Join Multiple Channels and IEEE 802.15.4e TSCH Protocol Use Effects on WSN Performance and Energy Efficiency

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Abstract: The goal of this paper is analysing the use of the IEEE 802.15.4e standard MAC layer protocol *Time-Slotted Channel Hopping* (TSCH) mode in the context of Internet of Things (IoT) and Industrial IoT (IIoT) aimed at reducing narrow-band interferences and the multi-path fading impact on available channels by using frequency hopping, with network time synchronization to achieve low-power operation. In low disturbances environments using several channels provides the diversity benefits. However, using several channels requires channel scanning and switching leads to extra power consumption. It could be accepted in harsh environments (industrial), due to its influence on channels features, requiring more channels, and it is necessary to continuously hop seeking for the best one to achieve the best performance. Several experiments have been simulated and implemented in real testbeds the laboratory as first validation approach. The performance and energy efficiency of the entire network is analysed for different scheduling methods, packet transmission rates, number of used channels and guard time. The relevant conclusion showed in this investigation is that using all the available channels of the standard is not required to achieve the best joint-results given that, regardless the scheduling method used, considering a higher number channels requires a higher power consumption for channels quality exploration and packet reception rate decreases.

1 INTRODUCTION

The term Internet of Things (IoT) has been used as a reference to a new generation of pervasive computing, i.e., representing the ubiquity of computing resources in people's consumer products. Usual industrial equipment and products such as cars, telephones, televisions, refrigerators, and sensors can have built-in connectivity to the Internet, with remote control, personalization, automation as well as performance analysis. This connection is possible through sensors installed in devices and places from where data are sent for analysis.

The concept of smart devices is closely linked to IoT, and Industrial IoT (IIoT) is the application of these technologies in industrial scenarios, such as in smart buildings, smart factories, and smart grids (Xu et al., 2014). IIoT is expanding the traditional automation systems and industrial informatics systems into a broader context.

A Wireless Sensor Network (WSN) is a self-configuring network of small sensor nodes (motes) communicating among them using radio frequency. They consist of a microprocessor with limited computational power and memory, one or more antennas, a power source and one or more sensors.

Among the roles the nodes can play, they can work as a simple sensor that transmits the sensor readings to a sink node (base station); as a sink node that receives the sensor readings from the other nodes and forwards these readings to a gateway for further processing/analysis; and as actuators, which are used to control the environment, based on triggers revealed by the sensor readings or by other inputs. In some cases, the nodes not only sense the environment, but also forward the data from/to other nodes until this infor-

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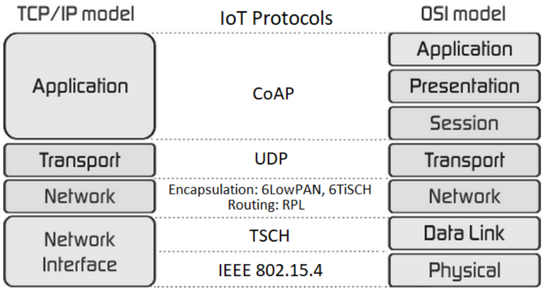

Figure 1: Standardization of low-power and resource-constrained wireless technologies.

mation arrives at the sink node. There is also the role of border router which interfaces the sensor network with the computer network, allowing a user to request node sensing information through the computer and from the Internet.

An application that may use the concept of border router is the Constrained Application Protocol (CoAP), depicted in Figure 1. CoAP is a specialized web transfer protocol for use with constrained nodes and constrained networks in the IoT. The protocol is designed for machine-to-machine (M2M) applications such as smart energy and building automation[1]. In this case, the user (CoAP client) requests resources from the sensors, represented as CoAP servers, distributed in different parts of the environment.

Like HTTP, CoAP is based on the Representational State Transfer (REST) architecture, i.e., servers make resources available under an URL, and clients access these resources using methods such as GET, PUT, POST, and DELETE. The need to maintain such constrained devices spending the minimum possible energy for a long time justifies the use of this protocol, keeping their communication active through the Internet.

The experiments performed in this work used a simple UDP client/server application, in which the nodes act as UDP clients and transmit packets to the UDP server, that works as the network coordinator. However, our scenario could also be implemented using the CoAP application.

IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) is the IETF development group that creates and maintains the specifications that allows to use IPv6 over IEEE 802.15.4 networks. Its most pertinent issues are fragmentation/defragmentation and compression of IPv6 headers. 6LoWPAN creates an adaptation layer between IEEE 802.15.4 and IPv6, with specific headers that can be added or removed, allowing only what is useful to be sent. A Working Group (WG) recently formed called 6TiSCH aims to link IEEE802.15.4e TSCH capabilities with prior IETF 6LoWPAN and ROLL standardization efforts and recommendations. Defining IPv6 over TSCH, which is a MAC layer protocol, 6TiSCH is a key to enable the further adoption of IPv6 in industrial standards and the convergence of Operational Technology (OT) with Information Technology (IT) (Thubert and Watteyne, 2018).

Besides 6LoWPAN and 6TiSCH, the IoT context includes another protocol in the network layer called IPv6 Routing Protocol for Low Power and Lossy Networks (RPL). It is a distance vector protocol that defines its routes through routing trees using the Directed Acyclic Graph (DAG) concept. RPL mainly meets the requirements of low data rates and high error rates, which makes the network throughput low. Each node can associate with more than one node, which differs RPL from other tree-based protocols, and it deals with alternative routes to avoid interrupting the data flow.

Contiki operating system provides two implementations of RPL with different attributes: RPL Classic and RPL Lite. RPL Classic is the continuation of the original Contiki's RPL implementation, ContikiRPL, and supports multiple instances and DODAGs, storing and non-storing mode, and multicasting. RPL Classic is more complex than RPL Lite, which removed support for storing mode in favor of non-storing mode, and removed the complexity of handling multiple instances and DODAGs. Through these changes, RPL Lite presents better performance[2] and has a considerably smaller ROM footprint. However, it has a lower interoperability level with other implementations, which may use storing mode for instance. In this work, we use the RPL Lite with non-storing mode.

Heading to the link layer, we have one of the most important protocols in IoT context, TSCH. In this protocol, the nodes communicate by following a Time Division Multiple Access (TDMA) schedule, and a timeslot in this schedule provides a unit of bandwidth that is allocated for communication between neighbor nodes. This approach avoids idle listening and extends battery lifetime for constrained nodes. Channel-hopping improves reliability in the presence of narrow-band interference and multi-path fading (Thubert and Watteyne, 2018).

This work aims to perform experiments using simulation with Cooja, which is the Contiki's simulator, and real testbeds M3 Open Node from FIT IoT-LAB[3]. This device is based on a STM32 (ARM Cor-

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[1] https://coap.technology/, accessed in 16/05/2019.

[2] https://github.com/contiki-ng/contiki-ng/wiki/Documentation:-RPL/, accessed in 16/05/2019.

[3] https://www.iot-lab.info/

tex M3) 32-bits micro-controller, at 72 MHz, 64kB RAM, and AT86RF231 2.4 GHz radio. Simulations use the Zolertia Z1 motes, with 16-bit RISC CPU, 16MHz clock, 8KB RAM, 92KB Flash memory, and a CC2420 transceiver, IEEE 802.15.4 compliant operating at 2.4GHz,i.e., lower performance than M3, and some parameters of TSCH and RPL protocols needed to be reduced to fit memory size.

FIT IoT-LAB is a laboratory that provides a large-scale infrastructure suitable for testing small wireless sensor devices. It provides full control of network nodes and direct access to the gateways to which nodes are connected, allowing researchers to monitor nodes energy consumption and network-related metrics, e.g. end-to-end delay, throughput or overhead.

In this work, we used the protocols UDP, 6TiSCH, RPL and TSCH, and focused the study especially on the TSCH protocol in relation to the scheduling method, frequency hopping and guard time in a network with direct connection between client and server.

The performance and energy efficiency of the entire network is analysed for different scheduling methods, packet transmission rates, number of used channels and guard time. The overall network performance is assessed in terms of network throughput where the PRR (Packet Reception Rate) seems to be a good indicator of the presence of disturbances impacting the network.

The rest of this paper is organized as follows. In Section 2, we introduce the TSCH characteristics, two main scheduling methods of TSCH, discuss the Guard Time and channel blacklisting. In Section 3, we present the performance evaluation with simulations and real testbeds, and finally in Section 4 we make concluding remarks.

