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TSCH Network Health: Identifying the Breaking Point

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Abstract. Composed of constrained devices, Low-Power and Lossy Networks (LLNs) have been applied for numerous Internet of Things (IoT) applications. In addition, the Time-Slotted Channel Hopping (TSCH) media access control has been specified by IEEE aiming at Industrial IoT (IIoT). TSCH brings in the deterministic factor over wireless communication; it balances energy, bandwidth and latency, offering reliable communication. This paper conducted an experiment to reach the Contiki-NG's TSCH Minimal Schedule breaking point. We analysed network factors to identify evidence that may lead to performance degradation. The located evidence might be employed by edge resilient counter-measures systems developers, vertical integration researchers or scheduling function designers to improve systems and increase the IIoT reliability.

Keywords. IIoT, IoT, TSCH, Minimal, Contiki-NG

1. Introduction

We are living in the fourth industrial age. Analogue hardware became digital after the third industrial age, whereas analogical hardware was upgraded. After that, the new digital devices gained interconnection capabilities. Last but not least, the Internet has been widely used to connect many pieces of equipment worldwide, and some of these are called things. A new vision called the Internet of Things (IoT) has risen through the connected things performing jobs. IoT creates a new interactive way with the physical world and a new business model, demanding trusted complex resources from interconnection infrastructure. Industrial Internet of Things (IIoT) concepts have been merged with the industry work plane, which takes advantage of its ubiquitous nature and helps produce a more efficient and agile production chain, thus enabling the fourth industrial revolution.

Time-slotted Channel Hopping (TSCH) has received efforts and improvements for its adoption by industrial applications. Media Access Control (MAC) scheduling plays

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a vital role, being responsible for preventing interfering transmissions and managing the traffic capacity. The Time Division Multiple Access (TDMA) and the channel hopping technique have been used by TSCH for providing the deterministic network behaviour with reliability and energy efficiency. Indeed, building a schedule is still an open problem, and many efforts have been devoted to achieving the ideal TSCH Scheduling Function (SF). In this paper, we have used the TSCH/RPL relation to identify network behaviours or patterns that might employ for predicting and avoiding performance degradation towards a smart and safe network. As the main contribution, this work presents a set of metrics that resilience mechanisms might employ to prepare nodes for disturbances.

This work is based on experiments for assessing the TSCH behaviour towards finding tipping points to assist counter-measures systems developers or scheduling function designers aiming at a reliable network. This paper is organised as follows: In Section 2, we describe TSCH. Next, in section 3 we present the related works. After that, in Section 4, we detail how the experiments were performed. In Section 5, we analyse our data and discuss new indications of network degradation. Finally, in Section 6 the main conclusions are presented.

2. Time-slotted Channel Hopping (TSCH)

The 802.15.4 IEEE standard evolution [1] has maintained the focus on industry applications. Since its first version, the IEEE 802.15 Working Group for Wireless Personal Area Networks (WPANs) has worked to create a standard that could make possible low-cost, low-power communications. In 2003, the initial standard release defined two physical layers (PHYs) and a MAC layer. Next, in 2016 the standard was revised with seven amendments (six of them to the PHY layer and one to the MAC layer).

Although 6LowPAN was designed to utilise IPv6 over IEEE802.15.4 by constrained devices, its application in the Low-power and Lossy Networks (LLNs) context has presented many new problems and questions. The work developed by the named 802.15 Task Group 4e (TG4e) resulted in an amendment to the MAC protocol released in 2012. The amendment was released defining five new MAC behaviour modes, among which we would point out the TSCH MAC.

However, the Internet Engineering Task Force (IETF) created a new Working Group (WG) denominated IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH), this group is motivated by the necessity to integrate Internet Protocol (IP) with industrial communication technologies. The WG efforts are to build an architecture based on open standards with a focus on best practices. The architecture tries to standardise the missing components to provide the IETF/IP standards of industrial performance. As a result, the architecture is a group of specifications that define the IPv6 control plane to manage and orchestrate a TSCH network [2,3].

