in [Table 5-1](#)).

Table 5-1 Traffic pattern of the nodes with different logical roles in an A-LLN.

| <b>Node Type</b>                     | <b>Supports of traffic pattern</b>   |
|--------------------------------------|--|
| A-LLN Edge router/ border router     | Sending a resource query request as 5 CoAP packet burst to a actuator in 60~90 seconds interval; ACK of received frames; |
| Common monitoring A-LLN sensor nodes | Periodic reporting in 25~30 seconds interval   |
| Local controller/Actuator            | Period reporting in 10~15 seconds interval; and sending ACK; sending resource query reply packet to edge router          |
| Malicious sensor nodes               | Periodic reporting in 25~30 seconds interval   |

Note that the reporting periods are not following any suggestions from related literatures because they are too short and the realistic reporting frequency could be only two to ten times per day, but the above node role design of general traffic patterns are very similar to a real-world system. Furthermore, all the A-LLN sensor nodes are able to turn their node types to malicious ones.

#### 5.2.1.3 Simulation parameters

Unlike the real deployments of other use cases defined by ROLL, which have existing simulation scenarios, the channel propagation model of A-LLN is difficult to be configured like the real-world environment. In addition, the heterogeneous devices and sensors of A-

LLNs cannot be easily mapped to emulation platform. For shortening the time of development, all the nodes in our simulation experiments run Contiki OS with the whole protocol stack (see [Figure 5-1](#)). Because the typical mote type of Tmote Sky cannot provide enough ROM for our protocol stack, we have compiled Contiki for a home-made platform based on MSP430x MCU and IEEE 802.15.4 compliant radio CC2520 module. Through the MSPSim hardware emulator, Cooja is able to introduce all the hardware constraints of the devices into our experiments.

All the Contiki OS and Cooja parameter setups are similar to the [Table 4-1](#), except that we added the CoAP application protocol to support resource information query function for the future vision of Web of Things (WoT). Notice that the simulation time is not fixed in the following tests since the network lifetime and average node lifetime are considered, and the simulation would be stopped in predefined conditions. The Powertrace model is adopted to monitor the energy consumption of each node. The configurations of different layers of Contiki uIPv6 protocol stack are set to the default parameter states including ContikiRPL model. But as the purpose of a comparison reference, our proposed RPAL model is also set the same configuration like ContikiRPL, so that the realistic comparing results between the original algorithms and the proposed algorithms can be observed.

### 5.2.2 Energy-aware routing metrics and SCAOF evaluation

We first focus on a 10 node network as a preliminary validation on the network construction by observation, and then the simulation topologies with 20 and 30 nodes for further performance evaluations.

#### 5.2.2.1 Preliminary validation: two cases of 10 nodes tree-like topology

A 10 node network (cf. [Figure 5-2](#)) is used to present the different network constructions between the SCAOF using energy-aware metrics and the OF using ETX metric.

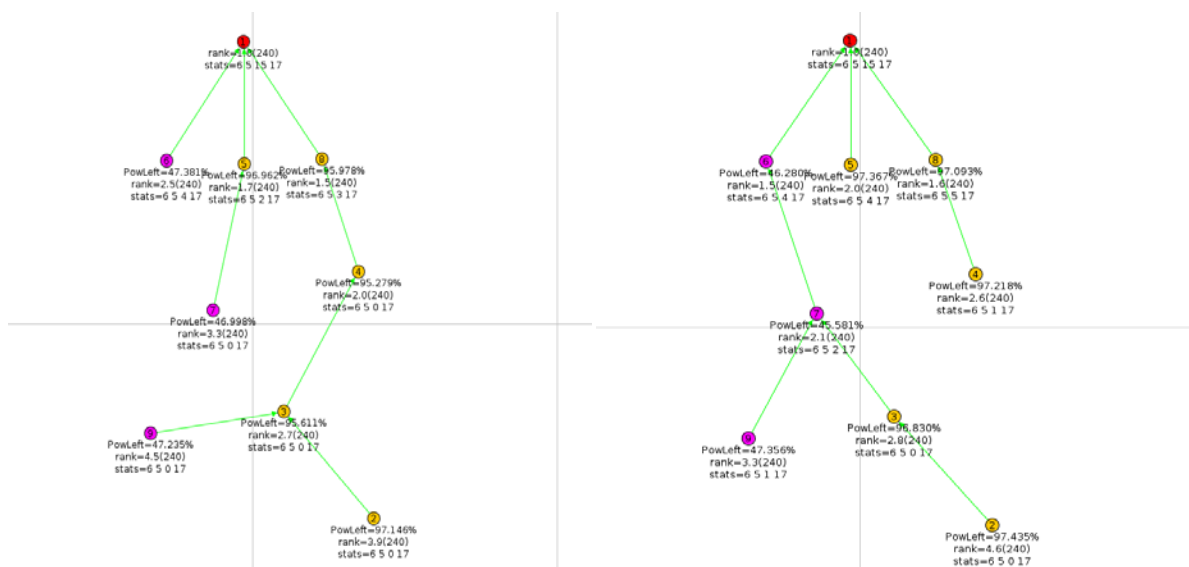


Figure 5-2 DODAG construction and initialization: SCAOF (left) and MrhOF (right)

As this preliminary validation is a qualitative experiment, the running simulation is used to observe the DODAG construction and the initialization procedures. Meanwhile, it is also helpful to check the correctness of our implementations. Obviously, in a network built by the sensor nodes with different energy level (i.e. 50% and 100%) as shown in Figure 5-2 and Figure 5-3, the SCAOF of our RPAL model is able to improve the preferred parents selection with avoiding the nodes (purple circles) which have less remaining energy. Contrarily, the MrhOF of the standard RPL only considers the ETX metric as well as the link quality so the route paths are shorter since all the nodes prefer the lower ranks of DODAG to obtain smaller ETX values, but this will certainly exhaust the energy of the purple nodes much sooner than the built DODAG by SCAOF in this case.

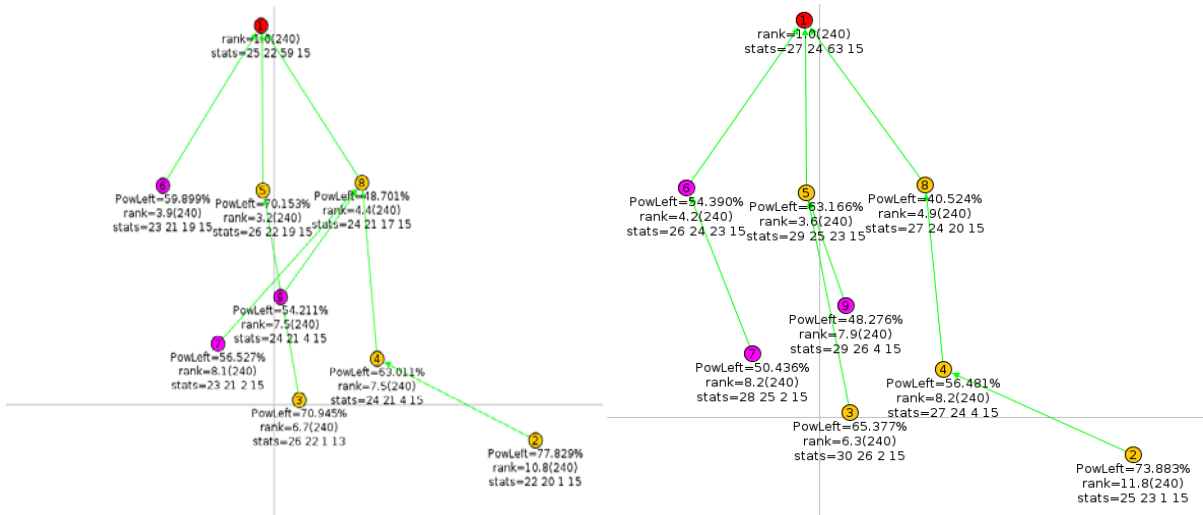


Figure 5-3 The adjustments of preferred parents controlled by SCAOF: node 7 and 9 change their previous preferred parents to the new ones with more remaining energy

Except the influence of the network constructions, SCAOF will also adjust its DODAG dynamically depending on the periodical energy consumption monitoring of Powertrace model (cf. Figure 5-3).

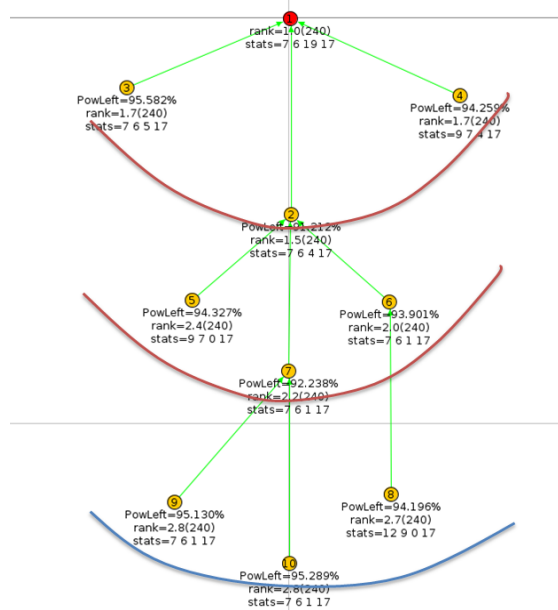


Figure 5-4 The case of 10 node network: common sensor nodes with 100% energy level



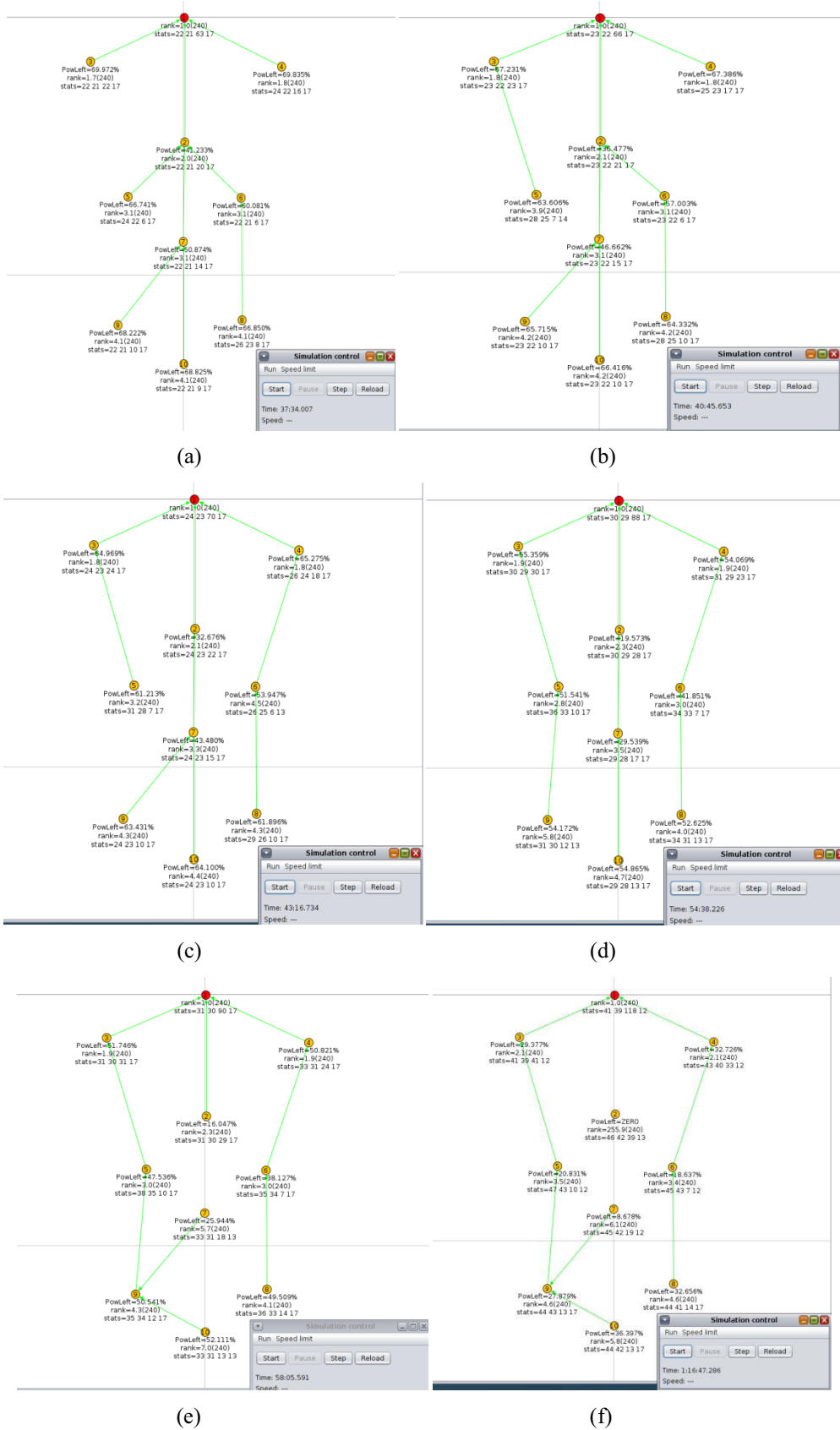


Figure 5-5 The case of 10 node network: the optional parent selection for avoiding hot spot.

For observing the DODAG's initialization and maintenance procedure of SCAOF, we manually locate 10 nodes in a three-hop topology showed in Figure 5-4. Moreover, six snapshots that are taken from the DODAG initialization to the appearance of first dead node

are also provided in Figure 5-5. At the beginning of network construction, node 2 becomes a hot spot but SCAOF is able to trigger the DIO messages broadcast with the sensing RDC and remained energy, so the children nodes of node 2 can choose another optional parent in this DODAG. These procedures can be observed in the (b), (c) and (d) of Figure 5-5.

5.2.2.2 Performance evaluation

Getting the results of performance evaluation is a must for any routing model. And we have evaluated RPL and RPAL model in terms of network lifetime, packet delays, packet loss rate, Round-Trip Time (RTT) for CoAP resource request/reply, routing table size, overheads and path hop distance. To test these performance metrics, we built three simulation scenarios.