2 IEEE 802.15.4E TSCH

The IEEE 802.15.4e MAC standard (IEEE, 2017) released in 2012, is an improved version of 802.15.4 MAC protocol. The IEEE 802.15.4e uses many ideas from WirelessHART and ISA-100.11.a standards, including slotted access, shared and dedicated slots, multi-channel communication, and frequency hopping. Specifically, IEEE 802.15.4e extends the previous IEEE 802.15.4 standard by introducing five new MAC behavior modes (protocols), designed to support specific application domains (De Guglielmo et al., 2016). Among them, only TSCH, Deterministic and Synchronous Multi-Channel Extension (DSME), and Low Latency Deterministic Network (LLDN) modes have been explored in the literature, so far (De Guglielmo et al., 2016).

TSCH standard aims to provide bounded delay and reliable communication in industrial wireless networks. It divides the time into slots and uses the Frequency Hopping Scatter Spectrum (FHSS) to reduce the impact of multipath fading and external interferences. This technique requires network synchronization and changes the communication frequency every packet is sent making the network more robust against disturbances affecting only a channels subset.

A link between nodes can be represented by a pair of timeslots in the slotframe (*n*), and the channel offset used by the nodes in that timeslot, defined as [*n, channelOffset*]. The transmit frequency f in timeslot n of the slotframe is given by $f = FHS\left[ASN + channel_{Offset} \% FHS_{length}\right]$, where ASN (Absolute Slot Number) represents the total number of timeslots incremented in each time interval from the beginning of the network, % is the modulus operator, and the length of the sequence (FHS_length) is 16 channels by default, without blacklisting in the calculation.

In addition to frequency hopping, TSCH uses blacklists for low quality channels. Other standards, as WirelessHART and ISA100.11a, use frequency hopping and blacklisting as well. WirelessHART employs a central network manager with frequency hopping and global blacklist. ISA100.11a uses local blacklists, where the nodes avoid transmitting on blacklisted channels, preventing unsuccessful transmissions. If packets are dropped before being transmitted the delay may increase and the PRR decrease at the application layer.

There are 16 different channels available but due to disturbances the channel quality of some channels is very and are blacklisted, reducing available ones. Hence, the FHS must be regenerated every time a channel is blacklisted.

2.1 Minimal Schedule and Orchestra

The IETF Working Group 6TiSCH is currently standardizing the mechanisms to use TSCH in low-power IPv6 scenarios (P. Thubert, 2019). 6TiSCH defines the sublayer for the management of TSCH nodes and schedules via a CoAP interface, and 6top, a sublayer that enables neighbor-to-neighbor slot installation/removal (Duquennoy et al., 2017).

In this paper, 6TiSCH is used with minimal schedule (Vilajosana et al., 2017) providing basic interoperability. The settings include a simple static scheduler with a single shared slot for all transmissions and receptions in a slotframe, and defines how TSCH interacts with upper layers and the RPL routing protocol, ensuring a consistent mapping between the RPL routing topology and the TSCH time-source graph. Additionally, we perform experiments using Orchestra, an autonomous scheduler for TSCH and RPL networks where nodes maintain their own schedule locally based on their local RPL state. It has neither central scheduler nor neighbors negotiation, reducing traffic overhead.

2.2 Guard Time

When the network has traffic, the nodes that communicate need to resynchronize to their time source neighbor(s) periodically not to drift in time. The periodicity of these control messages depends on the stability of the clock source and on how "early" each node starts listening for data using the Guard Time (GT) (Watteyne, 2015).

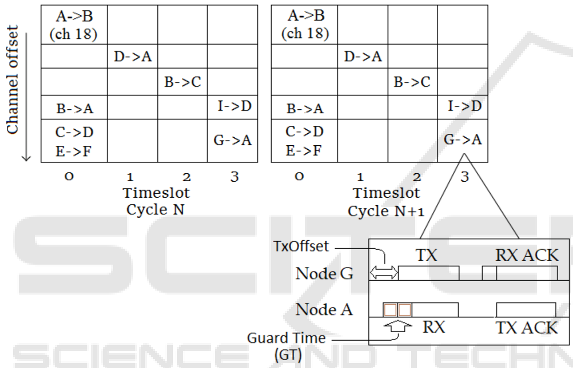

Figure 2: TSCH includes a GT to account for loss of synchronization.

