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Technical Report

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CISTER-TR-140524
Version:
Date: 6/15/2014

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Abstract

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Abstract—**Mobility support for wireless sensor networks has always been a challenging research topic. This paper addresses the issue of mobility support in the Routing Protocol for Low power and lossy networks (RPL), the recently adopted IETF routing protocol standard for low power wireless sensor networks. RPL was originally designed for static networks, with no support for mobility. In this work, we address this gap and propose Co-RPL as an extension to RPL based on the Corona mechanism to support mobility. To demonstrate the effectiveness of Co-RPL, we conducted an extensive simulation study using the Contiki/Cooja simulator and compared the performance against standard RPL. We study the impact of node speed, packet transmission rate and number of Directed Acyclic Graphs (DAG) roots on network performance. The simulation results show that Co-RPL decreases packet loss ratio by 45%, average energy consumption by 50% and end-to-end delay by 2.5 seconds, in comparison with the standard RPL.**

I. INTRODUCTION

The Internet of Things (IoT) has emerged as a paradigm over the last few years as a result of the tight integration of the computing and the physical world. The requirement of remote sensing makes low-power wireless sensor networks one of the key enabling technologies of IoT. These networks encompass several challenges, especially in communication and networking, due to their inherent constraints of low-power features, deployment in harsh and lossy environments, and limited computing and storage resources. The IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) [29] was proposed by the IETF ROLL (Routing Over Low-power Lossy links) working group and is currently adopted as an IETF standard in the RFC 6550 since March 2012. However, although RPL greatly satisfied the requirements of low-power and lossy sensor networks, several issues remain open for improvement and specification, in particular with respect to Quality of Service (QoS) guarantees and support for mobility [11].

In this paper, we extend RPL for supporting mobility in Mobile Wireless Sensor Networks (MWSNs). MWSNs are typically composed of mobile sensor nodes that are attached to mobile robots [20], or attached to mobile objects such as smart phones and people [26], [27]. Deploying mobile wireless sensor networks is a research topic that has recently received considerable interest with the emergence of IoT, since most sensor-based devices are inherently mobile. Mobile sensor networks differ from static sensor networks as the topology of the network is dynamic and continuously evolving over time. Thus, efficient protocols need to be conceived in order to maintain connectivity, support QoS, and avoid undesirable effects of frequent topology changes, such as loss of connectivity and network holes.

There are several motivating application scenarios of MWSNs that require mobility support at the routing layer. For instance, in typical sensor data collection applications using mobile robots [9], [8], it is important that the mobile robot, collecting sensory data through its attached sensor node, maintains connectivity with the network to avoid packet losses and degraded QoS. Body sensor networks is another application context where mobility must be supported. Indeed, patients use body sensor networks to monitor their vital signs (e.g. heart rate, blood pressure, etc.) which are transmitted to doctors and medical staff for tracking and monitoring patients health status [18]. In such scenarios, both patients (data sources) and doctors (data collectors) are mobile. This becomes an important consideration in the design of network and communication protocols to ensure QoS guarantees. Recently, handoff mechanisms were proposed for managing mobility at the MAC layer [10]. Some other approaches have proposed mobility support mechanisms at network layer [14], [19], [24], [4], [17], [25] for Low-Power and Lossy Networks (LLNs). While these are interesting approaches, they address only the master-slave communication pattern and do not deal with adhoc routing at network layer. We discuss these works in Section II.

In this paper we propose Co-RPL, an extension of RPL, that provides mobility support by keeping track of the mobile nodes' positions while moving in order to improve network performance. Our approach relies on the corona mechanism that allows localization of RPL routers in motion. This mechanism divides the network into circular areas around the DAG roots, called coronas, and allows the RPL routers to compute its coordinates based on its distance from the DAG root. The contributions of this paper are: (*i.*) Improve the RPL protocol to capture frequent topology changes; (*ii.*) Evaluate and compare performance of improved RPL, with native RPL, in mobile wireless sensor networks scenarios.

The reminder of this paper is organized as follows. In Section II, we survey recent research works that deal with mobility support for RPL. Section III presents a detailed description of Co-RPL. The ContikiOS/Cooja simulation results related to the comparison of Co-RPL against the standard specification of

RPL in mobile networks are presented in Section IV. Section V concludes the paper and discusses future works.

II. RELATED WORK

There has been some research addressing the problem of extending RPL to support mobility.

Hong et al. in [14] designed a multipath routing protocol called DMR, based on RPL, for mobile sensor networks, where any node can be mobile. By broadcasting DIO (DODAG Information Object) messages including rank and link quality indication, DMR constructs DAGs and provides path redundancy. This allows mobile nodes to find multiple alternative paths on local and global route failures. In order to provide fast local repair, they also propose the addition of sibling nodes to the routing table of each node; and if there are no more sibling nodes, the node detecting a broken link can initiate global repair by requesting its sink to rebuild a new DODAG. However, the authors used the same design of RPL without any modification. In addition, they compared the performance of DMR with AODV and AOMDV, although these protocols are not designed for LLNs nor for data collection protocols.

In [19], the authors studied RPL through a simulation performance study and concluded that many design elements from RPL are transferable to the vehicular environment (VANETs). They provided insights on RPL tuning, for its use in vehicular networks. They proposed immediate ETX (Expected Transmission Count) probing in the presence of a new neighbor and immediate DIOs and DAOs upon a new parent election (instead of waiting for the trickle timer). They also proposed a new loop avoidance and detection technique which consisted of stamping the DIO message with its parent's ID. However, their proposal is designed only for VANETs, and therefore assumes that the nodes move in a high speed except the access point, and this assumption cannot be applied for MWSNs.

In [24], the authors tackled the problem of repeatedly using nodes that are close to the sink for data forwarding due to frequent data transmission to the sink, which results in quickly depleting the energy of these nodes, and causing holes near the sink. They considered mobile sinks, which involves controlled movement of the sink towards nodes having higher energy to load balance the energy distribution of nodes and avoid network partitioning. Their proposal is a hybrid routing protocol that combines reactive and proactive approaches to enhance RPL in order to handle the movement of multiple sinks. The DAGs are only maintained by nodes close to the sink, while the nodes outside the sink range use on demand sink discovery to find the closest sink. However, the proposed approach was designed for the sole reason of saving energy of the nodes that are close to the sink. In addition, it was not validated through simulation or experimentation.

In [3], the authors evaluated RPL with two case studies which are mobile sinks and low power PLC (Power Line Communication) nodes. They evaluated the movement of sinks in wireless sensor networks in order to extend the network lifetime using a sensor network simulator, WSNet, augmented by their own RPL module. However, the goal of this work was to improve network lifetime. In addition, the authors did not propose any improvement to the RPL protocol and is an implementation of RPL with PLC nodes.