Scenario 1: 20 node network

In this scenario, we simulated 20 battery-powered sensor monitoring nodes in a grid topology. The comparison is made between standard RPL model and RPAL model. For the performance metrics of network lifetime, the time point when the first node runs out of energy is provided here, as well as the evaluation after integrating the nodes' lifetime. The lifetime of a single node ends when its value from Powertrace model arrives to the predefined energy storage threshold. To decide whether a node is active, it depends on the existence of its connection to the sink node.

Table 5-2 Simulation performance results comparison of scenario 1

(a)

| Routing Model | Performance Metrics   |  |  |  |
|---------------|-----------------------|--|--|--|
|               | Lifetime              |  |  |  |
|               | First dead node (min) | % of active nodes = 50% (min)<br>% of living nodes = 50% (min) | % of active nodes = 30% (min)<br>% of living nodes = 30% (min) | % of active nodes = 0% (min)<br>% of living nodes = 0% (min) |
| RPL MrhOF     | 10.766                | 19.622   | 19.693   | 36.02  |
| RPAL SCAOF    | 14.164                | 27.253   | 31.863   | 32.494   |
|               |                       | 22.022   | 24.264   | 32.51  |

(b)

| Routing Model | Performance Metrics       |                              |                                 |                                |                            |
|---------------|---------------------------|------------------------------|---------------------------------|--------------------------------|----------------------------|
|               | Average Packet Delay (ms) | Average Packet Loss rate (%) | Average number of route entries | Control plane overhead (bytes) | Average path hop distances |
| RPL MrhOF     | 104                       | 20.758                       | 2.37                            | ≈11875                         | 2.19                       |
| RPAL SCAOF    | 138                       | 17.134                       | 3.24                            | ≈14416                         | 2.81                       |

Average packet delay is measured as the time from the data packets being sent from the sender node until receiving the packets at the sink node. The average values of packet delay and packet loss rate performance metrics are generated by all messages from all the nodes. Note that the results are calculated from the log files of simulation output, which includes all the debugging information of network and data link layers.

To study the optimality of the constructed routes, we introduced path hop distance as performance metrics. The path hop distance is the average number of hops between a source and a destination. However, the relevant distance to the sink node for each sensor node is presented as rank in the DODAG. As rank is not a stable value in the procedures of DODAG maintenance, we decided to use the rank value as a snapshot value when the nodes run out of their energy.

Table 5-2 shows the results from the simulation tests and quantifies the performance difference between the SCAOF with energy-aware routing metrics and standard RPL MrhOF with ETX primary metric. In the Table 5-2 (a), the network lifetime is considered in two cases as we have mentioned before. We can observe that the differences in lifetime are not large since we assigned very little energy to each node. This leads to an unexpected result that some nodes using SCAOF cannot afford the energy consumption incurred by a parent reselection procedure when the time is near the end of the simulation. Nevertheless, the lifetime performance of RPL's SCAOF is better than RPL's MrhOF in most comparison items of testing, except the circumstance in which the percentage of alive or active node equals 0%.

For other network performance metrics (cf. Table 5-2 (b)), it is evident that OF using a single ETX primary metric will select the shorter path. While routing metrics combination solution is working, it is highly possible to choose a longer path (cf. 'Path hop distance' in Table 5-2 (b)) to sink node for avoiding the energy depleting node. This may lead to higher cost on packet delay, overhead on consumed memory and control messages. Moreover, as SCAOF is dedicated to keeping more nodes in active state, it can achieve lower average packet loss rate because busy routers have longer lifetime in these tests.

#### Scenario 2: 30 node network

This experiment is conducted with 30 nodes organized in a grid topology and located in the same size area like the previous test. From the Table 5-2 (a), we might find out that SCAOF gives better performance on both average node lifetime and network lifetime. Apparently, as increasing the network size and density, more redundant RPL routers will exist in the DODAG. And this lead to more serious hot spot issue when the standard RPL is adopted. Namely, more nodes cannot keep the communications with the sink node although more nodes are alive but they cannot essentially participate in the business of this network.

The Table 5-2 (b) reveals the network performance metrics of this simulation. The trade-off between the network lifetime and certain network performance are still like the last experiment. It should be stressing that we introduced CoAP application into 20% node of the testing network so they are able to reply the resource information organized by CoAP protocol, and sink node will periodically transmit resource request to these 6 nodes. The average CoAP Round-Trip Time (RTT) is the result we got from this simulation, and it proves that our Link Color metric is able to improve the communication performance of the nodes running CoAP applications by impacting the rank of DODAG topology.

We also noticed that the costs due to SCAOF become bigger as the number of nodes increasing. But the results would be better if the nodes are assigned as normal energy level since the SCAOF algorithm is very sensitive for the change of energy and its calculation of routing metrics that might lead to frequent parent reselections. Although the network churns only happen in local areas, RPL model will certainly trigger more times of local repair mechanism than the original RPL protocol. In addition, SCAOF still can achieve lower packet loss rate as its routing metric composition approach could balance the traffic (i.e. the routing metric brought RDC information) as well as avoid the energy depletion (i.e. RE routing

metric). Furthermore, a certain level of delay for the common periodical application packet transmission is not a serious issue comparing with network lifetime performance as A-LLNs are delay-tolerant network.

Table 5-3 Simulation performance results comparison of scenario 2

(a)

| <b>Routing Model</b> | <b>Performance Metrics</b> |  |  |  |
|----------------------|----------------------------|--|--|--|
|                      | <b>Lifetime</b>            |  |  |  |
|                      | First dead node (min)      | % of active nodes = 50% (min)<br>% of living nodes = 50% (min) | % of active nodes = 30% (min)<br>% of living nodes = 30% (min) | % of active nodes = 0% (min)<br>% of living nodes = 0% (min) |
| RPL MrhOF            | 11.517                     | 21.783   | 24.315   | 27.518   |
| RPAL SCAOF           | 14.556                     | 23.358   | 26.124   | 31.796   |
|                      |                            | 28.268   | 31.01  | 38.007   |
|                      |                            | 21.516   | 23.505   | 32.013   |

(b)

| <b>Routing Model</b> | <b>Performance Metrics</b>       |                                     |  |                                       |                                   |                              |
|----------------------|----------------------------------|-------------------------------------|--|---------------------------------------|-----------------------------------|------------------------------|
|                      | <b>Average Packet Delay (ms)</b> | <b>Average Packet Loss rate (%)</b> | <b>Average number of route entries</b> | <b>Control plane overhead (bytes)</b> | <b>Average path hop distances</b> | <b>Average CoAP RTT (ms)</b> |
| RPL MrhOF            | 116                              | 27.432                              | 2.44                                   | ≈13395                                | 2.97                              | 788.743                      |
| RPAL SCAOF           | 154                              | 18.252                              | 3.32                                   | ≈17119                                | 4.68                              | 678.015                      |

Scenario 3: 30 node network with runtime reconfiguration of node state

To evaluate the performance benefits brought by our proposed SCAOF and hybrid RPAL routing metrics, we have run a special scenario with different levels of penetrations of misbehaving nodes randomly distributed in the grid that is like previous experiments. These misbehaving nodes perform periodic reset of their watchdog that is implemented by controlling the emulator to trigger this behavior. After one time stamp of system restarting, these nodes will try to rejoin the DODAG, meanwhile they also can be considered as the sources of “grey hole attack” since they will randomly drop the received traffic during the time when the emulated devices start the bootstrap program until they are ready to be a member of their joint DODAG.

For simplifying the result analysis of this experiment, we give enough energy to all the nodes for running a 40mins simulation. A JavaScript-based simulation script is used to give runtime reconfiguration of the node state and generate random restart intervals for those misbehaving nodes. The results regarding the packet loss, latency, number of failed co-operations, and packet transmission cost, are depicted in Table 5-4. From the result data, we can observe that the original RPL cannot solve the problems brought by the misbehaving nodes. Its packet loss rises very rapidly if the number of misbehaving nodes is increased, even the ETX routing metric is able to alleviate the unreliable links but its cumulative feature will

still cause long-time delay for carrying out these measurements. Thus, since RPL's MrhOF does not have any mechanisms to promptly detect the misbehaving nodes, more failed packet forwarding will happen, and the cost for the successful delivering one data packet to the sink node is higher than RPAL. In the composite routing metrics solution, the Link Color metric is able to reflect the robustness of the RPL router device and SCAOF sets this metric as a precondition when a node selects its parent. The misbehaving nodes can actively broadcast their node state to their neighbors. This evaluation can prove that this is a better method than waiting the other nodes in normal state to detect these dangerous routers. Namely, SCAOF can prevent the A-LLN nodes to connect the unstable nodes but it needs to select longer path, and this is the reason why we obtained higher latency results in the performance comparison.

Table 5-4 Simulation performance comparison of scenario 3

| <b>Routing Model</b> | <b>Penetration of misbehaving nodes (%)</b> | <b>Performance Metrics</b>          |  |   |                                 |
|----------------------|---|-------------------------------------|--|---|---------------------------------|
|                      |   | <b>Average Packet Loss rate (%)</b> | <b>Average latency (ms) of successful transmission</b> | <b>Number of failed co-operations for packet forwarding</b> | <b>Packet transmission cost</b> |
| RPL MrhOF            | 10 %  | 23.48                               | 83.79  | ≈803  | 9.37                            |
|                      | 20 %  | 35.07                               | 84.23  | ≈1245   | 10.07                           |
|                      | 30 %  | 47.57                               | 85.56  | ≈2312   | 12.37                           |
| RPAL SCAOF           | 10 %  | 12.05                               | 93.32  | ≈57   | 7.68                            |
|                      | 20 %  | 13.55                               | 104.76   | ≈89   | 7.94                            |
|                      | 30 %  | 14.01                               | 106.64   | ≈112  | 10.13                           |

It should be noticed that considering the robustness of device as a context feature as well as routing metric, is also able to cooperate with the specific hardware. For example, the multi-core hardware platform like IWoTCore board [37] can provide accurate statistic results of the node state (i.e. restarting counts, power management, etc.), so that SCAOF could obtain the required context-aware data from the hardware level, which is able to highly increase the efficiency of this objective function algorithm.

### 5.2.3 CA-Trickle algorithm evaluation

In this subsection, we illustrate the performance evaluation results of CA-Trickle algorithm. Simulations are still carried out by means of Cooja and Contiki developing version. The following tests are hold in a regular topology, where nodes are placed to form a grid with a fixed distance in-between. In order to guarantee route stability, enough energy is assigned to each node and Powertrace model is still adopted to monitor the energy consumption. Furthermore, in order to focus on the evaluation of the CA-Trickle algorithm, in these simulations, we provide two sets of performance comparison between standard RPL model and RPAL model.

Scenario 1: 50 node network

In this first simulation scenario, a group of 50 nodes which are located in a grid topology is discussed. In this scenario, two performance metrics are evaluated: interval phase and average energy consumption. Both of these metrics are obtained at a dynamic state (i.e. K DIO messages per interval without full reachability) with the help of radio medium model provided by Cooja simulator, so the worst case might happen for CA-Trickle. However, even the interval synchronization fails completely, an interval of CA-Trickle will be  $\mathcal{T} - \omega_{synchro}(0)$ , which probably is a value of  $\frac{3}{4}\mathcal{T}$  in certain situations. Namely, the nodes running CA-Trickle algorithm still get the similar efficiency as the original Trickle when the intervals are impossible to be resynchronized. Note that all the simulation nodes are configured with default parameters recommended by ROLL WG.

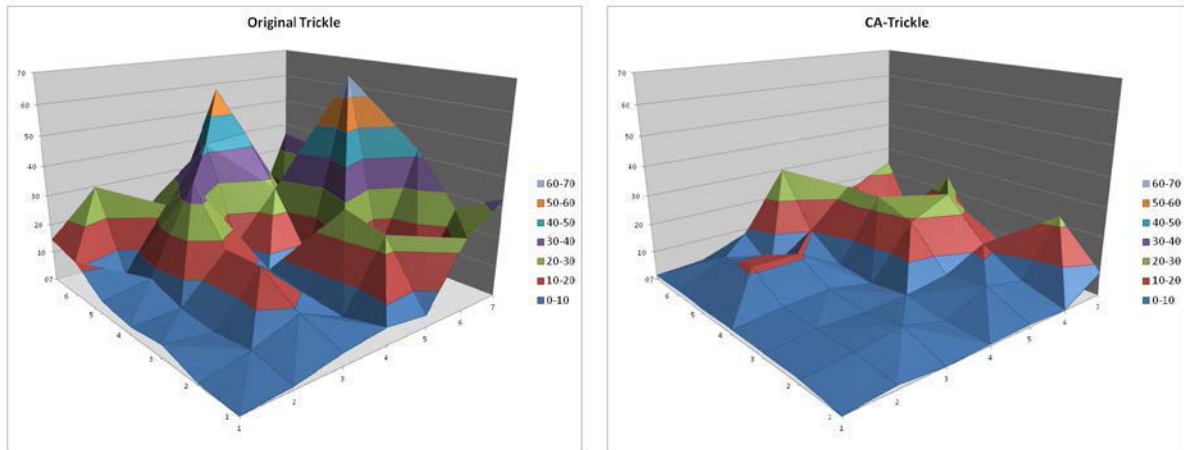


Figure 5-6 Interval phase of scenario 1 – The higher the degree, the interval is more out of synch.

