# Performance Evaluation the 6top Protocol and Analysis of its Interplay with Routing

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# Performance Evaluation the 6top Protocol and Analysis of its Interplay with Routing

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***Abstract*—Wireless Sensor Networks (WSNs) will represent a crucial enabling technology to interconnect sensors and actuators in future smart cities. Since many applications will demand for reliable and low-latency communication, current standardization efforts are focusing in the definition of novel wireless standard architectures, e.g., the 6TiSCH architecture, to improve reliability and introduce support for quality of service. In this paper, we evaluate the performance of the 6TiSCH architecture during the initial network formation. Specifically, the performance of the 6top protocol, defined in 6TiSCH for distributed negotiation of resources, is evaluated. Simulations highlighted how the initial negotiation of resources is influenced by the routing protocol and the link-quality estimation mechanism adopted. The performance evaluation allowed to draw a set of guidelines for network configuration to guarantee the reliability of the initial allocation of resources.**

***Keywords*—*6TiSCH; 6top; IPv6 Routing Protocol for Low-Power and Lossy Networks(RPL); Reliability; Network Bootstrap;***

## I. Introduction

The future smart city will greatly rely on interconnected devices to implement innovative smart services that could improve dramatically the quality of life of its citizens. These devices, such as sensors and actuators, will represent the technological foundation to build applications based on remote monitoring and control of heterogeneous physical systems.

In this context, Wireless Sensor Networks (WSN) will represent a crucial enabling technology to interconnect these devices with an infrastructure that can be rapidly deployed with limited costs to cover the large areas of a smart city and can provide the flexibility required to handle its rapid changes. In this heterogeneous environment, certain applications will be characterized by specific communication requirements, demanding for predictable low-latency and reliable communication to implement their functionalities. Monitoring of public transportation vehicles for telemetry, remote control of meters for anomaly detection in utility networks, and collection of traffic information for supervision are some examples of smart city applications that will require timed and reliable communications with sensors and actuators to obtain accurate information and enforce timed control, respectively.

The most popular standard for WSNs, namely the IEEE 802.15.4 standard, is unfit to provide such quality of service (QoS) guarantees as it does not provide support for reliable and timed delivery of information. In order to overcome such limitation, recently the IEEE 802.15.4e amendment has been standardized to improve reliability and provide QoS support [10]. Among them, the new Medium Access Control (MAC) protocol, the Time-Slotted Channel Hopping (TSCH), is considered as the major improvement to guarantee reliable data delivery with bounded latency. In order to foster interoperability of TSCH networks, the IETF created the 6TiSCH working group (WG) to enable their integration into existing IPv6 infrastructures. Specifically, the WG has defined the 6TiSCH architecture in which low-power and wireless devices can form a multi-hop low-power and lossy network using the IEEE 802.15.4 TSCH MAC protocol, which is connected into the Internet through one or more border routers. Since the IEEE 802.15.4e standard defines only the mechanisms for communication and leaves out of scope how network resources are managed, the 6TiSCH WG is currently standardizing the approaches to allocate network resources based on the QoS communication requirements. Among them, a distributed approach is currently being defined to enable dynamic allocation of resources between the nodes in a distributed manner. Specifically, the 6top protocol (6P) is under standardization to define a protocol for nodes to dynamically negotiate communication resources in a distributed manner at network bootstrap or during network regular network operations, when the traffic variations occur.

So far, the research efforts on this topic have focused on the definition of novel algorithms for the management of network resources, [6][7]. Although such scheduling algorithms leverage on the 6top protocol for resource allocation, all of them rely on the assumption that the protocol is effective and reliable. Such assumption, however, cannot be taken for granted, especially at network bootstrap when several nodes execute the protocol at the same time.

In this work, we present a performance evaluation of the 6top protocol during the crucial phase of the network bootstrap. Our goal is to investigate how its performance is affected by different settings and how the dynamics of the routing protocol influence its reliability. The performance evaluation carried out

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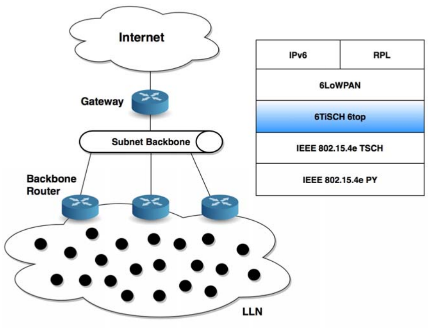


Figure 1. The 6TiSCH architecture.