In [4], the authors proposed an autonomous moving strategy of sinks to improve network lifetime. They considered a combination of three parameters in order to compute the weight of each sensor: number of hops, sensor energy and number of neighbors. At the beginning of a time period, each sink determines the leaf node with the highest weight and moves there. The chosen metrics in the mobility strategy aim to minimize only the consumed energy, and the performance evaluation focused only on the network lifetime without considering other quality of service criteria.

In [17], the authors tackled the problem of decreasing control traffic of RPL at the price of lower reactivity to topology changes. They introduced new mechanisms to the native RPL that reconcile decrease in control traffic and reactivity. These mechanisms are based on the identification of mobile nodes, and enhance RPL behavior in the case of node mobility. The authors proposed an explicit mobility advertisement, and thus, they proposed an improvement of the preferred parent selection such that a node will prefer a fixed node as parent. They also proposed an adaptation of the speed of solicitation messages. However, the proposed approach does not maintain backward compatibility as the modified message structures do not conform to the standard RPL specification. In addition, the process of parent selection is not based on routing metrics.

More recently, the paper in [25] presented GI-RPL, an improvement to RPL applied in VANETs. The authors proposed geographical information (GI) as a new routing metric for RPL in order to support highly dynamic topologies. The information used to localise the sensor nodes are distance to sink and direction of the vehicle. They used an adaptive DIO period instead of the trickle timer and divided the road into small DODAGs for better performance. They evaluated their proposal with the COOJA emulator and compared it with ETX-RPL ([19]). The performance evaluation showed that GI-RPL outperforms ETX-RPL in terms of packet delivery ratio, delay and overhead. However, the proposed mechanism can be applied only for VANETs as the direction of the movement of mobile nodes cannot be predicted.

In summary, when studying the proposed works related to RPL under mobility, it is clear that all of them cannot be generalized for mobile wireless sensor networks. Some works evaluated RPL under a special case (VANETs) [19], [25], and other works proposed improvement to native RPL for the singular purpose of improving network lifetime [24], [3], [4].

In this paper, we aim to not only improve network lifetime, but also the overall network performance including energy consumption and end-to-end delay. For this purpose, we considered a corona architecture that allows better localization of RPL routers while mobile. The corona architecture was originally proposed in [32] and used in several research works in the context of static [22], [30], [21] as well as mobile wireless sensor networks [23], [31], [7]. This architecture has been mainly used to extend network lifetime and to avoid network holes.

III. OVERVIEW OF CO-RPL

In this section, we describe the Co-RPL mechanism for mobile low power and lossy WSNs.

We performed several simulations with static node setups with RPL-based networks. These networks show a high packet loss ratio, mainly due to loss of connectivity. For instance, in [11], we found that the packet loss ratio exceeds 20%, and this number is even worse when the topology changes continuously (as in MWSNs). Our objective is then to maintain connectivity of nodes in their DODAG while providing quality of service guarantees at network level. In what follows, we present our improved mechanism of RPL, referred to as Co-RPL, that addresses the QoS requirement of MWSNs. In a nutshell, Co-RPL is based on the Corona mechanism that enables improved localization of nodes in motion, and thus reduces the impact of frequent node failures.

A. *Problem Statement*

Continuous change in network topology of a MWSN increases the risk of link failures, and consequently affecting the packet delivery ratio. Furthermore, real-time guarantees are a major requirement for many applications deployed on MWSNs. This becomes even more challenging when efficient use of energy comes into play. As a consequence, providing QoS guarantees is far more difficult for MWSNs than for static WSNs. In our previous work [12], we proposed an improved mechanism called OF-FL, which improves routing decisions using a fuzzy logic approach that combines different routing metrics, for static networks. In this paper, we target to support mobility in RPL for mobile MWSNs and fill a gap in the standard specification.

Indeed, the RPL routing protocol, in its current specification, does not incorporate efficient mechanisms for handling QoS in the presence of mobile nodes. Since RPL was originally designed for static LLNs, position of nodes is not updated in a timely fashion to reflect frequent topology changes. The slow response to topology changes results in frequent loss of connectivity. Moreover, the mobile node may select sub-optimal paths to the root, which may lead to severe degradation of the network performance.

As discussed in Section II, existing research that consider mobility in RPL aim only to improve the network lifetime. The lack of mobility support in RPL motivates us to design a new improved mechanism. This improvement, by building and maintaining dynamic DAGs, is able to provide QoS guarantees while also preserving backward compatibility with the standard specification.

B. *Network Model*

We consider a mobile network where the RPL routers move randomly. In this work, we assume that DAG roots are static; indeed, this is typical for data collection networks [28]. These roots are usually linked to the Internet gateway and therefore it is suitable to consider them as static nodes.

The proposed Co-RPL protocol is based on the Corona architecture for localization of mobile nodes. This architecture facilitates in quickly finding alternative parents as the next hop. The Corona architecture relies on the simple concept of dividing the network area into coronas [32]. A corona is defined as a circular region with a certain radius centered at the DAG root. In our simulations, we assume that the radius of each corona is equal to the maximum transmission range of a sensor node.

Fig. 1 presents an example of the corona-based network architecture. The nodes in the network are mobile routers running the RPL protocol. There are four DAGs, with each DAG centered on its DAG root. A corona is associated with each DAG. The RPL routers may belong to only one corona at a time (even in case of overlap of connectivity), and can switch from one corona to another (according to the algorithm we present in the next section. Refer to Algorithm 1).

In the RPL standard specification, every node uses a trickle timer to broadcast DIO messages in order to exchange connectivity information with local nodes. The interval of these transmissions is bounded, and increases with network stability. A mobile entity compromises this stability and the interval resets to its minimum value. Also, the issue with the trickle timer is that the discovery of topology changes can be slow in the case of temporary stability. Thus, this timer mechanism may not be efficient in the case of MWSNs as the topology changes continuously. As an alternative, we propose that the DAG root sends DIOs periodically in order to be aware of the positions of the nodes in real-time. The interval between the transmission of two DIOs should be adjusted based on the speed of the nodes. In addition, upon detection of an inconsistency, the neighboring nodes transmit DIO messages immediately without waiting for expiration of the periodic timer.

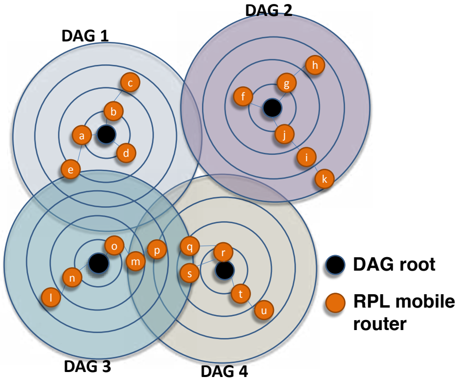


Fig. 1: Network architecture composed of four DODAGs with static DAG roots

C. *Control Messages*

For control we make use of the legacy RPL control messages rather than creating new control packets. This maintains backward compatibility with the standard. We have modified the DIS (DODAG Information Solicitation) and DIO messages by adding flags to distinguish between standard control messages and control messages used for Co-RPL mechanism. We now describe the control messages used in Co-RPL.

