Decentralized Traffic Aware Scheduling in 6TiSCH Networks: Design and Experimental Evaluation

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***Abstract*—This paper capitalizes on two emerging trends, i.e., the growing use of wireless at the edge of industrial control networks and the growing interest to integrate IP into said networks. This is facilitated by recent design contributions from the IEEE and the IETF, where the former developed a highly efficient deterministic time–frequency scheduled medium access control protocol in the form of IEEE 802.15.4e timeslotted channel hopping (TSCH) and the latter IPv6 networking paradigms in the form of 6LoWPAN/ROLL, and scheduling approaches in the form of 6TiSCH. The focus of the present work is on advancing the state-of-the-art of deterministic 6TiSCH schedules toward more flexible but equally reliable distributed approaches. In addition, this paper aims to introduce the first implementation of 6TiSCH networks for factory automation environments: it outlines the challenges faced to overcome the scalability issues inherent to multihop dense low-power networks; the experimental results confirm that the naturally unreliable radio medium can support time-critical and reliable applications. These developments pave the way for wireless industry-grade monitoring approaches.**

***Index Terms*—IEEE 802.15.4e, scheduling algorithms, 6TiSCH, timeslotted channel hopping (TSCH).**

I. Introduction

INDUSTRIAL networks, often referred to as operational technology (OT), and computer networks, referred to as information technology (IT), emerged simultaneously some 40 years ago, each designed with a specific aim and different range of applications in mind. After being developed for years in parallel, IT and OT technologies commence to converge and be mutually integrated, enabling OT traffic to be transported over a shared IP-based IT infrastructure. Due to their different goals, OT and IT have evolved in a radically different way one from another. Therefore, a number of new challenges have to be overcome, in order to make the IT/OT integration viable [1].

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The IP version 6 (IPv6) protocol [2] is the de-facto IP standard version for the IT/OT convergence. While the IP protocol has been used since the beginning at the networking layer of IT systems, OT needs to adapt not only to the IP standard itself but also to the whole IP protocols suite [3], including among others the IPv6 routing protocol for low-power and lossy networks (RPL) [4] and the constrained application protocol (CoAP) [5]. At the same time, it is necessary to adapt the IP suite to match the constraints and requirements of industrial networks (e.g., monitoring systems, motion detection, and control loops), which are deterministic by design and different from traditional IP QoS-based networks. To this aim, new protocols and an overall architecture tying the adapted protocol suite together should be defined by Standard Developing Organization (SDO) [1].

Following this trend, a new working group (WG), namely 6TiSCH [6], [7], has been created at the IETF to enable IPv6 over the deterministic timeslotted channel hopping (TSCH) mode of the IEEE802.15.4e standard [8]. In the 6TiSCH architecture, low-power wireless devices form a multihop low-power and lossy networks (LLN) that is plugged into Internet through one or more LLN norder routers (LBRs) [9].

Inside the LLN, nodes communicate by following a common schedule, which is a matrix of cells, each of them assigned to a pair of neighbor nodes for communicating at a given time, on a specific channel. The performance of the LLN (e.g., throughput, average packet latency, node energy consumption, network lifetime) is strictly dependent on the way this schedule is built.

The IEEE802.15.4e standard [8] defines the mechanisms to execute a communication schedule. At the same time, it leaves as out of its scope defining how the schedule is built, updated, and maintained, and designating the entity in charge of performing these tasks. Therefore, one of the goals of the 6TiSCH WG is to develop a standard approach to manage this schedule and build it according to the network requirements [10].

6TiSCH has been recently working on the definition of a so-called *minimal* schedule, a static one, which is either preconfigured, or learnt by a node when joining the network. Such schedule mode does not exploit the full benefits of IEEE802.15.4e TSCH, but it can be used during network bootstrap, as a fallback mode of operation when no dynamic scheduling solution is available or functioning, or during early interoperability testing and development [11].

At the same time, 6TiSCH aims to investigate and develop centralized and distributed scheduling solutions. In the *centralized* case, the schedule is built by a path computation element (PCE), a specific schedule entity, located into the Internet that continuously collects information from the network (e.g., traffic requirements from the nodes), in order to adjust the TSCH schedule accordingly. In the *distributed* case, there is no central entity, but nodes in the LLN agree on the schedule to be used, by applying distributed multihop scheduling protocols and neighbor-to-neighbor scheduling negotiation [12].

After the publication of the IEEE802.15.4e standard [8], both centralized and distributed scheduling approaches have been investigated by the research community, even before the birth of the 6TiSCH WG.

The first pioneer work [13] proposed a centralized solution, i.e., a traffic aware scheduling algorithm (TASA) that, by exploiting matching and coloring procedures, allows to schedule cells to all the nodes across the entire network topology graph. Briefly, with TASA, the TSCH schedule is settled based on the network topology and the traffic load. In detail, the PCE uses the information related to the paths, coming from the routing protocol (e.g., RPL), and those related to the traffic (e.g., average traffic load generated by each node) in order to assign cells within the schedule, and provide the required level of QoS (duty cycle, throughput, etc.) to each active flow [14]. However, such scheduling technique triggers the exchange of a huge amount of signaling overhead, since each node in the network is supposed to communicate end-to-end with the PCE for both: 1) sending topology and traffic load-related information and 2) receiving its own portion of the collision-free schedule. In addition, an underneath assumption is that the network churn is very low. This is somehow unrealistic also in nonmobile network scenarios, since the radio medium reliability is unpredictable in nature: to adapt the network topology to the best reliability available (i.e., the packet delivery ratio—PDR, of each link), the routing protocol will change the routing topology, thus triggering schedule recomputations and more signaling phases with additional signaling overhead in the end.

As a counterpart, in the context of the open wireless sensors networks (OpenWSNs) project [15], some distributed approaches have also been studied. For instance, uRes [16] proposes the use of a negotiation process between neighbor nodes to schedule cells. In detail, uRes allocates cells minimizing the number of collisions, based on the knowledge of their neighbors schedule. Since collisions can still occur, they are resolved by reallocating the colliding cells [17].

Recently, the decentralized traffic aware scheduling (DeTAS) technique [18] was proposed to address the scheduling needs of deterministic networks and was conceived to comply with the following guidelines:

1) ensure the smallest end-to-end latency between data generation and its reception at the application sink (i.e., the root node in an RPL-organized network);
2) keep the queue utilization as small as possible, through a strict alternation of transmitting and receiving cells into the TSCH slotframe structure;
3) use neighbor-to-neighbor signaling for gathering minimal information about the network and traffic features and for distributing minimal information to compute a collision-free schedule, thus bounding the signaling overhead;
4) compute deterministic time schedules in a decentralized fashion to manage networks rooted to multiple coordinated sinks, while leaving the channel offset computation based on the RPL rank of each node in the network.

The guideline expressed by item 1) was also exploited in designing TASA, while the other ones are inherent to DeTAS. In [18], it has been shown that the guideline of 2) allows nodes' queues to be almost empty, as a natural consequence of a better schedule organization w.r.t. to that of TASA. To shed some light into these and other features, after having introduced in Section II, the 6TiSCH architecture as the technical landscape behind DeTAS, we briefly recall its theoretical design in Section III.

With regard to item 3), in this paper a DeTAS neighbor-to-neighbor signaling is described in more details in Section IV. For the sake of completeness, we also mention here the work of Morell *et al.* [19], which defined a form of neighbor-to-neighbor signaling exchanges by exploiting the concept of label switching in TSCH networks and proposing the use of reservation to establish and manage tracks between nodes in the network. In that proposal, the TSCH schedule is built by collecting information along the track and installing it during the downstream reservation message, in an resource reservation protocol (RSVP)-like fashion [17]. It has to be noted that the neighbor-to-neighbor RSVP-like signaling computes the scheduled resources along a given path between a node in the network and the traffic sink. Instead, the neighbor-to-neighbor DeTAS signaling computes the scheduled resources for the routing subtree rooted at a given node in the network: that node spreads aggregated schedule information which are in turn hop-by-hop unbundled to compute the schedule of each node in the subtree. This feature is very important, because the signaling overhead is significantly small, since the schedule computation is distributed into the network with each DeTAS-enabled neighbor being able to decide how the schedule of its RPL-children has to be built.

It is worth noting that the original DeTAS proposal in [18] was only formulated as a high-level algorithm design and many missing items have been contributed in this manuscript to let DeTAS become a real protocol ready to use in industrial plants and beyond. They include a lightweight signaling protocol, the implementation in the OpenWSN stack, and an experimental evaluation which actually proofs the theoretical findings of the original DeTAS formulation. Thanks to these contributions, it is now possible to claim that DeTAS is a real protocol ready to be used and customized in different industrial settings. And thanks to the open freely available implementation in OpenWSN, it can be tested before deployment.

As a major contribution, in Section V, we deeply show and analyze DeTAS performances in terms of end-to-end latency, reliability, and duty-cycle by means of experimental results. Specifically, we only considered single-sink topologies and discovered that some assumptions on the channel offset reuse (made in [18] and cited in the guideline 4) are somehow unrealistic in practical scenarios. In this paper, we show that a neighbor-to-neighbor signaling can be used also to overcome this issue. Finally, Section VI draws concluding remarks and pictures the envisaged future works.

II. 6TiSCH Architecture

The IEEE802.15.4 PHY protocol [20] has been the de-facto standard with the longest-standing impact in low-power wireless mesh technology, and has been widely used by low-power battery-powered devices to build LLNs.

The need to interconnect IEEE802.15.4-based low-power networks to the Internet triggered the birth of various WGs within the IETF, including 6LoWPAN [21]—now 6lo [22], ROLL (the group behind the RPL routing protocol [4]), and CORE (behind the CoAP web transfer protocol [5]) that have defined how to fit an IPv6 protocol stack on top of IEEE802.15.4.

The IEEE802.15.4e standard [8] was published in 2012 as an amendment of the IEEE802.15.4-2011 medium access control (MAC) protocol only [20]. In other words, it did not amend the physical layer and therefore, it can still operate on any IEEE802.15.4-compliant hardware.

