The Love-Hate Relationship between IEEE802.15.4 and RPL

Oana Iova, Fabrice Theoleyre, Thomas Watteyne, Thomas Noel

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***Abstract*—Low-Power Lossy Networks (LLNs) are at the core of many Internet of Things solutions. Significant standardization effort has been put in creating a protocol stack suited for LLNs. Among these standards, IEEE802.15.4-2011 and RPL allow LLN devices to form a multi-hop mesh network. Today, RPL creates a routing topology without *a priori* knowledge about the topology created at the MAC layer. This negatively impacts the number of redundant paths, their quality, and the overall performance of the routing protocol. In this article, we highlight the need for an intermediate layer between MAC and network layers to solve these problems. We describe the protocols to be used in future Internet of Things, emphasize their weaknesses when deployed together, and provide areas of improvement.**

***Index Terms*—IEEE802.15.4, RPL, LLN, Internet of Things, joint optimization, topology control, link metric, dynamics.**

I. Introduction

Miniaturization of computation and communication solutions has enabled the creation of small, durable, and inexpensive wireless devices often called “motes”. Motes can be programmed to interconnect wirelessly, and form a multi-hop low-power wireless network, known as a “Low-Power and Lossy Network” (LLN). LLNs are one of the core technologies in the Internet of Things (IoT). LLN protocols and standards need to take into account their specific constraints in terms of energy, memory, and processing power.

The IEEE and IETF, two major Standards Development Organizations (SDOs) in the telecommunication arena, have published several standards that contribute to the creation of a fully standards-based protocol stack for LLNs. IEEE802.15.4 [1] is arguably the standard with the most impact on low-power wireless technology. It defines both the physical layer (i.e., modulation scheme, data rate) and the Medium Access Control (MAC) layer for low-rate Wireless Personal Area Networks (WPANs). In 2012, the IETF ROLL working group published the “IPv6 Routing Protocol for Low-Power and Lossy Networks” (RPL) [2], which enables low-power devices to form a multi-hop topology. Because of energy constraints, the focus was given to single interface nodes.

While blind layer separation allows modularity, it also comes with some limitations, especially in constrained environments. An LLN is a canonical example of a constrained network: a large number of low-end and energy-constrained devices form a multi-hop mesh network using unreliable links over which small packets can be transmitted at low data rate. In such an environment, there is a great potential for cross-layer optimization, where different (theoretically independent) layers could exchange information to coordinate their actions. In some cases, a sublayer might be introduced to perform adaptation between two layers otherwise unaware of each another. One such example is 6LoWPAN. Situated above the MAC layer, it compacts (long) IPv6 headers so they fit in (short) IEEE802.15.4 frames.

In this paper, we show the shortcomings of blind layer separation in the current protocol stack for LLNs, focusing on the MAC and network layers. In short, the contribution of this paper is:

- we propose to use the same topology control at the MAC and routing layer;
- we highlight the instability problem of RPL when using the current routing metrics;
- we propose to estimate the link quality by exploiting all the parents at the topology created by RPL.

II. A Standards-Based Protocol Stack for LLNs

This section discusses the standards with the most impact on the LLN technology.

A. MAC layer: IEEE802.15.4-2011

The IEEE802.15.4 standard was introduced in 2003 to be used in WPANs. Two revisions later (2006, 2011), and with one upcoming revision (2015), IEEE802.15.4 is arguably the standard with the highest impact on low-power wireless in general, and on the IoT in particular.

Link layer topology. In an IEEE802.15.4-2011 network, the devices are managed by a controller known as the “PAN coordinator” (or “sink”, two terms which we use interchangeably in this paper). The standard defines two types of network topologies: star and peer-to-peer, both illustrated in Fig. 1a.

In a star topology, all devices communicate only with the PAN coordinator, over a single hop. While devices can run on batteries, the PAN coordinator is usually mains powered, as it needs to keep its radio on at all times.

