2017 IEEE 31st International Conference on Advanced Information Networking and Applications

Braided on Demand Multipath RPL in the Mobility Context

Fatma Somaa*†, Inès El Korbi*‡ and Leila Azouz Saidane*
*National School of Computer Science, University of Manouba, 2010 Tunisia
†SESAME university, Tunisia
‡High Institute of Computer Science, University of Tunis El Manar, Tunisia
* {ines.korbi, leila.saidane}@ensi.rnu.tn, fatma.somaa@sesame.com.tn

***Abstract*—Wireless sensor networks (WSNs) are considered as the key technology for IoT (Internet of Things) applications thanks to their robustness and their deployment ease. The IPv6 Routing Protocol for Low power and Lossy Networks (RPL) is placed as the routing standard for multi-hop WSNs. However, RPL poorly adapts to sensor nodes' movement which rapidly alters the network performance. Therefore, we propose in this paper, a Bayesian model to accurately predict the sensor nodes' speed distributions. Then, we introduce the Mobility based Braided Multipath RPL (MBM-RPL) to support mobility over RPL. MBM-RPL establishes a primary path based on a new routing metric that exploits the predicted sensor nodes' speed values. An alternative path is established to prevent links expiration along the primary path. To evaluate the performance of MBM-RPL, we first validate the accuracy of the Bayesian model using the Cooja simulator. Then, we compare the performance of MBM-RPL with other RPL based approaches in terms of packet loss rate (PLR) and average transmission delay (ADT).**

I. Introduction

Today, the expansion of applications like smart homes, smart grids, intelligent transportation or e-heath made them more and more useful, even essential, in our everyday life. These applications deploy a large number of objects such as sensors, actuators, RFID tags to perform sensing/idenfication tasks and communicating the collected information, generally though wireless links, to particular sink nodes. These nodes will be in charge of transmitting this big data amount, through wired infrastructure, to control centers for treatment. The new paradigm of Internet of Things (IoT) is introduced to designate such a system of billions of connected objects.

Thank to their characteristics (autonomy, self configuration, fault tolerance, etc.), wireless sensor networks (WSNs) are considered as a key technology for IoT. Nevertheless, WSNs may suffer from some weaknesses inherent to sensor devices' proprieties (such as limited memory and limited battery). One of the most common issues in WSNs is how to optimize the data transmission while maximizing the network lifetime. In this context, the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [24] was proposed by the IETF, for low-power and lossy networks (LLNs), to comply with the sensor nodes' characteristics. With RPL, the routes are constructed in the sink direction and require few control traffic to be maintained. Moreover, as long as the network status is consistent (no topological changes, no broken links, etc.), RPL reduces the amount of routing updates, hence limiting the energy consumption in the network.

This particular RPL behavior is inappropriate for some networks' scenarios where sensor nodes may, unpredictably, quit their initial positions and move to other positions in the network. In this case, it would take a relatively long time to RPL to repair the DODAG resulting in an important packet loss rate. Several works highlighted the limits of RPL in the mobility context and proposed to adapt the native RPL to account for the nodes' movement [8], [17], [4] and [5]. But most of the existing solutions proposed to tune some options/variables in the native RPL to support the nodes' mobility. None of these solutions proposed to use the multipath routing in RPL to overcome the mobility issues. On the other hand, all the works that target the multipath routing in RPL [3] [7] and [9], only focused on load balancing, fault tolerance or quality of service (QoS) purposes.

Hence our contribution in this paper is two fold. First, we propose a Bayesian framework for sensor nodes' speed (velocity) prediction in WSNs. Then, we propose a multipath routing over RPL called Mobility based Braided Multipath RPL (MBM-RPL) to efficiently support the sensor nodes' mobility.

The rest of the paper is organized as follows. Section II presents 1) the fundamental concepts of RPL, 2) the works related to mobility support and multipath routing over RPL and 3) finally the problem statement. Section III presents the Bayesian framework we introduce to accurately predict the nodes' speed values in WSNs. Section IV presents the different mechanisms of the MBM-RPL scheme. Section V evaluates the performance of MBM-RPL and compares it to other RPL based approaches. Section VI concludes the paper and presents future directions.

II. Related Work and Problem Statement

A. The RPL Protocol Overview

RPL is a distance-vector routing protocol designed to present a specific routing solution for LLNs [24]. With RPL, a Destination-Oriented Directed Acyclic Graph (DODAG) is constructed to route the information to a single destination (the sink node). Each node in this graph has a rank which defines the node's individual position relative to other nodes. This rank is computed according to an Objective Function

1550-445X/17 $31.00 © 2017 IEEE
DOI 10.1109/AINA.2017.168

IEEE computer society

(OF) that depends on constraints and/or metrics. The default objective function in RPL is the minimum rank with hysteresis objection function (MRHOF) [18] which uses the estimated transmission count (ETX) as a metric. This metric estimates the amount of transmissions needed to successfully deliver a packet to a neighbouring node. To construct the DODAG and calculate a node 's rank, RPL defines four ICMPv6 control messages:

- The DODAG Information Object (DIO) allows a node to discover a RPL instance according to its configuration parameters (metrics, constraints, neighbor's rank, etc.).
- The DODAG Information Solicitation (DIS) is used to solicit a DIO from a RPL node. It is used when a node needs to join the network before receiving a DIO.
- The Destination Advertisement Object (DAO) is sent from a child node to a given parent along the upward (to the sink) path.
- The Destination Advertisement Object Acknowledgement (DAO-ACK) is sent from a parent to the child node as a DAO response.