Despite that, the IEEE802.15.4e TSCH MAC mode—which is the main focus of the activities within the 6TiSCH group, and also of our work—is very different from the "legacy" IEEE802.15.4 MAC protocol. TSCH combines time synchronization with channel hopping to achieve ultra low-power operation and high reliability, respectively. Moreover, unlike the industrial standards (i.e., wireless highway addressable remote transducer (WirelessHART) [23] and ISA100.11a [24], [25]) from which it inherits, the IEEE802.15.4e TSCH focuses exclusively on the MAC layer. This clean layering lets TSCH fitting under an IPv6-enabled "upper" protocol stack.

Given the aforementioned appealing features of the IEEE802.15.4e TSCH, members of both academia and industry have created a new WG, 6TiSCH, at IETF to build IPv6-enabled LLNs, rooted in the IEEE802.15.4e TSCH MAC layer. The final aim of 6TiSCH consists in filling the gaps between IEEE lower layers of an industrial IoT protocol stack and the IETF higher layers, to enable an open standards-based protocol stack for deterministic wireless mesh networks.

As described in [26], when possible, the 6TiSCH architecture will reuse existing protocols such as IPv6 neighbor discovery (ND) [27], IPv6 over low power wireless personal area networks (6LoWPAN) [21], and the RPL [4], with the minimum adaptation required to meet criteria for reliability and determinism within the mesh, and scalability over the backbone. 6TiSCH will fill the missing gaps within the architecture, so that IETF 6LoWPAN header compression and RPL, which enables, respectively, IPv6 encapsulation and routing, can optimally operate on top of the TSCH MAC layer.

A. MAC Layer: IEEE802.15.4e TSCH

The IEEE802.15.4e TSCH is suitable for deterministic traffic, i.e., traffic flows with an emission rate and routing path patterns that are well known in advance. In fact, it combines together time division multiplexing (TDM), time synchronization, and time formatted into slotframes, resulting in a *deterministic* wireless MAC standard.

All nodes in a TSCH multihop network are synchronized. Time is sliced up into timeslots which are grouped into one or more slotframes. A slotframe continuously repeats over time, and its duration can be fixed to meet the application requirements (e.g., available bandwidth, lower latency, power consumption). In a TSCH network, the bandwidth is preformatted in a TDM fashion. Thus, unlike the traditional CSMA/CA-based networks, there is no contention for gaining access to the channel (unless allowed explicitly in some specific timeslots, as detailed in the next paragraph).

Due to its scheduled nature, all nodes follow a common *schedule*. The latter is a matrix of scheduled cells, each of them identified by a `slotOffset`, and a `channelOffset` [28]. A cell represents an atomic unit of bandwidth that can be allocated by a centralized or distributed scheduling algorithm. A cell can be dedicated or shared: dedicated cells (those scheduled by DeTAS, as detailed in this paper) are assigned to the communication of a pair of neighbors; shared cells are used by more then two communicating neighbors in a CSMA/CA fashion (e.g., the static *minimal* configuration [11] deals only with this kind of cells).

Because of the channel hopping nature of TSCH, the scheduling algorithm does not care of the actual frequency the communication happens on, since it changes at each slotframe iteration. In fact, the `channelOffset` is translated into a frequency using a specific translation function which implies communicating neighbors to "hop" between the different available frequencies when exchaning data. Such channel hopping technique efficiently combats multipath fading and external interference.

By following the schedule, each node knows when (i.e., at which timeslot), and on which channel (based on the channel offset) it can exchange (either transmit or receive) data with its neighbor nodes.

B. Routing Protocol: RPL

The RPL routing protocol [4] plays a key role in the 6TiSCH architecture, in that it organizes the low-power mesh in the form of a directed acyclic graph (DAG), rooted at a small set of LLN sinks. For each sink, a destination-oriented DAG (DODAG) is created by accounting for link costs, node attributes/status information, and an objective function, which maps the optimization requirements of the target scenario. In this paper, we consider the simplest topology with a single sink, also referred to as $\mathrm{DODAGroot}$. Although RPL can manage several kinds of traffic flows (to and from the $\mathrm{DODAGroot}$ or between any pair of nodes in the network), we have focused on the dominant multipoint-to-point traffic, i.e., that flowing from the nodes in the network toward the $\mathrm{DODAGroot}$ and more related to monitoring applications in industrial environments.

RPL employs a gradient strategy, which introduces the concept of *rank* to define the individual position of a node with respect to its $\mathrm{DODAGroot}$. A fundamental property of an RPL-organized network is that the rank should monotonically decrease along the DODAG and toward the destination, in accordance to the gradient-based approach. In general, the rank is computed based on path metrics, but it is used to let the routing topology being loop-free. In details, the rank is a 2-bytes value, whose most significant byte, called $\mathrm{DAGrank}$, is used to compare the position of nodes within the network. As an example, if the DAGrank of a node A is lower than the DAGrank of another node B, A could be safely a parent for B; if the DAGrank of two neighbors tie, none of them can include the other as its own parent.

RPL can adopt several metrics for computing the rank and the DAGrank. In designing DeTAS, we have forced the DAGrank to be computed according to the minimum hop distance metric. According to the standard [4], the DODAGroot is assigned a DAGrank equal to 1. Hence, the DAGrank of given source node in the network is exactly equal to the minimum hop distance from the DODAGroot augmented by 1. However, this approach can be easily extended to account for different metrics, e.g., the expected transmission count (ETX).

III. DeTAS Algorithm Description

The DeTAS algorithm has been designed for building optimum collision-free schedules in multihop IEEE802.15.4e TSCH networks. Using a tiny amount of information, locally exchanged among neighbor nodes, DeTAS allow to compute the schedule in a distributed manner. While scheduling the traffic, DeTAS manages queue levels, avoiding traffic congestion and thus possible packet drops due to overflow of nodes' memory buffer. Finally, DeTAS can exploit the availability of the 16 IEEE802.15.4 frequencies [8] in order to: parallelize several transmissions at the same time, reduce the number of active slots per slotframe (i.e., the network duty cycle), and increase the reliability of wireless links.

In a 6TiSCH network running DeTAS, all devices are assumed to be synchronized with the same slotframe, having size equal to S timeslots. Moreover, all nodes follow a common TSCH schedule having width equal to L timeslot, with $L \leq S$, and height equal to W channel offset, with $W \leq 16$. Such schedule is set up minimizing its length, i.e., the number of active slots L needed for correctly delivering the network traffic (expressed as number of packets per slotframe) to the DODAGroot. More specifically, all transmissions are scheduled in consecutive L slots, leaving the remaining S–L slots within the slotframe available for packet transmissions related to other applications (e.g., other RPL instances). The length L of the schedule is computed by the DODAGroot using the formulation introduced in Section III-C. Instead, the width of the schedule, i.e., the number of available channel offsets, is at least $W = 3$, since frequencies can be reused every three-hops, thus avoiding also collisions due to interference[1] [29], [30].

A. Network Topology and Traffic

Being designed for 6TiSCH networks, hereafter we will use the 6TiSCH terminology [28], while describing the DeTAS technique. Fig. 1 shows an example network which is a destination-oriented tree graph coordinated by the DODAGroot. Given a network with N source nodes, let $\{n_i\}$, with $i = 1, \ldots, N$, be the set of all source nodes, and n_0 the DODAGroot. Furthermore, for each node n_i, it is possible to identify the set $ch(n_i)$ of its children, and the subtree ST_i, composed ofn_i itself and all the nodes connected to it through multihop paths. Moreover, Table I summarizes the notation used throughout this paper.

DeTAS is a traffic-aware algorithm that builds the schedule based on the traffic generated by each source node. We assume that the network supports a multipoint-to-point traffic. In detail,

[1]In our experiments (reported in Section III), we tested several values of W parameters in the range [3, 12].

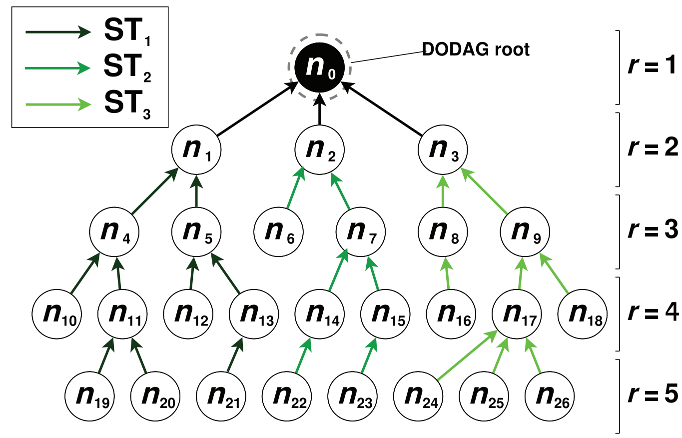


Fig. 1. Example of an LLN with a DODAGroot acting as application sink and 26 source nodes (r is the DAGrank).

TABLE I
LIST OF USED SYMBOLS

Symbol	Definition
S	Number of slots within a slotframe
L	Length of DeTAS schedule in slots
W	Height of DeTAS schedule in number of channel offset
N	Number of source nodes in the network
n_0	LLN sink node
$n_i, i = 1, \ldots, N$	Source nodes
$\mathrm{ch}(n_i)$	Children nodes of the node n_i
ST_i	Subtree rooted to the node n_i
q_i	Data traffic generated on the node n_i (local packet number)
Q_i	Data traffic generated from the subtree ST_i (global packet number)
p_i	Parent node of the node n_i
r	DAGrank of nodes representing the distance in number of hops from the DODAGroot augmented by 1
Q_M	Maximal global packet number among the children of the DODAGroot
n_M	Child of the DODAGroot having the maximal global packet number Q_i
q_M	Local packet number of the node n_M
α	Number of transmit slots scheduled consecutively in the node n_M
L_e	Length of the schedule of the even list
L_o	Length of the schedule of the odd list
Q_0	Data traffic generated from all the source nodes
Q_0^e	Data traffic generated in the subtrees rooted to nodes in even list
Q_0^o	Data traffic generated in the subtrees rooted to nodes in odd list
β	The parameter that balances even and odd data traffic (Q_0^e, Q_0^o)
n_{cut}	Node which schedule is divided between the even and odd list
ST_{cut}	Subtree rooted at the node n_{cut}

every source node in the set $\{n_i\}$ generates a constant[2] integer number of packets, i.e., the *local packet number* q_i within a slotframe, destined to the $\mathrm{DODAGroot}$. For each node n_i belonging to the network with $i = 1, \ldots, N$, we also define the *global packet number* Q_i as the total amount of packets generated within a slotframe by the nodes belonging to the subtree ST_i.