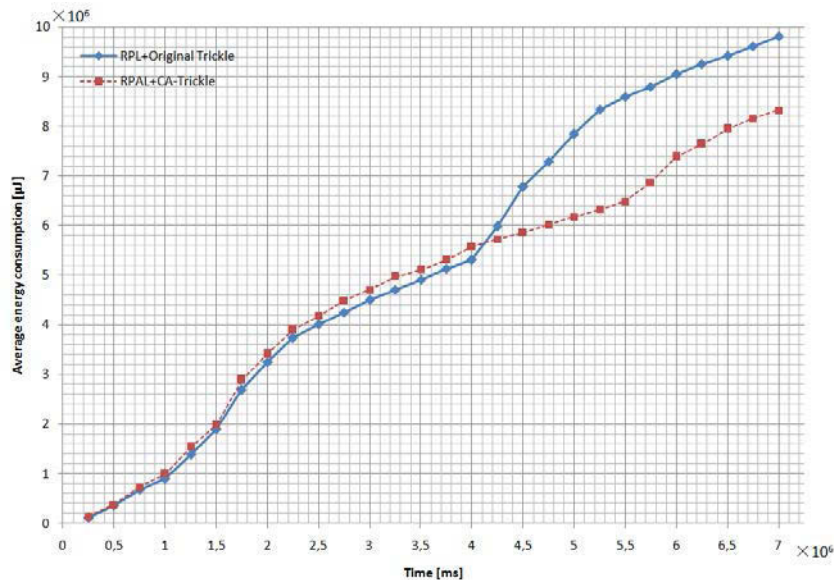


Figure 5-7 Average cumulative energy consumption with RPL+Original Trickle and RPL+CA-Trickle.

The observed results (cf. Figure 5-6) prove that CA-Trickle is able to achieve the best effort resynchronization. Figure 5-6 compares the synchronization properties of the original Trickle and CA-Trickle when the targeted DODAGs achieve steady state (i.e.  $I_{max}$ ). The intervals' schedules of the nodes across the network are evidently better synchronized in CA-Trickle algorithm. The phase shifts are well controlled in a limited level (i.e. less than 30%).

Based on our previous discussions, the DIO dissemination can become both more efficient and better load balanced in lossy networks by adopting this re-synchronous mechanism.

As shown in [Figure 5-7](#), the similar energy consumption is guaranteed during the period of DODAG building and maintenance (i.e.  $[0-4 \times 10^6]$  ms). The potential advantages are difficult to be observed in this test since we assign the redundant parameter  $K$  as 10, which is the default configuration. In other words, the node density (or node degree) of this DODAG is not big enough to activate the DIO suppression mechanism. However, we simulated a special weather condition at the time interval  $[4 \times 10^6-5.5 \times 10^6]$  (ms) through reducing the transmission range of all the nodes. Meanwhile, Cooja scripts simulate a trigger signal to the application layer of the nodes. This could be snow storm or flooding in the simulated field so the communication cannot keep anymore. The trend of two curves of [Figure 5-7](#) presents the average energy consumption rises rapidly for the nodes running original Trickle since all the nodes will be influenced by frequent rank changes and network churns, and DIO broadcasting interval becomes to  $I_{min}$ . When the intrinsic neighbor discovery mechanism realizes the disappearances of neighbors, a set of periodical DIS messages will broadcast instead, which is also a reason of consuming more energy. Furthermore, the CA-Trickle solves the relevant issues very well because it forces the nodes into frozen state after detecting the trigger signal from the application layer. When the special weather condition has passed, we could observe that CA-Trickle needs little more energy to validate the cached routing information, but this shortens the time of rebuilding the DODAG and make the network back to stable state as soon as possible.

It should be noticed that the emulated motes have a nominal current consumption of 21.8 mA when receiving (Rx), 19.5 mA when transmitting (Tx), 1.8 mA when the radio is off, and 0.0545 mA when both of MCU and radio are off. These parameters are based on the datasheet of the emulated device [163] in Cooja. Moreover, we can give the trigger signal to all the nodes at the same time slice, but the sensors monitoring may exist delay to some extent in real world.

#### Scenario 2: 100 node network

In this scenario, the node degree of the last scenario is increased by locating 100 nodes in a grid topology. One node near the sink node and positioned in a corner of this grid is chosen as reference to visualize the timer phase. We can find out that interval phase is like ocean waves across the testing network (cf. [Figure 5-8](#)). Meanwhile, when the hop count (Rank in the DODAG) nearly arrives to 7 or 8, a complete interval phase is shifted and CA-Trickle can detect this situation to avoid the redundant resynchronization.

[Figure 5-8](#) also proves the efficiency of CA-Trickle algorithm in a large-scale and multi-hop network. However, we also notice that there exist some nodes in worst case, and these nodes do not enable to be resynchronized during the period of exponential back-off in CA-Trickle. Since the simulation scenarios represent basic dynamic environments, the probability of a packet is received by a node will decrease exponentially according to the relations between distance and the transmit/receive ratio. Moreover, channels in busy condition also cause the packet retransmission or loss. These factors will impact on our simulation results and the efficiency of this algorithm. Thus, in this test, since a parameter of *Context\_coefficient'* has been introduced into CA-Trickle algorithm for presenting a specific context, the results, which can present whether the fairness of DIO dissemination can be achieved among the nodes, are expected to be observed.

Figure 5-9 illustrates the average number of suppressed DIO transmissions for each node in a set of repeated tests. For getting the observable results of expected traffic load, we reduced the 'K' parameter to 3 that can ensure the number of the neighbors is usually bigger than this value so the DIO messages can be suppressed. On one hand, the statistical results show that CA-Trickle succeeds into guaranteeing a more fairness in the distribution of the suppressed dissemination across the whole network. On the other hand, the original Trickle is difficult to provide the spatial fair DIO suppression. Thus, essentially, this will cause that more routes with better path weight cannot be found as well as the frequent formations of suboptimal routes. Furthermore, the left plotting of Figure 5-9 also presents a noticeable phenomenon. Some nodes located at the border of the grid (i.e. neighborhood size is smaller), or reflected by missing the hits of some DIO messages, suppress less DIO transmissions than other routers. In other words, this will certainly lead to imbalance of the traffic load, and if island nodes appear due to energy depletion, the network lifetime will be much worse than the networks which can achieve spatial fairness among the nodes.

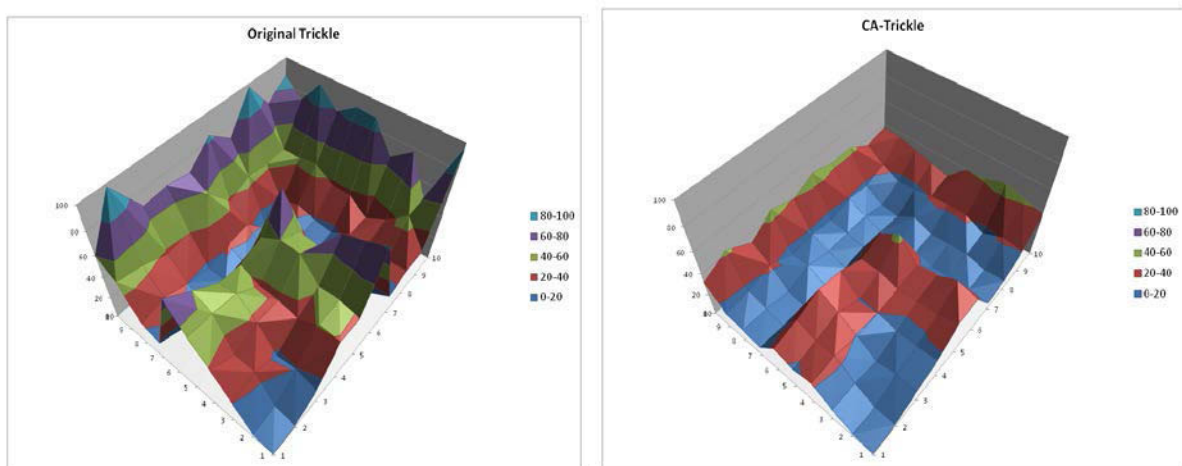


Figure 5-8 Interval phase of scenario 2 – the higher the degree, the interval is more out of synch.

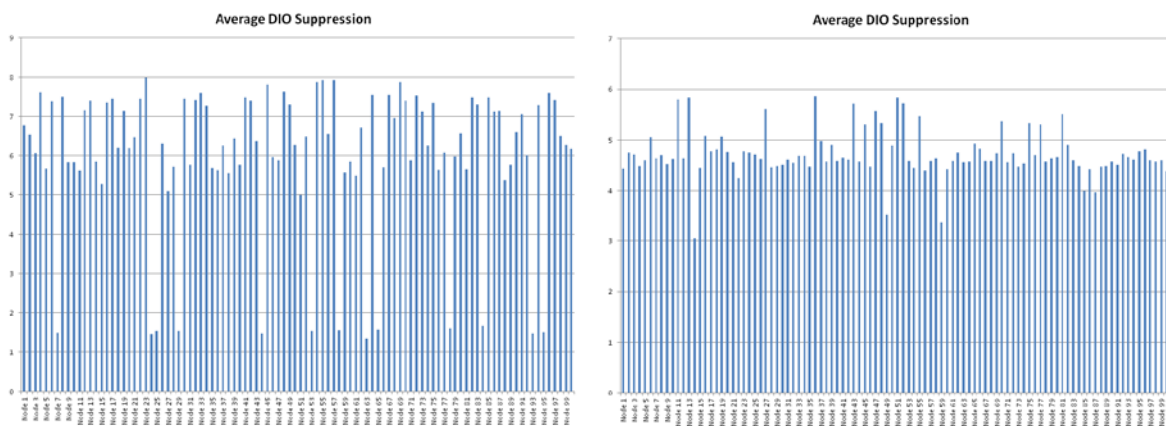


Figure 5-9 Average suppressed DIO messages per node Original Trickle (left) VS CA-Trickle (right), K=3.



## 5.3 Evaluation of RPL and RPAL routing protocols in real-world environment

To validate the results from the performed simulations, we performed a set of tests on a real-life testbed (IWoTCore plus Ext\_MiLive extend board [37]). For these tests, the maximal number of retransmissions was increased to 5 since some links in the real world were less reliable and the link quality are extremely dynamic due to obstacles, like trees, buildings or barriers. For the wireless multi-hop communication in these tests, the radio transmitter modules were tuned with using channel 19 and a transmit power of 3dBm (highest setting level of RF230bb's driver).

### 5.3.1 Testbed setup

The localization of deployed nodes are presented in the below [Figure 5-10](#). It is a prototype of environmental data collection system based on Contiki OS and uIPv6 protocol stack, which is located in the garden of IRSTEA research center. Currently, this testbed consists of 11 IWoTCore core nodes with Ext\_MiLive extend boards, which one of them is directly connected to a laptop (see [Figure 5-11](#)) by USB to serial line port as sink node, and an adapted version of collect-view application is running on the laptop for observing different types of measured data. The main objective of this testbed is to monitor the viable states of network, hardware, power supply, and scalar sensing data (air temperature, light). It is needed to clarify that one IWoTCore node (tagged by 11 in [Figure 5-10](#)) is put in an office as a contrast experimental object.

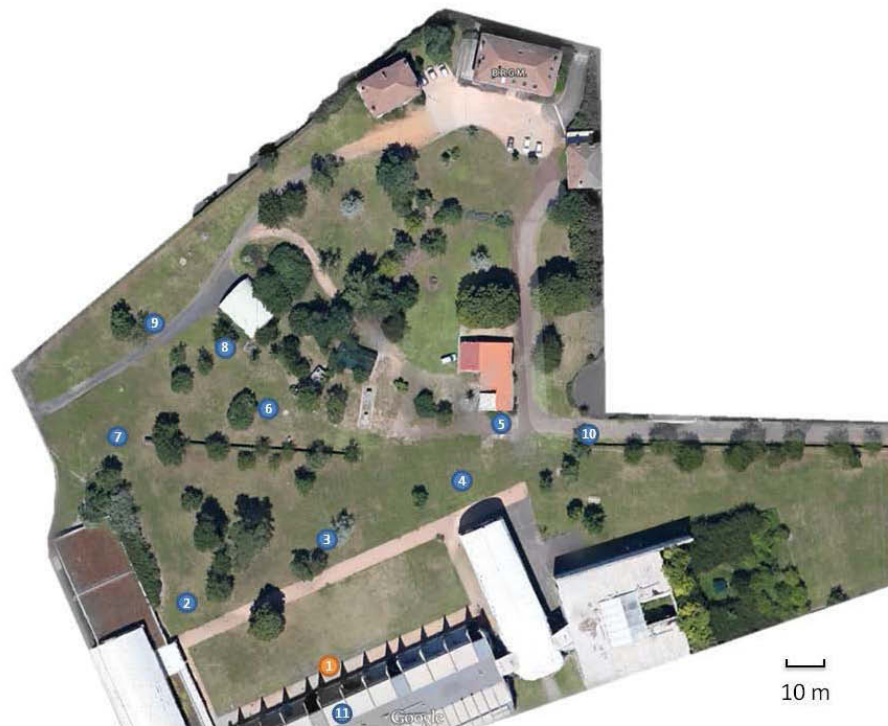


Figure 5-10 A plan of testbed deployment



Figure 5-11 Testbed setup: sink node and 9 IWoTCore Ext\_MiLive nodes for outdoor environment experiments



Figure 5-12 Testbed setup: photos of No.2 and No.3 deployed IWoTCore node

For running this testbed system in real-world environment, the boards and their rechargeable power source (Li Lon Battery Pack from ENIX ENERGIES) are well stuck in hermetical plastic container stably (see [Figure 5-11](#)). As shown in [Figure 5-12](#), the testbed devices are located where the deployment situation has certain geographical gradient (little to medium lean degree) as well as has numerous obstacles, like walls, buildings, shrubberies, trees, and facilities in the garden. To increase the reliability of transmission, a temporary

solution for raising the antenna height (to 45cm) of the testbed devices that are deployed in low gradient level area is depicted in [Figure 5-12](#).

There are two main considerations and attempting for succeeding the setup of this testbed. On one hand, because the IWoTCore node and its antenna are fixed in the bottom of the container, the antenna height is very low (10cm to the ground). From the empirical results of our previous tests, if the antenna's height is lower than obstacles, the link quality can be highly dynamic since the transmission would be mainly based on Non Line of Sight (NLOS) signal, and the link quality would be seriously affected by the phenomenons like reflection, refraction, diffraction or scattering. These phenomenons, which may produce error, delay and miss hit in wireless transmission, should expect to be mitigated. On the other hand, if the link quality cannot be guaranteed within an acceptable level, adapting the receiver elevation angle for different groups of tests will become more challenging. The radio chips have to be configured in the same settings like transmission power and identical hardware behaviors, so that most of the radio links are symmetrical in both directions. But even so, the radio channel is intrinsically unstable due to the impacts of various environmental factors and interferences. The easiest observation is that some links can occasionally disappear or re-appear, and this phenomenon would imply certain dynamics in the network. Thus, keeping all the testbed devices in homogeneous situation is significant for our later comparative tests.