1) Structure of modified DIS message: Fig. 2 presents the modified DIS message for Co-RPL.

```
 0                   1                   2
 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|F|    Flags    |    Reserved   |   Option(s)...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Fig. 2: Structure of modified DIS message of Co-RPL.

The DIS message is sent by a node when it does not find any parent in any DAG, and searches for immediate parents. We have added a new bit F as the first bit of the *Flags* field. The bit F is used to distinguish between the standard specification of RPL and Co-RPL. If $F = 0$, it is interpreted as being the standard DIS message. Else (that is, $F = 1$), the DIS message is assumed to be issued from a node running Co-RPL.

2) Structure of modified DIO message: As mentioned in Section III-B, we divide the MWSN into concentric coronas centered at the static DAG roots. Each corona is identified by a corona ID (C_ID). The C_ID is used as relative coordinate to localize mobile nodes to the DAG root (that is, the sink). The C_ID is then used in detecting node mobility and triggering neighbor discovery. Fig. 3 shows the modification in the DIO message for this ID.

```
0               1               2               3
0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0 1 2 3 4 5 6 7 0
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|RPLInstanceID| Version Number|              Rank               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|G|0| MOP | Prf |     DTSN      | F |   Flags   |  C_ID |Reserved |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                          DODAGID                              +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Option(s)....
+-+-+-+-+-+-+-+-+-+-+
```

Fig. 3: Structure of modified DIO message.

We use the two first bits of the *Flags* field to distinguish between the standard DIO and the updated DIO message. If $F = 0$, the DIO message is issued from an RPL router. Else, with $F = 1$ the DIO is issued from a node running Co-RPL. Also, the C_ID is placed in the reserved field of the DIO message (requires 3 bits). By integrating the corona ID in the DIO reserved field, nodes that do not implement Co-RPL can still operate based on the default objective function. This results in Co-RPL nodes co-existing in a transparent manner with nodes running plain RPL.

3) Neighbor table: Each node, including DAG roots, track its neighbors by maintaining a list. For each neighbor, a node maintains IDs of the node, DAG and corona, and the link quality. Table I shows an example neighbor table (of the node 'q' in Fig. 1). The neighbor table is updated upon receiving a new DIO message.

Node ID	DAG ID	Corona ID	Quality
p	3	3	45
s	4	2	60
r	4	1	80

TABLE I: Co-RPL neighbor table

D. The Co-RPL Protocol

The Co-RPL protocol incorporates three new mechanisms: (1) the corona mechanism for computation of corona IDs for each node belonging to a DAG, (2) distributed algorithms for both DAG root and mobile node operation, and (3) a path recovery mechanism that allows fast recovery in case of node failures.

1) The Corona Mechanism: The reason of adapting corona coordinates in a mobile wireless sensor network is to localize each sensor node based on its distance to the sink. Each sensor node belongs to only one corona. Algorithm 1 shows the pseudo code of the proposed corona mechanism.

The DAG root is the only node that has C_ID equal to 0. Each mobile node checks its neighbor table to compute its C_ID. It selects the neighbor with the minimum value of C_ID and increments it by one to set its OWN value. The node then broadcasts a DIO message to announce its new C_ID.

Algorithm 1 Corona mechanism

```
$C\_ID(DAGroots) \leftarrow 0$
DAG root broadcasts DIOs
for all mobile node receives DIO from a neighbor do
    $C\_ID(mobilenode) \leftarrow min(C\_ID(neighbors)) + 1$
    mobile node broadcasts DIO with new $C\_ID$
```

2) Operations of the DAG Root and the Mobile RPL Router: Co-RPL comprises two main operations depending on where it is implemented: (1) an algorithm implemented in DAG root as it is the only member that can construct a DAG and (2) an algorithm to be implemented in each RPL mobile Router.

The DAG root behavior At the beginning of the network deployment, the DAG root sends DIO messages to its neighbors in order to construct the DAG. The DIO message contains the DAG ID of the root and the objective function used to compute the ranks. The DAG root has a C_ID of 0.

The DAG root sends DIO messages periodically to its neighbors. On receiving a DIS message from a neighbor, the root broadcasts a DIO message immediately without waiting for timer expiration.

The Mobile router behavior Each RPL router listens to the DIOs from neighboring nodes. If it does not receive any DIO, it has no neighbors and is isolated from the rest of the network. The node will then be in idle mode and continue to send DIS messages until receiving a DIO to join a DAG (when it comes within range of a node). When an RPL router receives the first DIO, it joins the DAG, computes its rank and its C_ID using Algorithm 2, and broadcasts the updated DIO message to its neighbors. If it receives multiple DIOs (with more than one corona ID), the node selects a parent. This it does based on the minimum corona ID and the best quality advertised in the received DIOs. This operation is shown in Algorithm 2.

Algorithm 2 Operation of a mobile router