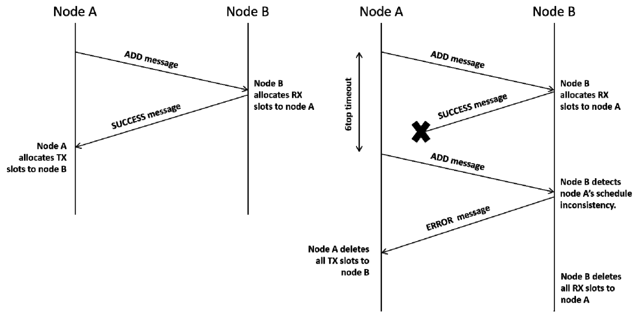


Figure 2. 6top message exchange.

by means of experiments allows to derive a set of guidelines to draw network configuration to guarantee a reliable bootstrap. The analysis also demonstrates that the initial resource allocation process is influenced by the routing protocol and particularly by the link-quality estimation mechanism adopted. Specifically, it is shown that an unreliable link quality measurement can result in the selection of unreliable routes that can consequently delay the allocation of resources at bootstrap. In order to mitigate this issue, the usage of an active link quality measurement strategy is proposed jointly with a more conservative policy for the route selection.

The remainder of the paper is organized as follows: Section II gives an overview of the technological background on the 6TiSCH architecture and the 6top protocol. Section III describes the simulation methodology while Section IV presents the performance evaluation results of the 6top protocol with static routing. Section V shows the performance with dynamic routing, and Section VI draws the conclusions.

## II. 6TiSCH Architecture

The goal of the 6TiSCH working group of the IETF [4] is to define the architecture and the protocols required to integrate WSNs that require high reliability and deterministic latency into existing IPv6 networks. Figure 1 shows the overall network architecture. For physical communication, the IEEE 802.15.4 standard [5] is adopted, as it is the de-facto standard for the communication of low-power devices, often used to build multi-hop networks. Instead of the legacy MAC protocol, the Time-Slotted Channel Hopping (TSCH), a MAC protocol proposed in the IEEE 802.15.4e amendment [5], is adopted. TSCH combines time synchronization and channel hopping to guarantee high-reliability and deterministic latency.

On top of the TSCH MAC, the 6LoWPAN adaptation layer is exploited to allow the adaptation of IPv6 packets for IEEE 802.15.4 networks. Using the standard IPv6 protocol, the WSN can be connected to external networks by means of one or more border router(s) that are responsible for rerouting IPv6 packets to/from the WSN. In order to implement multi-hop data delivery inside the WSN and to/from the border router(s), the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) routing protocol is adopted.

The standardization activity of the 6TiSCH WG focuses on filling the missing gaps within this architecture. Specifically, the WG is currently working on the standardization of the 6top sublayer that aims at guaranteeing that IPv6 and RPL messages can optimally operate on top of the TSCH layer.

### A. *IEEE 802.15.4e TSCH MAC*

The TSCH MAC has been specifically designed for WSNs that require high resiliency to interference and deterministic latency in data delivery. Unlike the traditional carrier sense multiple access / collision avoidance (CSMA/CA) contention based MAC, TSCH adopts time slotted channel access mode in which all nodes are time synchronized. Time is divided into chunks of fixed length, called *timeslots*, that are grouped into a *slotframe*. Each timeslot is scheduled in two different modes: *dedicated timeslots* and *shared timeslots*. Dedicated timeslots are timeslots allocated specifically to one node for its communication towards one neighbor. Shared timeslots, instead, are allocated to all the nodes for broadcast communication. Dedicated timeslots are guaranteed to be contention free, so they are accessed without contention; on the other hand, channel access in shared timeslots is contended and requires the execution of a CSMA/CA like protocol. The schedule of the timeslotframe continuously repeats over time.