B. Decentralized Scheduling

To setup the schedule in a distributed manner, each node n_i needs to know some traffic information: 1) the amount of traffic it will receive from its children and 2) the amount of traffic it will transmit to its parent node p_i. Therefore, n_i locally computes its *global packet number* Q_i as the sum of its *local packet number* q_i and the *global packet numbers* of its children, and then forward such information to its parent node p_i. In a recursive way, thanks to the information exchanged at one-hop distance, the $\mathrm{DODAGroot}$ n_0 will be able to calculate the overall traffic of the subtree Q_0 as well as the *local packet numbers* of its children. Starting from the aforementioned traffic information, exchanged at 1-hop distance, the schedule is built in a distributed fashion, where each node n_i allocates some slots within the schedule to its children. The built schedule is collision free for the whole network and keeps the queue utilization as low as possible. In what follows, we detail the rules adopted in designing DeTAS and the resulting scheduling technique.

1) Scheduling the Slot-Offsets: First of all, each DeTAS-enabled node in the network schedules, the transmission slot in such a way to be synchronized with the reception slot of its parent. Afterward, it allocates on its own cells it will use for receiving packets from its own children. In fact, a node n_i does not perform any scheduling decision until it is informed by its parent p_i about the Q_i cells to be allocated as transmitting (or *tx*) slots. The allocation of *rx* slots to the children is performed in a recursive way, starting from the $\mathrm{DODAGroot}$ and going downward toward the leaf nodes.

Once n_i has been made aware of which are its *tx* cells, it can decide its $Q_i - q_i$ *rx* cells (i.e., those needed for receiving packets from its children) and it makes sure that these two sets of cells are not overlapped. In particular, the *tx* and *rx* cells are alternated (i.e., as depicted in the example in Fig. 2), which means that if a type of cell is scheduled in an even slot, the other type should be scheduled in the next odd slot. Then, n_i splits its *rx* cells in subsets, with each subset being assigned to a child node. In order to fulfill the requirements of each child, the corresponding subset is sized according to the supplied *global packet number*. In the end, each child is made aware by n_i about the assigned subset of cells, and will configure such cells as *tx* ones. In the example of Fig. 2, the node $n4$ splits its subset of *rx* slots in two subsets, which in term should coincide with the set of their *tx* slots. Such policy does not allow two nodes having a common parent to transmit using the same cell; thus, it overcomes the hidden terminal problem.

[2]Such an assumption is supported by the fact that traffic is typically different between sensors, but relatively constant over time in emerging heterogeneous embedded applications. Actually, with an efficient signaling, DeTAS could also support variable bit rate traffic flows.

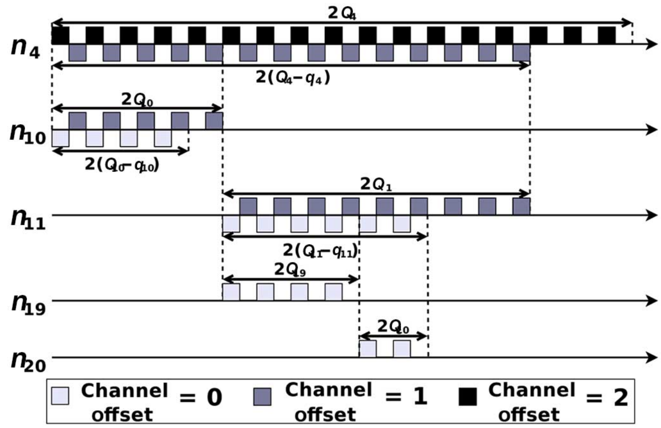


Fig. 2. *Odd*-schedule for nodes belonging to ST_4 of the destination-oriented tree in Fig. 1 (note that n_4 has an even $\mathrm{DAGrank}$).

To avoid any kind of collisions, DeTAS does not allow two nodes with the same $\mathrm{DAGrank}$ to schedule transmissions in the same timeslot. With this feature, DeTAS can build collision-free schedule, even being agnostic about the physical connectivity between nodes in the network. Eventually, DeTAS overcomes the exposed terminal problem too.

Interestingly, by alternating *tx* and *rx* cells, the queue of a node is emptied of one packet, as soon as it receives a new one, and vice versa. Thus, buffer overflow is avoided and queue utilization is kept as low as possible.

Obviously, to allow packets to be correctly sent and received, the *tx* cells of the children $\in ch(n_i)$ must be synchronized with the *rx* cells of n_i.

For the sake of clarity, and in order to add some formalization to the description, we introduce the following definitions.

Definition 1: A node n_i is *even-scheduled*, if its *tx* cells are located in *even* positions within the scheduling interval, while its *rx* cells are located in *odd* positions.

Definition 2: A node n_i is *odd-scheduled*, if its *tx* cells are located in *odd* positions within the scheduling interval, while its *rx* cells are located in *even* positions.

A subtree ST_i rooted at a node n_i can be *even-* or *odd-*scheduled, according to the following additional definitions.

Definition 3: A subtree ST_i is *even-scheduled*, if all nodes $\in \mathrm{ST}_i$ with *even* $\mathrm{DAGrank}$ are *even-scheduled* and those with *odd* $\mathrm{DAGrank}$ are *odd-scheduled*.

Definition 4: A subtree ST_i is *odd-scheduled*, if all nodes $\in \mathrm{ST}_i$ with *even* $\mathrm{DAGrank}$ are *odd-scheduled* and those with *odd* $\mathrm{DAGrank}$ are *even-scheduled*.

Therefore, Fig. 2 shows an example of an *odd schedule* followed by the subtree ST_4 of the destination-oriented tree in Fig. 1, and, details the timeslots reserved to the nodes n_4, n_{10}, n_{11}, n_{19}, and n_{20}. We can see that n_4, having *odd* $\mathrm{DAGrank}$, is *even-scheduled* and spends the Q_i *even* timeslots in transmission, the first Q_i–q_i *odd* timeslots in reception, and the last q_i *odd* timeslots in idle (having already received all the packets from its children n_{10} and n_{11}).

2) Scheduling the Channel-Offset: Besides the allocation of *tx* of *rx* cells, the channel offset is changed at each hop and the same channel offset is reused only after W-hops. In particular, for each source node n_i, DeTAS allocates *tx* cells with a channel offset equal to $[(\mathrm{DAGrank}-2) \mod W]$ (for transmitting packets to the correspondent parent p_i), and *rx* cells with channel offset equal to $[(\mathrm{DAGrank}-1) \mod W]$ [for receiving packets from children $\in \mathrm{ch}(n_i)$]. If $W=1$, there is a single channel offset used for the whole schedule, so this setting does not exploit the bandwidth increase available with multiple channel offsets and collisions can occur when two or more motes are transmitting at the same time. If $W=2$, packet collisions can happen when a node n_i and its parent p_i are, respectively, receiving (from a child) and transmitting (to the parent) at the same time. With $W \geq 3$, the channel offset is reused at least every three hops. This means that the absolute difference between the $\mathrm{DAGranks}$ related to two nodes transmitting in the same cell (i.e., on the same timeslot and channel offset) can be 0 or ≥ 3. In the latter case, there will be ideally no collision, due to the minimum hop count metric used for building the destination-oriented tree. Instead, if the aforementioned difference is 0, some collision due to mutual interference can occur.

3) Considerations: It is worth noting that a node n_i can accomodate all the schedule (i.e., *tx* or *rx* cells) in a *scheduling interval* of $2Q_i$ consecutive slots within the slotframe. In fact, within this interval, the Q_i even (odd) slot offsets could be used for scheduling *tx* cells (i.e., the needed cells to deliver Q_i to the parent p_i), while the first $Q_i - q_i$ odd (even) slot offsets could be used for scheduling *rx* cells (i.e., the cells needed by n_i for receiving $Q_i - q_i$ packets from the other nodes $\in \mathrm{ST}_i$). In the remaining q_i odd (even) slot offsets, the node will be idle. Hence, the node n_i must be informed only about the lowest boundary of such interval and about the policy for alternating *tx* and *rx* cells. Such information can be carried with a small overhead, with the additional advantage of having an easy management of allocated resources into constrained devices.

Moreover, the nodes in a scheduled subtree allowed to transmit in the same timeslot have all *even* (or *odd*) DAGrank. Moreover, with such scheduling technique, it is not possible that two nodes with the same $\mathrm{DAGrank}$ can transmit simultaneously. As a consequence, it is possible to schedule simultaneously two subtrees rooted at the $\mathrm{DODAGroot}$, with one being *even-scheduled* and the other one being *odd-scheduled*. The schedules will be perfectly interleaved, with at most a single node per $\mathrm{DAGrank}$ being allowed to transmit packets to its parent.

C. Schedule Length L

Even though the schedule is built with a distributed approach, it is initialized by the $\mathrm{DODAGroot}$ that computes the length L of the schedule, and selects, among the subtrees rooted at its children, the ones to be *even*-scheduled, and thus those to be *odd*-scheduled.

