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Multipath Opportunistic RPL Routing over IEEE 802.15.4

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ABSTRACT

We consider the problem of running RPL on top of the IEEE 802.15.4 MAC layer—the two layers operate over two different structures, a directed acyclic graph in the case of RPL and a cluster-tree for IEEE 802.15.4. We propose to adapt the cluster-tree of IEEE 802.15.4 so that it can efficiently work coupled with RPL. Nodes in our modified cluster-tree can associate with several parent nodes by taking advantage of an adequate organization of superframes at the MAC layer. Building on this modified MAC layer, we define an opportunistic forwarding scheme that extends RPL with the possibility of forwarding packets over multiple paths. Instead of always using a preferred parent, a node opportunistically forwards packets through other parents as long as their routes towards the sink are better. We take advantage of the opportunistic forwarding to support higher-priority delay-sensitive alarms that need to arrive in sink before a given deadline along with low-intensity monitoring data considered as best-effort. We compare our opportunistic version of RPL to its basic version through detailed simulations in terms of packet delivery ratio, incurred delay, and overhead.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: [Network Architecture and Design - Wireless Communication]

General Terms

Experimentation, Algorithms, Performance

Keywords

Wireless Sensor Networks, RPL, QoS, IEEE 802.15.4, opportunistic routing, multi-path

1. INTRODUCTION

We consider Wireless Sensor Networks (WSN) supporting IP connectivity and running over low-duty IEEE 802.15.4 wireless links. Such networks will lead to the development of the future Internet of Things and enable large deployments of sensors in various domains (smart homes, smart cities, smart grids, environmental sensing, critical infrastructure surveillance, etc.).

IP connectivity in sensor networks mainly relies on two IETF standards: 6LoWPAN [1] and RPL (Routing Protocol for Low power and Lossy Networks) [2]. 6LoWPAN enables IPv6 networking over low-power wireless networks thus bridging the gap between 802.15.4 and IP in a simple way—it defines a header compression and a fragmentation mechanism for IPv6 to run over IEEE 802.15.4 radio links.

RPL is a Distance Vector routing protocol that builds a DODAG (Destination Oriented Directed Acyclic Graph) anchored at a border router of a sensor network. Each node selects at most three parent nodes. It considers the best parent node (in the sense of some metric) as a preferred one and uses it for packet forwarding to the border router. Alternate parents provide backup routes to the border router making the network robust to unexpected changes in radio connectivity. However, the network structure built by RPL is different from the topology required in multi-hop networks with the 802.15.4 MAC layer—a *cluster-tree*. This latter topology allows a hierarchical organization in which a node can only select and associate with just one parent node. So, the main problem of running RPL on top of the 802.15.4 MAC layer is to make the two different structures work together.

In this paper, we propose to adapt the cluster-tree of IEEE 802.15.4 so that it can efficiently work coupled with RPL. Nodes in our modified cluster-tree can associate with several parent nodes by taking advantage of an adequate organization of superframes at the MAC layer. Building on this modified MAC layer, we define an opportunistic forwarding scheme that extends RPL with the possibility of forwarding packets over multiple paths. Instead of always using a preferred parent, a node opportunistically forwards packets through other parents as long as their routes towards the sink are better. We take advantage of the opportunistic forwarding to support higher-priority delay-sensitive alarms that need to arrive in sink before a given deadline along with low-intensity monitoring data considered as best-effort. We compare our opportunistic version of RPL to its basic version through detailed simulations in terms of packet delivery ratio, incurred delay, and overhead. Our scheme results in improved packet delivery, shorter delays, while keeping almost the same overhead.