In order to exploit frequency diversity and combat multi-path fading and interference, TSCH adopts a channel hopping technique. Specifically, a pre-defined channel sequence is shared among all the nodes to select the actual frequency for each transmission. Concurrent transmissions on the same timeslot can be performed applying an offset to the channel hopping sequence, thus resulting in the adoption of different frequencies. Every node can follow the schedule to know when and on which frequency can transmit or data is expected.

### B. *6top sublayer*

The IEEE 802.15.4e TSCH standard defines only the mechanisms for communication and leaves out of scope how network resources are managed. In order to fill this gap, a 6top operation sublayer is introduced. Such sublayer is responsible for regulating the allocation of TSCH timeslots to ensure timed and reliable communication. Among the others, the 6top standard [3] defines a distributed allocation mode, in which the nodes of the network collaboratively negotiate the allocation of transmission opportunities in a distributed manner, following a local allocation policy, called *scheduling function*.

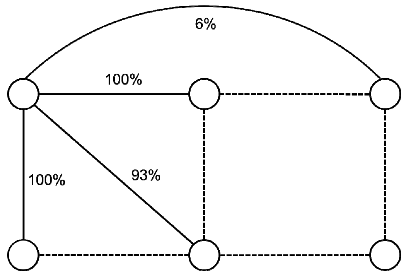


Figure 3. Link Packet Delivery Ratio (PDR).

Table 1. Simulation settings and parameters.

| Parameter | Value |
|---|---|
| TSCH slotframe length | 101 |
| TSCH timeslot duration | 15ms |
| TSCH number of channels | 16 |
| RPL redundancy threshold | 10 |
| RPL minimum interval | 128ms |
| RPL maximum doublings | 20 |
| RPL Objective Function | MRHOF - ETX |
| MAC Min BE | 1 – 4 |
| 6top Timeout | 10s – 60s |
| 6top Timeslots | 1 – 5 |

In order to allow coordination among neighbors, the 6top standard defines the 6top protocol (6P) that is exploited by nodes to negotiate timeslots. The protocol defines the set of messages exchanged to allocate and deallocate timeslots (the ADD, DELETE and CLEAR messages, exploited to request a new allocation, delete an existing allocation or clear the current allocation respectively) and to exchange information on the current schedule for synchronization (the COUNT and LIST messages, defined to count and retrieve the list of scheduled timeslots, respectively). The 6top standard defines different modes for the exchange of these messages; among them a two-step transaction is defined as illustrated in Figure 2. In the left side, a successful transaction is presented: a node requires the allocation of a specific timeslot to a neighbor that approves the request replying with a SUCCESS message (or with an ERR message in case the request cannot be received). In case a message of the transaction is lost or corrupted, as shown in the right side of Figure 2, a retransmission of the request is issued after a timeout. In order to keep track of subsequent 6top transactions between neighbors and detect inconsistencies, a sequence counter is included in the exchange of 6top messages between neighbors. In case a mismatch in the sequence counter is detected by one of the nodes involved, e.g., because a response message is lost, the node replies with an ERROR message that forces the originating node to send a CLEAR message to reset the schedule. After the reset, the node can start over the allocation process. The standard allows each node to execute only one 6top transaction at a time; in case multiple requests are issued when there is an outstanding transaction, the request is enqueued.

## III. METHODOLOGY

In order to evaluate 6top, the protocol has been implemented into the Contiki OS[1], a popular operating system for sensor nodes that includes an implementation of the basic functionalities of the IEEE 802.15.4 TSCH MAC. In addition to the TSCH MAC, the OS includes a complete implementation of all the 6TiSCH protocol stack, i.e., it implements 6LoWPAN header compression and the RPL routing protocol. For an extensive performance evaluation that covers a wide range of configurations, the Cooja simulator [8] - a network simulator available as part of the Contiki OS distribution - has been exploited. In our simulations, Cooja has been configured to simulate a network of Cooja motes, i.e., a generic sensor hardware equipped with an IEEE 802.15.4 radio interface. Although Cooja allows the emulation of real hardware, Cooja motes are adopted to overcome limitations in terms of memory and computation capabilities. The extension of this study including experiments with real hardware is left as future work. To simulate a realistic wireless channel, we adopted the Multipath Ray-tracer Medium (MRM) model, a propagation model that implements ray-tracing techniques with various propagation effects, e.g., multi-path, refraction, diffraction, etc.