The TSCH MAC enables nodes to communicate through a 10ms structure defined as a timeslot; the timeslot provides transmission and acknowledgement in its duration; the TSCH organises these timeslots into a group of repetitive structures over time named slot-frame. During every slot-frame cycle, the channel number changes according to the channel hopping schema defined by the standard. After the RFC 7554 [4] release, the 6TiSCH rises as an effort for enhancing the communication over IEEE 802.15.4. After that, the 6TiSCH Operation Sublayer (6top) Protocol (6P) was specified by RFC 8480 [5] and RFC 9033 [6] was released with Minimal Scheduling Function (MSF) specification.

As cited before, scheduling plays an essential role in IIoT networking, and the applications should rely on a schedule that avoids simultaneously interfering transmissions. In the same way, developing a scheduling function is challenging. The scheduling function allocates or deallocates cells between neighbouring nodes besides the previously cited challengers (balancing energy, bandwidth and latency). Still, cell assignments should consider the balance between dedicated and shared links allocation. Thus, this work focuses on the TSCH retransmission scheme as a metric source for improving the cell assignments.

3. Related Work

The TSCH schedule was not defined by the standard, but the informational RFC 7554 [4] mentions issues and goals that have been utilised as a guideline for investigation and advancements. Since then, the focus has been put on scheduling techniques. Therefore, many efforts have been made to elaborate the ideal TSCH SF. On top of that, an industry application demands from TSCH SF a reliable communication balancing among energy, bandwidth and latency. Hence, the application requirements define the priority of the three cited groups. E.g., higher bandwidth needs to compromise energy efficiency due to the need for more communication cells. On the other hand, spending less energy to increase the battery-based network survivability requires a long slot-frame length, impacting latency and bandwidth.

Concerning TSCH SF classification, even though the RFC 9030 [7] has defined four scheduling ways (Static, Neighbor-to-Neighbor, Centralised and Hop-by-Hop), the TSCH schedules have been classified in the literature as centralised, distributed and autonomous. Each TSCH SF method influences the network formation time, traffic capacity, energy consumption, and overhead.

As cited by Duquennoy et al. [8] the slot-frame length affects the latency, the traffic capacity and the energy. The major challenge for a TSCH schedule designer is balancing those three factors providing the application with a healthy network. Therefore, the slot-frame size has a significant influence on the TSCH network. The work by Kurunathan et al. [9] performed a comparative study among IEEE 802.15.4e standards, and the authors assessed the work through latency (time delay), throughput and nodes number. The work by Kwon et al. [10] analysed the End-to-End delay and cited the impact of long slot-frame on the network formation. In addition, Sourailidis et al. [11] note that the network stability relies on the interval of the DODAG Information Object (DIO) messages, as unstable networks have more additional DIO messages.

Timing requirements are vital in the manufacturing industry. For example, as discussed by Haerick and Gupta [12] process automation industries require 100ms cycle duration, factory automation industries are more restricted and require a 10ms cycle duration. The work by Kwon et al. [10] analysed the impact of slot-frame length over the delay.

Therefore, the application, the slot-frame length, the network issues (formation, stability and overhead) and energy concerns are important factors that we will use as the base for analysis. In addition, each possible disturbance around those factors might lead to derangement those impacts the network performance. Our consideration of a breakpoint can be defined as a stage or critical point when an application loses control over a situation and can no longer deal with its problems. Regardless, our remark concerning the tipping point is a moment when one or more metrics have started to decrease from their optimal state or degrade. Still, resiliency mechanisms usually mitigate their effects. Therefore, we will perform our analysis over slot-frame and data rate for locating points that have led to the previously cited network issues. E.g., is the TSCH Minimal Schedule capable of assuring the network stability over a longer slot-frame length and a higher application data rate?

4. Experimental Setup

Our empirical study uses the Contiki-NG ecosystem composed of a wide-adopted O.S and a simulator. Our objective is to analyse metrics disturbances such as latency, PDR and retransmissions by pushing the Minimal TSCH scheduling to reach a stress point perceived by metrics decay.