Initially, the DODAG ROOT (the sink) broadcasts a DIO message. Each node n_i, receiving this DIO, calculates its rank based on the rank included in the DIO message and the routing metric. The node n_i joins the DODAG by choosing a preferred parent, among its neighbors, based on the received rank values. The node n_i, then, broadcast a new DIO message to all its neighbors. This process is repeated until DIO messages reach all the nodes in the network. If a node wants to join the DODAG before receiving any DIO, it sends a DIS message to solicit a DIO and join the DODAG. The upward routes to the sink are created by the transmission of DAO messages. Each node receiving a DAO, must answer with a DAO-ACK message.

To reduce the overhead generated by control messages, RPL uses the Trickle timer [19]. This timer directly impacts the inter-DIO interval and is incremented as long as no topological changes are detected in the network. If any change is detected, the Trickle is reset, but DIO messages can not be sent before the expiration of the new Trickle value.

The above description of RPL clearly illustrates how the initial design of the protocol badly support some particular networks scenarios, for instance the nodes' mobility. In mobility conditions, the Trickle timer will preclude RPL from immediate repair of the failed paths upon the nodes' movement.

B. Mobility Support over RPL

Several approaches were proposed in literature to adapt RPL to the mobility context. [11] evaluates the behavior of the native RPL in fixed and mobile sink environments. It uses different network metrics (latency, packet delivery ratio (PDR) and energy consumption) under different mobility scenarios. The results show that fixed sinks in LLNs perform better than mobile sinks in terms of average power consumption, latency and PDR. The work in [8] classifies sensor nodes in two categories: mobile nodes and fixed nodes (Access points - AP). Mobile nodes send DIS messages to select their preferred parents among their neighboring APs based on their RSSI (Received Signal Strength Indication). APs answer with DIO messages and the AP with the highest RSSI is selected as the preferred parent. Then, a fixed number of data packets is transmitted by the mobile node. Mobile nodes alternate parent discovery and data transmission phases to be always attached to the AP with the highest RSSI in the DODAG. The main drawback of [8] is the large overhead induced by the periodic exchange of DISs, DIOs and DAOs. Moreover, APs must have a large storage capacity to save the mobiles nodes' packets while they are performing handover to another AP. Corona-RPL (Co-RPL) [17] uses Corona localization technique to estimate the sensor's position in motion. It divides the network into circular areas centered at each sink called Coronas. Each DAG root periodically sends DIOs to determine the actual positions of mobile nodes. The inter-DIO interval is adjusted based on the nodes'speed values. The problem with Co-RPL is that localization techniques are generally prone to errors especially when the error propagates from one location to another [1]. [4] proposes a new cross-layer protocol called Mobility-Triggered RPL (MT-RPL). MT-RPL introduces a new X-Machiavel MAC that prioritizes access to mobile nodes with data to transmit. Even though MT-RPL reduces the mobile nodes' disconnection time and increases their PDR, it is a MAC dependant routing protocol and requires a full synchronization with the superframe. This may not be easily achievable, especially, in the mobility context. [5] proposes a downward path mechanism for routing towards mobile nodes. Despite minimizing the probability of connectivity loss, [5] preconizes the periodic exchange of DIS messages for neighbors' discovery which significantly increases the overhead in the network.

Recently, the Bayesian based Mobility Prediction RPL (BMP-RPL) [6] proposes a new Bayesian model to accurately predict the nodes' speeds. Then, a new routing metric is introduced over RPL to calculate the best route to the sink based on the residual links' lifetimes. A link lifetime is evaluated based on its edging nodes' speeds. Even though BMP-RPL outperforms RPL in terms of delay and PDR, it completely rely on the native RPL update routines (based on the Trickle Timer). This may delay the routes' repair process in the case of fast nodes' movement.

C. Multipath Routing over RPL

Multipath routing protocols have been widely studied in wireless sensor networks [21] and mobile ad hoc networks [15]. They were proposed to ensure fault-tolerance, congestion-avoidance, load balancing and QoS. We can find either disjoint multipath or braided multipath routing schemes. In disjoint multipath, the nodes/links within each route are different. Thus, a failure on a given path does not affect any other path. However, maintaining all the alternative paths requires a global knowledge of the network topology, thus resulting in a high energy consumption level. In braided multipath however, we can establish for any node n_i, an alternative path that does not contain n_i. Thus, few energy resources are required to establish alternative paths as they overlay with primary paths. Recent works exploit the multipath routing over RPL for many purposes. In [9], the authors propose Congestion Avoidance-RPL (CA-RPL) that aims to increase the reliability and to reduce the latency in the network. CA-RPL proposes a new routing metric (DELAY ROOT) based on the ContikiMAC duty cycling protocol. In CA-RPL, a node sends packets to the parents that are already awake, instead of waiting for the preferred parent to wake up. CA-RPL dispatches the data on different paths to avoid congestion and to reduce delays in the network. However, the new metric introduced by CA-RPL assumes that all the nodes have the same wake-up interval which may not be true for all WSNs scenarios.

To increase the network lifetime, the authors in [3] propose an energy-balancing routing scheme where all paths have to consume the same amount of energy. Hence, each node sends a list of all known bottlenecks as part of the DIO message which, considerably, increases the original DIO size and henceforth the protocol overhead. Moreover, the algorithm proposed in [3] to maintain the DODAG is relatively complex since the ETX metric is used to construct the DODAG and the ELT (Expected LifeTime) metric is used to compute the rank of each node in the routing graph.
To improve the Packet Delivery Ratio (PDR), [7] uses the default RPL metric ETX, for the first path construction and proposes a new metric based on nodes' remaining energy for the second preferred parent selection. The rank calculation is based on the probability of unsuccessful transmissions. The results show that the proposed scheme improves the packet delivery ratio, especially for environments with a high bit error rate and balance the energy consumption in the network.