Meanwhile, as an important time-saving decision for our deployment work, we still use the same programs of Contiki kernel like our previous mentioned simulation thanks to the cross-level simulator - COOJA. Furthermore, integrating the appropriate drivers of IWoTCore and Ext\_MiLive extend board is necessary and most of the modules of Contiki also needs tuning and debugging before running on hardware testbeds. As our RPAL model is built upon Contiki and has be fully simulated in Cooja, which is able to be ported to testbed without any modifications, but the redesigned power consumption model brings accuracy loss of recorded data due to AVR MCU does not support floating point calculation.

To carry out this experiment, we propose here a plan to perform the following two steps and analysis methods:

1. To port our previous programs of RCB128RFA1 and Sensor Terminal board to IWoTCore core board and Ext\_MiLive extend board. Some components have to be adapted, such as the configurations of several drivers (GPIO, ADC, I<sup>2</sup>C), the utilization of the scalar sensing core board and extend board, the energy management module (NANO module), and interfaces of various sensors. Moreover, the optimization and porting of low power listening and radio duty cycle mechanisms of level 2 modules in Contiki have to be considered too.
2. To deploy our prototype system in the real-world environment with the following simplified considerations and corresponding explanations:
  - Testbed node 1 is the sink node to connect to a laptop for exploiting as data collector and remote controlling message emitter;
  - The deployed nodes are located at the same positions, and same relative angles and distances;
  - This prototype system could provide three categories of required measurements (see [Table 5-5](#));
  - The other 10 nodes would have different power supplies, but with the similar experimental environments, such as weather condition, duration of test, data collection frequency, and state of charge for all batteries, in three comparative experiments as listed in [Table 5-6](#) and [Table 5-7](#);

Table 5-5 Three main types of required measurements for statistical analysis

| Required data type  | Measurements gathered from the testbed  |
|---------------------|---|
| Sensor data         | Temperature; output voltage of battery; restart count; and light strength sensors ( <b>Depends on transparency of the containers</b> )                                |
| Network states      | Size of neighbor list and routing table; topology; controlling message interval; ETX value; Rank value; packet delivery ratio (PDR); number of hops; number of churns |
| Power supply states | Average power consumption; average radio duty cycle; battery indicator from online energy estimation model.   |

Table 5-6 Same settings of three comparative experiments

| Experiment settings                                       | Details and parameters  |
|---|---|
| Collecting frequency                                      | 60s-120s  |
| Duration of test  | 6 hours ( <b>expressed as 1:00 to 7:00</b> )  |
| Initial energy of power supply                            | 594000 mJ<br>(10% of nominal capacities in battery's fully recharged state)<br>When the battery is depleted, the radio chip is off. |
| Heavy task for fast energy consuming (reduce 70% battery) | The testbed node 3 and 6 pretend a 70% decrease of their remained energy by manual remote control application at [3:55, 4:00].      |
| Testbed node with Misbehavior of restarting               | Testbed node 4 has communication problem with its NANO module within a frequency of 600s-1200s during the periods of its lifetime.  |

Table 5-7 Different settings of three comparative experiments

| Sequence N. of comparative test | RPL model          | Routing metrics           | Testbeds with energy harvesting module (solar panel)                 |
|---------------------------------|--------------------|---------------------------|--|
| 1 <sup>st</sup> experiment      | Standard RPL model | ETX                       | No   |
| 2 <sup>nd</sup> experiment      | RPAL model         | ETX; Context-aware metric | No   |
| 3 <sup>rd</sup> experiment      | RPAL model         | ETX; Context-aware metric | Yes (testbed node 3 and 6 recover their batteries from 4:00 to 5:00) |

- To explain the consequence of introducing misbehavior node in our experiments, the concept and utilization of NANO module has to be clarified. It is a specific energy efficient SCM and its designed program is used to guarantee the robustness of targeted system. The mechanism is to force the software running on the AVR MCU to keep periodical communication (a loop of state reading) with NANO module. If this rule is broken, the whole

system will be reset and the interior counter of NANO will be increased for recording this restart behavior of system;

- As three comparative experiments should be carried out in the same scenario, the weather condition and system trouble are almost unpredictable, and the unbalance of energy consumption requires long-time accumulation. Thus a remote controlling application is implemented for sending commands (see Table 5-8) to achieve our expected settings of different tests. To ensure the command packets are well received, a repetition mechanism is performed until the receiver replies an ACK message.

Table 5-8 Remote control and fault injection functions

| <b><i>Functions</i></b>             | <b><i>Descriptions</i></b>  |
|-------------------------------------|---|
| <b>LED control</b>                  | ON and OFF switching the single LED on IWoTCore board.  |
| <b>Message collection</b>           | Prepare and send a collect-view application packet immediately.   |
| <b>RPL global repair</b>            | Trigger global repair in the current DODAG.   |
| <b>Collecting frequency control</b> | Change the frequency of sending collect-view application packet to [10, 15, 30, 60, 120]s.  |
| <b>Remained energy control</b>      | Modify the volume of battery [+10%, -5%]. The results can be observed in the battery indicator plotting.  |
| <b>NANO control</b>                 | Postpone the event timer of NANO communication process.   |
| <b>TX power control</b>             | Modify the transmission power of radio chip to a designated value.  |
| <b>Power supply mode control</b>    | Configure the targeted testbed using the below three types of power supply mode:<br>Mode 0: battery powered, residual energy is depleted by online energy estimation model<br>Mode 1: energy harvester module (solar panel) is able to produce enough power to active the testbed and cannot recharge the battery<br>Mode 2: energy harvester module (solar panel) is able to produce enough power for both testbed routine and recharging battery. |

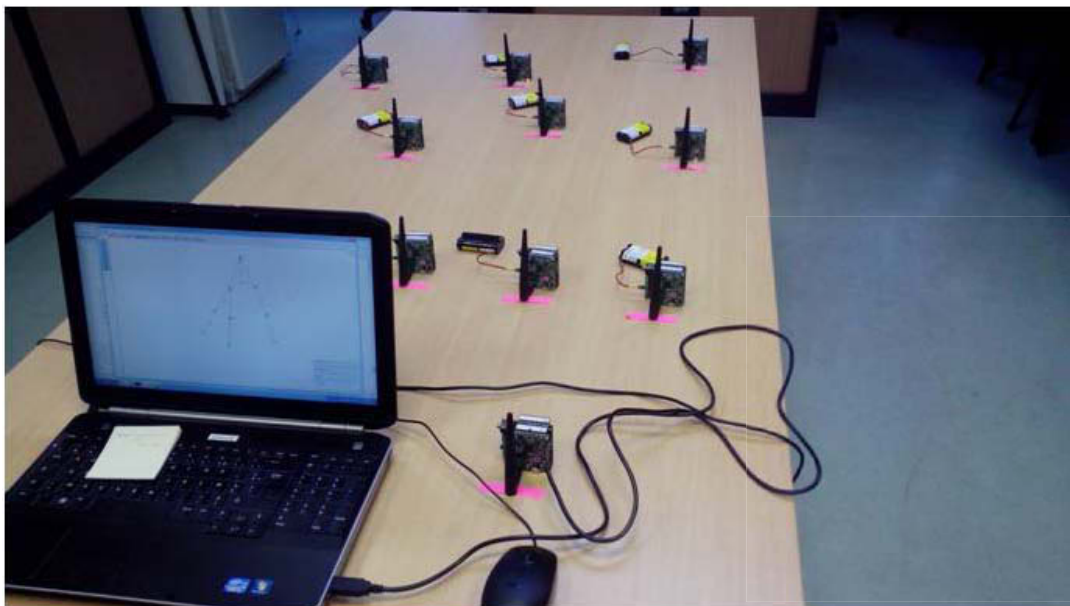


Figure 5-13 Building an indoor prototype before setting up operational testbeds

Setting up testbeds in real-world environment requires a large human effort, especially when organizing a multi-hop network. Thus, it is highly recommended to build an indoor prototype firstly. After the transmission power and receiving sensitivity threshold are configured respectively as -15 dBm and -61dBm, a 3-hops prototype system (depicted in Figure 5-13) is easily built on a large office table. It is very important to ensure the system program without fetal bugs, and we moved to the next step after our preliminary testbed can run over 7 days.

### 5.3.2 Evaluation results

The objective of the three comparative experiments is to reveal the characteristics of an IoT prototype system in different routing strategies. The evaluation comparisons can be achieved, especially for the influence of using RPL standard protocol or our RPAL protocol with specific OF and composite routing metrics (SCAOF).

#### 5.3.2.1 Influence of the SCAOF in RPAL model

Firstly, the effects of introducing fast energy consuming node (3 and 6), and misbehavior node 4 will be evaluated. Moreover, the performance results of 1<sup>st</sup> experiments are going to be compared with the 2<sup>nd</sup> one.

**Number of hops** In Figure 5-14, the results of average hops and last hop in 1<sup>st</sup> and 2<sup>nd</sup> experiment are depicted. As node 3, 4 and 6 are important routers in this network, and they will meet serious problems during the experiment, such as battery depletion and system unreliability, the augment of number of hops is an easily observed results to evaluate whether the tested routing strategy can do the corresponding answers. The RPL standard protocol only uses ETX as routing metrics for calculating minimum rank with hysteresis OF. Thus, according to the measurement data, the RPL model in 1<sup>st</sup> test has smaller hop counts since it didn't change routing path before node 3 and 6 consumed all their battery energy. Nevertheless, the RPAL model has the ability to move the exceptional nodes to lower rank position which may lead to larger rank value and more hops count in the 2<sup>nd</sup> experiment.

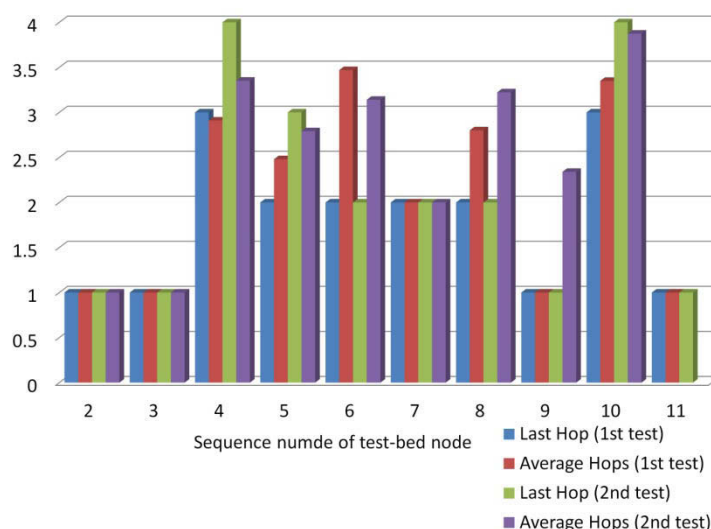


Figure 5-14 Hop count evaluation results of 1<sup>st</sup> test and 2<sup>nd</sup> test

For the case depicted in the Figure 5-14, Node 4 has more hops count in 2<sup>nd</sup> test than in the 1<sup>st</sup> test, because its counter value of NANO module is advertised by its emitting DIO messages as routing constraint and its neighbors will not choose it as preferred parents. Meanwhile, this also leads to the hops count increasing for node 5 and 10.

**Network churns** In Figure 5-15, the statistical oscillation count of targeted network is depicted. Since the captured DODAG structures during the test cannot be all listed here, the number of network churn is adopted to present the stability of the observed DODAG topology.

The results prove that RPAL model is able to reduce network oscillation comparing with the original RPL model. The first reason is that RPL standard protocol adopts ETX to find high throughput paths. Since ETX is always searching for the best instantaneous link quality and the packet delivery ratio (PDR) estimated by sending probes is a stochastic variable in real-world environment, instability may be unnecessarily induced in this static network, even hysteresis has been used to reduce churn in response to small ETX metric changes. As the existence of weight parameters in our RPAL model, the effect of hysteresis is magnified and decreases the count of switching parent. Secondly, node 4 is used to be a key router in 1<sup>st</sup> test, and its unreliable characteristic will lead to more churns to its potential children (node 5, 6 and 10). Last but not least, it should be noticed that RPAL model may also cause network churns due to selecting new routing path to keep away from the battery depleting nodes. However, in our case, this impact is very limited and the evaluation results prove that the mechanisms in our designed SCAOF algorithm will not produce serious oscillation in a wide range of existing DODAG.

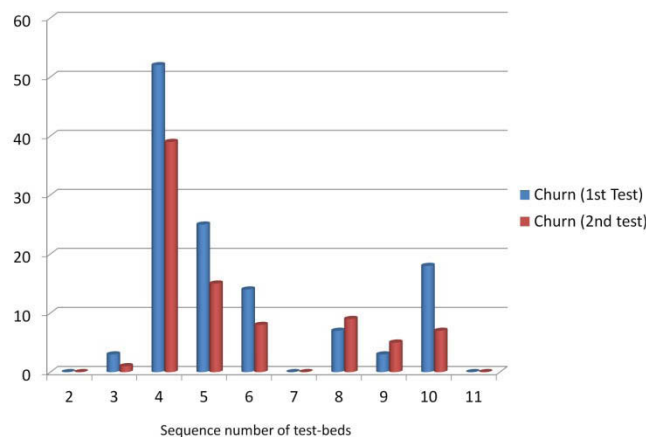


Figure 5-15 Number of network churn for the testbeds in 1<sup>st</sup> and 2<sup>nd</sup> experiments

**Packet lost** In Figure 5-16, the packet lost ratio is depicted. For nodes with an average number of hops lower than 2 from the sink, there was almost no packet loss detected. We believe that it is the effect of configuring for 4 retransmissions and existing of line of sight propagation. But when hop count near 3, the packet loss increases fast. On one hand, the bad packet delivery is caused by the bad link quality of some intermediate nodes. For example, the monitoring packets from node 5 and 10 have to traverse the optional parents 4, 3 or 6, but node 4 keeps rejoining the DODAG network and this also leads to frequent disconnections when it serves as parent. This causes higher packet loss for node 5 and 10 in 1<sup>st</sup> experiment than in the 2<sup>nd</sup> one. Besides, the statistical results also count the part of packet loss if node 3 and 6 are dead before the end of these two tests. As the SCAOF algorithm in RPAL model has the ability to adapt the network topology to avoid node 3 and 6 as busy routers, the results present that these two nodes loss less packets in 2<sup>nd</sup> test. Notice that node 8 and 9 have more

network churns in 2<sup>nd</sup> test thus they have more lost packets, since real-world network re-convergence normally requires longer time to achieve. On the other hand, the interference by other wireless equipments (i.e. office environment or weather station in the garden of IRSTEA center) and the signal attenuation by passing through the asymmetrical obstacles near the place where the testbeds are installed may also cause worse packet loss.