The Contiki was presented in 2004 by Dunkels et al. [13], and since then, Contiki has evolved and become one of the references regarding Operational Systems. That OS version for embedded systems provides a 6LoWPAN stack with 802.15.4-like radio transceivers. The developers focused on recent IoT platforms, e.g. ARM Cortex M3 and other 32-bit MCUs.

We planned four scenarios (Scenario 1 with two nodes, Scenario 2 with four nodes, Scenario 3 with nine nodes and Scenario 4 with sixteen nodes), each one with one border Router included. Those scenarios have been arranged as fixed nodes in a grid (Scenario 1 is 2 Nodes, Scenario 2 is 2x2Grid, Scenario 3 is 3x3Grid, and Scenario 4 is 4x4Grid). Figure 1 presents the scenarios arrangement. We developed a system using Python to run the scenarios and extract the metrics [14]. The scenarios have been arranged by slot-frame (SF) length and Application PPM. The system generates a new random seed for each scenario, and Cooja generates a log file. After the run, the log is processed, and the data is persisted in a database for metrics extraction.

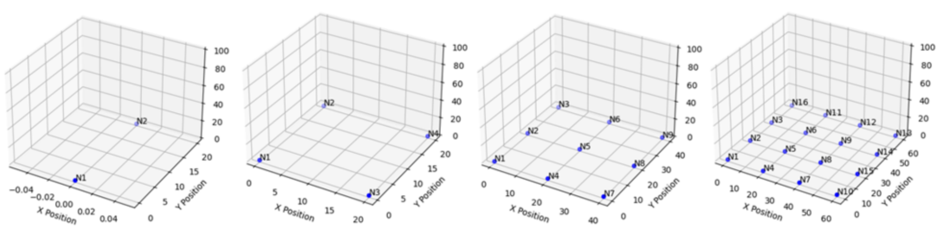


Figure 1. Experiments scenarios - 2 nodes, 2x2, 3x3 and 4x4 grids

Our arrangements are made for simulates a regular application in which the traffic is upstream (from nodes to sink), and a facility might create a mesh network by deploying devices over the RPL. For each experiment, we set the slot-frame length to 5, 7 and 11. Furthermore, the simulator was configured for generating data in intervals of 5, 4, 3, 2 and 1 second (respectively, rates of 12, 15, 20, 30 and 60 PPM). The nodes are spaced by 20 meters, and each one has a transmission range of 25 meters and an interference range of 30 meters. That node spacing allows managing the interference due to knowing that

Table 1. Simulation Parameters

Parameters	Value
Number of nodes	2, 4, 9 and 16
Slot-frame length	5, 7 and 11
Application PPM	0, 12, 15, 20, 30 and 60
Timeslot duration (ms)	10
Traffic pattern	upstream
Warm-up Time (s)	120
Simulation Time (s)	3600
Repetitions	5
Total Runs	360
Routing	RPL Lite
TSCH EB Period	16 seconds

the maximum number of neighbour nodes is four. We present the simulation parameters in Table 1.

For each scenario, an application generates UDP data packets in a defined period and sends them upstream to the sink (After a warm-up time). Even though, for assessing the network formation and stability, we performed a scenario run without any application data (zero Packet per Minute (PPM)) to evaluate the network formation and stability). As the Minimal TSCH scheduling attribute allocates one communication slot, we increased the packet generation rate in order to stress the network.

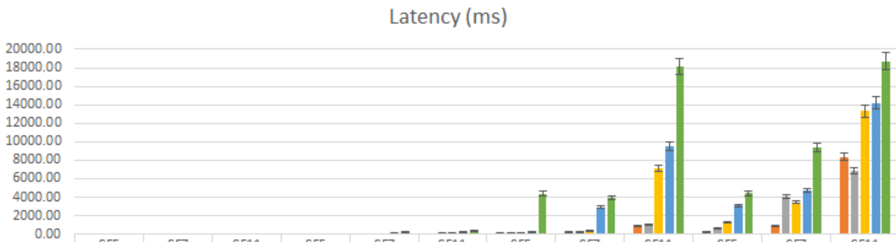
5. Identifying Tipping Points

In this section, we present our impressions and analysis of the experiments. We would like to start performing analysis over our two baselines: First, Scenario 1 with two nodes, which is the shorter possible set. Those baselines allow us to access a more concise communication scheme between two nodes and assess the RPL characteristics (e.g. network formation by the number of nodes, its depth and stability). Second, a run without application data was performed for each Scenario.