Figure 2 depicts the GT process, in which Node G transmits its data packet after *TxOffset*, while the receiver A uses a GT to avoid missing the incoming packet by turning its radio ON a little before the packet arrival.

Higher synchronization accuracy enables the reduction of idle listening time on receivers, saving more energy. In (Papadopoulos et al., 2016), a set of experiments were performed using Cooja to evaluate the minimum GT under different clock drift values (0, ±10, ±20, ±30 and ±40 *ppm* - parts per million). In the results, with a ±20 *ppm* drift, 390 μs is the minimum GT length for operation without compromising network reliability due to loss of synchronization using emulated Z1 motes. They decreased the GT duration when motes were closer to their sink and this approach saved energy significantly with good network reliability. In our work, we compared three different GT lengths, 2200 μs (Contiki's default), 1500 μs and 900 μs using the M3 platform. Reducing this value to 400 μs, the average power consumption per receiver node could decrease by more than 40% in the scenarios studied in (Papadopoulos et al., 2016).

One of the main reasons for clock drift is caused by oscillator crystals deviating from their nominal frequency due to production spread (Elsts et al., 2016). In OpenMote-CC2538, which is the platform we will use in future works to perform experiments in industry, a 32 MHz crystal clocks the radio, and has a drift of up to 30 *ppm* from -20 C to +70 C (Vilajosana et al., 2015). To achieve tight time synchronization, a second 32 kHz crystal clocks the microcontroller's RTC (Real Time Clock), allowing to keep track of time, even when in deep sleep. The second crystal is rated at 10 *ppm* from -40 C to +85 C, which is the industrial temperature range.

2.3 Channel Blacklisting

Appropriate blacklist is proposed in this investigation approach to improve the overall performance. Blacklist and transmissions node scheduling are used to avoid neighbor links interferences by restricting the simultaneous use of adjacent channels. This arrangement is critical to achieve the best overall network performance. There are two approaches to create blacklists: global and local. In the first one, all the nodes use the same channels-list. Nevertheless, this solution could become suboptimal, since the channels may present different qualities for distinct network links, even when nodes are close to each other (Gomes et al., 2017b). In the second approach, each nodes pair can use different sets of channels (Kotsiou et al., 2017), i.e., a specific blacklist is defined per link.

The use of local blacklists increase the complexity, and it could produce collisions when two or more nodes transmit in the same timeslot with different blacklists, resulting in multiple nodes broadcasting on the same channel at the same time. Besides, if the environment is very unstable and the blacklist is modified very often, the local blacklist is not useful due to the amount of signalling frames required for resynchronization.

Blacklists identify channels to be included using a Link Quality Estimator (LQE) which analyses interferences in the same frequency range in the 2.4 GHz band and blacklist them. In this paper, since harsh environment is not considered the LQE is not used. However, channels sets are randomly chosen to be blacklisted, while keeping active (whitelisted) up to four channels in the deployed test-beds, and eight channels in the simulations. This feature guarantees the required diversity and reduces the synchronization and resynchronization delay. Future works will include using LQE in industrial environments to blacklist channels before and after the network starts.

The relevance of setting the most appropriate channels blacklist in TSCH has been neglected by most of previous developments which mainly focus on scheduling strategies while ignoring the channels quality assessment.

The TSCH protocol is implemented in three types of topologies: star, tree and mesh. Tree and mesh topologies are more challenging than the star one because two or more nodes can send packets over the same channel at the same time (timeslot) causing packet losses. Even when transmitting on adjacent channels exits a certain level of interference which must be mitigated. In the star topology, each node connecting with the coordinator transmits over a different channel and timeslot, although it is possible to allocate shared slots for many nodes. In consequence, a contention-based approach is requires to manage packets collisions. This investigation focuses on mesh topology where nodes are connected directly to the sink node.

In (Queiroz et al., 2018), the authors analysed the channel blacklisting for networks with star and tree topologies using the TSCH protocol. In the case of tree topology, they divided the network into clusters, and in each cluster, there is a cluster head (CH) which acts as LQE, network coordinator and router, and forwards the packets from the leaves to the sink node. The quality estimation is performed locally, i.e., each leaf has its own blacklist. The authors conclude that implementing the blacklisting has a noticeable impact on the overall network performance, and there must be a limit in the number of blocked (black-listed) channels to avoid packet losses. It does not happen in the star topology since there is no simultaneous transmissions; each node has its own timeslot to transmit and receive an acknowledgement, and in that case, the more the blocked channels the higher the PRR, surviving only one and the best for each end node.