```
repeat
    broadcast $DIS$
until receive DIOs
for all replies do
    if $C\_ID(mobilenode) \leq C\_ID(neighbors)$ then
        Best parent ← Neighbor with best quality
    else
        Neighbor node will discard DIO {The mobile node should not select a parent with a higher corona ID in order too avoid loops}
if $C\_ID$(neighbor) changes then
    Broadcast $DIOs$
else
    wait until the timer expiration
```

An issue that needs to be addressed is when a node changes its position without having its C_ID changed (it is still near the same DAG root). This does not trigger a neighbor discovery and needs special attention. To deal with this situation, we enable the neighbor discovery mechanism whenever the neighbor table changes. This modification is sufficient as even when a mobile node maintains the same corona ID, the list of its neighbors will necessarily change with its changed position. If one of the C_IDs of the neighbor nodes changes or if a new neighbor is detected, the node triggers an immediate neighbor discovery.

3) Path Recovery Mechanism: The main issue of RPL in mobile networks is the presence of network holes, which means that part of the network can no longer reach the DAG root. These holes are caused by either isolation of nodes when they move, or failure of some nodes for some reasons. The network holes result in a high packet loss ratio. In fact, if the node loses the connectivity to its preferred parent, the data packets that should be sent to the sink will be lost until finding and pairing with another preferred parent. This problem causes a significant degradation of network performance. The RPL standard includes the specification of local and global repairs which are triggered when an inconsistency is detected in the DAG [29]. However, these two mechanisms are shown to lack of responsiveness, which makes them inefficient for mobile networks [13]. In order to overcome this problem, we propose to forward the coming packets of the mobile nodes that lost their parents to the neighbor nodes until finding another optimal parent.

If a mobile node cannot forward data packets to the next-hop neighbor (its parent), it backwards the data packets to any node in high corona level and informs its children to stop sending data by sending DIS messages. The RPL router will continue forwarding the data messages through its neighbors until finding a new forwarding candidate. Hence, the path recovery mechanism guarantees the prevention of dropping data packets at the mobile node or its children, which improves the reliability.

IV. PERFORMANCE EVALUATION

In this section, we detail the performance evaluation of CO-RPL using COOJA [2], a widely-used and reliable sensor network simulator/emulator under Contiki operating system [1].

A. Objectives of the Simulation Study

Our aim is to examine the impact of several parameters on the behavior of the network and compare results of Co-RPL with the standard RPL specification. The objectives of this simulation study are:

- To investigate the network behavior with the standard specification of RPL. As it is designed for static networks, it is important to measure the network performance and how long it can meet the quality of service requirements of mobile networks;
- To compare Co-RPL against RPL in order to investigate the impact of the proposed enhancement on the network performance;
- To point out the factors that influence the behavior of a mobile low power and lossy wireless sensor networks.

B. Simulation Setup

Fig. 4 presents a screenshot of the simulation environment. The metrics for the MWSN simulation are the packet transmission rate, the number of DAG roots and the speed of mobile nodes.

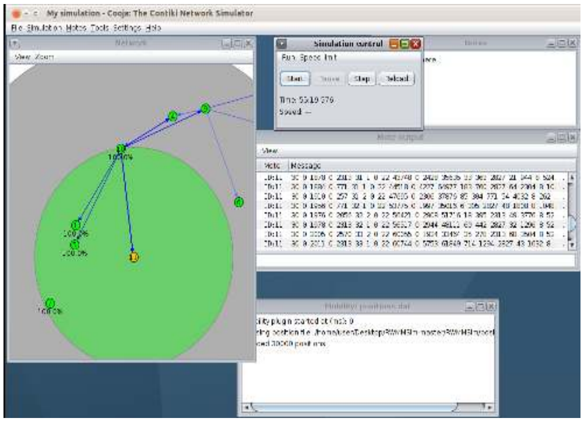


Fig. 4: Screenshot of the mobility simulation environment

Network simulator	COOJA under contiki OS (2.7)
Simulation time	1 hour
Radio environment	DGRM (Directed Graph Radio Medium)
Area of deployment	$600 * 600m^2$
Emulated nodes	Tmote Sky
Transmission power	$0dBm$ (Maximum available)
Transmission range	$50m$ (Radius of Coronas)
Mobility model	Random Waypoint Mobility Model

TABLE II: Simulation setup.

Table II summarizes the simulation settings. The node mobility is captured using the Random Waypoint Mobility Model [16]. This model has been proven to be useful and used by many others [6] [5]. Briefly, in this model, the destination, the speed and direction of a mobile node are all chosen independently and randomly for each moving node.