Being DeTAS a TASA, the length L of the schedule is a function of the network traffic. In fact, the $\mathrm{DODAGroot}$ can receive at most one packet per timeslot (i.e., $L \geq Q_0$). At the same time, the child of the $\mathrm{DODAGroot}$, referred hereafter as n_M, having the maximum *global packet number*, i.e., $Q_M = \max_{n_i \in \mathrm{ch}(n_0)} Q_i$, will need a schedule long enough for containing Q_M transmit slots and $Q_M - q_M$ receive slots, i.e., $L \geq 2Q_M - q_M$. For every randomly scattered physical topology, the proposed DeTAS scheme is able to find the optimum schedule with the minimum length, given by

$$L = \max\{2Q_M - q_M, Q_0\}. \tag{1}$$

To this aim, DeTAS simultaneously guarantees that a single subtree rooted at a sink's child is *even*-scheduled, while the subtree rooted at another sink's child is *odd*-scheduled; thus, they will not incur in any kind of collision, since the related schedules are perfectly interleaved. Therefore, a $\mathrm{DODAGroot}$ running DeTAS must divide its children into two lists, i.e., an *even* list and an *odd* one. The subtrees rooted at the children in the *even* list could be sequentially *even*-scheduled, in a time interval long L_e timeslots. At the same time, the subtrees rooted at the children in the *odd* list could be sequentially *odd*-scheduled, for a time interval long L_o timeslots. Since the schedules associated with the two lists can be perfectly overlapped, the longest schedule between the two determines the length L of the whole network schedule.

However, for allowing the coexistence of several applications sharing the same slotframe structure, the schedule length related to a given application running on a network must be bounded to the minimum possible given by (1). In this case, the $\mathrm{DODAGroot}$ can exactly calculate the length of the schedule based on the information about the *global* and *local packet numbers* provided by its own children.

As a consequence, DeTAS has to let the even and odd lists be load balanced, in order to get their schedule lengths as close as possible. This load balancing problem falls into the class of *multiprocessor scheduling problems* [31]. The greedy heuristic employed in this paper is the same described in [32]: the $\mathrm{DODAGroot}$'s children are ordered in a descending order, according to their *global packet number*. Then, they are appended subsequently to the list (*even* or *odd*) with the current smallest sum of *global packet numbers*.

DeTAS assumes a different behavior depending on the traffic loads of the children of the $\mathrm{DODAGroot}$. Specifically, if $Q_M \geq Q_0/2$, the node n_M will obviously be the only one in the *even*-list. With DeTAS, the subtrees rooted at the nodes in the *odd*-list will be subsequently *odd*-scheduled. At the same time, the subtree rooted at n_M will be *even*-scheduled for the first $2(Q_M - \alpha)$ slots, with

$$\alpha = \min\{2Q_M - Q_0, q_M\} \tag{2}$$

subsequently, the schedule of the node n_M will contain α additional consecutive slots for delivering α packets to the $\mathrm{DODAGroot}$. In the schedule related to n_M illustrated in Fig. 3(b), it can be noticed that the first $2(Q_M - \alpha)$ slots are even-scheduled (i.e., alternated transmit and receive slots), whereas the remaining α slots are scheduled consecutively. Moreover in [18], it has been shown that, with this technique, (1) is always fulfilled when $Q_M \geq Q_0/2$.

The previous strategy is applied in some bounded cases, i.e., when a child node of the $\mathrm{DODAGroot}$ is the bottleneck for at least one half of the traffic offered by the network. As a matter of fact, the $\mathrm{DODAGroot}$ will have more than two children in

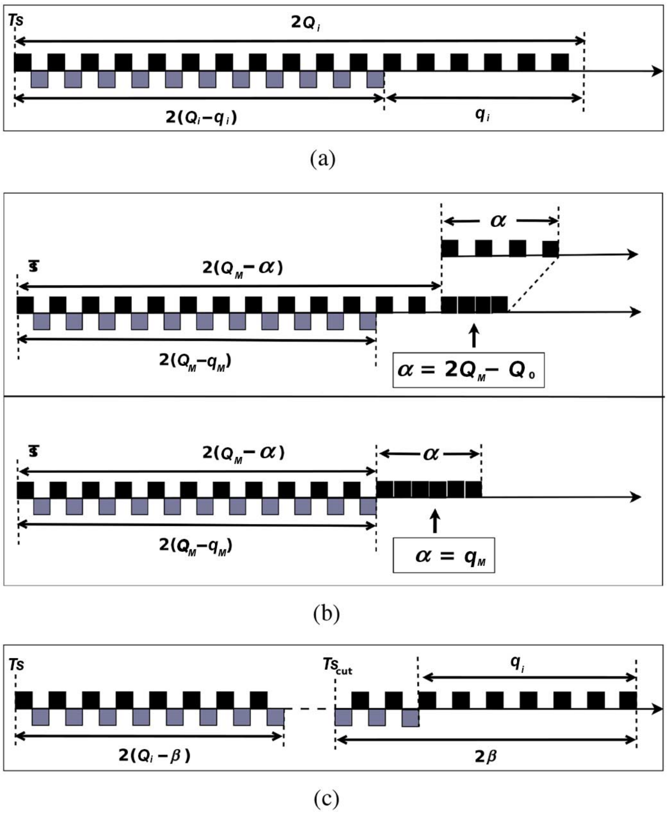


Fig. 3. Schedule patterns of a node n_i. (a) Schedule pattern of a generic node of the network. (b) Schedule pattern in the case $Q_M \geq Q_0/2$. (c) Schedule pattern of a node in the case $Q_M < Q_0/2$ and the $Q_0^e \neq Q_0^o$, which is divided between the even- and odd-list.

dense network deployments, and the routing protocol will load balance the traffic among the children. Hence, the most common network scenario entails the case $Q_M < Q_0/2$, i.e., the child of the $\mathrm{DODAGroot}$ having the maximum *global packet number* n_M will manage less than one half of the traffic flowing toward the $\mathrm{DODAGroot}$. In this case, many techniques could be found to load balance the *even*- and *odd*-list. We found that the easiest solution is to perform the following operations: 1) for each list, calculate the sum of the *global packets numbers* related to the root nodes of the subtrees in the list itself; 2) select the list with the biggest sum; 3) within this list, select the subtree rooted at the node n_{cut} with the highest *global packets number*; and 4) split the schedule of $\mathrm{ST}_{\mathrm{cut}}$ into two parts, so that the first part will be placed at the beginning of the network schedule according to the same scheduling parity of the selected list, while the second part will be scheduled in the end of the network schedule according to the opposite scheduling parity. In this context, DeTAS decides the sizes of the two parts of the schedule related to $\mathrm{ST}_{\mathrm{cut}}$: since the target is to compute the schedule with the minimum length (i.e., $L = Q_0$), DeTAS has to make sure that the resulting lengths of the *even* and *odd* schedules are as close as possible.

In details, DeTAS reduces the discrepancy between the sum Q_0^e, computed over the *global packet numbers* related to the *even* list, and the sum Q_0^o, computed over the *odd* list, to 1 (if Q_0 is odd) or 0 (if Q_0 is even). It is worth noting that $Q_0^e + Q_0^o = Q_0$. The $\mathrm{DODAGroot}$ computes the value β, which balances the two lists

$$\beta = \left\lfloor \frac{Q_0^e - Q_0^o}{2} \right\rfloor. \tag{3}$$

If $\beta \geq 0$ ($\beta < 0$)[3], DeTAS will first *even*-schedule (*odd*-schedule) the subtree $\mathrm{ST}_{\mathrm{cut}}$ for $2(Q_{\mathrm{cut}} - |\beta|)$ timeslots and, then, all the subtrees related to the other nodes appended in the *even*-list (*odd*-list). Simultaneously, it will first *odd*-schedule (*even*-schedule) all the subtrees related to the nodes in the *odd*-list (*even*-list), then the subtree $\mathrm{ST}_{\mathrm{cut}}$ for exactly $2|\beta|$ timeslots. The resulting schedule length is $L = Q_0$, as already shown in [18]. Note that in this traffic load conditions, n_{cut} should be informed by the $\mathrm{DODAGroot}$ about when to *even*- and when to *odd*-schedule $\mathrm{ST}_{\mathrm{cut}}$. This information must be accordingly updated and propagated along $\mathrm{ST}_{\mathrm{cut}}$. For the sake of clarity, Fig. 3(c) sketches an example schedule for n_{cut}.

IV. DeTAS Implementation

In order to evaluate the performance of DeTAS, we have implemented it in the OpenWSN project [15]. OpenWSN is an implementation of a standards-based stack and, to the best of our knowledge, it is the first and unique open-source implementation of the IEEE802.15.4e TSCH standard. On top of IEEE802.15.4e TSCH, OpenWSN implements Internet of Things-related standards [3], namely 6LoWPAN, RPL, and CoAP. In order to schedule some cells, each node must be able to exchange information with its parent and children. It should transmit the Q_i and q_i parameters to the parent node and receive back the necessary information. In a DeTAS enabled network, the portion of the network schedule related to a given node is shaped according to one of the three patterns described in Fig. 3 and discussed in the previous section. The amount and type of information needed from a node to build its own schedule will depend strictly on the schedule pattern of the node. However, despite some differences, the following parameters are used by all configuration patterns:

1) Ts: slotoffset of the first cell allocated for that node and it indicates where to start scheduling cells for its communication;
2) *EO*: parameter specifying if the subtree that a node belongs to is *even*- or *odd*-scheduled.

In the following, we describe in more details the different node patterns, by indicating the parameters needed by a DeTAS-enabled node to build them.

1) PATTERN 1: it is the most common node schedule installed by DeTAS, and it is pictured in Fig. 3(a). For building such node schedule, a node needs to get from its parent only the data set $\{\mathrm{Ts}, \mathrm{EO}\}$. The schedule will be built by simply alternating Q_i *tx* cells with $(Q_i - q_i)$ *rx* cells, starting from Ts. The parity of the schedule is computed based on the EO parameter and on the $\mathrm{DAGrank}$.

[3]In the rest of the paragraph, we indicate the alternative case and the related settings in brackets.