5.1. Application Layer

Scenario 1 shows the impact of slot frame length; with a standard time slot duration of 10 ms, the slot frame size of 5 results in a slot frame period of 50 ms. The measured simulated value near 30ms is expected; the data is enqueued and waiting for sending at the node's TSCH slot transmitting moment. The latency is reduced if the scheduling function allocates more cells. Figure 2 shows the measured latency.

As expected, a higher packet sending rate impacts the latency metric, and the number of nodes leads to increased latency values. However, due to the minimal scheduling, which allocates one communication cell, the impact of one cell over the latency is notorious. The shorter slot-frame length ensures a lower latency due to the fast slot-frame repetition. We would cite the work by Kurunathan et al. [15] which notes the TSCH MAC delay bound and impact of the average arrival rate.



	SF5	SF7	SF11	SF5	SF7	SF11	SF5	SF7	SF11	SF5	SF7	SF11
	2 Nodes			2x2 Grid			3x3Grid			4x4Grid		
12 PPM	31.18	43.53	61.17	31.78	45.32	73.13	125.62	221.23	891.40	327.07	887.70	8355.51
15 PPM	30.32	42.96	67.91	60.49	46.75	76.86	149.43	291.07	1081.46	600.46	4070.62	6840.61
20 PPM	30.63	43.48	64.59	33.17	47.65	92.77	130.09	400.50	7074.99	1279.78	3463.61	13325.87
30 PPM	30.28	41.75	63.09	31.64	134.74	205.45	303.50	2911.78	9524.26	3075.46	4716.32	14217.01
60 PPM	30.22	39.93	58.38	56.99	204.38	352.69	4385.86	3876.06	18119.19	4411.87	9347.04	18670.36

Figure 2. Application Metrics

After that measure, we performed an analysis of the PDR. As previously cited in Section 4, our PDR measurements are performed over that procedure, and for each generated application data, the keep the generation record and when it reached the sink. So, our Application PDR calculation is the sum of received packets (Prx) divided by sum of transmitted packets (Ptx). Indeed, the application level PDR plays a vital role for applications. If a piece of information is generated, it should be delivered. Figure 3 shows the values grouped by experiment and for each slot-frame length.

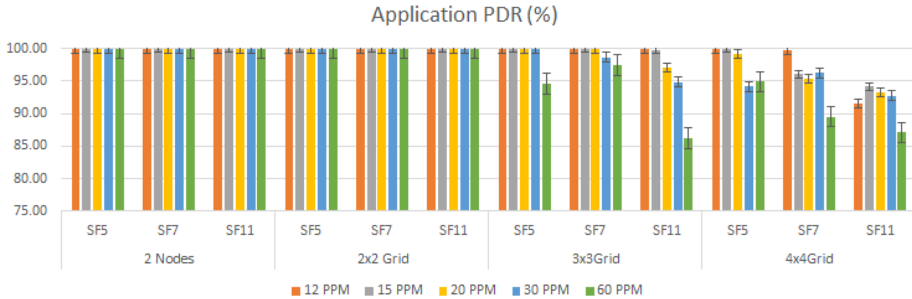


Figure 3. Application PDR

5.2. Link Layer Metrics

TSCH MAC was created to be used for industrial applications, and it is known for its reliability. We can observe a common network behaviour. Nevertheless, good metric values such as PDR close to 100% may hide relevant indicators for networking stability. The application PDR degrades with a higher sending rate, and a minor slot-frame length a better PDR. Overall, TSCH MAC plays its role, providing organisation and reliability. Our analysis focuses on the link level and embraces the MAC level frames, all frames