In a peer-to-peer topology, communication is not restricted to the PAN coordinator. In contrast to a star topology, devices communicate with one another, enabling multi-hop connectivity. Multi-hop is a key feature in many IoT applications where not all nodes are deployed sufficiently close to the PAN

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coordinator to be in its radio range. The drawback of the peer-to-peer topology is that a node must always stay awake as it can receive a packet from a neighbor at any time. A third topology, called "cluster-tree" can be used to overcome this. In a cluster-tree topology, a tree rooted at the PAN coordinator organizes the sleeping periods of the different router nodes to enable multi-hop communication with energy savings.

Medium access and energy efficiency. In IEEE802.15.4-2011, accessing the medium can be either done in a asynchronous (beacon-less) or synchronous (with beacons) mode.

In beacon-less mode, nodes use unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), without exchanging request-to-send and clear-to-send (RTS/CTS) messages. In a multi-hop topology, all routing nodes must stay awake to be able to receive packets, which can be sent at any time. Preamble-sampling can reduce energy consumption: the transmitter node pre-sends a long preamble (a series of well-known bytes) to its packet; a receiver periodically samples the medium and stays on when it hears an on-going preamble. Unfortunately (besides breaking compliance with IEEE802.15.4, which does not include it), preamble sampling puts the energy burden on the transmitter, and significantly lowers the throughput of the network.

In beacon mode, IEEE802.15.4 cuts the time into superframes. Each superframe starts when the coordinator (possibly a router) sends a `beacon`. As we can see in Fig. 1b, this is followed by an active period (in which all transmitters compete using slotted CSMA/CA), and an inactive period (in which nodes sleep until the next `beacon`). The beacon mode saves energy in multi-hop topologies only when using the cluster-tree topology. As previously stated, in the peer-to-peer topology nodes have to always keep their radio on.

B. Routing over LLNs with RPL

RPL is a distance-vector routing protocol designed to scale to thousands of devices in an LLN. It organizes the topology in a Destination Oriented Directed Acyclic Graph (DODAG), a directed graph with no cycle. This DODAG is rooted at the sink (or at each sink when multiple sinks are present). To build the DODAG, RPL assigns a *Rank* to each mote, i.e., a virtual distance to the sink. An *Objective Function* defines how routing metrics (e.g., link quality, hop count) are used to compute a node's *Rank*. For example, if the objective is to create shortest paths, a node computes its *Rank* by adding a scalar value to the *Rank* of its preferred parent.

DODAG construction. The DODAG construction starts when the sink is switched on. It periodically broadcasts a DODAG Information Object (DIO), a control packet containing its *Rank*, as well as configuration parameters. When a joining node receives a DIO, it inserts the transmitter's address in its list of possible parents. From that list, it chooses its preferred parent as the node that advertises the smallest *Rank*[1]. Once this parent-child relationship is established, a node forwards all packets for the sink through its preferred parent. After a node has computed its own *Rank* (usually using the *Rank* of its parent and link and node metrics), it starts periodically broadcasting its own DIOs.

[1] Alternatively, a node can choose its parent as the neighbor that gives it the smallest *Rank*; this takes into account the neighbor's *Rank*, and the cost of the link between the current node and the neighbor.

Fig. 2 illustrates this DODAG construction routine. For simplicity, we use *hop count* (the number of hops to the sink) as routing metric. The *Rank* of a node is computed as the *Rank* of its parent plus a constant *step value* of 1. The sink `R` starts broadcasting DIO messages (Fig. 2a). The neighbors of `R` choose it as their preferred parent, compute their *Rank*, and start broadcasting their own DIOs (Fig. 2b). The network is fully formed when all the nodes have chosen their preferred parent (Fig. 2d).

The Trickle algorithm. Even after the RPL DODAG has formed, nodes keep transmitting DIOs to update the DODAG to topological changes. Unlike IEEE802.15.4, which sends beacons at a fixed rate, the rate at which the DIOs are being sent is tuned using the Trickle algorithm [3]. The idea is for nodes to send less DIOs when the topology is stable, leading to a smaller energy consumption.