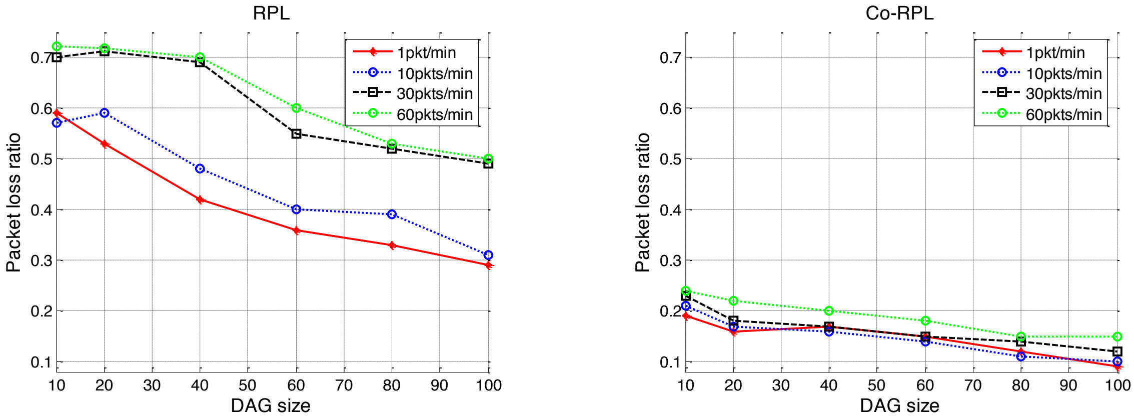
C. Simulation results

In order to understand the performance of Co-RPL, we performed extensive simulations comparing it with RPL. We varied the packet transmission rate, number of DAG roots and node speed, and we analyzed the effect on packet loss ratio, energy consumption, average hop count and end-to-end delay.

1) Impact of the packet transmission rate: A DAG is deployed consisting of a number of mobile nodes (varying between 10 and 100). To study the impact of data transmission rate on network behavior, we varied the rate from 1 to 60 packets per minute and measured energy consumption, packet loss ratio and average end to end delay. The results are summarized below.

Packet Loss Ratio

The simulation results in Fig. 5 show that the packet loss ratio decreases slightly with the increase in network size. This is obvious as when there is a high number of neighbors, mobile nodes are able to find alternate paths easily, which reduces packet loss. Even then we see that Co-RPL experiences lower packet loss than RPL (between 20% and 45%). This is primarily due to the forwarding strategy of Co-RPL, that uses corona, allowing it to detect mobile nodes and find alternative parents. In addition, the forwarding mechanism in Co-RPL is more flexible than that of RPL because it implements a path recovery mechanism to recover from node failures. Thus, Co-RPL reduces the unreachability periods when a mobile node



(a) RPL packet loss ratio

(b) Co-RPL packet loss ratio

Fig. 5: Impact of data transmission rate on packet loss ratio of RPL and Co-RPL.

cannot find a forwarding neighbor. In Fig. 5a, RPL exhibits increasing packet loss ratios with the increase of the packet transmission rate (Fig. 5a). However, Co-RPL is shown to be stable and experiences only small variances in packet loss with all transmission rates (Fig. 5b).

Energy Consumption

We measure the energy consumption by varying the network density in a network composed of a single DAG. Fig. 6 shows that both RPL and Co-RPL consume more energy with the increase of the packet transmission rate. This increase is due to the additional amount of data packets transmitted. But, the results in Fig. 6b also show that Co-RPL consumes nearly 50% less energy when compared to RPL. This high energy consumption for RPL is due to high packet loss. Indeed, a successful transmission consumes less energy than a unsuccessful one (due to CSMA retransmissions until failure). Packet loss also triggers control messages as the mobile node attempts to select another parent. Even with this amount of control packets caused by Co-RPL, the energy consumption remains low.

Average Delay

The end-to-end delay is defined as the total time taken by a packet from node to sink. As shown in Fig. 7, Co-RPL shows an average delay almost 2.5 seconds less than RPL. This is because of the forwarding mechanism in Co-RPL. Besides that, Fig. 7b shows that the maximum average end-to-end packet delay is around 9 seconds. This result is expected as heavy data traffic causes more collisions and the packets need to be buffered due to this which increases the overall delay all along the path to sink.

2) Impact of the Number of DAG roots: We investigated the impact of DAGs by varying the number of deployed DAGs and studied its effect on the metrics.

Packet Loss Ratio

Fig. 8 shows the impact of varying the number of DAG roots on the packet loss ratio. As expected, the packet loss ratio is reduced when the number of DAG roots increases. Fig. 8a shows that the packet loss ratio decreases by 10% for RPL when we add a DAG root. This is due to nodes getting closer to the sink and thus reducing the number of hops between nodes and their DODAG roots. This is also true for Co-RPL as shown in Fig. 8b but with lower values of packet loss. In fact, the packet loss ratio significantly decreases and reaches 0.1 for 3 DAG roots. This result demonstrates that deploying more roots enhances the performance of the MWSN using Co-RPL.

Energy Consumption

Fig. 9 shows the average energy consumption when varying the network size. It is clear that having more DAGs results in reduced energy consumption. This is also confirmed for static networks [13]. Thus, having multiple DAG roots in the network saves energy as the traffic is distributed among different DAG roots and the overall number of hops for data transmission are reduced.

Average Delay