2) PATTERN 2: this pattern is used when $Q_M \geq Q_0/2$. Fig. 3(b) shows an example of such pattern. As already detailed in the previous section, this pattern can be held by a single node in the network, i.e., the child of the $\mathrm{DODAGroot}$ with the highest *global packet number*. Such node will first *even*-schedule $(Q_M - \alpha)$ cells, then will schedule α consecutive *tx* cells, with α given by (2). In addition to the common data set, the α parameter is needed to schedule the final consecutive cells. Therefore, the related data set is given by $\{\mathrm{Ts}, \mathrm{EO}, \alpha\}$.
3) PATTERN 3: this schedule [pictured in Fig. 3(c)] can be present on a node when both $Q_M < Q_0/2$ and $Q_0^e \neq Q_0^o$ are satisfied. As described in Section III, the n_{cut} node will allocate its cells in two parts. The first part, composed of $Q_{\mathrm{cut}} - \beta$ cells, will be *even* (*odd*)-scheduled, while the second part, composed of β cells, will be odd (even)-scheduled, with β being set according to (3). In addition to the common data set, a node needs to be informed about the β parameter, for calculating the length of the two parts of its schedule, and the starting slot offset Ts_{cut} for the second part of the schedule. Therefore, the complete data set in this case is $\{Ts, EO, \beta, Ts_{\mathrm{cut}}\}$. It is worth noting that such kind of schedule can be present on a single node per $\mathrm{DAGrank}$ in the network.

DeTAS must be able to recompute schedules when nodes join or leave the network. To this aim, a DeTAS version number (DVN), similar to the DODAGversion number of RPL, is managed by the $\mathrm{DODAGroot}$ to control the schedule version. Such parameter is initialized to 0 at the network bootstrap and than incremented each time the $\mathrm{DODAGroot}$ triggers a new schedule-distributed computation. Indeed, a new schedule computation is needed during network formation and whenever the topology and the traffic conditions change.

A. DeTAS MAC Command Frames

The DeTAS information exchange has required the definition of two *ad hoc* MAC command frames. Although the IEEE 802.15.4e amendment introduces the enhanced beacons (EBs), which could be used for exchanging minimal information about the schedule, command frames are more appropriate to DeTAS for the inherent possibility of quickly building the schedule. For the sake of completeness, we mention that the 6TiSCH W is defining new information elements (IEs) to be used for cell negotiation and scheduling [33]. However, the schedule objects defined in such draft are still not suitable for the requirements of DeTAS. One of the aim of this paper is to highlight another form of schedule object that eventually could be integrated in such working draft.

According to the signaling required by DeTAS, a node n_i has to transmit to its preferred parent p_i some information about its Q_i and/or q_i parameters. For this purpose, the request MAC command frame (REQ) has been defined and structured as shown in Fig. 4(a). This command frame is sent as unicast only to the preferred parent, either when a node joins the network or when Q_i changes (i.e., in the case the node n_i receives a new REQ from one of its children).

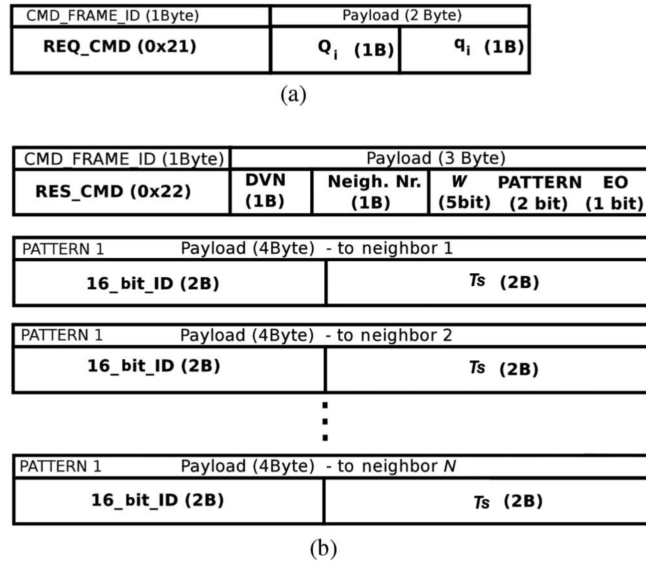


Fig. 4. Frame formats for (a) REQ command and (b) RES commands in the PATTERN 2 case.

In turn, with a broadcast response MAC command frame (RES), a parent can instruct its own children about the rules to be followed for building the DeTAS schedule. The RES payload contains detailed information for each of the children receiving the message, as shown in Fig. 4(b).

As introduced earlier, the amount of scheduling information to be sent by a node to a specific child depends on the pattern shape that the child must follow when building its schedule. The most common pattern to be communicated is PATTERN 1, which requires 4 bytes per child (2 bytes for the node ID and 2 bytes for the Ts time offset). It has to be noted that a node can have only a single child to be made aware about a different pattern: a single child of the $\mathrm{DODAGroot}$ can be selected to schedule according to PATTERN 2 (which requires a 5-bytes long field); a single node per $\mathrm{DAGrank}$ can be selected to schedule according to PATTERN 3 (which requires a 7-bytes long field), so that a single child of a given node can be selected to schedule according to PATTERN 3. In Fig. 4(b), the RES command format in the case where all the neighbors have PATTERN 1 schedule is shown. If a neighbor has PATTERN 2 (or a PATTERN 3) schedule, the last field of the RES command frame (i.e., the data related to the Nth neighbor) is substituted with the field shown in Fig. 5(a) [or in Fig. 5(b)]. Therefore, the RES command payload contains: 1) three bytes where common information to all the neighbors are stored; 2) $N - 1$ fields with 4 bytes each, required for the PATTERN 1 scheduled neighbors; and 3) the last field which can be 4, 5, or 7 bytes according to the particular PATTERN scheduled for the last neighbor.

As a consequence, when a RES command frame is built by a node, the common information useful to all neighbors is appended at the beginning of the payload: 1) the DVN; 2) the number of neighbors that are notified in the command; 3) the channel reuse factor W (whose setting has been widely described and analyzed in Section V); 4) the schedule PATTERN of the last neighbor; and 5), finally, the EO flag (which is common to all children). The scheduling information

PATTERN 2	Payload (5 Byte) - to neighbor N	
16_bit_ID (2B)	Ts (2B)	α (1B)

(a)

PATTERN 3	Payload (5 Byte) - to neighbor N		
16_bit_ID (2B)	Ts (2B)	β (1B)	Ts_{cut} (2B)

(b)

Fig. 5. Format of the last neighbour (nth) field for the RES command. (a) Format for the PATTERN 2 case. (b) Format for the PATTERN 3 case.

DeTAS IE				Termination IE		
Bit: 0–6	7–14	15	Byte 1	Bit: 0–6	7–14	15
Length	IE – ID	Type	DeTAS V N	Length	IE – ID	Type
1	0x19	0	DVN	0	0x7e	0

Fig. 6. IE format that contains the DVN information.

related to each child is then appended, making sure that, if a child has to be scheduled according to PATTERN 2 or 3, the correspondent field will be appended as last. This technique is used for a fast parsing of data on the receiving side. Note that the length of the RES command frame depends on the number of children and on the scheduling pattern related to the last field appended.

B. DeTAS Signaling

The command frames described in the previous subsection are sent by a node according to some triggering events and trigger other events when received on a given neighbor. In the following list, we describe the protocol used to exchange such command frames, thus making DeTAS a viable solution for scheduling in large networks; in details.

1) REQ Transmission: The REQ command is sent from a node n_i to its preferred parent p_i. This event is triggered: a) when the node has just joined the network and it has not yet a DeTAS schedule; b) when traffic load of the node has changed (i.e., Q_i or q_i) and, therefore, it requests a new schedule; and c) when the node has recognized that it is using a DVN which is smaller than the one advertised from the LLN sink. When n_i sends a REQ, it waits for receiving a RES command from p_i. It may happen that one between the REQ and RES commands is lost. In order to cope with this issue, the node n_i will transmit periodically REQ commands until it receives a RES command with the scheduling information required.
2) REQ Reception: A node n_i receives this command from one of its children $\in \mathrm{ch}(n_i)$ in two cases: 1) when the child is asking for a schedule and 2) the child recognizes to have an outdated schedule and sends an REQ command to get an update. In the first case, if n_i is not a $\mathrm{DODAGroot}$, it will update its own Q_i parameter and trigger an REQ transmission to its parent p_i. Hence, at each hop, a new REQ will be created until the $\mathrm{DODAGroot}$ is reached. When the $\mathrm{DODAGroot}$ receives a new request, it calculates the new schedule with the updated data and triggers an RES command transmission. In the second case, the node n_i will send a RES command containing the information necessary to build the current schedule.
3) RES Transmission: The RES command is sent from a node to all its children as a broadcast frame. Four condition can trigger the transmission of a RES command: 1) the $\mathrm{DODAGroot}$ has just (re)computed the schedule after receiving a REQ; 2) a non-$\mathrm{DODAGroot}$ node has just processed an RES command frame and has (re)computed the schedule for its children; 3) an update request has been received; and 4) a node recognizes that one of its children has not received a schedule belonging to the current DVN, so it sends an update with the right schedule.
4) RES Reception: When receiving a RES command, a node n_i first checks if it has a new DVN, then it checks the payload to find if there is any scheduling information to be consumed. If both conditions are verified, the node builds its schedule according to the information received, and it calculates and sends the schedule to its children (if any).

Since an RES command is sent in broadcast, many children will receive such information at the same time. As they compute the schedule for their own children, they will start sending RES commands simultaneously, with possible collisions. In fact, RES commands are sent according to the 6TiSCH "minimal" schedule, which provides a set of shared cells known by all nodes in the network and used in Slotted Aloha mode. If the network is dense, collisions among RES commands could happen. To encompass this problem, the RES command transmission is delayed by a random time period.[4]

Another important facet related to the DeTAS signaling is that related to the DVN. A DVN is communicated into a RES command and used by the receiving nodes to determine its validity: only RES commands which contain a DVN greater than the current one will be accepted. In addition, the DVN is inserted into the IEs of data and EB frames. Fig. 6 illustrates the IE that contains the DVN and the termination IE. A node can check in each received frame the DVN and recognize if there is any action to be taken. For example, if the node n_i receives a frame with a DVN bigger than the one it is using, then it recognizes that it has to send a REQ. If it receives a frame from a child with DVN smaller than the one it is using, it recognizes that it has to send a RES.

C. Implementation in OpenWSN

Fig. 7 describes the software architecture of the OpenWSN project. Each protocol in the stack is depicted as a horizontal layer, whereas the vertical module implements some common functions which are used from all the different layers of the stack.