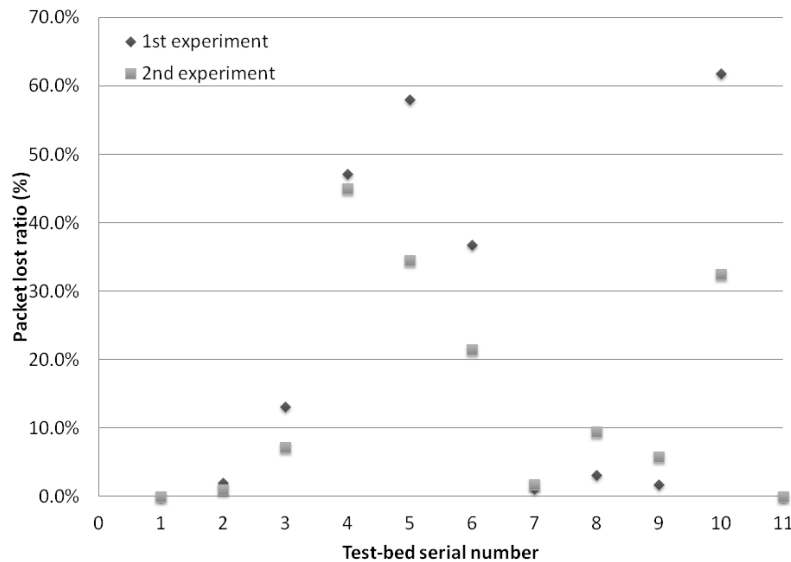


Figure 5-16 Percentage of packets that get lost on the testbed of 11 IWoTCore nodes

**Energy usage** In [Figure 5-17](#), the effects of two routing models on the performance of energy consumption is illustrated. In comparison to the simulation results in subsection 5.2, we have to admit that the behavior is not like our expectation. The consequence can be explained by the following reasons. Firstly, the nodes in the tests of simulation have the same link condition but the tests on testbed have not. In other words, the repair mechanism for detected routing loop is more often initiated in the real-world tests, and this could be responsible for an increase in the power consumption. Furthermore, the current prototype system cannot provide low power mode of MCU due to the lack of appropriate solution using Contiki process management to deal with the correlation between AVR MCU and NANO module. Thus keeping MCU in normal working mode is a safe and temporary method to evade the potential issues. Besides, in our tests, if the radio chip enters sleeping mode or uIPv6 process is trying to send/receive a packet, and at the same time, the process of reading NANO's state has a certain level of communication delay, the wake-up interval in this node will become unstable and loss the synchronization with its neighbor nodes, and this leads to the failures of subsequence radio transmissions. Although this is an event with very small possibility, the tests show that it will happen within the duration of 20 to 30 hours. Thus, the radio duty cycle mechanism (i.e. fast sleeping and low power listening) in ContikiMAC model and the transmission of collect-view application packet are designed to have a short intermission when they have conflicts with the NANO process. This could also cause the augments of radio duty (depicted in [Figure 5-18](#) and [5-19](#)).



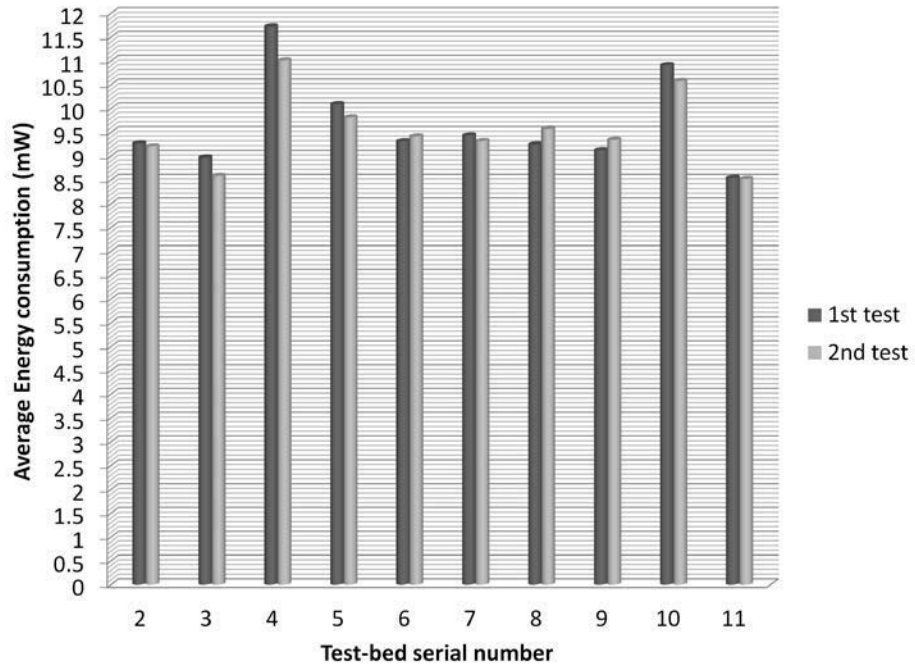


Figure 5-17 Average energy usage of the testbeds in 1<sup>st</sup> and 2<sup>nd</sup> experiments

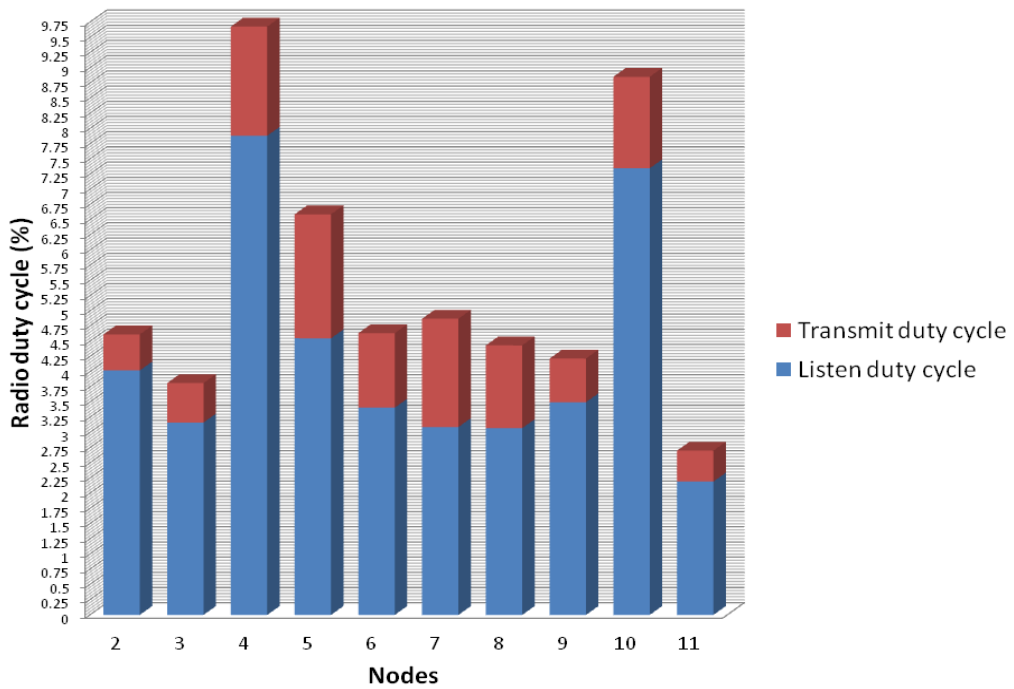


Figure 5-18 Radio duty cycle of the testbeds using standard RPL model in 1<sup>st</sup> test

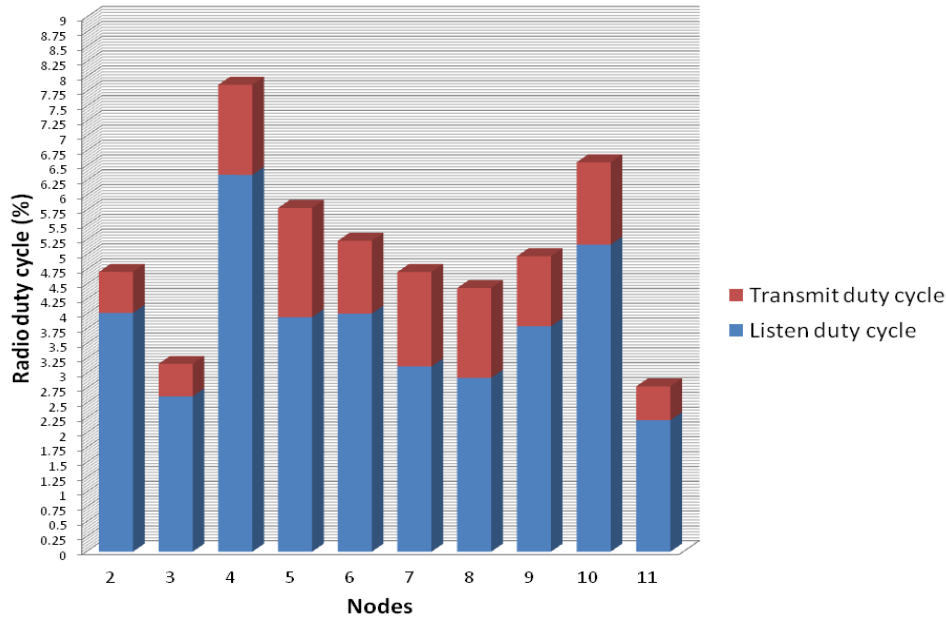


Figure 5-19 Radio duty cycle of the testbeds using RPAL model in 2<sup>nd</sup> experiments

From the radio duty cycle results of [Figure 5-18](#) and [5-19](#), they further prove that RPAL model can prevent the network churns and adverse effects on energy usage due to misbehavior node, and improve the stability of topology by increasing the effects of hysteresis. For example, node 3 has smaller radio duty cycle when the network is organized according to RPAL protocol model (with SCAOF) since after the energy consuming task is carried out, it sinks to lower rank of the DODAG and the other nodes will move it from preferred parent list. In other words, standard RPL model will continue relatively greedier PDR searching algorithm (MrhOF) to treat node 3 as key router. In the case of our designed experiments, the tested two routing strategies will impact the lifetime of these two exceptional nodes (3 and 6). According to our recorded data, node 3 and 6 can survive around 31 and 14 minutes longer respectively in 2<sup>nd</sup> experiments than in 1<sup>st</sup> one. However, the obtained results cannot be said to ensure the RPAL model is energy efficient since the number of redundant router and the duration of experiments are still limited. But at least, we can observe that it have better performance than the standard RPL model on the respect of energy balance, which can lead to longer lifetime of the whole network.

### 5.3.2.2 Influence of the energy harvester module

As the only difference between the 2<sup>nd</sup> test and 3<sup>rd</sup> test is whether nodes 3 and 6 have a chance to recharge their battery from emulated solar panel, the energy power mode become the single factor to impact the structure of this network. However, we do not observe any improved network performance in 3<sup>rd</sup> experiment except it has better packet reception ratio. But it has more network churns comparing with the results in 2<sup>nd</sup> test. We also notice that the network topology is not stable during the period when the battery depleting nodes have up-and-down battery volume because they will become optional key routers along with the restoration of their battery, and this enables them to be selected as preferred parents again.

## 6 Conclusions and future Work

This chapter will summarize the above proposals in this thesis, and discuss the future work that can be built upon what we have designed and implemented.

### 6.1 Summary of this thesis

We have achieved the following four main contributions in previous three years while working on the routing protocol for LLNs.

Firstly, we have proposed a unique architecture A-LLN for adapting the traditional WSN of precision agriculture application to IPv6 low power and lossy network in our drafted RPL applicability analysis. As the routing issue is our most concern, we have considered the challenges, requirements and features of this specific application similar to the IEFT drafts about adapting RPL paradigm to the scenarios of smart city, industry, home and building automation. Moreover, we believe that the adapted routing protocol has to possess the abilities to resist the highly dynamic environments in real world, which is also the key requirement related to the robustness of whole system and the dominating challenge waiting to be overcome. In other words, the environmental data collection application of precision agriculture essentially needs its carrier network to keep reliable monitoring function as long as possible.

Secondly, we have designed an enhanced model RPAL based on RPL standardized by ROLL WG. This model integrates three main proposals: Energy-aware routing metrics, SCAOF with hybrid routing metrics, and Context-aware Trickle algorithm, which are designed and developed for introducing context features into the RPL's mechanisms. We believe that our solutions can mitigate the hot spot issue induced by using RPL's MrhOF algorithm and ETX metric, prolong network lifetime and improve the QoS of A-LLNs by combining remained energy routing metric into path weight calculation, as well as considering the resource-aware factors including RDC, device robustness and information availability. Furthermore, RPAL model will not impact on the compatibility and scalability of A-LLNs as a part of future IoT paradigm. Meanwhile, CA-Trickle algorithm is able to provide higher efficiency (i.e. load balance) than the original Trickle that is the only adopted mechanism to reduce overhead of the control message dissemination in RPL. The proposal of coagulable trickle timer is designed to endow RPAL model with weather disruption-tolerant feature. This proposal is also dedicated to the real-world environments confronted by the deployments of A-LLNs. These proposals have been compared with the original standard in the simulation experiments containing specifically designed scenarios, and partially evaluated in a prototype system deployed in the garden of IRSTEa.