D. The Problem Statement

All the solutions proposed to support mobility over RPL only focused on the establishment of a unique path towards the sink from each node in the DODAG. None of these solutions preconized to use an alternate path to prevent the primary path failure. On the other hand, multipath routing schemes were introduced in RPL to ensure congestion avoidance, energy balancing or fault tolerance in LLNs. None of these solutions targets the mobility issue in RPL. Hence, we propose in this paper a multipath routing scheme called Mobility based Braided Multipath RPL (MBM-RPL) to support mobility over RPL. MBM-RPL enhances the single path BMP-RPL scheme [6] discussed in Section II-B. BMP-RPL is a novel routing approach over RPL that constructs the routes to the sink based on the nodes' speeds estimated by a Bayesian inference approach. BMP-RPL achieves high performance in the mobility context, but presents a major problem. Although sensor nodes' movements are rapidly detected thank to an RPL-independent beaconing protocol, the routes are updated using the native RPL messages that obey to the Trickle rules. As a consequence, the BMP-RPL behavior roughly capture the sensor nodes' movements despite being accurately predicted by the Bayesian model. Hence, by introducing the braided multipath routing over RPL, we aim to overcome the limitations of BMP-RPL. In the following, we present the Bayesian model we adopt to predict the sensor nodes' speeds in WSNs.

III. A Bayesian Framework for Nodes Mobility Prediction

As stated earlier, WSNs are considered as the key technology for IoT applications. In many network configurations/scenarios, sensor nodes are prone to mobility. In the multi-hop context, routing protocols must be aware of such movement to guarantee that the information is correctly transmitted in the network. Several approaches were proposed to detect the nodes' mobility either based on the routing information [2], [12] or on the analytical models [20], [23]. But all these approaches roughly estimate the nodes' movement and do not provide accurate information about the nodes' speed values (velocities). An accurate prediction of sensor nodes' mobility can obviously aid the network to reactively adapt to rapid topological changes.

Hereafter, we present a Bayesian inference framework to predict sensor nodes' velocities [22]. In short: a node maintains an estimate of its speed as a distribution (the probability that the speed equals a certain value). The inference consists in having sensor nodes to update their speed estimates upon the occurrence of particular "link expiration" events. A "link expiration" event occurs if two sensor nodes get out of each other's communication range. Starting from any given unknown initial velocity distribution, the estimate will be gradually updated towards the actual values.

A. Assumptions and Notations

To derive the Bayesian model, we deliberately consider that sensor nodes have no information about their positions, velocities, speed variation, etc. The only information that allows predicting accurate speed values is the occurrence of the "link expiration" events caused by the sensor nodes' movement. Hence, we present the following assumptions:

- **Assumption 1:** Sensor nodes have limited resources and have no information to derive their speed values (GPS, accelerometer, etc.).
- **Assumption 2:** Sensor nodes' velocity magnitudes are constant over the time. Sensor nodes can however change direction.
- **Assumption 3:** We assume that the sensor nodes' directions are independently distributed [14].

We introduce the main notations:

- Let $\mathcal{E}$ be the particular event representing the link duration (before expiration) between two nodes U_1 and U_2; $\mathcal{E} = \{$ a link between U_1 and U_2 lasted for τ $\}$. $p_\tau(t)$ is the associated probability density function (*pdf*) of the link duration between two given nodes in the network.
- We also define $p_i(v_i)$, the *pdf* of the node U_i speed. $p_i(v_i)$ is called the prior speed distribution of the node U_i (prior to the event $\mathcal{E}$).

- Similarly, we have $p_{i,j}(v_i, v_j)$ the prior joint speed distribution.
- We also use the notation $p^+_{...}(...)$ for all the posterior distributions (after the occurrence of the event $\mathcal{E}$).

B. General Bayesian Inference

Exploiting the network dynamics, Bayesian inference allows updating posterior sensor nodes' speed distributions using the Bayes' rule. We consider a two nodes' scenario U_1 and U_2 having respective speeds v_1 and v_2, which were neighbor, and just observed the event $\mathcal{E}$ = their link has expired. Then, using the Bayes' rule, we have:

$$P(U_1 \text{ has a speed } v_1 \text{ and } U_2 \text{ has a speed } v_2| \text{ event } \mathcal{E}) = \frac{P(U_1 \text{ has a speed } v_1 \text{ and } U_2 \text{ has a speed } v_2)}{Pr(\mathcal{E})} \quad (1)$$

where $Pr(\mathcal{E})$ is the probability of the event $\mathcal{E}$. Therefore, the posterior speed joint distribution of v_1 and v_2, resulting from the prior joint distribution $p_{1,2}(v_1, v_2)$ and the observed broken link event $\mathcal{E}$, is:

$$p^+_{1,2}(v_1, v_2|\mathcal{E}) = \tfrac{1}{Pr(\mathcal{E})} p_\tau(\mathcal{E}|v_1, v_2) p_{1,2}(v_1, v_2) \quad (2)$$

Moreover, using the *assumption 3*, related to the independence of speeds v_1 and v_2, we have

$$p_{1,2}(v_1, v_2) = p_1(v_1) \times p_2(v_2) \quad (3)$$

As common in the Bayesian inference, $Pr(\mathcal{E})$ is a normalizing constant: it can be ignored, under condition to later normalize posterior distributions (e.g. $\int p = 1$).

$$p^+_1(v_1|\mathcal{E}) = \int_{v_2=0}^{+\infty} p^+_{1,2}(v_1, v_2|\mathcal{E}) dv_2 \quad (4)$$