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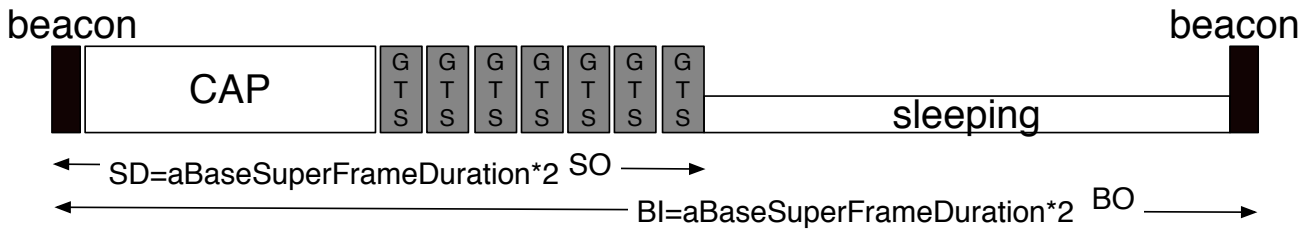


Figure 1: The superframe structure in IEEE 802.15.4

2. RELATED WORK

We briefly review here the work related to IEEE 802.15.4 and RPL.

2.1 IEEE 802.15.4

IEEE 802.15.4 defines PHY and MAC layers for wireless sensor networks [3]. In the non-beacon mode, it implements a classical CSMA-CA approach in which a receiver periodically initiates communication (the period is implementation dependent) and the PAN (wireless Personal Area Network) coordinator has to remain awake to receive frames from its children and cannot save energy. This feature increases the overhead and has a significant impact on the end-to-end delay.

IEEE 802.15.4 also offers the beacon-enabled mode in which a coordinator periodically sends a beacon to delimit its superframe (cf. Figure 1). The Contention Access Period (CAP) follows the beacon: all associated nodes may send a packet according to a slotted CSMA-CA. The superframe finishes after the Contention Free Period (CFP): nodes reserve dedicated Guaranteed Time Slots (GTS). In the beacon mode, nodes wake-up just before a beacon transmitted by the coordinator to save energy—a node may sleep during the inactive period if $BO > SO$. We consider the beacon mode in this paper, because it leads to better energy savings.

IEEE 802.15.4 requires a cluster-tree topology anchored at the PAN coordinator for multihop operation [4]. Once a node associates with a coordinator, it begins to periodically send beacons to maintain its own superframe and control the access to the channel of the associated nodes. Thus, different nodes may have overlapping superframes, which may create collisions between beacons and data frames. To alleviate this problem, two main approaches exist in the literature:

- *Beacon-Only Period (BOP)*: at the beginning of each superframe, nodes reserve a period of several slots with each slot able to contain a beacon [5] (cf. Figure 2). Interfering coordinators should choose different BOP slots. This method only solves collisions between beacons: it is only suitable for low-intensity traffic.
- *Superframe Scheduling*: nodes implement a distributed scheduling algorithm so that interfering coordinators maintain non-overlapping superframes [6][7]. Although such a collision-free scheduling is more complex, it results in better capacity.

An experimental comparison of both techniques [8] showed that Superframe Scheduling outperforms BOP in terms of the number of delivered packets: if two interfering coordinators do not have overlapping superframes, the number of collisions between `data` packets and between `beacons` is reduced. Nevertheless, its parameters (BO) should be carefully set to avoid excessive battery consumption.

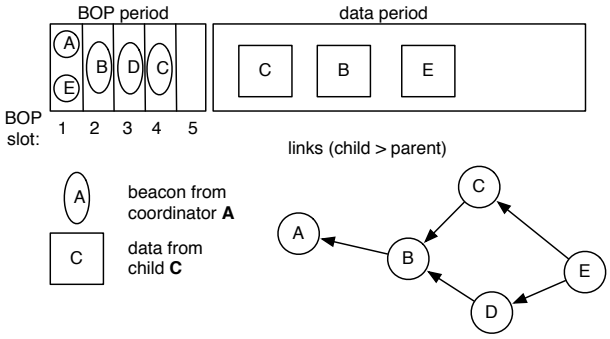


Figure 2: Beacon-Only-Period superframe organization

2.2 Routing in multihop wireless networks

RPL has recently emerged as the standard for routing in wireless sensor networks. It defines a framework for constructing a routing topology and efficiently forwarding packets while saving energy.

The topology is based on a Destination-Oriented Directed Acyclic Graph (DODAG) anchored in the sink (the PAN coordinator in the IEEE 802.15.4 jargon). This kind of structure is particularly suitable for *convergecast* traffic: the sink is the destination for all data packets. Each node maintains its *rank* towards the sink and includes its value in periodical DIO (DODAG Information Object) messages. This rank represents more or less its *depth* in the DODAG.