When a node receives DIO messages which contain the same information as the last ones, it doubles its own period for sending DIOs. When an inconsistency is detected (e.g., the *Rank* of the preferred parent has changed), the Trickle algorithm resets this period to an initial value. This causes the nodes to send DIOs more frequently, and the DODAG to adapt more quickly to the change.

C. Gotchas when Using Lossy Links

Wireless phenomena such as external interference and multi-path fading cause links to be unreliable. It is therefore crucial for a mote to continuously estimate the quality of the links to its neighbors, in order to choose the subset of "good" links to forward packets on. Routing metrics such as hop count are not enough, as nodes might elect a preferred parent which is close to the sink, but with which it has poor connectivity.

De Cuoto *et al.* propose to use the Expected Transmission count (ETX)[4] as a link metric, and use only "good" links. ETX estimates the number of required transmissions needed before the neighbor correctly receives the frame. It can also be used to estimate the energy cost associated with communicating over that link.

Yet, as highlighted by Liu *et al.* [5] and Passos *et al.* [6], using ETX causes network churn (i.e., nodes changing routing parent) because of its greedy approach. That is, a node always searches for the link with the best (instantaneous) quality.

The IETF has defined several routing metrics [7] that can be used by RPL to construct the DODAG:

- node metrics: node characteristics, hop count to the sink, and residual energy of the node;
- link metrics: throughput, latency, link reliability, and link color (a semantic constraint).

Unlike RPL, IEEE802.15.4 does not specify any metric for the construction of its cluster-tree. Cuomo *et al.* propose to select the routing nodes based on the LQI (Link Quality Indicator) from the physical layer, or a combination of LQI and hop count [8].

It is very common for each layer (network, MAC) to use its own (routing, link) quality metric. We will show in the next section the limits of such approach.

III. Evaluation, Limits and Recommendations

In this section, we simulate a LLN and highlight its poor performance when the MAC and routing protocols are used independently, while offering guidelines for improvement.

A. Methodology

We simulate the behavior of RPL and IEEE802.15.4 on multi-hop networks in WSNet, a well-known network simulator for LLNs [9]. We use either the peer-to-peer topology of IEEE802.15.4 operating in beacon-less mode, or the cluster-DAG topology from [10] for the beacon-enabled mode (as stated in Section II-A, the peer-to-peer topology cannot be used together with the beacon mode). Table I lists the simulation parameters.

B. Topology Control

We are interested in how a node chooses the neighbors to communicate with, both at the MAC and routing layers. The problem is that under blind layer separation, decisions made by these layers might conflict. In this section, we evaluate how this affects network performance.

Context. Usually, the MAC layer only filters the neighbors a node may use. However, IEEE802.15.4 (the MAC layer) imposes a topology to the network: star, peer-to-peer or cluster-tree. If the MAC layer structures the network as a cluster-tree (Fig. 3a), the routing layer is presented with a topology without redundancy, and has to stick to the neighbors selected by the MAC layer (Fig. 3b).

A better solution is for the MAC layer to structure the network as a peer-to-peer topology (Fig. 3c). RPL then creates a redundant DODAG (see Fig. 3d, where `D` and `E` have redundant paths to the sink). The peer-to-peer mode does not, however, implement low radio duty-cycle, so the network's energy consumption is high.

To introduce redundancy at the MAC layer, while remaining energy efficient, Pavkovic *et al.* [10] propose to use a cluster-DAG in IEEE802.15.4-2011. This allows RPL to select multiple parents (Fig. 3e), at no extra costs: the same amount of DIOs are sent regardless the number of parents selected.

To avoid loops in the cluster-tree or the cluster-DAG, a path metric is required at the MAC layer, but none is defined in IEEE802.15.4. Here again, MAC and routing layers can be in conflict: if the MAC layer uses hop count, it creates a cluster-DAG with long and potentially bad links. Even if the routing protocol uses a different metric, it can only choose from MAC links. Hence, it will keep on using long and bad radio links, negatively impacting the network's reliability and energy consumption.