From equations (2), (3) and (4) we obtain:

$$p^+_1(v_1|\mathcal{E}) \propto p_1(v_1) \int_{v_2=0}^{\infty} p_\tau(t|v_1, v_2) p_2(v_2) dv_2 \quad (5)$$

In this paper, w focus on "link expiration" events. Thus, from the inference formula in equation (5), deriving posterior speed distributions depends on the quantity $p_\tau(t|v_1, v_2)$: the probability that a link lasts for a duration t given prior speed distributions v_1 and v_2. Link duration is a random variable because the angle between the nodes is unknown (supposed uniform in $[0, 2\pi]$). To evaluate the link duration, different studies focused on link dynamics using the GPS approach [26] or the empirical residual link lifetime [13], etc. Here, we propose to derive a simple expression of link duration using the property: the *"minimum distance during the encounter"* between two nodes is uniformly distributed in $[-R, R]$ [16]. Two nodes encounter each other when the distance between them becomes smaller than the communication range R.

We first start with a normalized/unit parameters assuming that $v = 1$ and the communication radio range $R = 1$. We denote by $p_{\bar\tau}(t)$ the pdf of link duration with unit parameters. Let U_1 and U_2 be the nodes of the link (U_1 has speed 0, U_2 has speed v). To simplify the notation, without loss of generality, we assume that U_2 is moving horizontally. Let y be the closest distance between U_1 and U_2 when they are in the communication range of each other. We assume that y is an instance of a random variable Y, uniformly distributed in $[0, 1]$ with density $p^*_Y(y) = 1$. The relation between Y and the duration t is given by $t = f(y) = 2\sqrt{1-y^2}$. As in [25], we define:

$$p_{\bar\tau}(t) = |\frac{1}{f'^{-1}(t))}|p_Y(f^{-1}(t)) = |1/f'^{-1}(t))| \quad (6)$$

After calculating $f'(x)$ and $f^{-1}(x)$, we get:

$$p_{\bar\tau}(t) = \frac{t}{2\sqrt{4-t^2}} \quad (7)$$

Now, if we remove the assumption about v and R, we have $\tau_{actual} = \dfrac{R}{v}\tau_{normalized}$. Thus, we apply the change of variable $\tau = g(\bar\tau) = \frac{R}{v}\bar\tau$

$$p_\tau(t) = \frac{1}{g'^{-1}(t))} p_{\bar\tau}(g^{-1}(t)) = \frac{v}{R} p_{\bar\tau}(\frac{v}{R}t) \quad (8)$$

This value is only defined when $0 \le \frac{v}{R}t < 2$, in other words $t < \frac{2R}{v}$. In the following, we assume that $R = 1$ and v will be expressed in the following units: *"radio-range per unit time"* (instead of *"unit distance per unit time"*). Then:

$$p_\tau(t) = v p_{\bar\tau}(vt) \quad (9)$$

The speeds v_1 and v_2 result in a relative speed v equal to $v = h(\theta) = \sqrt{v_1^2 + v_2^2 - 2v_1v_2\cos(\theta)}$, where θ is the angle between the nodes and is uniformly distributed in $[0, 2\pi]$. Using the same computations as in (6) and (8), we have for $v \in]|v_1 - v_2|, v_1 + v_2[$:

$$p_V(v|v_1, v_2) = \frac{2v}{\pi\sqrt{4v_1^2v_2^2 - (v_1^2 + v_2^2 - v^2)^2}}$$

We can then express the conditional probability $p_\tau(t|v_1, v_2)$ that a link lasts for a duration τ when nodes have speeds v_1 and v_2. Notice that:

- The minimum possible relative speed is: $|v_1 - v_2|$ (two nodes in the same direction).
- The maximum possible relative speed is: $v_1 + v_2$ (two nodes crossing each other in the opposite direction).
- The maximum possible relative speed that could result in a link of duration t, is $v = \frac{2}{t}$.

We denote $v_\ell(v_1, v_2, t) = \min(v_1 + v_2, \frac{2}{t})$ the maximum relative speed, given v_1 and v_2, that could possibly yield a link of duration t. Thus:

$$p_\tau(t|v_1, v_2) = 0 \text{ if } \frac{2}{|v_1 - v_2|} < t, \text{ otherwise :}$$

$$\begin{aligned} p_\tau(t|v_1, v_2) &= \int_v p_\tau(t|v) p_V(v|v_1, v_2) dv \\ &= \int_{v=|v_1-v_2|}^{v=v_\ell(v_1,v_2,t)} \frac{v^3 t}{\pi\sqrt{(4-v^2t^2)(4v_1^2v_2^2-(v_1^2+v_2^2-v^2)^2)}} dv \end{aligned} \quad (10)$$

C. The Bayesian Inference Implementation

To implement the Bayesian inference model in WSNs, sensor nodes have to detect "link expiration" events. Then, Bayesian inference can be performed with discretized quantities: each node U_i maintains a vector V_i of n discrete velocity values representing its discretized pdf and initialized it with random distribution. Upon the occurrence of a link expiration event $\mathcal{E}$ between two nodes U_1 and U_2, the node U_1 evaluates the matrix $M(\tau_{\mathcal{E}}) = \left[p_\tau(\tau_{\mathcal{E}}|v_1, v_2)\right]$ for all possible values of v_1 and v_2, $p_\tau(\tau_{\mathcal{E}}|v_1, v_2)$ is given by equation (10). Then the posterior speed distribution V_1^+, is computed as follows:

$$V_1^+ \propto V_1 \circ (M(v_{\mathcal{E}})V_2) \tag{11}$$

where $\circ$ is the element-wise product (Hadamard product). V_1^+ is obtained by renormalizing the right hand of the expression. The node U_2 performs the same evaluation steps. Once U_1 computed its posterior distribution V_1^+, it broadcasts it to its neighbors, hence to be considered in the next velocity estimation round when another "broken link" event occurs. To reduce the overhead generated by periodic exchange of posterior speed distributions, actual speed distributions can be modelled as Gaussians. Therefore, each node U_i computes its posterior speed distribution vector V_i^+, evaluates the mean $\mu_{V_i^+}$ and the standard deviation $\sigma_{V_i^+}$ values and send them to its neighbors. The receiver reconstructs the pdf of the posterior distribution as:

$$p_{v_i}^+(v_i) = \frac{1}{\sigma_{V_i^+}\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{v_i - \mu_{V_i^+}}{\sigma_{V_i^+}}\right)^2} \tag{12}$$

From equation (12), we derive discretized values of speed distribution $p_{v_i}^+(v_i)$.

IV. MOBILITY BASED BRAIDED MULTIPATH RPL

The Bayesian model, we derived in the previous Section, accurately predicts the nodes' speed values upon the occurrence of "link expiration" events. To detect these events, each node needs to maintain a consistent information of its neighborhood that is periodically refreshed. In the context of RPL, DIO messages are subject to the Trickle timer that fluctuates depending on the topological changes. Thus, DIOs can not be used to correctly detect the "link expiration" events. Hence, we introduce an RPL-independent Hello-beaconing mechanism that allows sensor nodes to update their posterior speed distribution, as described in Section III-C, upon the occurrence of a "link expiration" event. This event is detected if no Hello message is received within a Hello-timeout period. A Hello message, described in Figure 1, is a 16-byte short message comprising the following fields:

- "0x00": The first byte differentiates the Hello beacon from other RPL messages.
- "node-id": This field states for the node's identity and is compliant with the IEEE 802.15.4 [10] short addresses.
- "seq-nbr": This sequence number identifies the message and is incremented each inter-Hello period.
- "M": The mean of the predicted velocity distribution transmitted by each node.
- "V": The standard deviation of the predicted velocity distribution.

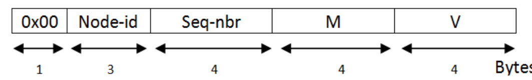

Fig. 1. Hello message format

Hence, each node periodically sends a Hello beacon with the mean and the standard deviation of its predicted velocity distribution. Upon the reception of Hellos messages, nodes update their local neighboring tables with the received information. Posterior speed distributions are updated, based on the Bayesian inference, if no beacon is received within a Hello-timeout period. The RPL protocol can therefore be modified to support the mobility information derived by the Bayesian model. In the following, we present our Mobility based Braided Multipath RPL (MBM-RPL) that executes in two steps. A primary path is established in RPL based on a new routing metric that evaluates the link duration based on actual nodes' speeds. An alternative path is then established to prevent the primary path failure caused by links expiration.

A. Primary Path Establishment in RPL based on the Mobility Metric

The RPL standard uses the estimated transmission count (ETX) as a default metric to construct the DODAG in the sink direction. However, the standard allows users to introduce their own metrics depending on the QoS they intend to achieve in the network. To support sensor nodes' mobility over RPL, we introduce a new mobility metric that estimates links durations based on the sensor nodes' speed distributions. The DODAG is then constructed in such a way to go through the most stable routes (i.e. the routes with the highest links durations). Then, each Hello period T, a node n_i evaluates the duration of the link e_{ij} with each of its neighbors n_j. If we denote by t_0, the arrival time of the current Hello beacon and τ the duration of the link e_{ij}, $P_{\exp}(e_{ij})$ can be defined as the probability that e_{ij} expires before the arrival of the next Hello message:

$$P_{\exp}(e_{ij}) = \Pr[t_0 < \tau \leq t_0 + T / \tau > t_0] = \frac{\int_{t_0}^{t_0+T} p_\tau(t|v_1, v_2)}{\int_{t_0}^{\infty} p_\tau(t|v_1, v_2)} \tag{13}$$

$p_\tau(t|v_1, v_2)$, given by the equation 10, is the conditional pdf that the link e_{ij} lasts for a duration τ when the nodes n_i and n_j have speed values v_1 and v_2. By assuming the independence of the links durations along a given path P, we define an additive routing metric, based on the routes' stability as:

$$-\log(P) = \sum_{e_{ij} \in P} (-\log(P_{\exp}(e_{ij}))) \tag{14}$$

Therefore to account for nodes' mobility, the objective function that will be executed by RPL aims to maximize the additive metric defined in equation (14).

B. On Demand Alternative Path Establishment in RPL

The mobility based metric we introduced in the previous Section allows the creation of the DODAG routes in such a way to avoid the up to fail links (henceforth called loose links). Nevertheless, effective routes are updated based on the native RPL DIOs messages, subject to the Trickle timer. On the other hand, links durations are periodically refreshed thank to Hellos beacons. The problem that may occur in this case is that links may expire along one of the DODAG routes, but the path wouldn't be repaired until the next Trickle period. To prevent such an anomaly, we propose to establish an on demand alternative path braided with the primary path before this latter effectively fails. In the opposite to disjoint multipath, braided multipath requires only the replacement of loose links along the primary path. We can keep all the other primary path links unchanged.