In (Zorbas et al., 2018), the algorithm LOST is introduced and relies on information gathered by its 1-hop neighbours only. It multiplexes the different transmissions across different channels by allocating properly the channel offsets. A localized blacklist method is employed in the scheduler to avoid using the bad radio channels.

In (Du and Roussos, 2012), the authors introduced the Adaptive TSCH (A-TSCH), which uses channel blacklisting. The transmitting nodes become aware of the neighbors' blacklist, and both the transmitter and receiver use the same hopping sequence to communicate by inserting the list information into transmission packets.

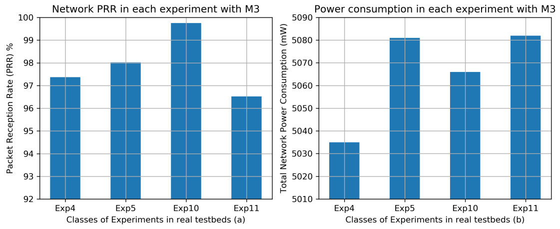

Figure 3: Exp4-5 with Orchestra, Exp10-11 with Minimal Schedule, one and four channels with M3 motes.

In (Gomes et al., 2017a), the algorithm MABO-TSCH assigns in a centralized manner a collection of cells for each radio link considering local blacklists. Several channel offsets are assigned within the same timeslot, so that a radio link can pick one of the channel offsets that does not give a blacklisted physical frequency. A pair of nodes locally decides the channels to be blacklisted, and to maintain a consistent list for the link, they insert it into the ACK package, combined with a sequence number. Channel quality MABO-TSCH is based on Stochastic Multi-Armed Bandits (MAB).

Dynamic whitelisting method is used in (Tavakoli et al., 2015) and proposes improved TSCH (Enhanced TSCH, ETSCH), which uses a non-intrusive channel quality estimation technique called NICE. The ETSCH uses the Energy Detection (ED) method to estimate the channels quality at every time interval. It frequently updates a channel stream and sets-up a secondary list with the best channels to transmit the EBs. At least two samples of channel energy are taken per time interval. Using a secondary list reduces the likelihood of losing EBs.

In (Kotsiou et al., 2019) is proposed grouping radio links to guarantee links in a group share the same whitelist, and different groups have distinct ones. The goal is avoiding a global whitelist, which decreases network performance, and a local whitelist, which may cause collisions. The solution forces all the nodes sharing the same timeslot using the same whitelist, performing better than approaches without blacklist, with global blacklist, with a common blacklist per timeslot, and better than MABO-TSCH algorithm.

3 PERFORMANCE EVALUATION

This section analyses the performance of TSCH using the settings depicted in Table 1. From the 1st to the 12th, Cooja was used for simulating a network with ten nodes (nine UDP clients and one sink node - UDP server), and from 13th to 17th real testbeds were used.

Table 1: Experiments performed, some of them with both simulation and real testbeds. The last three for two hours.

Experiments	Powertrace (s) Simulations	PTR	Scheduling Method	Number of Channels	Maximum Payload Length	Simulation	Real Testbeds	Number of Nodes	Guard Time
Exp1	10	1 pkt / 30 s	Orchestra	1	30	Yes	-	10	Default
Exp2	10	1 pkt / 30 s	Orchestra	4	30	Yes	-	10	Default
Exp3	10	1 pkt / 30 s	Orchestra	8	30	Yes	-	10	Default
Exp4	10 / -	1 pkt / 5 s	Orchestra	1	30	Yes	Yes	10	Default
Exp5	10 / -	1 pkt / 5 s	Orchestra	4	30	Yes	Yes	10	Default
Exp6	10	1 pkt / 5 s	Orchestra	8	30	Yes	-	10	Default
Exp7	10	1 pkt / 30 s	Minimal Schedule	1	30	Yes	-	10	Default
Exp8	10	1 pkt / 30 s	Minimal Schedule	4	30	Yes	-	10	Default
Exp9	10	1 pkt / 30 s	Minimal Schedule	8	30	Yes	-	10	Default
Exp10	10 / -	1 pkt / 5 s	Minimal Schedule	1	30	Yes	Yes	10	Default
Exp11	10 / -	1 pkt / 5 s	Minimal Schedule	4	30	Yes	Yes	10	Default
Exp12	10	1 pkt / 5 s	Minimal Schedule	8	30	Yes	-	10	Default
Exp13	-	1 pkt / 10 s	Orchestra	4	30	-	Yes	30	Default
Exp14	-	1 pkt / 10 s	Minimal Schedule	4	30	-	Yes	30	Default
Exp15	-	1 pkt / 10 s	Orchestra	4	30	-	Yes	29	2200
Exp16	-	1 pkt / 10 s	Orchestra	4	30	-	Yes	29	1500
Exp17	-	1 pkt / 10 s	Orchestra	4	30	-	Yes	29	900