Having several applications run on the same network imposes further requirements. RPL can implement a DODAG instance per application, each DODAG potentially using a different routing metric. This requires the MAC layer to offer sufficient neighbor choices.

Evaluation. We quantify the impact of blind layer separation on topology control, through simulation.

Fig. 4a shows the Complementary Cumulative Distribution Function (CCDF) of the number of routing neighbors a node has, when using both cluster-DAG and peer-to-peer MAC topologies. The peer-to-peer MAC topology gives RPL a larger choice of neighbors, hence more diversity.

Fig. 4b illustrates the CCDF of the end-to-end Packet Delivery Ratio, when using either hop count or ETX at both MAC and routing layers. The network performs best when both MAC and network layers use ETX, offering the largest end-to-end reliability. In this case, MAC and routing layers make consistent decisions and use the links with the smallest ETX, improving the end-to-end reliability.

Recommendations. We recommend that the MAC protocol does not impose a topology to the network, but only filters out bad links (e.g., link with the quality below a certain threshold). It is up to the routing protocol to use the set of good links presented by the MAC layer and construct a multi-hop redundant routing topology.

C. Routing Topology Dynamics

Context. When a node changes its preferred parent, it resets its trickle timer, which generates more DIOs and a higher energy consumption. Changing parent too often is not efficient. One option is to limit parent changes by reducing the number of MAC neighbors. However, this also comes with the price of limiting routing diversity.

Evaluation. We quantify the impact of the number of neighbors on network dynamics by simulation. We implement the Minimum Rank with Hysteresis Objective Function (MRHOF) [11], in which a node changes its preferred parent only when its new rank differs significantly from the old one.

Fig. 4c shows the CCDF of the average number of parent changes for a node, over a simulated hour, when both RPL and IEEE802.15.4 use ETX. A node changes its preferred parent more frequently when using a peer-to-peer MAC topology. It offers more choices, and a small variation in the link quality estimation can result in changing the preferred parent. Fig. 4c also confirms the conclusions of [12] that parent changes are more frequent in larger networks.

Recommendations. To reduce the number of RPL parent changes, we recommend the use of hysteresis when estimating the link quality, such as the Window Mean with Exponentially Weighted Moving Average (WMEWMA). Several other techniques have been proposed in the literature, still WMEWMA offers the highest performance [13].

D. Estimating Link Quality

Context. To estimate the quality of a link to a neighbor, a node can use statistics of data packets exchanged in the network. The main problem with this passive approach is that the estimation is done only for the neighbors the node communicates with. In an active approach, the node can send probe packets, at the cost of extra overhead. OpenWSN 1.9.0, Contiki 2.6 and TinyOS 2.1.2 all use the passive approach.

In RPL, a node communicates only with the preferred parent, so there is no way to estimate the link quality to the other neighbors. The preferred parent can be a *set* of parents if those parents are equally preferred. Still, RPL does not specify the forwarding rule. [14] proposes for a node to send outgoing traffic to all its neighbors simultaneously. One parent will be selected opportunistically to forward the packets.

Evaluation. Fig. 4d plots the CCDF of the number of parent changes, when using a single parent or a set of parentst. Not only that the latter approach allows a node the estimate the link quality to several neighbors, but it also increases the stability of the routing topology.

Recommendations. We propose for a node to use all parents in its parent set to route packets to the root (not just the preferred one), allowing the quality to the links to all parents to be passively monitored.

E. Computing ETX

Context. The ETX of a link is defined as $\frac{1}{PDR}$, with PDR the Packet Delivery Ratio of that link. The PDR is computed as the ratio between the number of acknowledgments received and the number of packets sent. Both Contiki and TinyOS compute ETX by simply counting the number of retransmissions, without taking into account packets dropped by the MAC layer (because of successive CCA failures or buffer timeout). Still, these dropped packets reflect the quality of those links.