Hence, a node n_i triggers an alternative path establishment if the probability $P_{\exp}(e_{ij})$, that the link e_{ij} expires, is above a certain threshold P_{Thresh}. e_{ij} is the link between n_i and its preferred parent, in the current DODAG, n_j. The node n_i, then, determines the node $n_{k'}$ with whom it maintains the most stable link $e_{ik'}$ among its neighboring list N_i. We have:

$$P\exp(e_{ik'}) = \min_{n_j \in N_i} (P_{\exp}(e_{ij})) \tag{15}$$

Therefore, n_i adds $n_{k'}$ in its parent set, then sends a DAO message in the upward path to be considered as one of $n_{k'}$ descendants in the updated DODAG. The alternative path establishment algorithm is detailed in Figure 2.

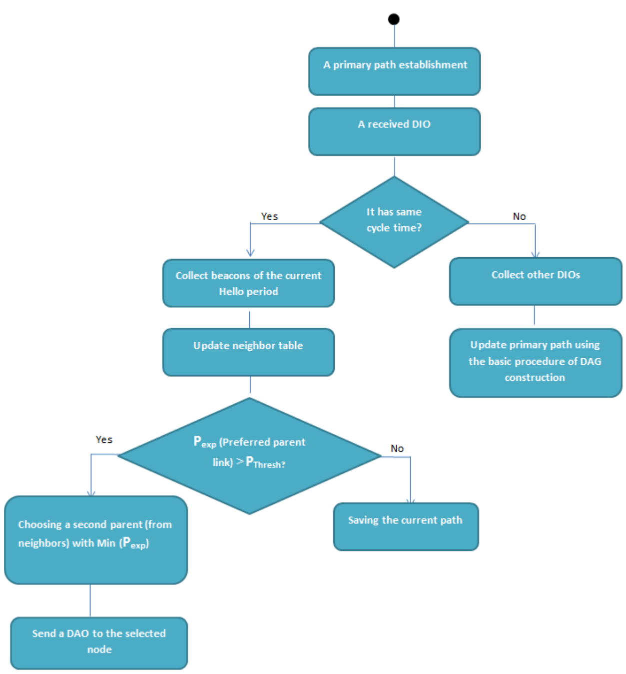

Fig. 2. Alternative path establishment algorithm

V. Performance Evaluation

In this Section, we first start by the validation of the Bayesian inference model. We then evaluate the performance of the proposed MBM-RPL scheme and compare it to the single path BMP-RPL [6] and the native RPL approaches. All the implementations are performed under the COOJA simulator using the Contiki 2.6 operating system. The simulation parameters are given in table I.

TABLE I
SIMULATION PARAMETERS

Deployment's area	600*600 m2
Radio environment	Directed Graph Radio Medium
Emulated nodes	Cooja Tmote
Transmission power	0dBm (Maximum available)
Transmission range	50m (Radius of Coronas)
Mobility model	Random Waypoint

A. The Bayesian Model Validation

To validate the Bayesian inference model, we first consider a 2 nodes' scenario with two speed values 1 m/s and 2 m/s. Initially, the two nodes use an arbitrary speed distribution. At each iteration, corresponding to a link expiration event, each node refines its speed distribution using the Bayesian inference. Figure 3 illustrates how the distribution of the velocity is concentrated around its actual value 1, after 100 events, indicating excellent convergence of the estimate.

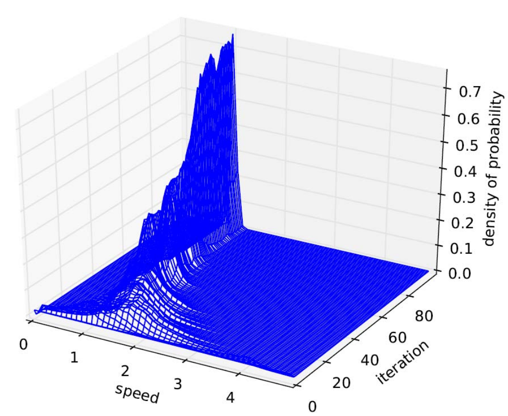

Fig. 3. Bayesian model validation using random link duration

In Figure 4, we use the Random Waypoint (RWP) model to generate movement traces of two nodes with real velocity values equal to 0.9 m/s and 1.8 m/s. The results show that with real mobility scenario, the Bayesian inference model converges after the given iteration number 100.

We generalize the above results to a 50 nodes' network scenario with 20 mobile nodes. Mobile nodes may have one of the 5 velocities: $1m/s$, $1.5m/s$, $2m/s$, $3m/s$ and $4m/s$. After

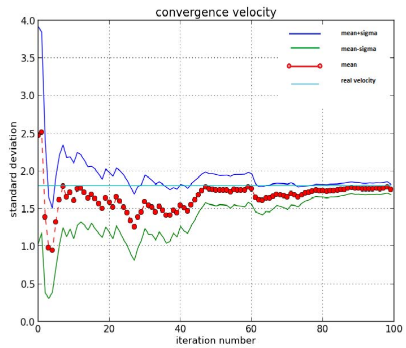

Fig. 4. Bayesian model validation using real link duration

a fixed number of iterations, the final speed density curves are presented in Figure 5. The Figure shows that the estimated velocity values are very close to the real ones.

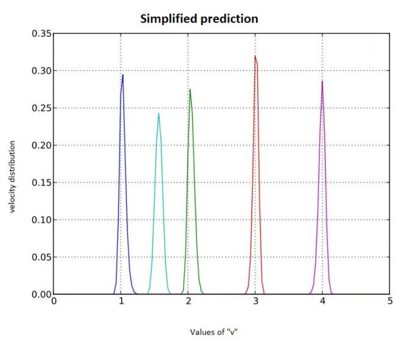

Fig. 5. Bayesian model validation using different velocity values

All the above simulation results confirm the accuracy of the Bayesian inference model in predicting actual sensor nodes speed distributions in a timely way. In the following, we evaluate the performance of MBM-RPL in terms of Packet Loss Rate (PLR) and Average Transmission Delay (ATD).