Four simulation experiments were also evaluated using real M3 testbeds. Contiki's Powertrace application is used in the simulations allowing monitoring nodes energy consumption every ten seconds. In the testbed at the FIT IoT Lab, Powertrace was not required as a manager node was used to monitor the radio channels power and consumption.

Packet Transmission Rate (PTR) was fixed at 1 packet every 30, 10, and 5 sec. A predefined list of whitelisted channels. In the last five experiments we chose four channels to provide diversity, despite the slightly higher energy consumption compared to the network with one channel, as depicted in Figure 3.

Figure 4 depicts the results obtained after 12 simulation experiments aimed at assessing network performance, energy efficiency and the number of synchronization requests. In *Orchestra* (Exp1-Exp6), the number of synchronization requests is directly related to the PRR, the number of channels and power consumption. As the number of whitelisted channels increases the nodes require a longer time interval to synchronize with the network, and consequently the PPR decreases and the energy efficiency drops. The energy efficiency regards the amount of energy required to successfully transmit and receive a data packet. In this work power consumption absolute values are not considered but relative ones.

In the case of *Minimal Schedule* (Exp7-Exp12), using several channels impacts negatively on the PRR. However, the energy consumption is directly related to the number of synchronization requests. Using four channels instead of one or eight led to a higher number of synchronization requests, consequently to a higher energy consumption. This behavior was evaluated through the real nodes in the laboratory in Figure 3.

Figures 3 and 4 show that simulation results fit testbeds conclusion, but the PRR with Orchestra (Exp4 and Exp5). In this case, the PRR with one and four channels showed almost the same results with M3 testbeds. More experiments are needed to achieve stronger conclusions because even considering that the laboratory environment is somehow stable, it's always changing, since the lab is used by other researchers who develop independent experiments at the same time producing interferences impacting the channels behaviour.

In all the simulation scenarios of PRR, the network with a single channel performed better than with four and eight channels, as depicted in Figure 5. This can be explained by the fact that, as mentioned previously, the simulated environment and the channel model of Cooja does not implement harsh environments such as the industrial one, that harms the quality of a subset of channels. The RSSI value remains almost the same during the simulation period, which does not happen in industrial environments, already studied in several papers (Queiroz et al., 2017). A fairly stable RSSI value is considered in the laboratory environment with static nodes. Orchestra and Minimal Schedule showed very close results in PRR.

Regarding the experiments with M3 motes and four channels in Figure 6, both Orchestra and Minimal Schedule presented almost the same results using the Guard Time with its default value, 2200 μs.

To implement the expected fully autonomous network next steps consider the autonomous scheduler Orchestra to evaluate GT values. Figure 7 shows the PRR and energy consumption with GTs 2200 μs, 1500 μs and 900 μs, respectively, using Orchestra. In the topology with 28 motes sending packets every 10 sec. to a single sink node without confirmation (ACK), where nodes connect directly to the sink, the GT with 1500 μs showed the best result, with 99.5% of PRR and the least energy consumption. Reducing the GT, the receiver wakes up earlier and is able

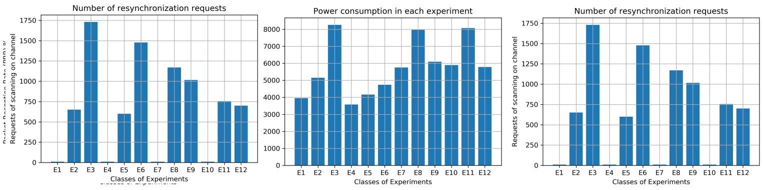

Figure 4: Relation among the PRR, energy efficiency and synchronization requests in simulations (E1 stands for Exp1).