Evaluation. Using the simulation setting from Section III-A, we observed that while only 0.05% of packets are dropped when using a peer-to-peer MAC topology, this ratio shockingly increases to 12% with the cluster-DAG. The latter can be attributed to additional contention because of the inactive periods of the beacon mode, and clearly should be taken into consideration when evaluating the quality of a link.

Recommendations. We recommend that the computation of ETX accounts for the packets dropped by the MAC layer, including because of successive CCA failures or buffer timeout.

IV. TOMORROW'S LLN TECHNOLOGY: IEEE802.15.4E TSCH AND IETF 6TISCH

The IEEE802.15.4e amendment was published in 2012, and introduces a radically new medium access control technique: Time Slotted Channel Hopping (TSCH). In a TSCH network, nodes are tightly synchronized, and time is cut into time slots. Slots are grouped in a slotframe, which continuously repeats over time. As depicted in Fig. 5, a slot is long enough (typically 10ms) for a node to send a packet to its neighbor, and for that neighbor to indicate successful reception through a link-layer acknowledgment (ACK).

Communication is orchestrated by a schedule which indicates to each node what to do in each slot: transmit, receive, or sleep. "Scheduling" a network corresponds to populating the slotframe with communication slots. Fig. 5 shows a canonical example schedule for the depicted topology. When `E` needs to communicate data to `A`, it sends the data packet to `C` at slot offset 1, on channel offset 2. `C` acknowledges successful reception (causing `E` to clear the data from its transmit buffer), after which `C` sends to `A` at slot offset 4, channel offset 3. The slotframe repeats continuously, giving the nodes repeated opportunities to communicate. Fig. 5 is simplified to be easily explained, real-world slotframes are 10's to 1000's slots long, with typically 16 channel offsets (when using the IEEE802.15.4 physical layer at 2.4GHz).

There is a subtle but important difference between channel offset and frequency. The schedule indicates the former; the channel offset is translated on-the-fly into a frequency through a pseudo-random hopping pattern each time the device turns its radio on. This means that, in successive slotframe iterations, the same channel offset translates into different frequencies. The result is "channel hopping": when two nodes communicate, successive retransmissions happen at different frequencies, thereby combating external interference and multi-path fading. [15] highlights the effectiveness of channel hopping in IEEE802.15.4 networks.

TSCH allows the network to be abstracted by its communication schedule. This schedule must be built to match link-layer resources (the cells) to the requirements of the applications running on the network. This allows a clean trade-off between throughput, latency and energy consumption. IEEE802.15.4e does not define how to build or maintain the TSCH schedule. A "standardization gap" hence exists between the IEEE802.15.4e link-layer standard and upper layer standards such as 6LoWPAN, as neither define the entity responsible for building and managing the TSCH schedule.

The IETF 6TiSCH standardization working group was created in 2013 to fill this standardization gap by defining mechanisms to manage the TSCH communication schedule. 6TiSCH defines the 6top sublayer which operates at layer 2.5, between IEEE802.15.4e and 6LoWPAN. 6top offers a management interface (detailed below), and gathers statistics about each communication cell. Statistics include the number of transmitted frames in that cell, and the portion of those frames which were acknowledged.

6top supports centralized and distributed scheduling. In a centralized approach, the 6top sublayer of each node implements a CoAP-based management interface. This allows a central scheduling entity (called a Path Computation Element, PCE) sitting outside of the network to gather information about the topology of the network, compute an appropriate schedule, and configure each node with the cells of the schedule it participates in (using the CoAP application-level protocol). When using the distributed approach, no PCE is present in the network, and nodes need to agree on the schedule to use in a distributed fashion. The 6top sublayer implements a management interface allowing two neighbor nodes to negotiate adding/removing cells to one another. Communication happens through "Information Elements" in the IEEE802.15.4e header, fields which can serve as containers for a layer 2.5 protocol. In this distributed approach, a node monitors the transmission queue to each of its neighbors: if the queue overflows (resp. underflows), the node contacts its neighbor to negotiate to add (resp. remove) cells.