Thirdly, we held a set of experiments including two real-world deployments and one simulation test to validate the performance of RPL and its mechanisms with default configuration in the specification. The results of the performance evaluation studies present that RPL do not behave optimally, and this encourages us to do more improvements, especially on the perspectives of prolonging the network lifetime and increasing the reliability and survivability of the LLN nodes over the topologies, and motivates our above proposals.

Fourthly, we have drafted the CLAS architecture dedicating to the routing over LLNs. The CLAS is a combination of distributed and centralized mechanisms for organizing the DODAG topology in a more efficient manner. The expected purposes of this design are to provide a context-aware tool-set that is able to integrate simulation and real world for mutual

optimization, and achieve conducting more precise routing-targeted simulations, as well as improving the network topology and the routing model configurations of the deployed LLN in real world.

## 6.2 Future work items

Routing in IPv6 low-power and lossy networks (LLNs) for real-world environmental data collection is a nascent area. Although many applications, precision agriculture, etc., highly depending on environmental monitoring, what we have studied presented that many current research and engineering work are still stepping stones towards practical building of LLNs and connecting conventional WSNs to existing IP world. The future directions of our work after this thesis could be various and they can be extended to carry out different directions.

The composite routing metric approach is the main theory for our SCAOF proposal, which can derive primary metrics ETX and RE and hold our desired properties inside the routing control message. Moreover, SCAOF with hybrid RPAL routing metrics further extend this finding with the consideration about OF and specific properties related to the needs for precision agriculture application. We have provided its deep performance evaluation comparing with the original RPL in the simulation scenarios, and a real-life evaluation in the garden of Irstea. Since the simulated scenarios cannot achieve to reflect all the effects when nodes are deployed in an experimental field, it is our intuition, that the network topology will be much different and difficult to approach towards the optimum performance. Thus, a set of more comprehensive tests in a large-scale real-world environment are required to prove and evaluate our proposals.

Finally, implementation of CLAS architecture and its inherent tool-set along with relevant RPL modifications are another future work direction. The current platform is built in a prototype of two simulated network, and used to present its main basic procedures. So more verification of proper and intended operations in real-life deployment as well as performance evaluations are our future targets. Last but not least, the anticipated challenges and more important issues about the costs of carrying out this system, such as the energy consumption of multicast transmissions for the centralized CLAS controlling messages, and the delay of required time due to running simulation, essentially need more discussions, considerations and theoretical studies before we declares its position in the real-world applied research.

## 6.3 Summary of publications

1. Chen, Yi-bo; CHANET, Jean-pierre; Kun-Mean HOU; ZHOU, Peng; ,A context-aware tool-set for routing-targeted mutual configuration and optimization of LLNs through bridging virtual and physical worlds, NICST 2014, New Information Communication Science and Technology for Sustainable Development, Wei Hai.

2. Chen, Yi-bo; Hou, Kun-Mean; Chanet, Jean-Pierre; El Gholami, Khalid; ,A RPL based Adaptive and Scalable Data-collection Protocol module for NS-3 simulation platform,NICST 2103 New Information Communication Science and Technology for Sustainable Development: France-China International Workshop.

3. Chen, Yi-bo; Chanet, Jean-Pierre; Hou, Kun Mean; Shi, Hong Ling; ,Extending the RPL Routing Protocol to Agricultural Low Power and Lossy Networks (A-LLNs),International Journal of Agricultural and Environmental Information Systems (IJAEIS),4,4,25-47,2013,IGI Global

4. Chen, Yi-bo; Chanet, Jean-Pierre; Hou, Kun Mean; ,RPL Routing Protocol a case study: Precision agriculture,First China-France Workshop on Future Computing Technology (CF-WoFUCT 2012)

5. Chen, Yi-bo; Hou, Kun-mean; Zhou, Haiying; Shi, Hong-ling; Liu, Xing; Diao, Xunxing; Ding, Hao; Li, Jian-jin; De Vault, Christophe; ,6LoWPAN stacks: a survey,"Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on" ,,1-4,2011,IEEE

## 7 References

- [1] T. Winter, P. Thubert, and R. A. Team, "RPL: IPv6 Routing Protocol for Low Power and Lossy Networks, RFC 6550," *IETF ROLL WG, Tech. Rep.*, 2012.
- [2] O. Bello, O. Jumira, and S. Zeadally, "Communication issues in the Internet of Things (IoT)," *Journal of Network and Computer Applications*, 2012.
- [3] P. Salami and H. Ahmadi, "Review of Farm Management Information Systems (FMIS)."
- [4] M. Takai, J. Martin, and R. Bagrodia, "Effects of wireless physical layer modeling in mobile ad hoc networks," in *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing*, 2001, pp. 87-94.
- [5] B. Pavkovic, A. Duda, W.-J. Hwang, and F. Theoleyre, "Efficient topology construction for RPL over IEEE 802.15. 4 in wireless sensor networks," *Ad Hoc Networks*, 2013.
- [6] F. Österlind, A. Dunkels, T. Voigt, N. Tsiftes, J. Eriksson, and N. Finne, "Sensornet checkpointing: Enabling repeatability in testbeds and realism in simulations," in *Wireless Sensor Networks*, ed: Springer, 2009, pp. 343-357.
- [7] C. Peoples, G. Parr, S. McClean, B. Scotney, and P. Morrow, "Performance evaluation of green data centre management supporting sustainable growth of the internet of things," *Simulation Modelling Practice and Theory*.
- [8] B. C. Villaverde, D. Pesch, R. De Paz Alberola, S. Fedor, and M. Boubekeur, "Constrained application protocol for low power embedded networks: A survey," in *Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), 2012 Sixth International Conference on*, 2012, pp. 702-707.
- [9] T. Sánchez López, D. Ranasinghe, M. Harrison, and D. McFarlane, "Adding sense to the Internet of Things," *Personal and Ubiquitous Computing*, vol. 16, pp. 291-308, 2012/03/01 2012.
- [10] A. Whitmore, A. Agarwal, and L. Da Xu, "The Internet of Things—A survey of topics and trends," *Information Systems Frontiers*, pp. 1-14, 2014.
- [11] K. El Gholami, N. ELKAMOUN, and K. M. HOU, "FF-MAC: Fast Forward IEEE 802.15. 4 MAC Protocol for Real-Time Data Transmission," *International Journal*, vol. 4, 2013.
- [12] J. Vasseur, N. Agarwal, J. Hui, Z. Shelby, P. Bertrand, and C. Chauvenet, "RPL: The IP routing protocol designed for low power and lossy networks," *Internet Protocol for Smart Objects (IPSO) Alliance*, 2011.
- [13] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Computer networks*, vol. 54, pp. 2787-2805, 2010.
- [14] A. Brandt and J. Buron, "Home automation routing requirements in low-power and lossy networks," 2010.
- [15] R. Cragie, P. V. d. Stok, A. Brandt, and E. Baccelli, "Applicability Statement: The use of the RPL protocol set in Home Automation and Building Control," *Consultant*, 2013.
- [16] J. Zhao, J. Zhang, Y. Feng, and J. Guo, "The study and application of the IOT technology in agriculture," in *Computer Science and Information Technology (ICCSIT), 2010 3rd IEEE International Conference on*, 2010, pp. 462-465.
- [17] (2013). *Libelium Comunicaciones Distribuidas*. Available: <http://www.libelium.com/squid>
- [18] N. Tsiftes, J. Eriksson, and A. Dunkels, "Low-power wireless IPv6 routing with ContikiRPL," in *Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, 2010, pp. 406-407.

- [19] F. Österlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Demo abstract: Cross-level simulation in cooja," in *Proceedings of the First IEEE International Workshop on Practical Issues in Building Sensor Network Applications*, 2006.
- [20] H.-L. Shi, K. M. Hou, H.-Y. Zhou, and X. Liu, "Energy Efficient and Fault Tolerant Multicore Wireless Sensor Network: E<sup>2</sup>MWSN," in *Wireless Communications, Networking and Mobile Computing (WiCOM), 2011 7th International Conference on*, 2011, pp. 1-4.
- [21] E. Kim and D. Kaspar, "Design and Application Spaces for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)," 2012.
- [22] M. Slade, M. H. Jones, and J. B. Scott, "Choosing the right microcontroller: A comparison of 8-bit Atmel, Microchip and Freescale MCUs," Faculty of Engineering, The University of Waikato 2011.
- [23] S. Duquennoy, N. Wirström, N. Tsiftes, and A. Dunkels, "Leveraging IP for Sensor Network Deployment," in *Proceedings of the workshop on Extending the Internet to Low power and Lossy Networks (IP+ SN 2011)*, 2011.
- [24] M. Magno, S. Marinkovic, D. Brunelli, E. Popovici, B. O'Flynn, and L. Benini, "Smart power unit with ultra low power radio trigger capabilities for wireless sensor networks," in *Proceedings of the Conference on Design, Automation and Test in Europe*, 2012, pp. 75-80.
- [25] A. Harb, "Energy harvesting: State-of-the-art," *Renewable Energy*, vol. 36, pp. 2641-2654, 2011.
- [26] Z. Wan, Y. Tan, and C. Yuen, "Review on energy harvesting and energy management for sustainable wireless sensor networks," in *Communication Technology (ICCT), 2011 IEEE 13th International Conference on*, 2011, pp. 362-367.
- [27] A. Baggio, "Wireless sensor networks in precision agriculture," in *ACM Workshop on Real-World Wireless Sensor Networks (REALWSN 2005)*, Stockholm, Sweden, 2005.
- [28] I. Ishaq, D. Carels, G. K. Teklemariam, J. Hoebeke, F. V. d. Abeele, E. D. Poorter, *et al.*, "IETF Standardization in the Field of the Internet of Things (IoT): A Survey," *Journal of Sensor and Actuator Networks*, vol. 2, pp. 235-287, 2013.
- [29] J. Hui, D. Culler, and S. Chakrabarti, "6LoWPAN: Incorporating IEEE 802.15. 4 into the IP architecture," *Internet Protocol for Smart Objects Alliance, white paper*, vol. 3, 2009.
- [30] D. De Guglielmo, G. Anastasi, and A. Seghetti, "From IEEE 802.15. 4 to IEEE 802.15. 4e: A Step Towards the Internet of Things," in *Advances onto the Internet of Things*, ed: Springer, 2014, pp. 135-152.
- [31] J. A. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Mitter, and B. Heile, "IEEE 802.15. 4: a developing standard for low-power low-cost wireless personal area networks," *network, IEEE*, vol. 15, pp. 12-19, 2001.
- [32] G. Mulligan, "The 6LoWPAN architecture," in *Proceedings of the 4th workshop on Embedded networked sensors*, 2007, pp. 78-82.
- [33] Z. Shelby, K. Hartke, C. Bormann, and B. Frank, "Constrained application protocol (coap)," *draft-ietf-corecoap-07*, 2011.
- [34] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki-a lightweight and flexible operating system for tiny networked sensors," in *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*, 2004, pp. 455-462.
- [35] S. N. Meera, A. Jhamtani, and D. Rao, "Information and communication technology in agricultural development: A comparative analysis of three projects from India," *Network Paper No*, vol. 135, 2004.

- [36] G. D. Abowd, A. K. Dey, P. J. Brown, N. Davies, M. Smith, and P. Steggle, "Towards a better understanding of context and context-awareness," in *Handheld and ubiquitous computing*, 1999, pp. 304-307.
- [37] H. Shi, K. M. Hou, X. Diao, X. LIU, J.-J. Li, and C. de VAULX, "A Wireless Multimedia Sensor Network Platform for Environmental Event Detection Dedicated to Precision Agriculture."
- [38] J. K. Patil and R. Kumar, "Advances in image processing for detection of plant diseases," *Journal of Advanced Bioinformatics Applications and Research*, vol. 2, pp. 135-141, 2011.
- [39] J. Wang, Y.-B. CHEN, and J.-P. CHANET, "An Integrated Survey in Plant Disease Detection for Precision Agriculture using Image Processing and Wireless Multimedia Sensor Network," in *International Conference on Advanced in Computer, Electrical and Electronic Engineering (ICACEEE 2014); 07/2014*, 2014.
- [40] K. Dang, H. Sun, J.-P. Chanet, J. Garcia-Vidal, J. Barcelo-Ordinas, H. Shi, *et al.*, "Wireless Multimedia Sensor Network for plant disease detections," in *NICST'2103 New Information Communication Science and Technology for Sustainable Development: France-China International Workshop*, 2013.
- [41] A. M. V. Reddy, A. P. Kumar, D. Janakiram, and G. A. Kumar, "Wireless sensor network operating systems: a survey," *International Journal of Sensor Networks*, vol. 5, pp. 236-255, 2009.
- [42] C. F. García-Hernández, P. H. Ibarquengoytia-Gonzalez, J. García-Hernández, and J. A. Pérez-Díaz, "Wireless sensor networks and applications: a survey," *IJCSNS International Journal of Computer Science and Network Security*, vol. 7, pp. 264-273, 2007.
- [43] I. F. Akyildiz and M. C. Vuran, *Wireless sensor networks* vol. 4: John Wiley & Sons, 2010.
- [44] X. Yu, P. Wu, N. Wang, W. Han, and Z. Zhang, "Survey on Wireless Sensor Networks Agricultural Environment Information Monitoring," *Journal of Computational Information Systems*, vol. 8, pp. 7919-7926, 2012.
- [45] T. Arampatzis, J. Lygeros, and S. Manesis, "A survey of applications of wireless sensors and wireless sensor networks," in *Intelligent Control, 2005. Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation*, 2005, pp. 719-724.
- [46] A. Z. Abbasi, N. Islam, and Z. A. Shaikh, "A review of wireless sensors and networks' applications in agriculture," *Computer Standards & Interfaces*, vol. 36, pp. 263-270, 2014.
- [47] L. L. L. H. L. Hui, "Greenhouse Environment Monitoring System Based on Wireless Sensor Network," *Transactions of the Chinese Society for Agricultural Machinery*, p. S1, 2009.
- [48] J. Vasseur, "Overview of Existing Routing Protocols for Low Power and Lossy Networks," 2008.
- [49] T. Watteyne, A. Molinaro, M. G. Richichi, and M. Dohler, "From MANET to IETF ROLL standardization: A paradigm shift in WSN routing protocols," *Communications Surveys & Tutorials, IEEE*, vol. 13, pp. 688-707, 2011.
- [50] U. Herberg and T. Clausen, "A comparative performance study of the routing protocols LOAD and RPL with bi-directional traffic in low-power and lossy networks (LLN)," in *Proceedings of the 8th ACM Symposium on Performance evaluation of wireless ad hoc, sensor, and ubiquitous networks*, 2011, pp. 73-80.