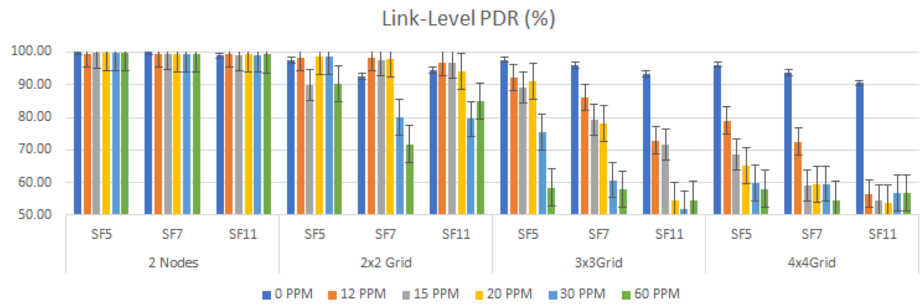


Figure 4. Link-level PDR

sent, and their acknowledgement. The TSCH standard provides a retransmission scheme that contributes to network reliability. Figure 4 shows the PDR at link-level.

The TSCH retransmission backoff algorithm accomplishes its duty working at the link level, contributing to better application PDR. We would remark that even with a link-level PDR of 71.80% (2x2 Scenario, slot-frame length of 7 and rate of 60 PPM), the application PDR is still close to 100%. In that case, the TSCH countermeasures are enough for maintaining the PDR at 100%, but there is a breaking point at which those countermeasures are not sufficient. Looking at Figure 4, the link-level PDR degrades with higher sending rates.

Table 2. Summary of Symbols

Symbols	Description
Rt	Retransmission
Rt_{Eff}	Retransmission Effectivness
Rt_{Frames}	Retransmitted Frames
WUp_{Time}	WarmUp Time
Sim_{Time}	Simulation Duration Time
$ExpGen_{Pkt}$	Expected Generated Packet
$Send_{Int}$	Send Interval (s)

Although retransmissions are a normal part of wireless communication, in the case of creating a new schedule or at the planning device deployment phase, a metric like that might assist in measuring a network overstrain or the usage of too much energy. Equation 1 illustrates the proposed metric Retransmission Effectiveness Rt_{Eff}. In the case of a value near one, the retransmissions demand fewer network resources. That metric can analyse the impact of interference over the network and assess the necessity of nodes relocation or a frequency spectrum analysis.

$$Rt_{Eff} = \sum Rt_{Frames} / \sum Rt \tag{1}$$

From our TSCH model, we extracted the frames retransmitted and received an acknowledgement. In other words, we selected frames assisted by the TSCH retransmission

Table 3. Number of packets generated by the application (estimate)

Scenario (# Nodes)	1 (2)					2 (4)					3 (9)					4 (16)				
Packet Rate (PPM)	12	15	20	30	60	12	15	20	30	60	12	15	20	30	60	12	15	20	30	60
Estimated Packets	696	870	1160	1740	3480	2088	2610	3480	5220	10440	5568	6960	9280	13920	27840	10440	13050	17400	26100	52200

backoff algorithm that was transmitted. Despite that, the Figure 5 represents an analysis of TSCH retransmission effectiveness when looking into retransmission.

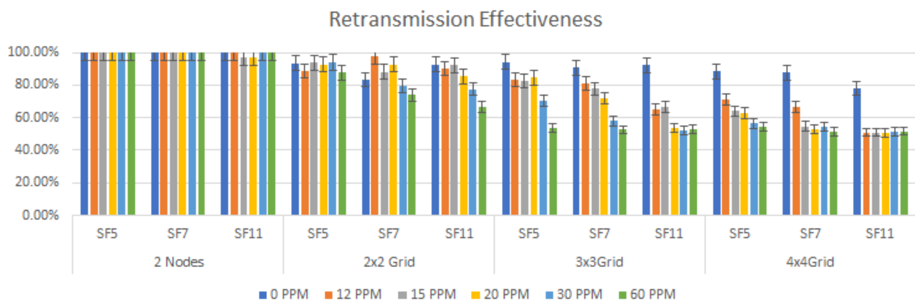


Figure 5. Retransmission Effectiveness

5.3. *Overall Assessment*

Other relevant data gathered from our experiments were the relation between the application expected to generate data and the real generated data. As described in Table 1, each experiment has a duration (Sim_{Time}) of 3600 seconds and a warm-up (WUp_{Time}) time of 120 seconds. At the simulation end, the PDR is calculated by the generated packets over the received packets.