To avoid loops, an objective function determining the rank is defined so that it monotonically decreases toward the sink. A simple way proposed by ROLL for computing the rank is to closely track ETX (Expected Transmission Count). This metric estimates the average number of transmissions required to send a data packet to a neighbor. By summing up the ETX along the path toward the sink, a node may obtain the cumulative ETX, strictly decreasing and consequently forbidding loops. RPL uses trickle timers to adapt the overhead incurred by the maintenance of a DODAG to the topology stability—when it is stable, nodes increase the period for sending routing advertisements.

RPL is currently under extensive implementation and experimentation work so little results are published so far.

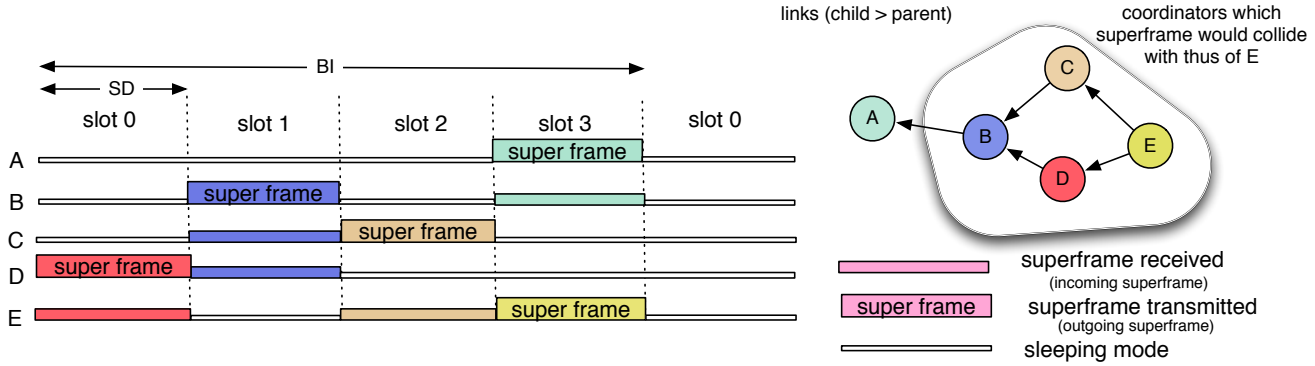


Figure 3: Scheduling of 802.15.4 superframes

Vasseur et al. experimentally evaluated RPL and showed that the use of trickle timers decreases the number of control traffic necessary to construct and maintain a stable DODAG [9]. They also observed the amount of control traffic in the case of the general repair. Clausen et al. pointed out some under specifications of the protocol, especially concerning downward traffic and point-to-point routing [10].

Since nodes in a wireless sensor network are prone to failures, RPL builds a DODAG with several paths towards the sink so that each node maintains several parents: if the preferred one fails, the node can switch to another one. The existence of several paths may improve resilience and performance [11], help to guarantee QoS [12], or allow to deal with real-time traffic [13].

Instead of providing backup routes, opportunistic routing dynamically chooses the next hop on a per packet basis [14]. Since the transmission conditions are highly time-varying, a node may estimate the link quality and the best next hop just before the transmission.

To the best of our knowledge, no work so far considered the joint RPL and IEEE 802.15.4 operation.

3. MULTIPATH OPPORTUNISTIC RPL OVER IEEE 802.15.4

Our objective is to integrate RPL and IEEE 802.15.4 to enable QoS multipath routing and improve packet delivery before a deadline, while minimizing overhead and energy consumption. We assume that there are two types of traffic in the network:

1. **low-intensity monitoring data** that can be considered as best-effort;
2. **higher-priority delay-sensitive alarms** that need to arrive in sink before a given deadline.

We want to provide support for such service differentiation over RPL and multi-hop wireless network by taking advantage of multiple paths.

The first problem to consider is the tree structure of IEEE 802.15.4: in the current standard, a node can only associate with one parent to avoid loops. Indeed, all the nodes at a given depth in a tree maintain their superframe simultaneously. To take advantage of several parents in the DODAG structure, we need to allow a node to associate with several parents in the IEEE 802.15.4 structure (we consider this problem below in Section 3.1). Then, we propose an extension to RPL for using several parents in an opportunistic way—as soon as a node can send a frame to a parent in a synchronized way, it will do it, which increases the probability of packet delivery and reduces delay (cf. Section 3.2).