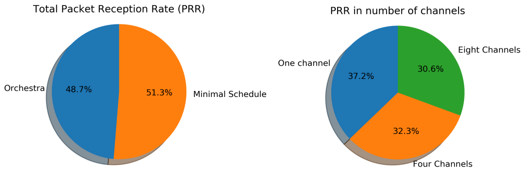

Figure 5: The total PRR comparing the schedule methods and number of channels in simulations.

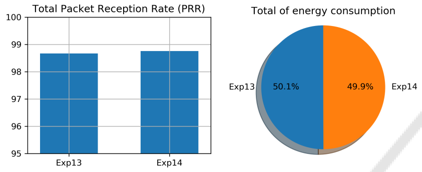

Figure 6: Comparison with Orchestra and Minimal Schedule in terms of PRR and energy consumption with M3.

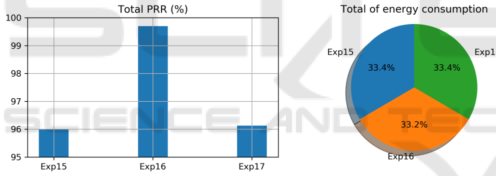

Figure 7: Orchestra with 2200 μs, 1500 μs, and 900 μs GT.

to receive more packets. However, when this value is too low, it may lead to packet losses due to synchronization failure. Energy consumption differences were small given just one node receives packets, any change in the value of the GT will generate a small change in the total network energy consumption. Using more sink nodes the increment is more remarkable.

TSCH parameters impact analysis is important to achieve the best network performance and energy efficiency. It's worthy to note that some of them are configured with the M3 testbeds, as follows:

- To estimate the drift of the time-source neighbor and compensate for it:

  ```
  TSCH_CONF_ADAPTIVE_TIMESYNC 1
  ```

- With *TSCH_ADAPTIVE_TIMESYNC* enabled, keep-alive timeout used after reaching accurate drift compensation:

  ```
  TSCH_CONF_KEEPALIVE_TIMEOUT(20*CLOCK_SECOND)
  TSCH_CONF_MAX_KEEPALIVE_TIMEOUT
  (60*CLOCK_SECOND)
  ```

- Enhanced Beacon Advertising Period; the shorter the period, the higher the advertising packets frequency, smaller the synchronization errors, in contrast, the higher the network traffic:

  ```
  TSCH_CONF_EB_PERIOD(16*CLOCK_SECOND)
  TSCH_CONF_MAX_EB_PERIOD(50*CLOCK_SECOND)
  ```

- 6TiSCH minimal schedule length. Larger values in less active slots, reducing capacity and saving energy. With Orchestra the TSCH schedule length must be set to zero:

  ```
  TSCH_SCHEDULE_CONF_DEFAULT_LENGTH 3
  ```

4 CONCLUSIONS

This investigation showed and compared the results of several experiments carried out by using both a simulation tool and actual testbeds where the TSCH protocol is used to improve the overall network. The goal was evaluating the impact of using one or several channels on packet transmissions. Various experiments has been conducted in the laboratory and using a simulator, where both the laboratory and simulation environments didn't affect noticeably channels quality. This feature lead to a remarkable conclusion: sensor-nodes using a single channel could show a performance superior than that showed by set-ups using several channels. In real industrial environments, given the level of interferences is stronger and multipath is present affecting the network performance, using just one channel leads to worse performance because transmitting over only one channel affected by strong interferences and multipath disturbances provokes loosing lots of packets. The results obtained along the various experiments show that, regardless the scheduling method, increasing the number of used channels decreases the PRR, considering set-ups using up to 30 motes in non-hard-harsh environments such as offices, homes and laboratories. Next steps will consider networks with more motes, since the probability of simultaneous transmissions over the same and/or adjacent channels increases, leading to a higher number of collisions and packet losses. However, in harsh environments, the network performance when using few channels would decrease, due to more channels suffer from interferences and multipath disturbances. In these cases using a link quality estimators should be considered in order to use only those channels showing the best quality. In future works, the investigation will focus on developing experiments using the Openmote-CC2538 in industrial environments to evaluate the GT with a Link Quality Estimator, and a Transmission Power Manager to ensure an appropriate overall network performance and energy efficiency.

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