When the queue is complete, or disconnections occur, the application holds the information generation until the network communication has been restored and the application data can be enqueued for delivery. Equation 2 shows how we estimated the number of packets generated by the application. Table 3 shows the amount of the expected packet for each simulation scenario. We would like to cite that by definition, the PDR uses the generated packets, so the misstep is higher when using the expected packets.

$$ExpGen_{Pkt} = \frac{Sim_{Time} - WUp_{Time}}{Send_{Int}} * \sum Nodes - 1 \tag{2}$$

The relation between the expected ($ExpGen_{Pkt}$) and the total, or real, generated packages is an interesting topic due to looking for causes to avoid that effect over our applications. The Figure 6 shows the simulation generated packages. We would like to show that when we performed a comparison between that figure and Table 3, we can notice that the generated packets have been impacted by the slot-frame size and the data sending rate. At this point, the TSCH schedule has to assess the necessity for allocating more cells between nodes, which impacts the energy consumption.

An important clue might be in the link-level retransmission. In that case, the number impacts network stability that we can remark the link-level node synchronization as pre-

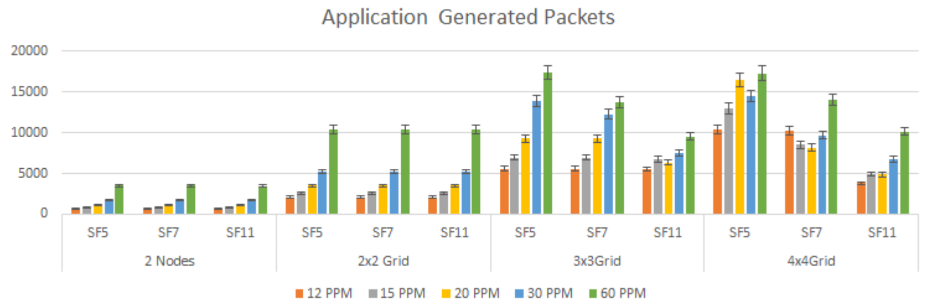


Figure 6. Application Generated Packets

dicted in Section 6.5.4.2 of IEEE 802.15.4 standard [1]. In addition, the impact over high depth mesh networks may affect the RPL Objective Function metrics and change the trickle timer forcing RPL message overhead, e.g. rising the amount of DIO and DODAG Information Solicitation (DIS) messages has been discussed by Sourailidis et al. [11]. In addition, the lack of DAO-ACK messages causes the nodes to generate new Destination Advertisement Object (DAO) messages.

We would like to point out that application generated packets have been used for calculating PDR, so the application must create data for delivery. If the node is disconnected or the queue is complete, the generated data is enqueued for further processing. But we are dealing with constrained devices. In case of a full queue, the O.S. is responsible for notifying the application to hang the data generation.

6. Conclusions

This paper presented an experimental simulation analysis over the TSCH MAC that identified abnormal networking behaviour. We viewed the link-level PDR, and the retransmission schema revealed substantial clues about the network. TSCH scheduling developers might transversely use those two factors; their effects impact the application and affect network stability and energy consumption. Even with a PDR close to 100%, the link-level network provides pieces of evidence that the performance can be improved. The lower value retransmission efficiency metric indicates an abnormal behaviour and can be used by scheduling functions for allocating more cells. In addition, The TSCH border router can act as an endpoint for providing information as a service about the industrial network for allowing vertical technology integration.

To wrap up, the LLNs is a mixture of software, networking and embedded engineering, and the software part creates its data for network sending. The IETF already cited several constrained devices issues [16]. Those limitations have been reflected in the hardware and software. However, the node's point of view is an essential source of networking behaviour and metrics that distributed TSCH SF can employ to anticipate issues for maintaining network healthiness.

The following steps are to generate an algorithm that uses the node level identified metrics as input for anticipating disturbances and assessing its performance under industrial application parameters.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.