In order to implement the algorithm, the *DeTAS* component has been added to the OpenWSN stack. The relations of the

[4]In our implementation, we have considered a delay which varies in the range from [1:5] slotframes with a uniform distribution of probability.

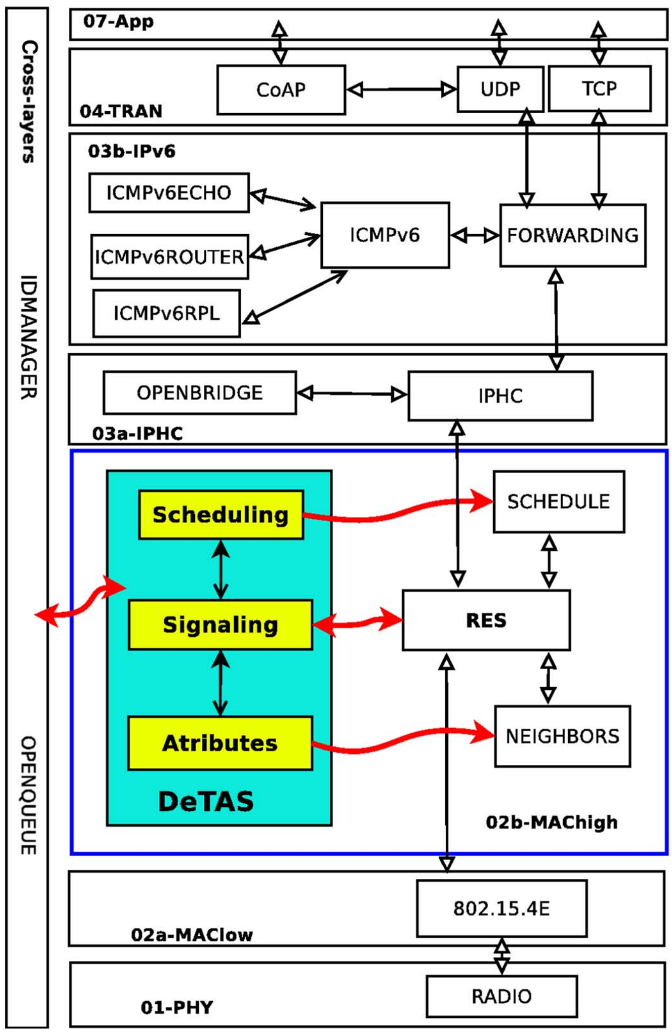


Fig. 7. DeTAS module inside OpenWSN stack.

DeTAS component with the existing modules of OpenWSN are also described in Fig. 7.

In particular, the new component is positioned inside the MAChigh module. The *DeTAS* component in its own is divided into three logical parts.

1) *Signaling* is the component that handles the reception and the transmission of REQ and RES command messages described in the previous subsection.
2) *Scheduling* implements the scheduling functions. It has access to the existing *SCHEDULE* component in order to execute the schedule calculated according to DeTAS algorithm, and at the same time, it is accessed from the *signaling* component to create the RES command payload.
3) The last part, *attributes* implement the data structures which are necessary to store all the DeTAS-related information and the functions to handle them.

The relations of the *DeTAS* components with the existing OpenWSN components, as it can be verified from Fig. 7, are mainly unidirectional and the existing modules are accessed without any need to modify them. The only exception is the relation with the *RES* component. In this case, the existing

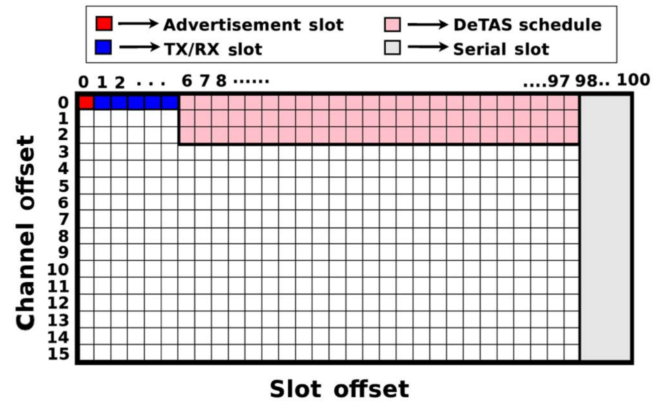


Fig. 8. Slotframe structure used in the experiments.

"RES" component, which handles the forwarding of the packets from the lower layer to the upper ones and vice versa, is modified to handle the command packets defined for DeTAS. In addition, it accesses the *signaling* component for two reasons. First, when it needs to create the DVN IE in the data packets that are transmitted from the mote. Second, to notify the *signaling* component in the case there is a mismatch between the DVN of the mote and the DVN of a received packet.

As the rest of the existing module, *DeTAS* will have access to the cross-layer functions. Among other functions accessed, from the *IDMANAGER,* it will retrieve the rank, which is obtained originally from the RPL protocol.

V. Experimental Evaluation

The performance of the DeTAS implementation in the OpenWSN protocol stack (described in Section IV) has been evaluated over some network topologies deployed with TelosB motes [34].

OpenWSN by default provides a very basic schedule for all nodes in a network. In details, it implements the "minimal" configuration schedule [11] over a slotframe structure long exactly 101 timeslots. Each timeslot can be configured as one among the following possibilities.

1) Advertisement (ADV): slot reserved for the transmission of EBs.
2) Transmission (TX) or receive (RX): slots, respectively, scheduled for data transmission or reception.
3) TX/RX: shared slots used for both transmissions and receptions of all kinds of frames with slotted aloha contention access.
4) Serial receive (SERIALRX): slots reserved for the communication with the serial port.

At bootstrap, each node is preconfigured to run an initial schedule formed by an ADV slot followed by five shared TX/RX slots (with an associated channel offset equal to 0). Such slots are positioned at the very beginning of the slotframe structure. In addition, three SERIALRX slots positioned in the end of the slotframe are reserved for serial communication. Fig. 8 shows such basic schedule. This configuration could be exploited for maintenance operations and data exchange as well.

However, in very dense networks with huge traffic requirements, such setting is not sufficient in terms of bandwidth. Some dedicated cells (i.e., TX or RX) could be installed to avoid collisions and increase the network bandwidth. Hence, the remaining 93 slots, as pictured in Fig. 8, are scheduled by DeTAS, which provides indeed a technique for configuring dedicated cells. Although the example shows a DeTAS schedule using three channel offsets (i.e., $W = 3$), we have explored the adoption of several values for W. The impact of this setting on the network performance has been thoroughly evaluated and will be discussed in the remaining part of this section.

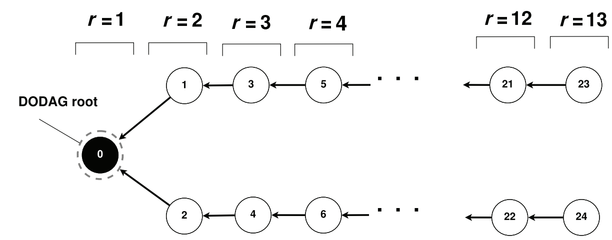
In order to evaluate the efficiency of DeTAS in managing multipoint-to-point traffic flows, each source node runs an application to send dummy data toward the $\mathrm{DODAGroot}$. In details, at the network bootstrap, whereas nodes join the network, DeTAS updates the network schedule through some signaling packets (those described in Section IV). When a node joins the network, signaling packets are conveyed in both "minimal" shared slots (i.e., for TSCH joining, RPL DIO exchange, and DeTAS RES command frames) and dedicated slots just allocated by DeTAS (i.e., for DeTAS REQ command frames). Once the network is formed, source nodes starts sending periodically data according to the aforementioned application.[5] Specifically, a node generates a packet every two slotframe cycles, i.e., 1 packet every 3.03 s.

Since packets can be lost due to the mutual interference among nodes using the same cell, we have overprovisioned the number of cells installed by DeTAS in order to allow for retransmission (RTX). In details, the *local packet number* related to each node n_i in the network has been configured as $q_i = 2$. In other words, a source node will install at least two cells per slotframe to deliver the data it has generated toward the $\mathrm{DODAGroot}$. Since the traffic generation rate is equal to 0.5 packet per slotframe, the available cells for the transmission of a single packet are 4. In general, a data packet can be retransmitted several times until either it is acknowledged at the MAC layer (i.e., it has been correctly received by a neighbor) or the number of maximum retries has been reached [8]. In the experiments, we have varied also this parameter, in order to understand the tuning rule of thumb to be used in industrial deployments.

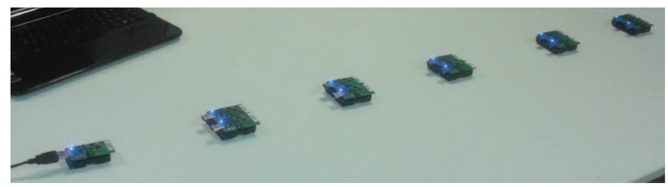
For testing the efficiency of DeTAS, the network topologies deployed are described in the following list.

1) A double chain topology is able to characterize the network depth and complies with DeTAS. In fact, at each instant, only a single node per $\mathrm{DAGrank}$ is allowed to transmit. Among these, nodes with an odd $\mathrm{DAGrank}$ belong to the subtree related to a child of the $\mathrm{DODAGroot}$, whereas nodes with an even $\mathrm{DAGrank}$ belong to the subtree related to another child of the $\mathrm{DODAGroot}$. Both subtrees can be represented with a chain topology without loss of generality. Fig. 9(a) pictures an example of double-chain topology.

[5] We have used the DVN field to let nodes know that the network is completely formed.



(a)



(b)

Fig. 9. Double-chain. (a) Topology. (b) Testbed (the first five hops).