The simulation scenario considered is a network with a regular grid topology. Different network sizes are considered, i.e., a 4x4 grid with 16 nodes and a 5x5 grid with 25 nodes. The distance between nodes is set to 33m. MRM channel parameters are set in order to result in a packet delivery ratio (PDR) of 100% at such distance as the maximum transmission power. The PDR of the other links is reported in Figure 3, while the configuration settings of TSCH are reported in Table 1. The configuration is performed following the guidelines provided in the 6top protocol draft [3]. In order to implement multi-hop communication, we employ the RPL routing protocol which is configured following the default settings as summarized in Table 1. In our simulations, the top-left corner is selected as the RPL-root node.

Simulations are run for 60 minutes. To obtain statistically sound results, 30 independent replications with different seeds are run for each scenario. The average value of each metric with its 95% confidence interval is reported.

## IV. STATIC ROUTING PERFORMANCE ANALYSIS

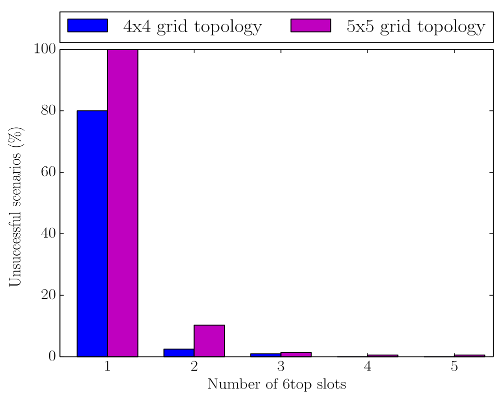


Figure 4. Unsuccessful scenarios.

[1] Contiki OS, http://contiki-os.org/

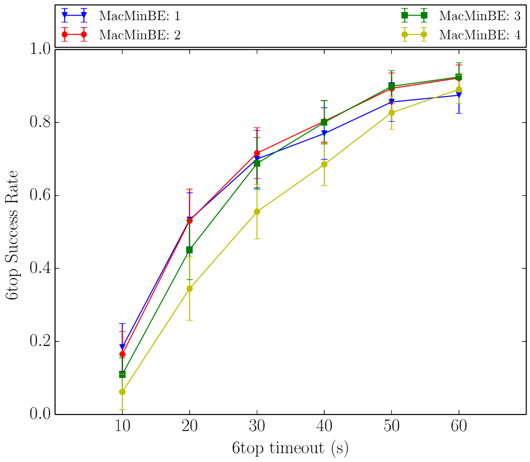


Figure 5. 6top success rate.

In this section, we present the result of a preliminary performance evaluation of the 6top protocol in which the effects of the configuration parameters are evaluated. Our goal is to derive a set of guidelines for network configuration to ensure a reliable bootstrap phase. The evaluation focuses on assessing the network bootstrap, as the most challenging phase for the protocol performance, considering that many nodes at the same time are expected to issue a 6top transaction with neighbors as the routing protocol discovers new routes for forwarding data traffic. Specifically, in our simulations, nodes are programmed to issue one 6top transaction with the selected preferred parent in order to negotiate the allocation of a dedicated timeslot for data forwarding. The timeslot is selected randomly in the slotframe.

The following parameters are considered for the evaluation: (i) *6top timeslots*, the number of shared timeslots dedicated for the transmission of 6top messages; (ii) *6top Timeout*, the timeout value for the retransmission of 6top transactions; (iii) *MacMinBE*, the minimum value of the Backoff Window Exponent (BE), $[0, 2^{BE} - 1]$, of the TSCH CSMA/CA protocol for shared timeslots. Such settings have been selected for the evaluation as they play a significant role in the performance of the protocol when a large number of transactions are issued at the same time, as it is expected at bootstrap.

The performance is assessed through the following metrics:

- *Success rate*, defined as the ratio between the number of transactions successfully completed, i.e., resulted in the successful allocation of a slot, and the number of transactions issued by each node.
- *Allocation delay*, defined as the time between the transmission of the request and the successful allocation of a timeslot. Transactions that are not completed because a packet is lost or have received a negative response due to the detection of an inconsistency, are not considered.
- *Number of inconsistencies*, defined as the overall number of inconsistencies detected in the network through the evaluation of the sequence counter. This metric measures also the number of times the allocation has been reset.