- [51] S. Kim, O. Lee, S. Choi, and S.-J. Lee, "Comparative analysis of link quality metrics and routing protocols for optimal route construction in wireless mesh networks," *Ad Hoc Networks*, vol. 9, pp. 1343-1358, 2011.
- [52] K. Heurtefeux and H. Menouar, "Experimental Evaluation of a Routing Protocol for Wireless Sensor Networks: RPL under study."
- [53] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*, 2000, p. 10 pp. vol. 2.
- [54] M. S. Ali, T. Dey, and R. Biswas, "ALEACH: Advanced LEACH routing protocol for wireless microsensor networks," in *Electrical and Computer Engineering, 2008. ICECE 2008. International Conference on*, 2008, pp. 909-914.
- [55] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, "Highly-resilient, energy-efficient multipath routing in wireless sensor networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, pp. 11-25, 2001.
- [56] X. Huang and Y. Fang, "Multiconstrained QoS multipath routing in wireless sensor networks," *Wireless Networks*, vol. 14, pp. 465-478, 2008.
- [57] B. Deb, S. Bhatnagar, and B. Nath, "ReInForM: Reliable information forwarding using multiple paths in sensor networks," in *Local Computer Networks, 2003. LCN'03. Proceedings. 28th Annual IEEE International Conference on*, 2003, pp. 406-415.
- [58] O. Gaddour and A. Koubâa, "RPL in a nutshell: A survey," *Computer Networks*, 2012.
- [59] J. Vasseur, M. Kim, K. Pister, N. Dejean, and D. Barthel, "Routing metrics used for path calculation in low power and lossy networks," *draft-ietf-roll-routing-metrics-19 (work in progress)*, 2011.
- [60] J. Tripathi, J. de Oliveira, and J. Vasseur, "Performance evaluation of routing protocol for low power and lossy networks (RPL)," *IETF, Draft, January*, 2011.
- [61] N. Tsiftes, J. Eriksson, N. Finne, F. Österlind, J. Höglund, and A. Dunkels, "A framework for low-power IPv6 routing simulation, experimentation, and evaluation," in *ACM SIGCOMM Computer Communication Review*, 2010, pp. 479-480.
- [62] M. Afanasyev, D. O'Rourke, B. Kusy, and W. Hu, "Heterogeneous traffic performance comparison for 6lowpan enabled low-power transceivers," in *Proceedings of the 6th Workshop on Hot Topics in Embedded Networked Sensors*, 2010, p. 10.
- [63] B. Pavković, F. Theoleyre, and A. Duda, "Multipath opportunistic RPL routing over IEEE 802.15.4," in *Proceedings of the 14th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*, 2011, pp. 179-186.
- [64] U. Herberg, T. Clausen, Y. Igarashi, J. Yi, and A. Verdiere, "Observations of RPL: IPv6 Routing Protocol for Low power and Lossy Networks," 2012.
- [65] N. Accettura and G. Piro, "Optimal and Secure Protocols in the IETF 6TiSCH communication stack."
- [66] P. Bahl, R. Chandra, and J. Dunagan, "SSCH: slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks," in *Proceedings of the 10th annual international conference on Mobile computing and networking*, 2004, pp. 216-230.
- [67] L. Grieco, "6TiSCH T. Watteyne, Ed. Internet-Draft Linear Technology Intended status: Informational MR. Palattella Expires: January 5, 2015 University of Luxembourg," 2014.
- [68] X. Vilajosana, Q. Wang, F. Chraim, T. Watteyne, T. Chang, and K. Pister, "A Realistic Energy Consumption Model for TSCH Networks," 2014.
- [69] D. De Guglielmo, G. Anastasi, and A. Seghetti, "From IEEE 802.15.4 to IEEE 802.15.4e: A Step Towards the Internet of Things," in *Advances onto the Internet of*

- Things*. vol. 260, S. Gaglio and G. Lo Re, Eds., ed: Springer International Publishing, 2014, pp. 135-152.
- [70] A. Brachman, "RPL Objective Function Impact on LLNs Topology and Performance," in *Internet of Things, Smart Spaces, and Next Generation Networking*, ed: Springer, 2013, pp. 340-351.
- [71] M. Dohler, D. Barthel, T. Watteyne, and T. Winter, "Routing requirements for urban low-power and lossy networks," 2009.
- [72] J. Martocci, P. Mil, N. Riou, and W. Vermeulen, "Building automation routing requirements in low-power and lossy networks," 2010.
- [73] P. Karkazis, H. C. Leligou, L. Sarakis, T. Zahariadis, P. Trakadas, T. H. Velivassaki, *et al.*, "Design of primary and composite routing metrics for RPL-compliant Wireless Sensor Networks," in *Telecommunications and Multimedia (TEMU), 2012 International Conference on*, 2012, pp. 13-18.
- [74] A. Barbato, M. Barrano, A. Capone, and N. Figiani, "Resource Oriented and Energy Efficient Routing Protocol for IPv6 Wireless Sensor Networks."
- [75] M. Nuvolone, "Stability analysis of the delays of the routing protocol over low power and lossy networks," *Masters Degree Project, KTH, Sweden*, 2010.
- [76] T. Clausen, U. Herberg, and M. Philipp, "A critical evaluation of the ipv6 routing protocol for low power and lossy networks (rpl)," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2011 IEEE 7th International Conference on*, 2011, pp. 365-372.
- [77] O. Gnawali, "The Minimum Rank with Hysteresis Objective Function," 2012.
- [78] J. Faruque and A. Helmy, "Gradient-based routing in sensor networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 7, pp. 50-52, 2003.
- [79] P. Thubert, "Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)," 2012.
- [80] S. Dawans, S. Duquennoy, and O. Bonaventure, "On Link Estimation in Dense RPL Deployments," 2012.
- [81] P. O. Kamgueu, E. Nataf, T. D. Ndié, and F. Olivier, "Energy-based routing metric for RPL," 2013.
- [82] C.-Y. Liao, L.-H. Chang, T.-H. Lee, and S.-J. Chen, "An Energy-Efficiency-Oriented Routing Algorithm over RPL."
- [83] X. Liu, J. Guo, G. Bhatti, P. Orlik, and K. Parsons, "Load balanced routing for low power and lossy networks," in *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, 2013, pp. 2238-2243.
- [84] C. Abreu, M. Ricardo, and P. Mendes, "Energy-aware routing for biomedical wireless sensor networks," *Journal of Network and Computer Applications*, vol. 40, pp. 270 - 278, 2014.
- [85] T. H. N. Velivasaki, P. Karkazis, T. V. Zahariadis, P. T. Trakadas, and C. N. Capsalis, "Trust - aware and link - reliable routing metric composition for wireless sensor networks," *Transactions on Emerging Telecommunications Technologies*, 2012.
- [86] R. Laufer, T. Salonidis, H. Lundgren, and P. Le Guyadec, "Xpress: a cross-layer backpressure architecture for wireless multi-hop networks," in *Proceedings of the 17th annual international conference on Mobile computing and networking*, 2011, pp. 49-60.
- [87] S. Duquennoy and O. Landsiedel, "Opportunistic RPL," in *EWSN'13: Proceedings of the 10th European Conference on Wireless Sensor Networks*, 2013.
- [88] T. H. Amit Dvir, Levente Buttyan, "VeRA - Version Number and Rank Authentication in RPL," Budapest University of Technology and Economics, Hungary.

- [89] S. Duquennoy, O. Landsiedel, and T. Voigt, "Let the tree Bloom: scalable opportunistic routing with ORPL," in *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, 2013, p. 2.
- [90] M. Doddavenkatappa, M. C. Chan, and A. L. Ananda, "Indriya: A low-cost, 3D wireless sensor network testbed," in *Testbeds and Research Infrastructure. Development of Networks and Communities*, ed: Springer, 2012, pp. 302-316.
- [91] O. Landsiedel, E. Ghadimi, S. Duquennoy, and M. Johansson, "Low power, low delay: opportunistic routing meets duty cycling," in *Proceedings of the 11th international conference on Information Processing in Sensor Networks*, 2012, pp. 185-196.
- [92] G. Oikonomou and I. Phillips, "Stateless multicast forwarding with RPL in 6LoWPAN sensor networks," in *Pervasive Computing and Communications Workshops (PERCOM Workshops), 2012 IEEE International Conference on*, 2012, pp. 272-277.
- [93] P. Di Marco, C. Fischione, G. Athanasiou, and P.-V. Mekikis, "MAC-aware routing metrics for low power and lossy networks," in *INFOCOM, 2013 Proceedings IEEE*, 2013, pp. 13-14.
- [94] P. Di Marco, G. Athanasiou, P.-V. Mekikis, and C. Fischione, "MAC-aware Routing Metrics for the Internet of Things," *arXiv preprint arXiv:1310.4632*, 2013.
- [95] W. Gan, Z. Shi, C. Zhang, L. Sun, and D. Ionescu, "MERPL: A more memory-efficient storing mode in RPL," in *Networks (ICON), 2013 19th IEEE International Conference on*, 2013, pp. 1-5.
- [96] W. Xie, M. Goyal, H. Hosseini, J. Martocci, Y. Bashir, E. Baccelli, *et al.*, "A performance analysis of point-to-point routing along a directed acyclic graph in low power and lossy networks," in *Network-Based Information Systems (NBIS), 2010 13th International Conference on*, 2010, pp. 111-116.
- [97] E. Baccelli, M. Philipp, and M. Goyal, "The P2P-RPL routing protocol for IPv6 sensor networks: Testbed experiments," in *Software, Telecommunications and Computer Networks (SoftCOM), 2011 19th International Conference on*, 2011, pp. 1-6.
- [98] P. Levis, T. Clausen, J. Hui, O. Gnawali, and J. Ko, "The trickle algorithm," *IETF ROLL working group, [RFC 6206]*, 2011.
- [99] J. Hui and R. Kelsey, "Multicast forwarding using trickle," *draft-ietf-roll-trickle-mcast-00 (work in progress)*, 2011.
- [100] M. C. Richardson, "ROLL Applicability Statement Template," 2013.
- [101] X. Hu and S. Qian, "IoT application system with crop growth models in facility agriculture," *School of Information Sci. & Eng. Fudan University*.
- [102] D. Popa, J. Jetcheva, N. Dejean, R. Salazar, J. Hui, and K. Monden, "Applicability Statement for the Routing Protocol for Low Power and Lossy Networks (RPL) in AMI Networks," IETF Internet Draft draft-ietf-roll-applicability-ami, 2011.[Online]. Available: <http://tools.ietf.org/html/draft-ietf-roll-applicability-ami-052011>.
- [103] Y. Chen, J. P. Chanet, and K. M. Hou, "RPL Routing Protocol a case study: Precision agriculture," in *First China-France Workshop on Future Computing Technology (CF-WoFUCT 2012)*, 2012.
- [104] R. Jaichandran, A. A. Irudhayaraj, and J. Raja, "Effective strategies and optimal solutions for Hot Spot Problem in wireless sensor networks (WSN)," in *Information Sciences Signal Processing and their Applications (ISSPA), 2010 10th International Conference on*, 2010, pp. 389-392.
- [105] A. Dunkels, J. Eriksson, N. Finne, and N. Tsiftes, "Powertrace: Network-level power profiling for low-power wireless networks," 2011.

- [106] C. A. Boano, K. Römer, F. Österlind, and T. Voigt, "Demo abstract: Realistic simulation of radio interference in COOJA," *Universität zu Lübeck, Germany, Swedish Institute of Computer Science*, 2011.
- [107] M. Kovatsch, S. Duquennoy, and A. Dunkels, "A low-power CoAP for Contiki," in *Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on*, 2011, pp. 855-860.
- [108] J. Romkey, "Nonstandard for transmission of IP datagrams over serial lines: SLIP," 1988.
- [109] G. Gangsto, A. Aas, and R. Sorasen, "Single chip microcontroller including battery management and protection," ed: Google Patents, 2012.
- [110] Y.-b. Chen, K.-M. Hou, J.-P. Chanet, and K. El Gholami, "A RPL based Adaptive and Scalable Data-collection Protocol module for NS-3 simulation platform," in *NICST 2103 New Information Communication Science and Technology for Sustainable Development: France-China International Workshop*, 2013.
- [111] L. B. Saad, C. Chauvenet, and B. Tourancheau, "Simulation of the RPL Routing Protocol for IPv6 Sensor Networks: two cases studies," in *International Conference on Sensor Technologies and Applications SENSORCOMM 2011*, 2011.
- [112] F. Dressler and D. Neuner, "Energy-efficient monitoring of distributed system resources for self-organizing sensor networks," in *Wireless Sensors and Sensor Networks (WiSNet), 2013 IEEE Topical Conference on*, 2013, pp. 145-147.
- [113] Y. Chen, J.-P. Chanet, K. M. Hou, and H. L. Shi, "Extending the RPL Routing Protocol to Agricultural Low Power and Lossy Networks (A-LLNs)," *International Journal of Agricultural and Environmental Information Systems (IJAEIS)*, vol. 4, pp. 25-47, 2013.
- [114] R. Palit, A. Singh, and K. Naik, "energy Cost of Software Applications on Portable Wireless Devices," *Green Mobile Devices and Networks: Energy Optimization and Scavenging Techniques*, p. 53, 2012.
- [115] J. Varley, M. Martino, S. Poshtkouhi, and O. Trescases, "Battery and ultra-capacitor hybrid energy storage system and power management scheme for solar-powered wireless sensor nodes," in *IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society*, 2012, pp. 4806-4811.
- [116] H.-C. Luo, E.-K. Wu, and G.-H. Chen, "From spatial reuse to transmission power control for CSMA/CA based wireless ad hoc networks," in *Parallel Processing Workshops (ICPPW), 2011 40th International Conference on*, 2011, pp. 75-80.
- [117] D. Tian and N. D. Georganas, "A coverage-preserving node scheduling scheme for large wireless sensor networks," in *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, 2002, pp. 32-41.
- [118] R. Madan, S. Cui, S. Lall, and A. Goldsmith, "Cross-layer design for lifetime maximization in interference-limited wireless sensor networks," *Wireless Communications, IEEE Transactions on*, vol. 5, pp. 3142-3152, 2006.
- [119] Q. Xue and A. Ganz, "On the lifetime of large scale sensor networks," *Computer communications*, vol. 29, pp. 502-510, 2006.
- [120] M. Bhardwaj, T. Garnett, and A. P. Chandrakasan, "Upper bounds on the lifetime of sensor networks," in *Communications, 2001. I CC 2001. I IEEE International Conference on*, 2001, pp. 785-790.
- [121] B. Cărbunar, A. Grama, J. Vitek, and O. Cărbunar, "Redundancy and coverage detection in sensor networks," *ACM Transactions on Sensor Networks (TOSN)*, vol. 2, pp. 94-128, 2006.
- [122] S. Baydere, Y. Safkan, and O. Durmaz, "Lifetime analysis of reliable wireless sensor networks," *IEICE transactions on communications*, vol. 88, pp. 2465-2472, 2005.