6TiSCH defines the mechanisms which support both centralized and distributed schedule management (packet formats and typical interaction). As a standardization entity, IETF 6TiSCH does not define the policy (when to use centralized/distributed, and the scheduling algorithm). Identifying the scheduling approach to adopt, and the associated limits is an open research problem. Intuitively, a centralized approach can compute near-optimal schedules, provided it has up-to-date information about the network topology and the needs of the applications running in the network. A distributed approach might be preferred when the topology is highly dynamic (e.g. a swarm of mobile robots), or when a PCE cannot be installed (e.g. a very simple home network where a PCE is not cost-efficient).

This paper highlights several issues which are closely related to the current standardization work at IETF 6TiSCH.

Topology control. The choice of the topology at the MAC layer impacts the diversity of the routes. 6TiSCH proposes to use shared slots for exchanging broadcast control packets such as DIOs. This allow RPL to use any neighbor as a parent; 6top is then in charge of negotiating dedicated slots between the node and its parent. This is directly in line with the recommendations done in Section III-B. What is missing in the 6TiSCH solution is a mechanism to modify the schedule on-the-fly in a distributed fashion.

Using different metrics. The 6top sublayer gathers cell statistics, which RPL uses to select the best routes. However, link metrics are needed to aggregate these statistics, some of which being TSCH-specific (e.g., per-frequency transmission counters). One option is to develop a unified link metric which encompasses both MAC and routing metrics. This remains an open research problem, especially when several applications run on the same network and RPL has to implement a DODAG instance per application.

Routing topology dynamics. TSCH uses channel hopping to make links more reliable, and the connectivity in the network more stable. However, capturing the variations over time, while not overreacting to inaccurate estimators remains an open challenge.

Link quality estimation (ETX) with 6TiSCH. 6top maintains per-cell statistics (including the number of packets sent and acknowledged). The ETX between two neighbor nodes is calculated by aggregating the statistics from the different cells scheduled between those nodes. What is missing is a way to discover neighbors a node is not communicating with, and estimate the quality of the link to that neighbor.

V. Conclusion

Network performance depends not only on the MAC and routing protocols used, but also on their interaction. This article highlights the interaction between the topology defined at the MAC layer and the decision made by the routing protocol. Through simulation, we show that a peer-to-peer MAC topology yields higher performance compared to cluster-DAG topology, as it presents more neighbors to the RPL routing protocol. However, having more neighbors does mean that RPL might change a node's preferred parent more often (especially with large networks). Still, this article shows how using a set of parents and passive link quality estimation, reduces network churn.

These observations are being addressed by the new IETF 6TiSCH working group, which defines 6top, a sublayer between the link-layer (IEEE802.15.4e) and networking/routing layers (RPL). The resulting architecture, which combines the performance of IEEE802.15.4e TSCH with the an IPv6-based upper stack has the potential of revolutionizing LLN technology. With the work already done, IETF 6TiSCH is starting to do so, but several challenges remain open, including the ones highlighted in this paper, i.e., an on-the-fly distributed reservation mechanism, and a link metric that combines MAC and routing statistics.