In order to evaluate only the influence of such parameters, this first set of simulations is run with static routing.

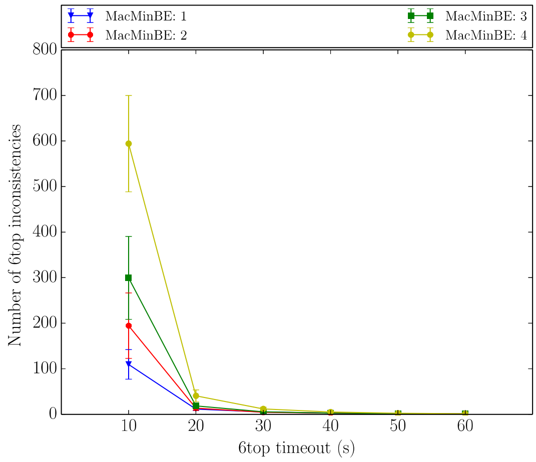


Figure 6. Overall number of inconsistencies detected.

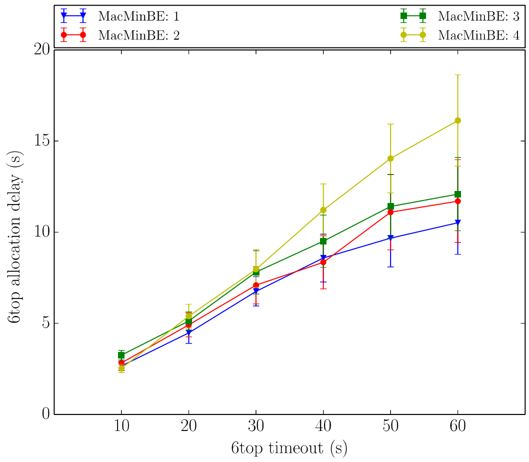


Figure 7. 6top allocation delay.

Specifically, the RPL protocol is disabled and static routing entries are pre-installed on each node. The routing entries are computed based on the shortest path towards the root node. Such initial set of experiments allows to evaluate the effects of 6top and TSCH parameters, in a controlled scenario that is not affected by routing dynamics.

An exhaustive set of simulations is run, considering all the possible combinations of parameters and their values in the range reported in Table 1. First, the number of unsuccessful scenarios in the overall number of simulations is evaluated. A scenario is considered unsuccessful, when at least one node could not successfully complete its 6top transaction. Results shown in Figure 4 are grouped considering the number of 6top timeslots. As can be seen, with certain configurations the successful completion of at least one 6top transaction per node cannot be guaranteed, especially when only one 6top timeslot is allocated. As the number of allocated timeslots increases, the number of unsuccessful scenarios decreases significantly as more slots can reduce contention level allowing more messages to be delivered. Summarizing, at least two 6top timeslots have to be allocated in order to reduce the likelihood of high congestion in the delivery of 6top messages. Such results show that an allocation of 3 timeslots is a good compromise between bootstrap performance and overhead. For this reason, in the reminder of the section, only results obtained with 3 timeslots will be shown.

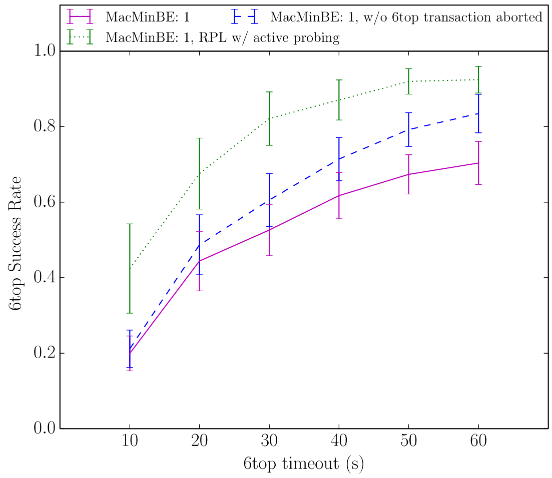


Figure 8. 6top success rate with different RPL configurations.