3.1 Support for Multiple Paths in IEEE 802.15.4

A node joining an IEEE 802.15.4 cluster-tree needs to associate with a neighbor coordinator. It may implement an active scan method: it sends a solicitation to retrieve the information of the cluster-tree from listening neighbors. This method only works when nodes never sleep, which is not the case of the applications we are targeting. In a passive scan, a node waits for `beacons` from a neighbor coordinator that define a superframe even if it is not yet associated with the cluster-tree. Then, an `association-request` / `ack` / `data-request` / `association-reply` / `ack` exchange is required to finalize the association. Thus, a node can associate with one parent during a given superframe. In the original IEEE 802.15.4, an incoming superframe directly follows an outgoing superframe (i.e. the superframes of a node and its children are immediately consecutive). To avoid loops, a node should only associate with a parent closer to the PAN coordinator. Thus, there is no way of maintaining several parents in the original IEEE 802.15.4.

To implement a DAG structure maintaining several parents, we have to appropriately schedule superframes: a node should be able to receive `beacons` from different neighbors during non-overlapping superframes. We assume that all the nodes have the same BO and SO values (duration and interspacing between superframes). Consequently, a schedule of superframes corresponds to a TDMA assignment with timeslots of a fixed length. We propose to extend the algorithm proposed by Muthukumaran *et al.* [7] with a random assignment of slots to interfering nodes in a given neighborhood.

3.1.1 Detailed Schedule Construction

We assume that only 1-hop and 2-hop neighbors may interfere. To avoid collisions, we have to schedule superframes so that no pair of interfering coordinators use the same slot. The number of these slots depends on the BO and SO pa-

rameters: BO is the repetition period of superframes during which we can place at most N_{slots} superframes:

$$N_{slots} = 2^{BO-SO} \quad (1)$$

We propose a simple algorithm that each node executes to find a valid slot to transmit its superframes:

1. Each node retrieves the slots used by its 2-neighbors (i.e. interfering coordinators). A node considers only nodes with at least one child since other coordinators maintain an empty superframe and do not create collisions for `data` frames;

2. A node randomly selects one free slot.

While Muthukumaran *et al.* schedule the slots to be immediately consecutive, we rather chose a random assignment approach for the following reasons:

- it presents a trade-off to reduce the delay for both upload and download directions (Muthukumaran *et al.* focus only on the upload case);

- it accelerates convergence: two interfering nodes have little chance to choose the same slot when they have the same parent.

The resulting structure has an interesting property: a node can access the channel during several superframes coordinated by different parent neighbors, which provides the basis for multipath forwarding supported by RPL.

3.1.2 Distributed version

To obtain the list of interfering nodes, each node maintains a neighborhood table. It piggybacks in its `beacons` the list of neighbors and the slots they have already chosen. Thus, a node has just to select one free slot to avoid collisions. This procedure can be safely integrated in the association procedure of IEEE 802.15.4: a new coordinator chooses its slot just after having received its `association-reply` scheduling immediately its future superframes.

As long as a node does not have children, it may safely change its slot without impacting the MAC performance: there is no domino effect. Besides, colliding `beacons` often avoid children to associate with interfering coordinators. In other words, a coordinator without any child means perhaps that its slot collides with another one. Thus, a coordinator reapplies the assignment rule to choose its slot at the end of each of its superframes, except for an `association-request` during the current superframe (i.e. at least one child is associated).

3.1.3 Example

Figure 3 illustrates the principle of slot assignment. We assume here for the sake of simplicity that the interfering range is twice the radio range so that B and E cannot choose the same superframe. If we consider that each superframe slot is a different color, we face a classical graph coloring problem. The reader can notice that the number of slots in this example should be at least 4 since B, C, D, and E interfere with each other.

Let us focus on node E assuming that all other coordinators have already chosen a slot for their superframes. E will collect `hellos` from C and D, and will be able to construct the list of its 2-neighbors (interfering nodes). Finally, E has just to randomly select one slot not yet present in this list. In our case, it will select slot 0 since it is the only one remaining free.