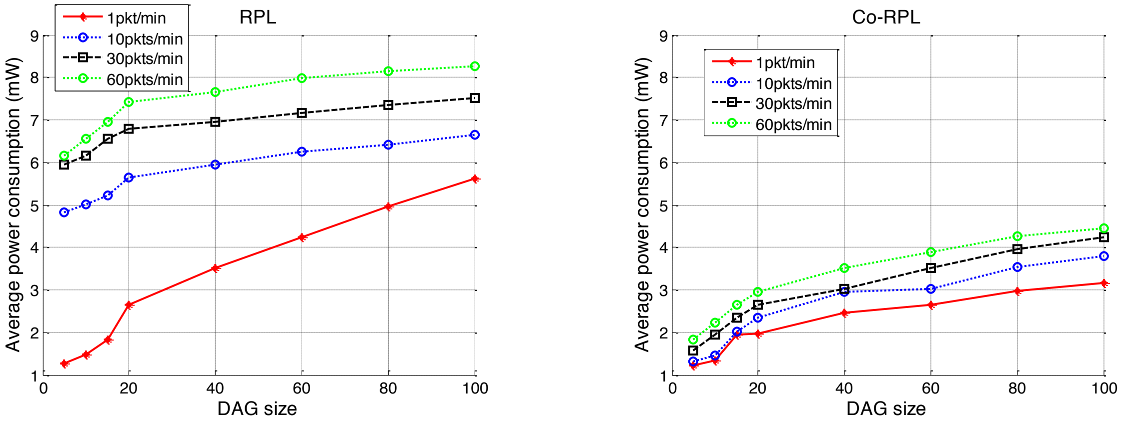
We measured the average network delay while varying the number of DAG roots from 1 to 3. From Fig. 10, the impact of adding DAG roots on the delay is not significant in small networks (less than 40 nodes). For networks of large sizes, the average end-to-end delay decreases when the number of DAG roots increases. Fig. 10a shows that adding a DAG root minimizes network delay by at least 1 second in large scale networks. The presence of multiple DAG roots reduces the number of hops between the RPL router and the mobile sink, and thus minimizing the number of hops, which significantly impacts the delay in both static and mobile networks. Fig. 10b shows that Co-RPL experiences lower delays (up to 2 seconds), which demonstrates the efficiency of the corona mechanism.

3) Impact of Node Speed: The speed of mobile nodes is an important factor that affects the performance of MWSNs. We investigated this issue by varying the speed of mobile nodes from 1m/s$(tocapturehumanwalkingspeed)to4m/s$ (to emulate scenarios with a high speed robot, such as Kurt3D [15].

Packet Loss Ratio

Fig. 11 shows the average packet loss ratio with respect to node speed. RPL suffers from packet losses greater than 0.39% when the node speed is $4m/s$. Co-RPL manages to maintain a packet loss ratio as small as 0.2% even at high node speeds. This improvement of Co-RPL is due to its responsiveness to frequent topology changes.

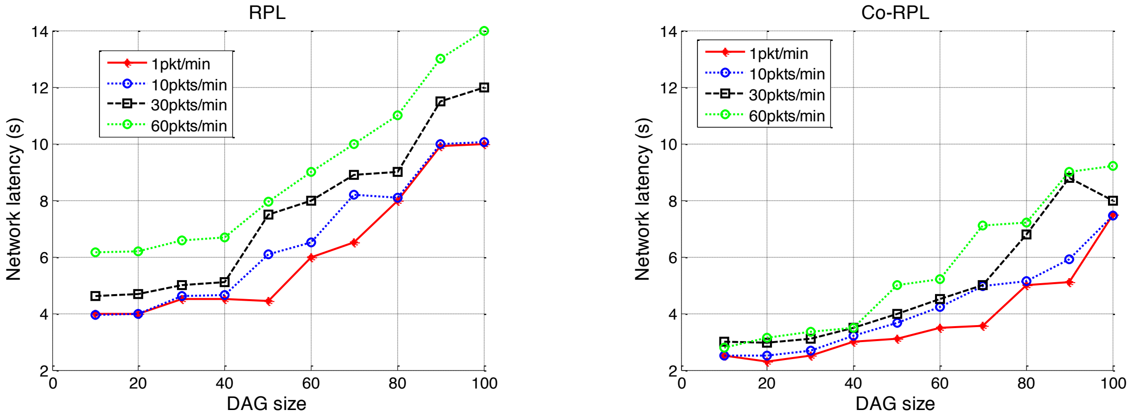
Energy Consumption Fig. 12 shows the impact of the node speed on the average energy consumption. Mobile nodes



(a) Average energy consumption for RPL

(b) Average energy consumption for Co-RPL

Fig. 6: Influence of the data trasmission rate on RPL and Co-RPL in term of energy consumption



(a) Average delay for RPL

(b) Average delay for Co-RPL

Fig. 7: Influence of the data trasmission rate on RPL and Co-RPL in term of energy consumption

consume almost the same amount of energy when the speed varies from $1m/s$ and $3m/s$. For a speed equal to $4m/s$, the energy consumption becomes high (around $7mW$). This is due to the high packet loss ratio affecting the power of mobile nodes. In addition, Fig. 12b shows that there is only a small variation in energy consumption at all speeds (less than $1mW$), for any network size. This result clearly reflects the stability of Co-RPL.

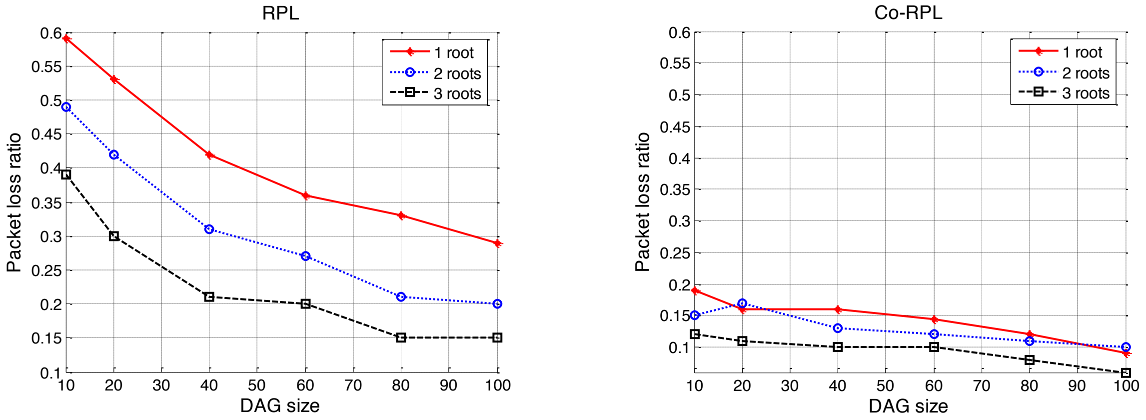
Average Delay

Fig. 13 presents the network delay results. For RPL, the network delay increases with the speed of mobile nodes. Indeed, at $4m/s$, the delay is equal to 14.2 seconds, for 100 nodes. This shows that RPL induces large delays in high node speed scenarios. This is expected as higher speeds result in higher numbers of parent changes due to the dynamic changes of the network topology. Using Co-RPL, the average delay is reduced to 10 seconds for 100 nodes. This is due to the corona mechanism that reduces the average hop count between each mobile node and the DAG root (and results in lower packet loss ratio). In addition, there is a smaller variation between all speeds of mobile nodes in Co-RPL reflecting its stability.

V. CONCLUSION

In this paper, we proposed Co-RPL, an enhancement of RPL using the corona mechanism that supports mobility of RPL routers. Co-RPL requires minimal add-ons as it reuses the same control messages and preserves backward compatibility with the standard specification. We evaluated RPL and Co-RPL in a MWSN scenario, composed of fixed DAGs and mobile nodes with varying speeds. We have demonstrated that the standard RPL is very limited in terms of provision of QoS guarantees for MWSNs. In addition, we found out that, when compared to RPL, Co-RPL experiences lower packet loss ratios by up to 45%, lower average energy consumption by up to 50% and lower end to end delay by up to 2.5 seconds. We have shown that Co-RPL can be used efficiently for mobile low power and lossy wireless sensor networks.

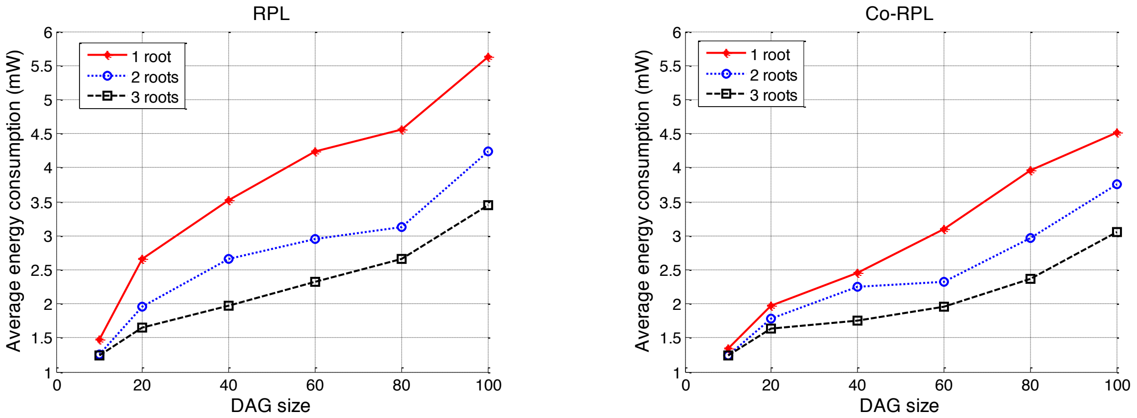
We are currently working towards the experimentation and testing of Co-RPL to evaluate its performance in real deployment. We also aim at using the proposed Co-RPL mechanism for sensor data collection applications using mobile robots, where the robots play the role of the mobile nodes. In addition, we will also work on investigating the case of



(a) Packet loss ratio for RPL

(b) Packet loss ratio for Co-RPL