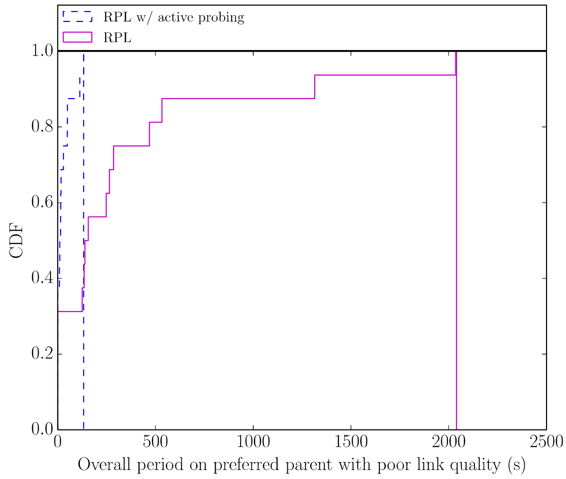


Figure 9. CDF overall period on preferred parent with poor link quality.

In Figure 5, the 6top success rate obtained in the 4x4 grid network versus the 6top timeout is shown. Different lines show the results obtained with different values of the MacMinBE. Results obtained with the 5x5 grid are omitted for the sake of brevity as they show the same trend of the results obtained with the 4x4 grid. As it can be seen, the timeout value influences significantly the success rate: the higher the timeout, the higher the transaction rate. This behavior can be explained considering the large number of 6top messages that are considered lost and retransmitted, even if they are just waiting due to the high contention in the shared 6top timeslots. Instead the retransmission of 6top messages that, have been successfully received causes the desynchronization of the sequence counter, and consequently the allocation reset, which, eventually, produces additional messages. This is confirmed by the data in Figure 6, which shows that the overall number of inconsistencies increases when a short timeout is selected. The setting of the MacMinBE parameter, on the other hand, seems to influence less the performance of the protocol. Only the results obtained with MacMinBE set to 4 seem to underperform noticeably, as the transmission of packets on the shared timeslots is delayed significantly. Eventually, the 6top allocation delay is analyzed in Figure 7. As expected, the lower the timeout, the lower is the delay for the completion of a transaction. This can be explained considering the lower success rate: more transactions are terminated earlier because of the inconsistencies, resulting in a lower amount of 6top messages exchanged, which decreases the congestion level. When different MacMinBE values are considered, it can be seen that a low value for the backoff algorithm results in slightly lower delays for the successful transactions to be completed. This is the effect of a more immediate retransmissions after a collision.

To summarize, the following guidelines can be drawn for the 6top configuration: the number of allocated slots has to be at least 2, the timeout should be set to a value in between 40s and 60s to maximize the success rate, while the MacMinBE should be set to 1 to minimize the delay.

## V. Performance Evaluation with RPL

In this section, the performance of the 6top protocol is assessed when the RPL routing protocol is employed instead of a static routing. Also in this case, simulations are run considering all possible combinations of the different values for the number of 6top timeslots, the 6top timeout and the MacMinBE parameter. However, since the same trend obtained with the static routing is confirmed, for the sake of brevity only the results obtained in the scenario with 3 timeslots and MacMinBE set to 1 are shown.

Figure 8 reports with the solid line the 6top success rate vs. the timeout. Compared with the results obtained with static routing, the same trend is displayed, however, the overall success rate is significantly reduced. This can be explained considering the dynamics of the routing protocol: during bootstrap RPL changes several times the neighbor selected for data forwarding, the so-called *preferred parent*. During bootstrap, the selection of a new preferred parent happens so frequently that they might be taken place shortly one after another, especially when dense networks are considered. In these cases, a new preferred parent might be selected before the completion of a 6top transaction, which is consequently aborted, thereby reducing the resulting success rate. This is demonstrated in Figure 8 that reports also, with the dashed curve, the 6top success rate without counting the 6top transaction aborted due to a new preferred parent selection.