3.2 Deadline Oriented Opportunistic RPL over IEEE 802.15.4

As we aim at service differentiation of best-effort and time-sensitive traffic, we propose to adapt RPL so that it can take into account delay and packet delivery before a deadline. We only consider convergecast (multipoint-to-point) traffic.

We consider three classes of service:

min-delay: critical packets for which we need to minimize the end-to-end delay without concerns for energy consumption

deadline: alarm packets to deliver before deadline D while minimizing energy consumption

best effort: packets that do not require any guarantee, but their forwarding needs to take into account energy consumption.

3.2.1 Notation

We adopt the following notation:

- N: a node that forwards a packet
- $deadline(p)$: deadline associated with packet p
- t: current time
- $d(N)$: hop distance between node N and the sink
- $slot(t)$: current superframe slot (node N has just received a beacon in this slot so it will be able to forward it)
- $slot(NH)$: slot used by the superframe of node NH
- $PDR_{bcn}(NH)$: beacon packet delivery ratio for neighbor NH
- $PDR_{data}(NH)$: data packet delivery ratio over the link to neighbor NH;
- $t_{tx_{data+ACK}}$: time needed for data and acknowledgement frame transmissions
- $queue(NH)$: queue of packets scheduled for transmission during the superframe of NH
- $STEP$: a constant to extend the local time budget if no parent can satisfy it at the first attempt

3.2.2 Taking into account deadlines with RPL

When a node generates a packet, it assigns a deadline according to the class of service it belongs to. Nodes maintain a queue of packets ordered by their deadlines. When a node has a packet to forward, it waits for a successful `beacon` reception from one of its parents. Then, it needs to decide to transmit its packets during the current superframe or later if another parent offers better performance (e.g. smaller energy consumption, better reliability).

The node extracts the first packet from its queue: if the deadline is elapsed, the packet is simply dropped and the next packet is extracted. Then, it must find the next hop that guarantees the deadline. It assumes the time before

the deadline can be uniformly shared among the nodes in the route. Thus, the transmission has to meet the local *time budget* constraint:

$$budget = \frac{deadline(p) - t}{d(N)} \quad (2)$$

When a packet is at node N, the delay before the packet is correctly transmitted to the next hop NH depends on:

1. the delay until the superframe of NH starts while taking into account the average number of superframes to wait in case of beacon losses:

$$D_{sframe} = SD * \mid slot(NH) - slot(t) \mid + BI * max\left(0, \frac{1}{PDR_{bcn}(NH)} - 1\right) \quad (3)$$

   where SD denotes the superframe duration while BI represents the time separating two beacons. For the currently received beacon, this delay is zero, since the node can immediately try to send the packet.

2. the average delay until NH correctly receives the packet, it is estimated via the packet probability delivery ratio:

$$D_{tx} = \frac{t_{tx_{data+ACK}}}{PDR_{data}(NH)} \quad (4)$$

Finally, nodes need to satisfy the following deadline constraint:

$$budget \geq D_{sframe} + D_{tx} \quad (5)$$

As several candidate next hop nodes may satisfy the deadline constraint, the protocol will choose the best one based on the cumulative Expected Transmission Count (ETX) routing metric: it represents the cumulative number of packet transmissions required to reach the sink, also used as the node *rank* in the DODAG. It should be noted that per link ETX is simply calculated as inverse value of measured $PDR_{data}(NH)$ (link to neighbor NH). A node chooses among all the possible next hops the node with the lowest cumulative ETX so packets will experience the smallest delay.

If a node cannot satisfy the budget constraint, it reconsiders all the parents for an increased time budget hoping that the packet will benefit from shorter delay further in the network. We gradually extend the budget up to two times the initial value given by Eq. 2 ($STEP$ and $relax$ parameters in Algorithm 1)

4. PERFORMANCE EVALUATION

We have compared our opportunistic version of RPL to its basic version in terms of packet delivery ratio, incurred delay, and overhead through detailed simulations. Both protocols take advantage of the 802.15.4 superframe scheduling so that even the basic version of RPL can dynamically adapt the choice of the preferred parent node in function of performance.