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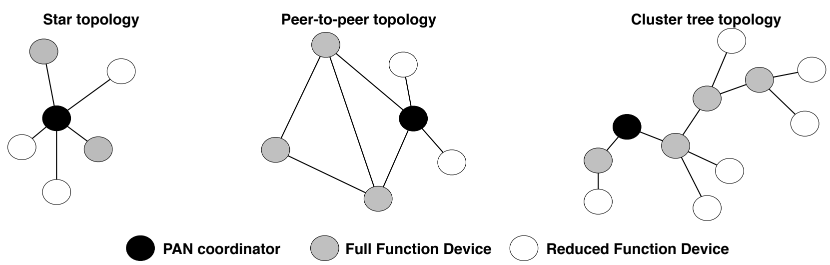
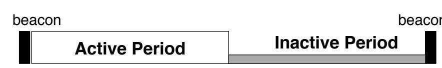
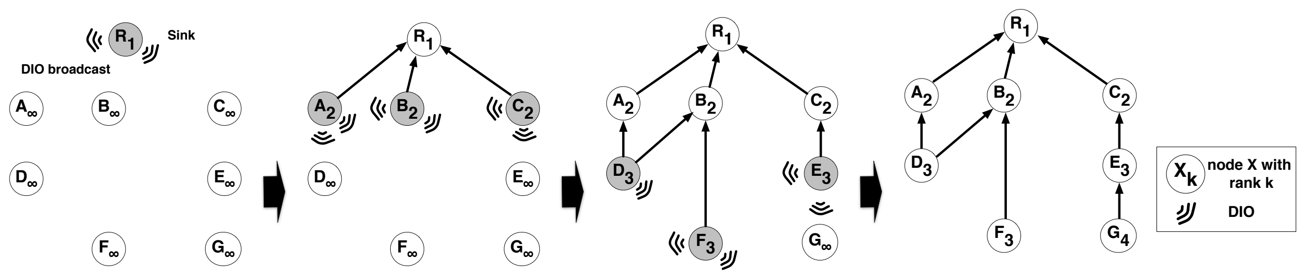


(a) Topology examples.



(b) Superframe structure of IEEE802.15.4.

Fig. 1: IEEE802.15.4-2011 concepts.



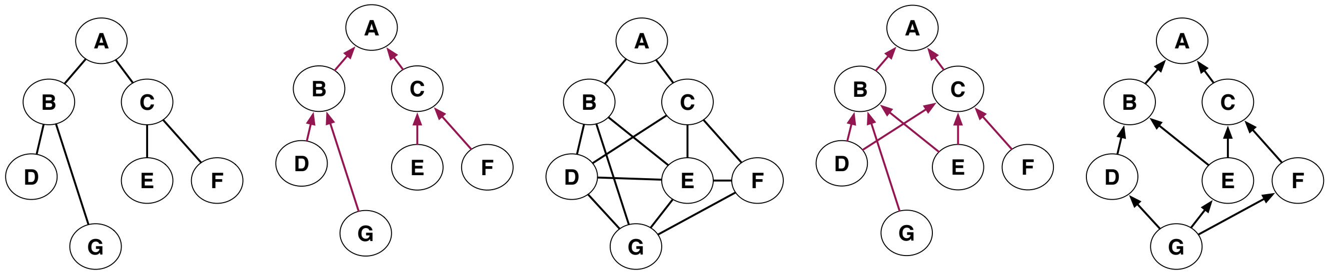
(a) Bootstrap. The sink starts broadcasting DIO messages.

(b) The neighbors of the sink choose it as the preferred parent.

(c) DIO propagation continues until reaching all the nodes.

(d) After all the nodes chosed their preferred parent, a DODAG is formed.

Fig. 2: DODAG construction with hop count as a routing metric.



(a) Cluster-tree MAC topology.

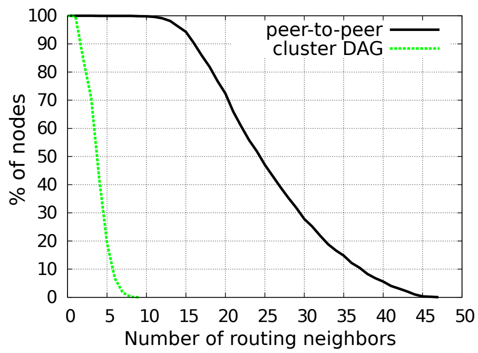
(b) Running RPL on top of a cluster-tree MAC topology.

(c) Peer-to-peer MAC topology.

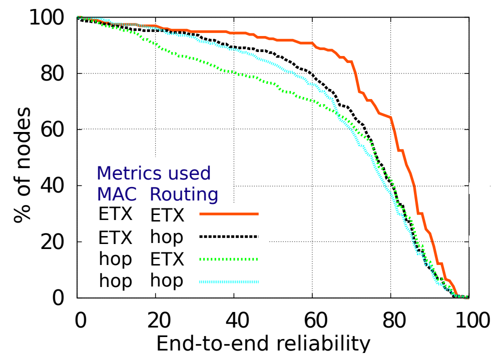
(d) Running RPL on top of a peer-to-peer MAC topology.