Even if the success rate without the transactions terminated prematurely is higher, it is still lower than the success rate obtained with static routing. This can be explained considering the methodology adopted by the RPL protocol to estimate the link quality. Since the RPL protocol does not specify a mechanism to estimate the quality of links towards neighbors, different approaches have been proposed in the literature [2]. The default strategy adopted in the Contiki OS estimates the link quality using a passive monitoring approach in which data packets are used to derive the link quality. Such approach, however, measures the quality only towards the current preferred parent. In order to obtain an almost exhaustive evaluation of all the links towards other neighbors, a policy that opportunistically favors the selection of recent discovered neighbors as preferred parent is implemented. Specifically, when a link to a new neighbor is discovered, the link is by default assumed to be good. By doing this, the new neighbor is likely selected as the new preferred parent and a link quality

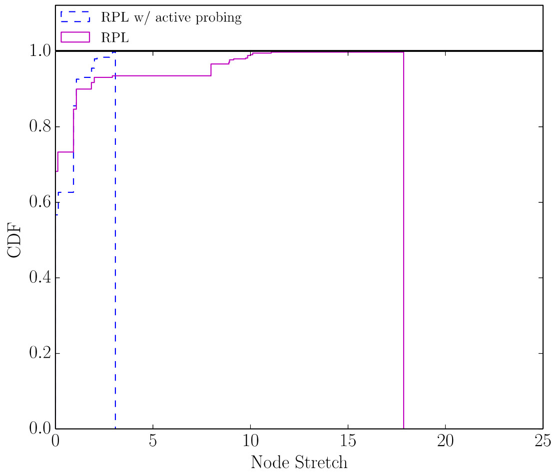

Figure 10. Node route stretch distribution.

estimate is obtained by passively monitoring the data traffic. Although simple, such policy facilitates rotation among next-hop candidates but it results in routing instability during the network bootstrap. In addition, it results in periods in which nodes select a neighbor with poor link quality [1]. When a neighbor with bad link quality is selected as preferred parent, 6top transactions are expected to fail continuously.

This behavior is highlighted in Figure 9 that shows the cumulative distribution function (CDF) of the overall period in which a node selects as preferred parent a neighbor with poor link quality. A link is considered of poor quality when it has an expected transmission count (ETX) of at least 5, i.e., the average number of retransmissions required to successfully transmit a packet is greater than 5. The results obtained using the default link-quality estimation strategy are reported using a solid line. As can be seen, at least the 30% of the nodes spend at least 100s during each experiment with a neighbor with poor link quality, thus explaining the increase in the number of unsuccessful 6top transactions.

In order to overcome this issue, an active monitoring strategy is commonly adopted. With this strategy, special control messages, called probe packets, are sent over each link to derive link quality information. In order to test the performance with active probing, an additional set of simulations is run. Specifically, the active probing implemented in Contiki is enabled to probe neighbors, other than the preferred parent, every 60s on a round robin fashion. In order to avoid the transmission of probe packets on shared timeslots, which would result in an inaccurate link quality estimation due to collisions, each node negotiates one timeslot with each neighbor at the time of its discovery. In order to configure RPL with a conservative selection of the preferred parent, the protocol is configured to assume that newly discovered neighbors have bad link quality. This configuration will avoid route instability, as a new neighbor is selected as preferred parent only after an estimation of the link quality.

In Figure 8 the 6top success rate with active probing is reported using a dotted line. The success rate now reaches the same level obtained with static routing. This is obtained through a more conservative RPL configuration and through the active probing strategy, which reduces the periods in which nodes select a preferred parent with low link quality, as reported in Figure 9 using a dashed line. Moreover, as expected, active probing increases also the quality of the routes selected by nodes. Figure 10 reports the distribution of the node route stretch [9], defined as the difference between the cost of the route selected by a node (in terms of the average number of transmissions, ETX) and the cost of the shortest path. A comparison between the stretch obtained with active probing (dashed line) and with passive monitoring (solid line) shows how the former can also help in selecting better routes.

## VI. Conclusions

In this paper, a performance evaluation of the 6top protocol used in 6TiSCH networks for the dynamic negotiation of timeslots is presented. The results of the performance evaluation allow to derive a set of guidelines for the configuration of the system parameters so as to ensure a reliable network bootstrap. In addition, the interplay between 6top transactions and the dynamics of the RPL routing protocol is analyzed, showing how the route instability that characterizes the initial operations of RPL can significantly affect 6top negotiations. Finally, it is shown that the usage of active probing for link quality estimation and a more conservative configuration of RPL can be beneficial in ensuring a reliable network bootstrap. For future work, we plan to evaluate the 6top protocol during regular operations considering different dynamic scheduling policies.

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