B. Packet Loss Rate Evaluation

The packet loss rate (PLR) is one of the network performance metrics that is directly affected by the routes failures. In Figure 6, we depict the PLR of MBM-RPL, BMP-RPL and the native RPL approaches as a function of the mobile nodes' number and for different inter-Hello periods. The results show that with the native RPL, the PLR rapidly increases with the number of mobile nodes. For both MBM-RPL and BMP-RPL, this rate remains low ($< 0.4\%$). We can however, notice that the gap between MBM-RPL and BMP-RPL PLRs decreases (from 0.02% to 0.5%) as we increment the inter-Hello period (from $0.5ms$ to $2.5ms$). This behavior illustrates the fast reactivity of MBM-RPL to create an alternative path when a "link expiration" event is up to occur.

The same results are obtained in Figure 7 where PLRs are depicted as a function of P_{Thres}, the threshold probability

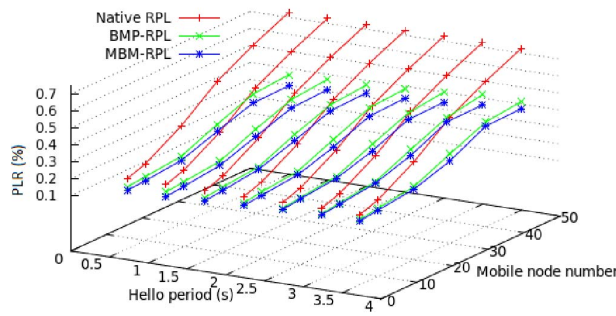

Fig. 6. PLR with different inter-Hello periods

above which a link is considered as a loose link. The curves show that MBM-RPL PLR decreases with P_{Thres}. For instance, with 20 mobile nodes, the MBM-RPL PLR decreases from 0.38 to 0.27 when P_{Thres} drops from 0.5 to 0.1. If P_{Thres} is very low, alternative paths are triggered early before links expiration resulting is a very low PDR. In the opposite, when P_{Thres} is high, alternative paths would be established only upon imminent links expiration leading to higher PDR.

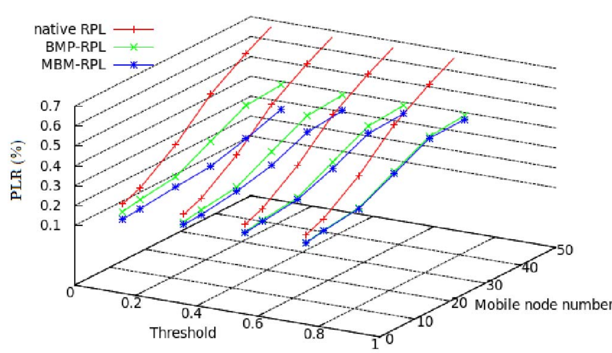

Fig. 7. PLR with different threshold values

C. Average Transmission Delay Evaluation

The Average Delay Transmission (ADT) represents the average time spent by each sensor node to transmit its data to the sink. As for the PLR, the curves in Figures 8 and 9 show that MBM-RPL provides the lowest ADT compared to the BMP-RPL and the native RPL ADTs no matter the number of mobile nodes present in the network, the inter-Hello periods or the link expiration probability threshold.

This behavior is explained by the fact that MBM-RPL allows nodes to send their data along the primary or the alternative paths as long as the primary path loose links did not expire.

VI. Conclusion and Future Work

In this paper, we addressed the mobility issue over RPL in the WSN context. Hence, we proposed a Bayesian based approach to accurately predict the sensor nodes' speed distribu-

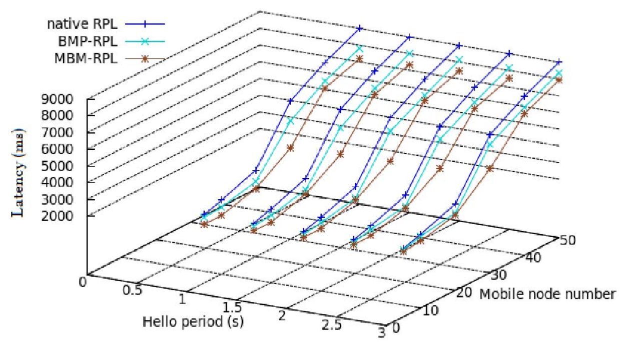

Fig. 8. Latency value with different inter-Hello periods

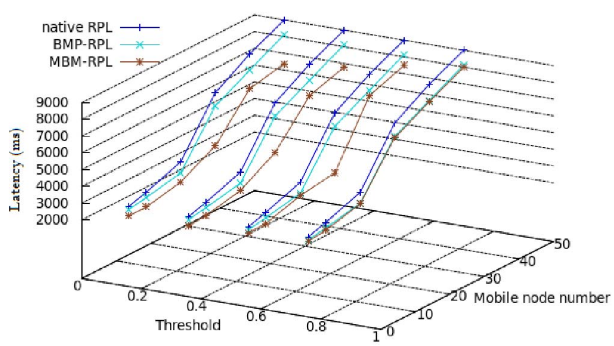

Fig. 9. Latency value with different threshold values

tions. Then, we proposed the MBM-RPL scheme, a multipath routing over RPL that accounts for sensor nodes' mobility. MBM-RPL establishes a primary path based on a new routing metric that considers the sensor nodes' speed distributions to determine the links durations. The DODAG is constructed in such a way to pass through the highest durations' links. A braided alternative path is established to prevent the failure of loose links. The results show that, for all the simulation scenarios, the MBM-RPL scheme outperforms the native RPL and the single path BMP-RPL approaches in terms of packet loss rate and average transmission delay. As a future work, we intend to test the MBM-RPL scheme with real applications' scenarios such as smart grids or e-health applications.