- [123] J. F. A. Diaz, H. B. Guerrero, A. J. Tiberti, R. A. Tabile, G. T. Tangerino, C. J. Torres, *et al.*, "AGRIBOT-MOBILE ROBOT TO SUPPORT OF AGRICULTURAL PRECISION ACTIVITIES," in *22nd International Congress of Mechanical Engineering-COBEM*, 2013.
- [124] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis, "An empirical study of low-power wireless," *ACM Transactions on Sensor Networks (TOSN)*, vol. 6, p. 16, 2010.
- [125] R. Fonseca, O. Gnawali, K. Jamieson, S. Kim, P. Levis, and A. Woo, "The collection tree protocol (CTP)," *TinyOS TEP*, vol. 123, p. 2, 2006.
- [126] V. C. Gungor, C. Sastry, Z. Song, and R. Integlia, "Resource-aware and link quality based routing metric for wireless sensor and actor networks," in *Communications, 2007. ICC'07. IEEE International Conference on*, 2007, pp. 3364-3369.
- [127] A. Sivagami, K. Pavai, D. Sridharan, and S. Murty, "Energy and Link Quality based Routing for Data gathering tree in wireless sensor networks under TINYOS-2. X," *arXiv preprint arXiv:1005.1739*, 2010.
- [128] H. Zhang, A. Arora, and P. Sinha, "Learn on the Fly: Data-Driven Link Estimation and Routing in Sensor Network Backbones," in *INFOCOM*, 2006.
- [129] C.-K. Toh, H. Cobb, and D. A. Scott, "Performance evaluation of battery-life-aware routing schemes for wireless ad hoc networks," in *Communications, 2001. ICC 2001. IEEE International Conference on*, 2001, pp. 2824-2829.
- [130] W.-y. Cai, X.-y. Jin, Y. Zhang, and K.-s. Chen, "A load-balanced minimum energy routing algorithm for Wireless Ad Hoc Sensor Networks," *Journal of Zhejiang University SCIENCE A*, vol. 7, pp. 502-506, 2006.
- [131] P. Trakadas and T. Zahariadis, "Design Guidelines for Routing Metrics Composition in LLN," 2012.
- [132] Y. Yang and J. Wang, "Design guidelines for routing metrics in multihop wireless networks," in *INFOCOM 2008. The 27th conference on computer communications. IEEE*, 2008, pp. 1615-1623.
- [133] Y. Yang, J. Wang, and R. Kravets, "Designing routing metrics for mesh networks," in *IEEE Workshop on Wireless Mesh Networks (WiMesh)*, 2005.
- [134] M. G. Gouda and M. Schneider, "Maximizable routing metrics," *IEEE/ACM Transactions on Networking (TON)*, vol. 11, pp. 663-675, 2003.
- [135] A. Boukerche, B. Turgut, N. Aydin, M. Z. Ahmad, L. Bölöni, and D. Turgut, "Routing protocols in ad hoc networks: A survey," *Computer Networks*, vol. 55, pp. 3032-3080, 2011.
- [136] M. Becker, T. Pötsch, K. Kuladinithi, and C. Goerg, "Deployment of CoAP in Transport Logistics," in *Proceedings of 36th IEEE Conference on Local Computer Networks (LCN), Bonn, Germany*, 2011, pp. 4-7.
- [137] P. A. Levis, N. Patel, D. Culler, and S. Shenker, *Trickle: A self regulating algorithm for code propagation and maintenance in wireless sensor networks*: Computer Science Division, University of California, 2003.
- [138] A. Dunkels, L. Mottola, N. Tsiftes, F. Österlind, J. Eriksson, and N. Finne, "The announcement layer: Beacon coordination for the sensornet stack," in *Wireless sensor networks*, ed: Springer, 2011, pp. 211-226.
- [139] H. Kermajani, C. Gomez, and M. H. Arshad, "Modeling the Message Count of the Trickle Algorithm in a Steady-State, Static Wireless Sensor Network," *Communications Letters, IEEE*, vol. 16, pp. 1960-1963, 2012.
- [140] M. Becker, K. Kuladinithi, and C. Görg, "Modelling and simulating the trickle algorithm," in *Mobile networks and management*, ed: Springer, 2012, pp. 135-144.

- [141] T. Clausen and U. Herberg, "Comparative study of rpl-enabled optimized broadcast in wireless sensor networks," in *Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2010 Sixth International Conference on*, 2010, pp. 7-12.
- [142] J. Eriksson and O. Gnawali, "Synchronizing Trickle Intervals."
- [143] C. Vallati and E. Mingozzi, "Trickle-F: Fair broadcast suppression to improve energy-efficient route formation with the RPL routing protocol," in *Sustainable Internet and ICT for Sustainability (SustainIT), 2013*, 2013, pp. 1-9.
- [144] K. Machado, D. Rosário, E. Cerqueira, A. A. Loureiro, A. Neto, and J. N. de Souza, "A Routing Protocol Based on Energy and Link Quality for Internet of Things Applications," *Sensors*, vol. 13, pp. 1942-1964, 2013.
- [145] A. Dunkels, "The contikimac radio duty cycling protocol," 2011.
- [146] P. Gonizzi, P. Medagliani, G. Ferrari, and J. Leguay, "RAWMAC: A Routing Aware Wave-based MAC Protocol for WSNs."
- [147] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "An adaptive energy - efficient and low - latency MAC for tree - based data gathering in sensor networks," *Wireless Communications and Mobile Computing*, vol. 7, pp. 863-875, 2007.
- [148] R. Perlman, "Fault-tolerant broadcast of routing information," *Computer Networks (1976)*, vol. 7, pp. 395-405, 1983.
- [149] J. Guo, C. Han, P. Orlik, J. Zhang, and K. Ishibashi, "Loop-Free Routing in Low-Power and Lossy Networks," in *SENSORCOMM 2012, The Sixth International Conference on Sensor Technologies and Applications*, 2012, pp. 59-66.
- [150] T. H. Clausen and U. Herberg, "Multipoint-to-Point and Broadcast in RPL," 2010.
- [151] T. Narten, E. Nordmark, W. Simpson, and H. Soliman, "RFC 4861-Neighbor discovery for IP version 6 (IPv6), 2007," URL <http://www.ietf.org/rfc/rfc4861.txt>. Updated by RFC, vol. 5942, 2011.
- [152] J. Ko, S. Dawson-Haggerty, O. Gnawali, D. Culler, and A. Terzis, "Evaluating the Performance of RPL and 6LoWPAN in TinyOS," in *Workshop on Extending the Internet to Low Power and Lossy Networks (IP+ SN)*, 2011.
- [153] X. Liu, K. M. Hou, H. Shi, C. Guo, and H. Zhou, "Efficient and portable reprogramming method for high resource-constraint wireless sensor nodes," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2011 IEEE 7th International Conference on*, 2011, pp. 455-460.
- [154] M. Strübe, "RealSim and DryRun: Tools for a deployment-targeted development of WSNs," 2011.
- [155] K. El Ghomali, N. Elkamoun, K. Hou, Y. Chen, J. Chanet, and J. Li, "A new WPAN Model for NS-3 simulator," in *NICST'2103 New Information Communication Science and Technology for Sustainable Development: France-China International Workshop*, 2013.
- [156] L. Bartolozzi, T. Pecorella, and R. Fantacci, "ns-3 RPL module: IPv6 routing protocol for low power and lossy networks," in *Proceedings of the 5th International ICST Conference on Simulation Tools and Techniques*, 2012, pp. 359-366.
- [157] P. O. Kamgueu, E. Nataf, T. Djotio, and O. Festor, "Fuzzy-based routing metrics combination for RPL," 2014.
- [158] K. Kadam and N. Srivastava, "Application of machine learning (reinforcement learning) for routing in Wireless Sensor Networks (WSNs)," in *Physics and Technology of Sensors (ISPTS), 2012 1st International Symposium on*, 2012, pp. 349-352.
- [159] U. Prathap, D. Shenoy, K. Venugopal, and L. Patnaik, "Wireless sensor networks applications and routing protocols: survey and research challenges," in *Cloud and Services Computing (ISCOS), 2012 International Symposium on*, 2012, pp. 49-56.

- [160] A. Dunkels, F. Österlind, and Z. He, "An adaptive communication architecture for wireless sensor networks," in *Proceedings of the 5th international conference on Embedded networked sensor systems*, 2007, pp. 335-349.
- [161] F. P. Correia, M. S. Alencar, F. Carvalho, W. T. Lopes, and B. G. Leal, "Propagation analysis in Precision Agriculture environment using XBee devices," in *Microwave & Optoelectronics Conference (IMOC), 2013 SBMO/IEEE MTT-S International*, 2013, pp. 1-5.
- [162] B. Sharkawy, A. Khattab, and K. M. Elsayed, "Fault-tolerant RPL through context awareness," in *Internet of Things (WF-IoT), 2014 IEEE World Forum on*, 2014, pp. 437-441.
- [163] J. Eriksson, A. Dunkels, N. Finne, F. Österlind, F. Voigt, and N. Tsiftes, "Demo abstract: MSPsim-an extensible simulator for MSP430-equipped sensor boards," in *European Conference on Wireless Sensor Networks (EWSN 2008), Demo Abstract, Bologna, Italy*, 2008.

## RESUME

### **Algorithme de routage dédié à la collecte de données environnementales: Agriculture de précision**

Les Réseaux de Capteurs Sans Fil (RCSF ou Wireless Sensor Network - WSN) sont l'une des technologies les plus importantes du 21<sup>ème</sup> siècle. La plupart des chercheurs et les analystes estiment que, dans un proche avenir, ces micro-capteurs seront intégrés partout dans l'environnement de notre vie quotidienne. Ces dernières années, l'Internet des Objets (Internet of Things - IoT) est également une des technologies émergentes qui se développe rapidement. Deux nouveaux standards permettent de déployer des réseaux sans fil de faible consommation énergétique connectés à internet : le protocole 6LoWPAN (Low power Wireless Personal Area Networks) qui permet notamment d'apporter l'adressage IPv6 aux capteurs grâce à l'encapsulation et la compression des données et le protocole de routage RPL (IPv6 routing protocol for low-power and lossy network) qui permet à l'information de circuler dans les WSN de proche en proche à un faible coût énergétique. Bien que le développement de ces techniques soit extrêmement rapide, plusieurs problèmes causés principalement par le manque de ressources des micro-capteurs (puissance limitée de traitement, problèmes de bande passante et de connexion des liens avec perte de données, problème de ressource énergétique limitée) demeurent et doivent être résolus, notamment pour les applications agro-environnementales.

**MOTS-CLÉS:** Réseau de capteurs sans fil; RPL protocole de routage; 6LoWPAN; Protocole de simulation; internet des objets.

## ABSTRACT

### **Routing algorithm dedicated to environmental data collection: Precision Agriculture**

The wireless sensor network (WSN) is one of the most important technologies of the 21st century. Most researchers and technical analysts believe that in the near future, these micro-sensors will be integrated into the environment of our daily lives. In recent years, the IoT (Internet of Things) and WoT (Web of Things) technologies also have great forwarding. Especially, the IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) protocol has allowed the use of IPv6 protocol stack in the field of WSN, thanks to its encapsulation and compression mechanisms in IPv6 packet header. Moreover, the RPL (IPv6 Routing Protocol for Low-power and Lossy Network) provides such a powerful routing function that can be applied for a variety of application scenarios. These two key standards of IoT and WoT technologies for WSN can be used in an IPv6 stack, and they will successfully achieve the connection between Internet and micro-sensors. Thus, due to the availability of IPv6 address (128-bit), all the communicating objects, such as smart device, sensor, and actuator, can be connected to the Internet. That is the greatest advantage brought by the IoT. Although the progress of these techniques is extremely fast, several issues caused by resource constraints of micro-sensor (limited processing power, bandwidth and lossy connection link, and energy), such as QoS, energy efficient, robustness and lifetime of WSN, and the most important, the special requirement of agricultural applications. Notice that Precision Agriculture is are still very challenging and waiting to be solved. Essentially, these open questions would dabble in the aspects like telemedicine, remote home automation, industrial control etc. Thus, the results obtained in this work will have a significant impact on both economic and scientific. Economically, it can offer a solution for WSN to support sustainable development in the field of agriculture automation. While scientifically, we will contribute to the routing protocol standardization of wireless micro-sensors in the domain of environmental monitoring.

**KEYWORDS:** WSN, RPL routing protocol, 6LoWPAN, Protocol Simulation, Internet of Things.