Fig. 8: Comparison of the packet loss ratio between RPL and Co-RPL by varying the number of DAG roots



(a) Average energy consumption for RPL

(b) Average energy consumption for Co-RPL

Fig. 9: Comparison of the network delay between RPL and Co-RPL by varying the number of DAG roots

mobile sinks, and the effect of sink mobility on the network performance.

ACKNOWLEDGEMENTS

This work was partially supported by the North Portugal Regional Operational Programme (ON.2 O Novo Norte), under the National Strategic Reference Framework (NSRF), through the European Regional Development Fund (ERDF), and by National Funds through FCT (Portuguese Foundation for Science and Technology), within project ref. NORTE-07-0124-FEDER-000063 (BEST-CASE, New Frontiers); by National Funds through FCT and by ERDF (European Regional Development Fund) through COMPETE (Operational Programme Thematic Factors of Competitiveness), within projects FCOMP-01-0124-FEDER-037281 (CISTER), FCOMP-01-0124-FEDER-020312 (SMARTSKIN) and FCOMP-01-0124-FEDER-028990 (PATTERN); by FCT and the EU ARTEMIS JU under grant nr. 621353 (DEWI); also by FCT and ESF (European Social Fund) through POPH (Portuguese Human Potential Operational Program) under PhD grant SFRH/BD/67096/2009.

This work is also partially supported by CES Research Lab of the National School of Engineering of Sfax (Tunisia) and by Prince Sultan University (Saudi Arabia).

REFERENCES

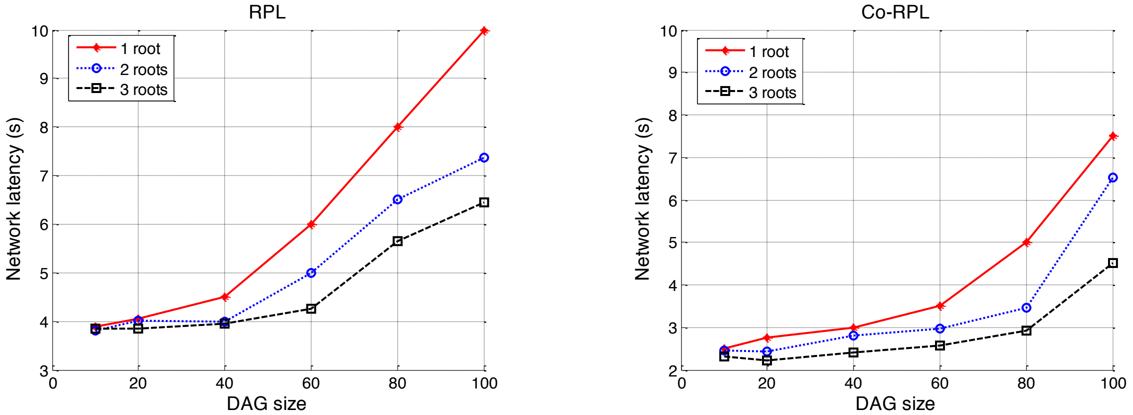
[1] "Contiki operating system." [Online]. Available: http://www.contiki-os.org/

[2] Cooja simulator. [Online]. Available: http://www.sics.se/ fros/cooja.php

[3] L. Ben 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*. Nice, France: IARIA, Aug. 2011. [Online]. Available: http://hal.inria.fr/hal-00647869

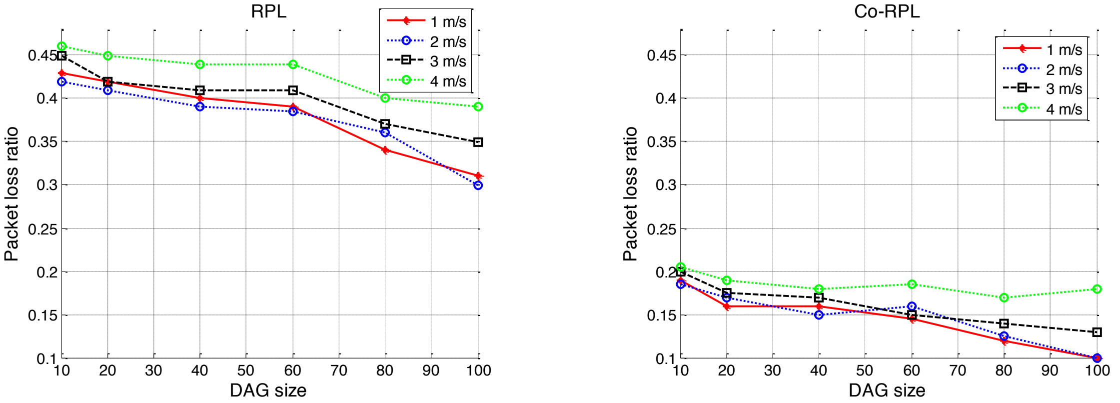
[4] L. Ben Saad and B. Tourancheau, "Sinks Mobility Strategy in IPv6-based WSNs for Network Lifetime Improvement," in *International Conference on New Technologies, Mobility and Security (NTMS)*. Paris, France: IFIP, 2011. [Online]. Available: http://hal.inria.fr/inria-00563724

[5] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," in *Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, ser. MobiCom '98. New York, NY, USA: ACM, 1998, pp. 85–97. [Online]. Available: http://doi.acm.org/10.1145/288235.288256



(a) Average network delay for RPL (b) Average network delay for Co-RPL

Fig. 10: Comparison of the network delay between RPL and Co-RPL by varying the number of DAG roots



(a) Packet loss ratio for RPL (b) Packet loss ratio for Co-RPL

Fig. 11: Comparison of the packet loss ratio between RPL and Co-RPL by varying the speed of mobile nodes

[6] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," *Wireless Communications and Mobile Computing (WCMC): Special Issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, vol. 2, pp. 483–502, 2002.

[7] M. Cardei, Y. Yang, and J. Wu, "Non-uniform sensor deployment in mobile wireless sensor networks," in *World of Wireless, Mobile and Multimedia Networks, 2008. WoWMoM 2008. 2008 International Symposium on a*, June 2008, pp. 1–8.

[8] T.-C. Chen, T.-S. Chen, and P.-W. Wu, "On data collection using mobile robot in wireless sensor networks," *Trans. Sys. Man Cyber. Part A*, vol. 41, no. 6, pp. 1213–1224, Nov. 2011. [Online]. Available: http://dx.doi.org/10.1109/TSMCA.2011.2157132

[9] M. Di Francesco, S. K. Das, and G. Anastasi, "Data collection in wireless sensor networks with mobile elements: A survey," *ACM Trans. Sen. Netw.*, vol. 8, no. 1, pp. 7:1–7:31, Aug. 2011. [Online]. Available: http://doi.acm.org/10.1145/1993042.1993049

[10] H. Fotouhi, M. Alves, M. Zuniga, and A. Koubaa, "Reliable and fast hand-offs in low-power wireless networks," *IEEE Transactions on Mobile Computing*, vol. 99, no. PrePrints, p. 1, 2014.

[11] O. Gaddour and A. Koubáa, "Survey rpl in a nutshell: A survey," *Comput. Netw.*, vol. 56, no. 14, pp. 3163–3178, Sep. 2012. [Online]. Available: http://dx.doi.org/10.1016/j.comnet.2012.06.016

[12] O. Gaddour, A. Koubâa, N. Baccour, and M. Abid, "Of-fl: Qos-aware fuzzy logic objective function for the rpl routing protocol," in *12th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, Mai 2014, pp. 365–372.

[13] O. Gaddour, A. Koubaa, S. Chaudhry, M. Tezeghdanti, and M. Abid, "Simulation and performance evaluation of dag construction with rpl," in *Communications and Networking (ComNet), 2012 Third International Conference on*, 2012.