For the sake of simplicity, we implemented a centralized coloring solution to assign slots for each superframe as described in Section 3.1.1. However, we may use any scheduling algorithm creating a Directed Acyclic Graph such that the distributed version described in Section 3.1.2.

Algorithm 1: Does a packet has to be transmitted in the current superframe?

```
src ← waitBeacon();
nexthopcandidate ← ∅
if empty(queue) or end(superframe, src) then
  return false
else
  repeat
    p ← getFirstPacket(queue);
    if (p.deadline ≤ t) then
      DropPacket(p);
    end if
  until (p.deadline > t)
  budget ← computeHopBudget(p, src.hops + 1);
  relax ← 0;
  while (nexthopcandidate = ∅) and (relax < 2 * budget) do
    for neigh NH do
      D_sframe ← computeDelaySuperframe(NH.sframe, NH.pdr);
      D_tx ← computeExpectedTransmissionTime(NH.pdr);
      if (budget + relax > D_sframe + D_tx) then
        nexthopcandidate ← nexthopcandidate + {NH}
      end if
    end for
    relax += budget * STEP;
  end while
  if (src = getBestETX(nexthopcandidate)) then
    return true
  else
    return false
  end if
end if
```

4.1 Simulation setup

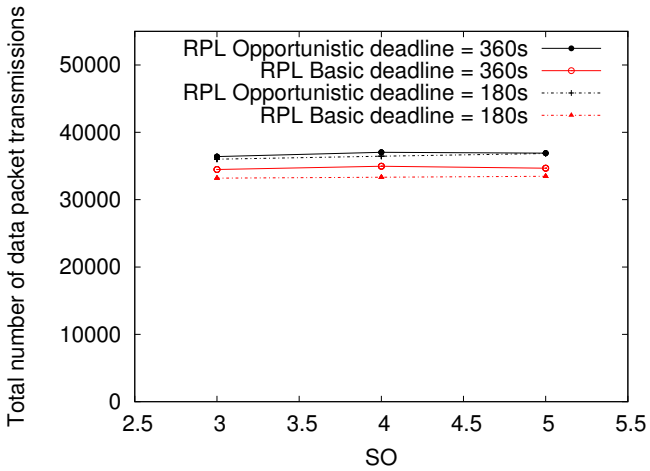
We have used the WSNet/Worldsens event-driven simulator for large scale wireless sensor networks [15]. We have ported the Contiki RPL implementation [16] to WSNet. We used the IEEE 802.15.4 implementation in bacon-enabled mode [17]. We have additionally implemented the superframe scheduling mechanism.

The simulations have considered 10 different topologies and randomly deployed up to 256 nodes in a square area 400 x 400 m. To make the simulations as close as possible to the reality, we have not adopted the Unit Disk Graph assumptions commonly used in the literature, but rather the Rayleigh propagation model and the parameters of the IEEE 802.15.4 radio.

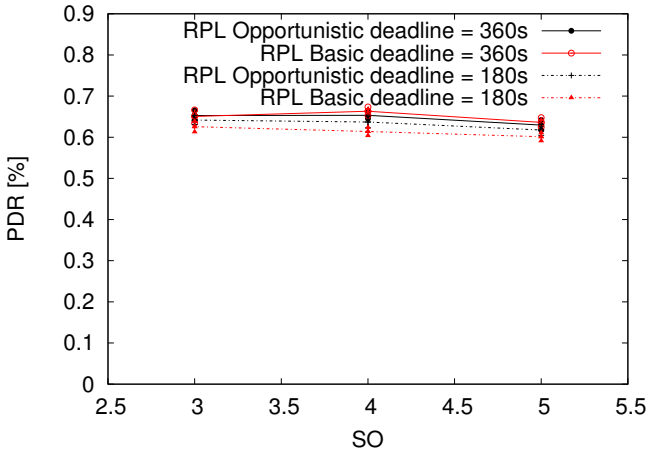
We have only considered low intensity traffic with the av-

Simulated area	400m x 400m
Number of nodes	up to 256
Traffic type, rate	periodic, 1/7.5 minutes
Simulation duration	50000 s
SO	3, 4, 5
Deadline	360s, 180s