(e) Using a cluster-DAG topology.

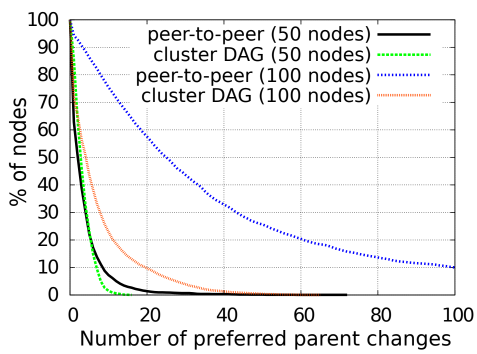
Fig. 3: Topology control using hop count as a metric.



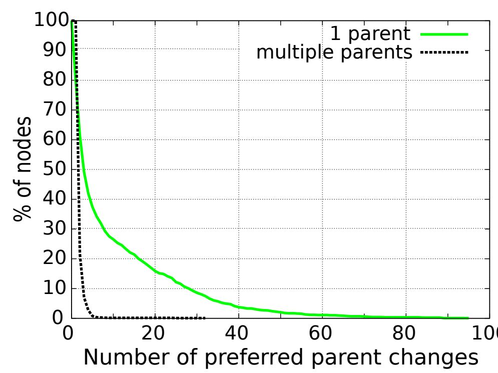
(a) A node has more routing neighbors when using a peer-to-peer rather than a cluster-DAG MAC topology (the network has 50 nodes)



(b) The network has the highest end-to-end reliability when both MAC and routing layers use the same metric ETX (the topology is a cluster-DAG and has 50 nodes)



(c) The difference in the number of preferred parent changes between the beacon and the non beacon mode increases with the size of the network.



(d) The number of preferred parent changes decreases when using a multipath technique for RPL (the topology is a cluster-DAG and has 50 nodes)

Fig. 4: Simulation results.

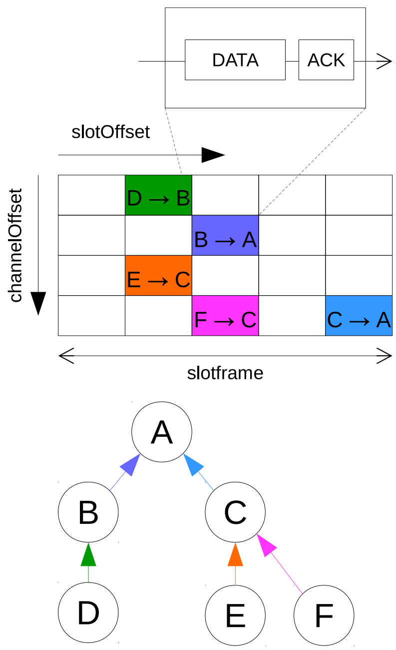


Fig. 5: IEEE802.15.4e TSCH network example

Parameter	Value
Simulation duration	3600 s (1 hour)
Number of nodes	50 or 100 nodes deployed uniformly on a disk
Simulated area	400m^2 (50 nodes), 800m^2 (100 nodes)
Traffic model	CBR, 1 pkt/min, convergecast
Data packet size	127 bytes
RPL parameters	MinHopRankIncrease $= 256$
RPL Objective Function	MRHOF (for ETX) and OF0 (for hop count)
MRHOF parameter	PARENT_SWITCH_THRESHOLD = 0.5
Trickle parameters	$Imin = 2^7 ms$, $Imax = 16$, $k = 1$
MAC protocol	IEEE802.15.4-2011
Beacon mode parameters	BO=7, SO=2
PHY model	path-loss shadowing
PHY parameters	path loss $= 1.97$, standard deviation $= 2.0$, $Pr(2m) = -61.4dBm$
Simulation runs	10 (results are average over 10 random topologies)

TABLE I: Simulation parameters.