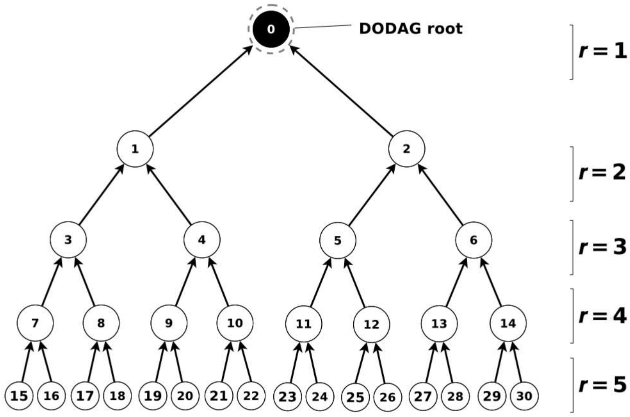
2) A binary tree topology is able to characterize the network width. Hence, this topology [sketched in Fig. 10(a)] permits us to assess the DeTAS performance when used in almost realistic dense networks.

With the double-chain topology, it is possible to investigate how the performance of DeTAS changes by increasing the diameter of the network. On the other side, the binary tree topology allows to investigate the sensitivity of DeTAS to the density of nodes. As a such, the findings of this experimental campaign can be also used to approximately characterize DeTAS also in different scenarios, based on the network diameter and node density.

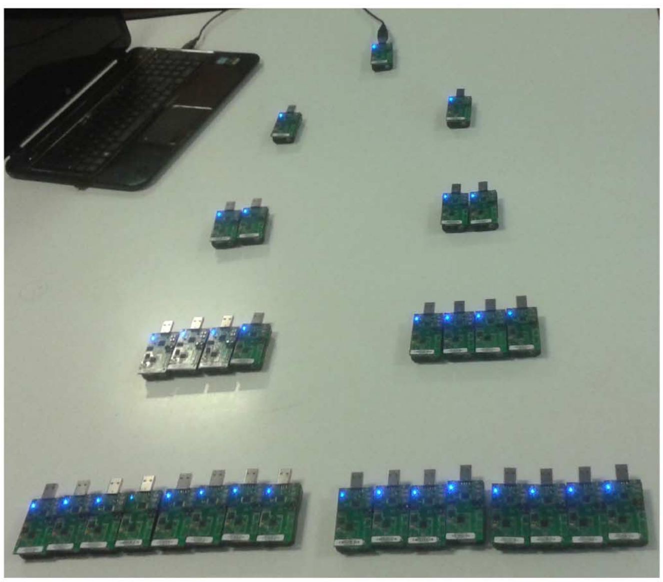
For the sake of clarity, Table II summarizes the list of parameters used in the experiments.

Nodes with the same $\mathrm{DAGrank}$ have been positioned as close as possible, in order to increase the effect of mutual interference. In fact, we have investigated the effect of channel reuse. Furthermore, the transmission power of the cc2420 radio present in the TelosB mote has been reduced in order to position the motes in a closer distance (between 25 and 30 cm) and to have complete control of the deployed network. The experiments have been conducted without interference from other wireless technologies, since we are interested in evaluating the effect of the mutual interference among nodes in the same network. As a consequence, the reduction in the transmission power is acceptable for this experimental environment. Figs. 9(b) and 10(b) show some pictures of the actual testbed deployed.

For each experimental scenario, we have collected five 40-min-long traces. In the remaining part of this section, we present the plot related to some performance indices, specifying also the 95% confidence interval. In particular, we have evaluated: 1) the end-to-end delay, i.e., the latency between the data generation and its reception at the $\mathrm{DODAGroot}$; 2) the end-to-end and link packet loss ratio (PLR); and 3) the node duty cycle, calculated considering for each active slot only the time when the radio is on (i.e., TX or RX mode).



(a)



(b)

Fig. 10. Binary tree. (a) Topology. (b) Testbed.

TABLE II
SET OF PARAMETERS USED FOR EXPERIMENTS

	Binary tree (%)	Double chain (%)
Freq. reuse (W)	$3, 4$	$3, 4, 6, 12$
Retransmissions	$1, 2, 4$	$1, 2, 3, 4$
No. Source nodes	30	24
Max rank	4	12

A. Experiments Results: Double-Chain Topology

The results related to the experiments on a double-chain topology are shown in Figs. 11–18.

Fig. 11 shows the average duty cycle as a function of the DAGrank, for any value of channel offsets used and RTXs allowed. As a general expected behavior, it can be seen that the average duty cycle linearly decreases as the DAGrank increases. In fact, nodes with smaller DAGrank are those closer to the DODAGroot, hence bottlenecks for the traffic directed to the DODAGroot.

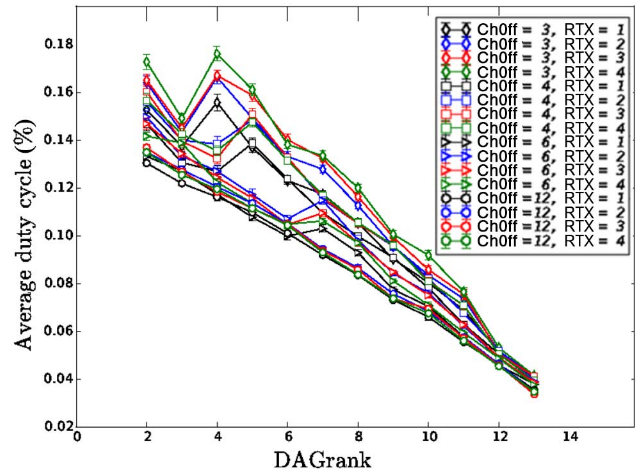


Fig. 11. Duty cycle as a function of the DAGrank, a node has inside the network in the double-chain topology.

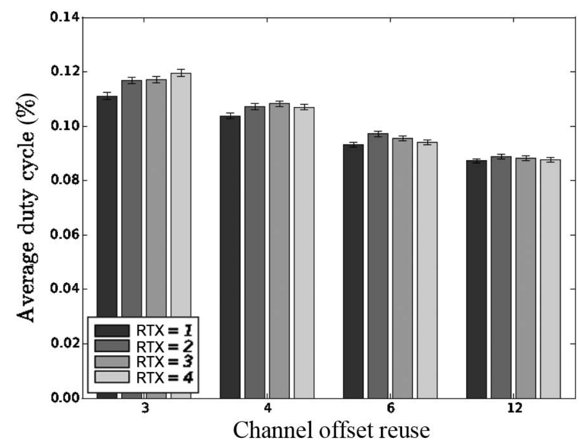


Fig. 12. Average network duty cycle as a function of W in the double-chain topology.

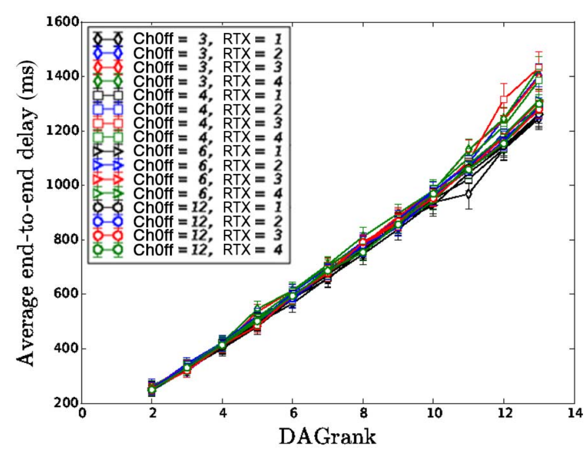


Fig. 13. Network delay as a function of the DAGrank that a node has inside the network in the double-chain topology.

In Fig. 12, the average duty cycle (regardless of DAGrank) has been plotted with histograms. In details, we have grouped results according to the value W of the number of channel offsets used. As it can be seen, as the W increases, the duty cycle decreases, because with more channel offsets available, there

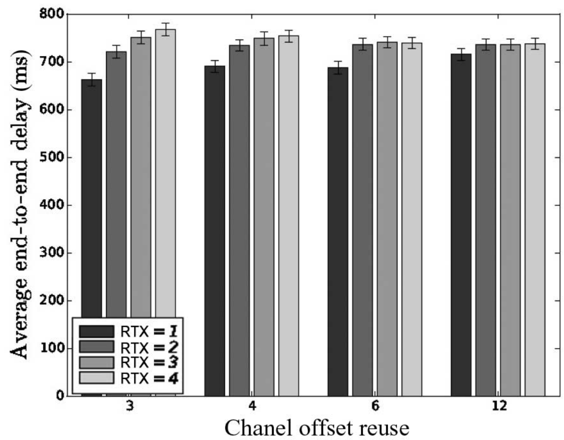


Fig. 14. Average network delay as a function of W in the double-chain topology.

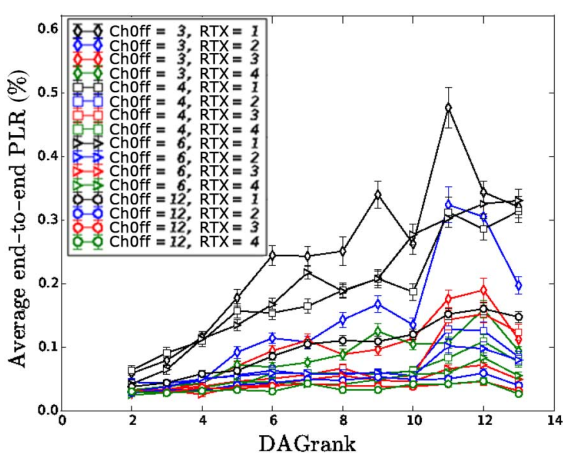


Fig. 15. End-to-end PLR as a function of the DAGrank that a node has inside the network in the double-chain topology.