Table 1: Simulation parameters

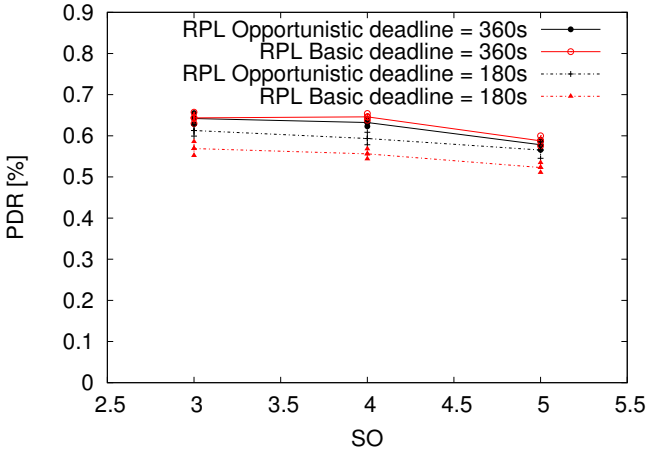


(a) total number of transmitted packets

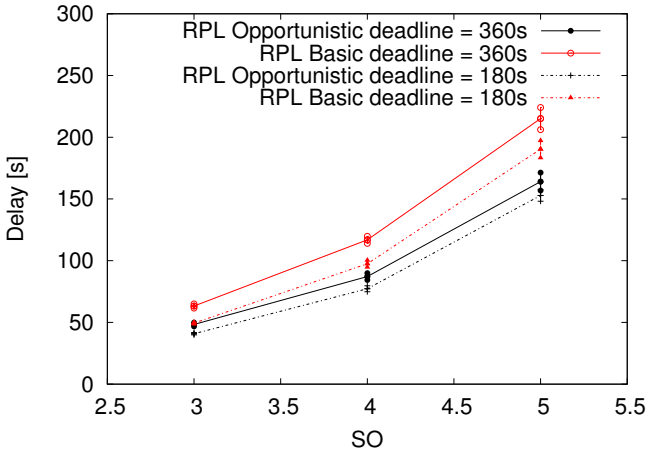


(b) PDR for *all* packet types

Figure 4: General comparison of basic and opportunistic RPL



(a) PDR



(b) delay

Figure 5: Comparison of basic and opportunistic RPL, *deadline* traffic type

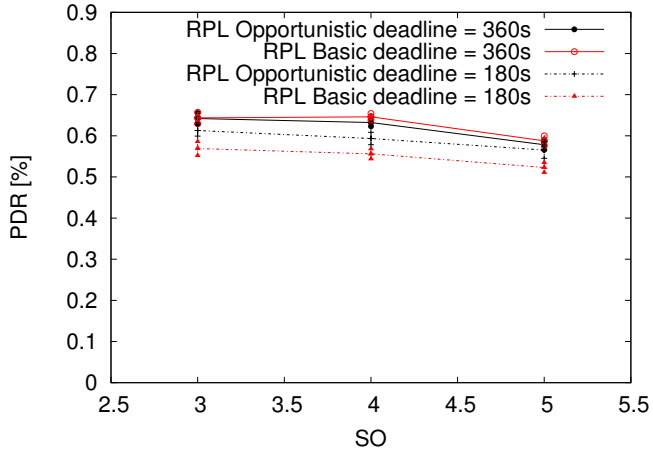
erage interval between data of 7.5 minutes. We have empirically established this value to avoid performance degradation of IEEE 802.15.4 under heavy traffic. We divide the traffic into three classes with the respective proportions: 70%-20%-10% (best-effort, min-delay, deadline). We vary the SO parameter from 3 to 5 and choose the BO parameter so that the number of superframe slots is sufficient to avoid colliding superframes (Eq. 1). We run a simulation for each of the topologies during 50.000 s and average the results over multiple runs to obtain 95% confidence intervals. Table 1 summarizes the important simulation parameters.