References

[1] A. Pal. *"Localization Algorithms in Wireless Sensor Networks: Current Approaches and Future Challenges"*. Network Protocols and Algorithms Journal, Vol. 2, No. 1, 2010.

[2] A. Somov, C. Dupont, and R. Giaffreda. *"Supporting Smart-city Mobility with Cognitive Internet of Things"*. Future Network and Mobile Summit,2013.

[3] B. Iova, F. Theoleyre, and T. Noel. *"Using Multiparent Routing in RPL to Increase the Stability and the Lifetime of the Network"*. Elsevier Ad Hoc Networks Journal, 2015.

[4] C. COBÂRZAN, J. MONTAVONT and T. NOEL. *"Integrating Mobility in RPL"*. European Conference on Wireless Sensor Networks. Springer International Publishing, 2015.

[5] D. CARELS, E. POORTER and I. MOERMAN. "*RPL mobility support for point-to-point traffic flows towards mobile nodes"*. International Journal of Distributed Sensor Networks, 2015.

[6] F. Somaa, I. Korbi C. Adjih and L. Saidane. "*A Modified RPL for Wireless Sensor Networks with Bayesian Inference Mobility Prediction"*. International Wireless Communications and Mobile Computing Conference, IWCMC, 2016.

[7] G. Srinivasarao and M. Dharavatu. *"An Improved PDR (Packet Delivery Ratio) Defined Routing Protocol in Low-power and Lossy Networks"*. International Journal for Development of Computer Science and Technology (IJDCST), 2015.

[8] H. Fotouhi, D. Moreira and M. Alves. *"Mobile IoT: smart-HOP over RPL"*. CISTER-Research Centre in Realtime and Embedded Computing Systems, 2014.

[9] H. Soliman *"Toward Improved RPL: A Congestion Avoidance Multipath Routing Protocol with Time Factor for Wireless Sensor Networks*". Journal of Sensors, Volume 2016, Hindawi, 2016.

[10] IEEE Std 802.15.4-2996, September, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), IEEE, 2006.

[11] I. Wadhaj, I. Kristof, I. Romdhani and A. Al-Dubai, "*Performance Evaluation of the RPL Protocol in Fixed and Mobile Sink Low-Power and Lossy-Networks"*. The IEEE International Conference on Computer and Information Technology (CIT 2015), 2015.

[12] L. Meng, W. Fu, Z. Xu, J. Zhang and J. Hua. *"A Novel Ad hoc Routing Protocol Based on Mobility Prediction"*. Information technology journal, 2008.

[13] M. Gerharz, C. de Waal,, M. Frank, and P. Martini, *"Link Stability in Mobile Wireless Ad Hoc Networks"*. IEEE Conf. Local Computer Networks, Nov. 2002.

[14] M. Grossglauser and D. Tse. *"Mobility Increases the Capacity of Ad Hoc Wireless Networks"*. IEEE/ACM TRANSACTIONS ON NETWORKING, 2002.

[15] M. Tarique, K. Tepe and S. Adibi. *"Survey of multipath routing protocols for mobile ad hoc networks"*. Journal of Network and Computer Applications, 2009.

[16] N. Aschenbruck, R. Ernst, E. Gerhards-Padilla, and M. Schwamborn. *"BonnMotion - a Mobility Scenario Generation and Analysis Tool"*. The 3rd International ICST Conference on Simulation Tools and Techniques (SIMUTools), 2010.

[17] O. Gaddour, A. Koubaa and R. Rangarajan. "*Co-RPL: RPL routing for mobile low power wireless sensor networks using Corona mechanism"*. The 9th IEEE International Symposium on Industrial Embedded Systems (SIES 2014), 2014.

[18] O. Gnawali. *"The Minimum Rank with Hysteresis Objective Function"*. In: Internet Engineering Task Force (IETF) 6719, 2012.

[19] P. Levis, T. Clausen, J. Hui, O. Gnawali and J. Ko, *"The Trickle Algorithm"*, RFC 6206, March 2011.

[20] P. Samar and S. B. Wicker *"On the behavior of communication links of a node in a multi-hop mobile environment"*, MobiHoc, 2004.

[21] S. Kewei, G. Jegnesh and G. Robert. *"Multipath routing techniques in wireless sensor networks: A survey"*. Wireless personal communications Journal, 2013.

[22] T. M. Mitchell, *"Bayesian Learning in Machine Learning"*. McGrawHill, 1997.

[23] T. The Son, H. Le Minh, G. Sexton, N. Aslam and Z. Ghassemlooy. *"Bayesian Model for Mobility Prediction to Support Routing in Mobile Ad-Hoc Networks*". The 24th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'13, 2013.

[24] T. Winter, P. Thuber, B. Brandt, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, JP. Vasseur and R. Alexander. *"IPv6 Routing Protocol for Low-Power and Lossy Networks"*. Internet Engineering Task Force (IETF), RFC 6550, 2008.

[25] V. Vasanthi, M. R. Kumar, N. A. Singh AND M.Hemalatha. *"A Detailed Study of Mobility Models in Wireless Sensor Networks"*. Journal of Theoretical and Applied Information Technology, 2011.

[26] W. Su, S.-J. Lee, and M. Gerla. *"Mobility Prediction and Routing in Ad Hoc Wireless Networks"*. International Journal of Network Management, vol. 11, no. 1, pp. 3-30, Jan./Feb. 2001.