[14] K.-S. Hong and L. Choi, "Dag-based multipath routing for mobile sensor networks," in *ICT Convergence (ICTC), 2011 International Conference on*, 2011, pp. 261–266.

[15] Project kurt3d. Institute of Computer Science Knowledge-Based Systems Research Group. [Online]. Available: http://www.inf.uos.de/kbs/KURT3D.html

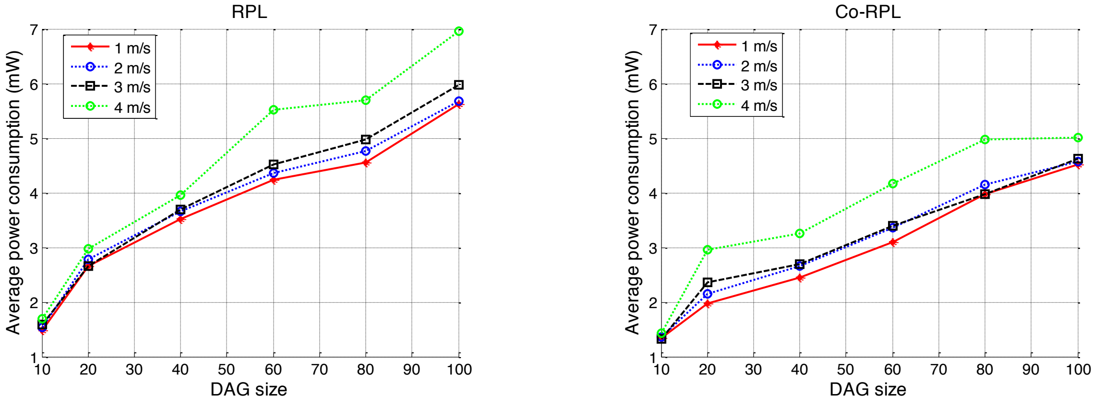
[16] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*. Kluwer Academic Publishers, 1996, pp. 153–181.

[17] I. Korbi, M. Ben Brahim, C. Adjih, and L. Saidane, "Mobility enhanced rpl for wireless sensor networks," in *Network of the Future (NOF), 2012 Third International Conference on the*, 2012, pp. 1–8.

[18] X. Lai, Q. Liu, X. Wei, W. Wang, G. Zhou, and G. Han, "A survey of body sensor networks," *Sensors*, pp. 502–521, 2013.

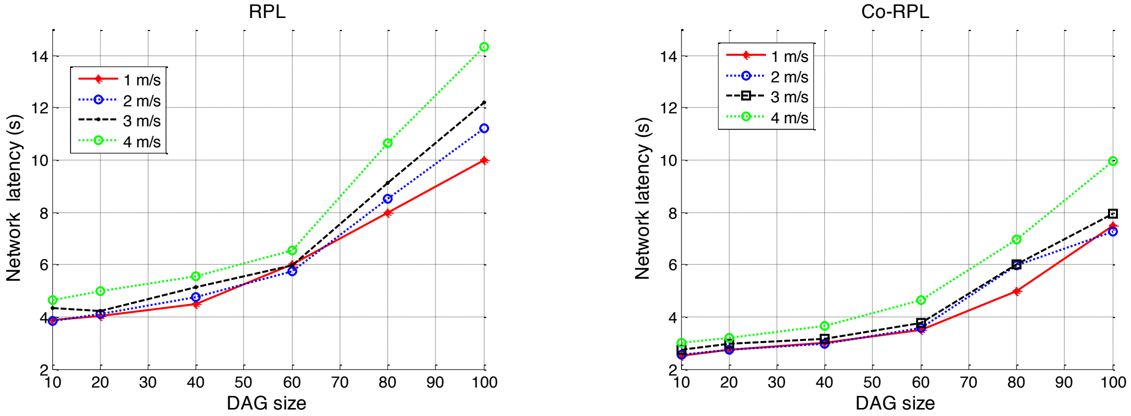
[19] K. C. Lee, R. Sudhaakar, and J. Ning, "A comprehensive evaluation of rpl under mobility," *International Journal of Vehicular Technology*, 2012.

[20] J. Li, K. Li, and Z. Wei, "Improving sensing coverage of wireless sensor networks by employing mobile robots," in *Robotics and Biomimetics,*



(a) Average energy consumption for RPL (b) Average energy consumption for Co-RPL

Fig. 12: Comparison of the average energy consumption between RPL and Co-RPL by varying the speed of mobile nodes



(a) Average end to end delay for RPL (b) Average end to end delay for Co-RPL

Fig. 13: Comparison of the network delay between RPL and Co-RPL by varying the speed of mobile nodes

2007. ROBIO 2007. IEEE International Conference on, Dec 2007, pp. 899–903.

[21] A. Liu, X. Jin, G. Cui, and Z. Chen, “Deployment guidelines for achieving maximum lifetime and avoiding energy holes in sensor network,” *Inf. Sci.*, vol. 230, pp. 197–226, May 2013. [Online]. Available: http://dx.doi.org/10.1016/j.ins.2012.12.037

[22] S. Olariu and I. Stojmenovic, “Design guidelines for maximizing lifetime and avoiding energy holes in sensor networks with uniform distribution and uniform reporting,” in *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, April 2006, pp. 1–12.

[23] A. A. Papadopoulos, A. Navarra, J. A. McCann, and M. C. Pinotti, “Vibe: An energy efficient routing protocol for dense and mobile sensor networks.” *J. Network and Computer Applications*, vol. 35, no. 4, pp. 1177–1190, 2012. [Online]. Available: http://dblp.uni-trier.de/db/journals/jnca/jnca35.html

[24] V. Safdar, F. Bashir, Z. Hamid, H. Afzal, and J. Y. Pyun, “A hybrid routing protocol for wireless sensor networks with mobile sinks,” in *Wireless and Pervasive Computing (ISWPC), 2012 7th International Symposium on*, 2012, pp. 1–5.

[25] B. Tian, K. M. Hou, H. Shi, X. Liu, X. Diao, J. Li, Y. Chen, and J.-P. Chanet, “Application of modified rpl under vanet-wsn communication architecture,” in *Computational and Information Sciences (ICCIS), 2013 Fifth International Conference on*, 2013, pp. 1467–1470.

[26] H. Turner, J. White, B. Dougherty, and D. Schmidt, *Building Mobile Sensor Networks Using Smartphones and Web Services: Ramifications and Development Challenges*, I. Global, Ed. Handbook of Research on Mobility and Computing: Evolving Technologies and Ubiquitous Impacts, 2011.

[27] Y. Wang, H. Wu, F. Lin, and N.-F. Tzeng, “Protocol design and optimization for delay/fault-tolerant mobile sensor networks,” in *Distributed Computing Systems, 2007. ICDCS ’07. 27th International Conference on*, June 2007, pp. 7–7.

[28] S. R. Wankhade and N. A. Chavhan, “A review on data collection method with sink node in wireless sensor network,” *International Journal of Distributed & Parallel Systems*, vol. 4, pp. 67–74, Jan2013.

[29] T. Winter, P. Thubert, A. Brandt, J. Hui, and R. Kelsey, “RPL: IPv6 Routing Protocol for Low Power and Lossy Networks,” *IETF Request for Comments 6550*, March 2012.

[30] X. Wu, G. Chen, and S. Das, “Avoiding energy holes in wireless sensor networks with nonuniform node distribution,” *Parallel and Distributed Systems, IEEE Transactions on*, vol. 19, no. 5, pp. 710–720, May 2008.

[31] Y. Yang, M. I. Fonoage, and M. Cardei, “Improving network lifetime with mobile wireless sensor networks,” *Comput. Commun.*, vol. 33, no. 4, pp. 409–419, Mar. 2010. [Online]. Available: http://dx.doi.org/10.1016/j.comcom.2009.11.010

[32] H. Zhang and H. Shen, “Balancing energy consumption to maximize network lifetime in data-gathering sensor networks,” *Parallel and Distributed Systems, IEEE Transactions on*, vol. 20, no. 10, pp. 1526–1539, 2009.