4.2 Result analysis

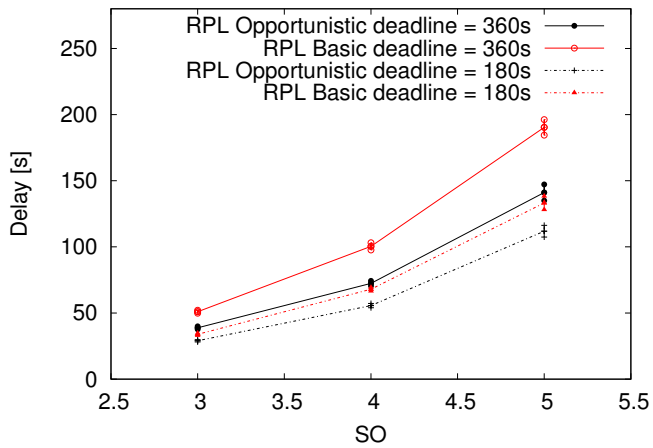
Figure 4(a) presents the total number of transmitted packets for the basic and opportunistic RPL. We measure the raw number of packets transmitted by the MAC layer, i.e. a data frame transmitted for the first time or retransmitted after a failure. The IEEE 802.15.4 MAC layer drops a frame when the number of retransmissions exceeds 3 or the number of Clear Chanel Assessments exceeds 4. Packet are also dropped if the deadline is missed. At the end of the simulation, these values are summed up for all generated packets. Both protocols generate the same fixed amount of application data packets and none of them is destroyed before the end of the simulation.

We can notice that our opportunistic solution results in a slightly greater number of transmitted packets (9%). This increase may come from better performance: since less packets are dropped, this mechanically results in more transmissions at the MAC layer. A larger overhead also comes from the forwarding rule: if the deadline is short, the node will privilege the forwarding delay compared to minimizing the number of transmissions (i.e. ETX). This aggressive decision would privilege short deadlines, but also negatively impacts the number of transmissions.

Figure 4(b) presents the packet delivery ratio for all packet types. As soon as the deadline becomes more critical, the fact that we use alternative parents results in a higher PDR. Less packets get dropped because of the short packet deadline, since the fact that we have missed a beacon from our preferred parent could still be caught up with the reception of beacons from some alternative parents. In the same situation, the basic RPL version needs to wait for the whole



(a) PDR



(b) delay

Figure 6: Comparison of basic and opportunistic RPL, *min-delay* traffic type

inter-beacon period (BI) and thus there is a risk that the short packet deadline incurs more packet drops.

We have considered above the performance of the tested protocols from the global point of view. Let us analyze performance with respect to the QoS delay requirements of *min-delay* and *deadline* data packet types. We can notice a similar behavior as previously for both types of traffic when it comes to PDR (Figures 5(a) and 6(a)) and for the experienced delay (Figures 5(b) and 6(b)). If we consider delay, it is clear that our opportunistic scheme exhibits much shorter delay than the basic RPL version due to the possibility of interchangeably using alternative parents. With respect to the PDR performance, our opportunistic scheme presents a real gain when we deal with packets with harsh deadline constraints.

Finally, we can notice an interesting property of our opportunistic approach that directly comes from its forwarding policy even if we do not show it in the numerical results. Our opportunistic scheme spreads traffic over parents by not only selecting the preferred parent as the next hop, but the alternative ones as well. In realistic scenarios with a limited battery capacity and limited queue lengths, this may appear as the primary concern since it would increase the overall network lifetime and prevent packet drops due to full queues. We plan to include this kind of realistic constraints in the future work.

5. CONCLUSION AND PERSPECTIVES

We have presented a scheme allowing the coexistence of two structures in emerging IP enabled wireless sensor networks: RPL routing and IEEE 802.15.4 MAC. We have modified the cluster-tree operation of IEEE 802.15.4 to support RPL DODAG so that nodes are able to follow multiple parents and use them for traffic forwarding when needed. Our simple opportunistic routing scheme benefits from an interesting feature: traffic is spread more uniformly over all possible parents instead of going through the preferred one. It results in improving the network lifetime and optimizing fairness to avoid quick energy depletion. Our solution achieves slightly better results with respect to end-to-end packet reliability (PDR) and delay while keeping almost the same amount of generated traffic.

In the future, we plan to validate the proposed scheme on an experimental testbed and take into account additional constraints of limited packet buffers. We also want to explore how reliability can improve with the use of more advanced multi-path routing schemes or by adapting the parameters of IEEE 802.15.4 to accommodate higher traffic loads.

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