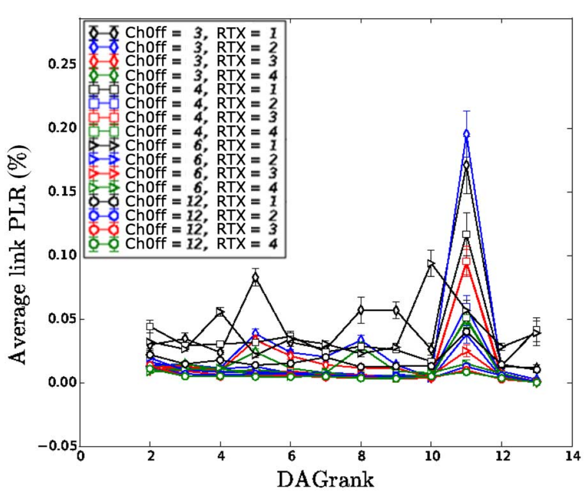


Fig. 16. Link PLR as a function of the DAGrank that a node has inside the network in the double-chain topology.

will be less mutual interference. For instance, with $W = 3$, 4 couple of nodes in the double chain topology will be allowed to interfere in the same cell. Although some of these couples will not be exchanging data (1 cell every 4 will be used for data

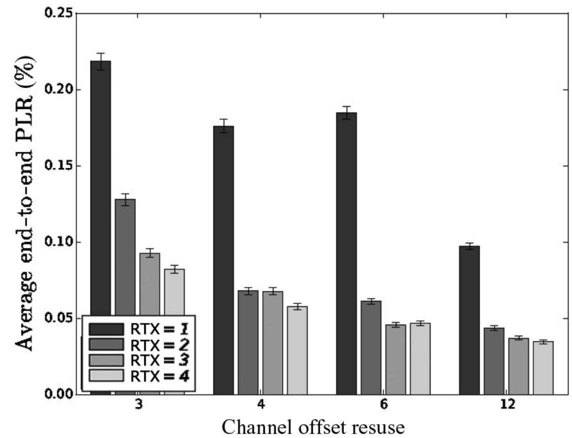


Fig. 17. Average end-to-end PLR of the network as a function of W in the double-chain topology.

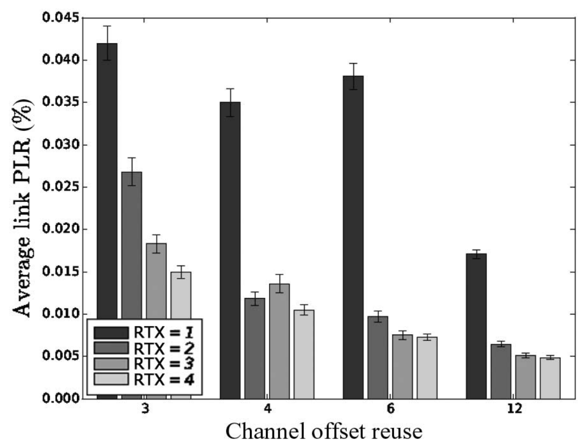


Fig. 18. Average link PLR of the network as a function of W in the double-chain topology.

packet exchange), the receiving side of each couple will detect a transmission and will continue receiving the packet. Therefore, some nodes will increase their duty cycle because overhearing the radio medium, even though they will later realize that the packet was not addressed to themselves.

In addition, it can be also noticed that for lower values of W, the duty cycle increases as the maximum number of RTXs increases. For higher values of W, results are almost identical when varying the RTXs number. This behavior was expected too, since with higher W values, the mutual interference is lower, thus making the RTX mechanism useless.

The end-to-end average delay as a function of the DAGrank is shown in Fig. 13. As expected, the delay linearly increases as the number of hops (which is directly correlated to the DAGrank) augments. It is also worth noting that the average maximum delay is lower than 1.5 s. On average, a data packet will reach the DODAGroot in less than half of the slotframe duration.[6] This feature is inherent to DeTAS: given a path between a source node and the DODAGroot, the transmission on a link belonging to that path will be always scheduled before the transmission on the following link in the same path toward

[6]In OpenWSN, a timeslot is 15-ms long; therefore, a 101-sized slotframe is 1.515-s long.

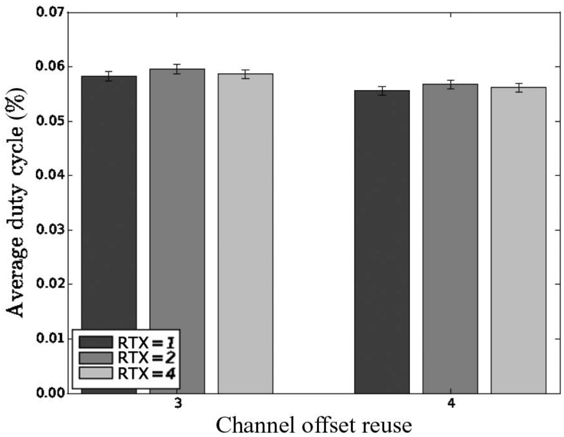


Fig. 19. Average network duty cycle as a function of W in the binary tree topology.

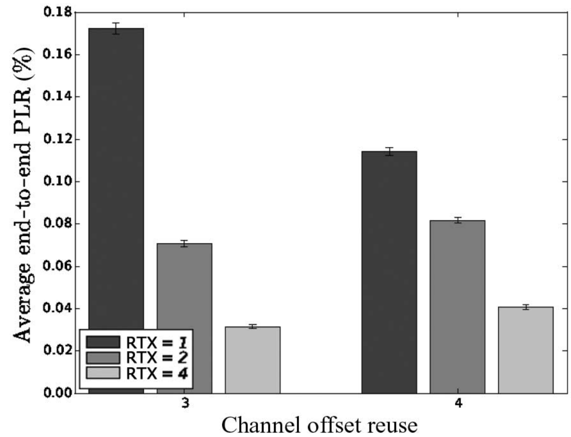


Fig. 21. Average end-to-end PLR of the network as a function of W in the binary tree topology.

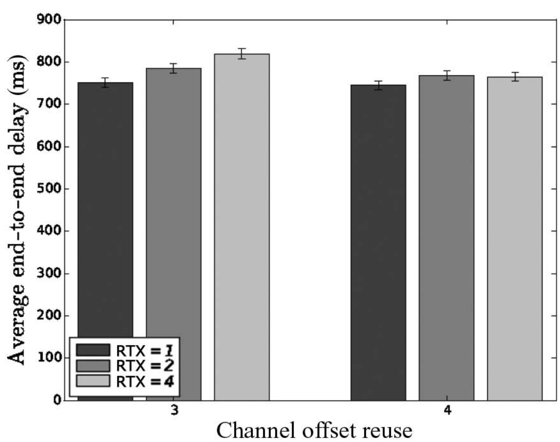


Fig. 20. Average network delay as a function of W in the binary tree topology.

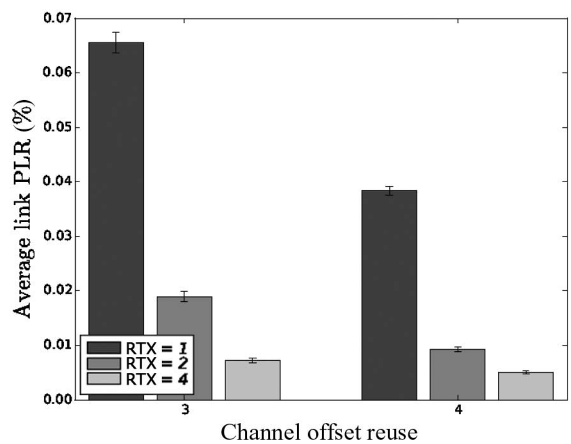


Fig. 22. Average link PLR of the network as a function of the W in the binary tree topology.

the $\mathrm{DODAGroot}$. In other words, if a node has to relay packet toward the $\mathrm{DODAGroot}$, a given receiving cell in the schedule of that node will be always followed by a transmitting cell. This feature is very important with reference to time-critical monitoring application in industrial plants.

Fig. 14 clearly shows that augmenting the number W of channel offsets available, the number of maximum RTX has a lower effect. With $W = 3$, more collision can happen, so more allowed RTXs give more reliability to the network at the cost of bigger delays.

Obviously, the end-to-end PLR increases as the hop distance between a node and the $\mathrm{DODAGroot}$ augments. This is confirmed by the results plotted in Fig. 15. Such increase depends on the link PLR measured at each hop, which is also plotted in Fig. 16. The average link PLR does not depend on the $\mathrm{DAGrank}$, and the not aligned values for the link PLR (e.g., the average link PLR at $\mathrm{DAGrank} = 10$) can be explained as due to device misbehavior.

Finally, in Fig. 17, it can be seen that the end-to-end PLR is significantly reduced with at least an RTX allowed then a regular transmission ($\mathrm{RTX} \geq 2$). Increasing the number of available channel offsets, there is an additional improvement of the reliability. Similar arguments can be used when considering the link PLR (as pictured in Fig. 18).

B. Experiments Results: Binary Tree Topology

The performance results related to the experiments performed for exploring the efficiency of DeTAS on a binary tree topology are shown in Figs. 19–22.

In this topology, a number of available channel offset equal to 4 is sufficient for avoiding collisions and radio overhearing. In fact, the maximum $\mathrm{DAGrank}$ is 4 with a binary tree topology made by 30 source nodes (as in our experiments). The results clearly confirm that DeTAS has the same performance independently from the network topology. This is what we expected, since DeTAS has been designed to manage all kinds of topology and to be scalable in all scenarios.

VI. Conclusion

In this paper, we have described in more details the very first implementation of the decentralized TASA in the OpenWSN protocol stack. Some experimental results related to real network deployments have been assessed confirming the effectiveness of DeTAS in time-critical applications especially needed in industrial environment for monitoring and control purposes.

In details, we have described the efforts being spent within the IETF 6TiSCH WG to the aim of standardizing an adaptation layer which can let IETF standards be employed on top of the novel IEEE802.15.4e TSCH MAC protocol.

Then, we have described the DeTAS scheduling technique, highlighting its theoretical effectiveness in building a multihop schedule in a distributed fashion.

We have also reported details of the real implementation of DeTAS, by picturing the signaling required and explaining how it can be integrated into 6TiSCH-enabled networks.

The experimental results confirm what we already expected for the DeTAS performance in terms of duty cycle, end-to-end delay, end-to-end, and link packet loss ratio.

We strongly believe that the strength of DeTAS relies in its design: it enables a fast communication between the DODAGroot and any node in the network; it avoids queues being congested; and it reduces the packet loss ratio through a proper scheduling of resources.

In future work, we will extend DeTAS to manage topologies where each node can route traffic to more than one parent.

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