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Impact of Guard Time Length on IEEE 802.15.4e TSCH Energy Consumption

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***Abstract*—The IEEE 802.15.4-2015 standard defines a number of Medium Access Control (MAC) layer protocols for low-power wireless communications in the IoT. Originally defined in the IEEE 802.15.4e amendment, TSCH (Time Slotted Channel Hopping) is among the proposed mechanisms. TSCH is a scheme aiming to guarantee network reliability by keeping nodes time-synchronised at the MAC layer. In order to ensure successful communication between a sender and a receiver, the latter starts listening shortly before the expected time of a MAC layer frame's arrival. The offset between the time a node starts listening and the estimated time of frame arrival is called guard time and it aims to reduce the probability of missed frames due to clock drift. In this poster, we investigate the effect of the guard time duration on energy consumption. We identify that, when using the 6tisch minimal schedule, the most significant cause of energy consumption is idle listening during guard time. Therefore, the energy-efficiency of TSCH can be significantly improved by guard time optimisation. Our performance evaluation results, conducted using the Contiki operating system, show that an efficient configuration of guard time may reduce energy consumption by up to 30%, without compromising network reliability.**

***Index Terms*—Internet of Things, IEEE 802.15.4-2015, TSCH, Synchronisation, Performance Evaluation, Energy Consumption.**

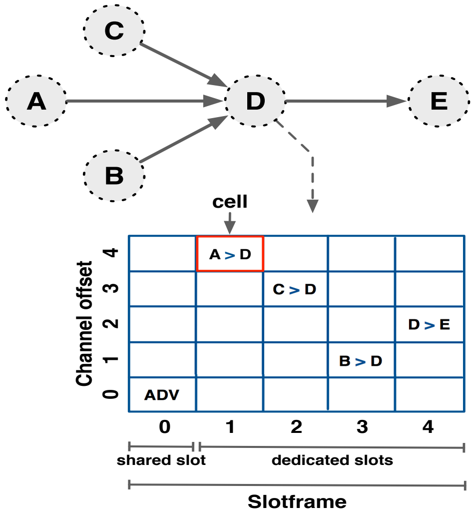
I. INTRODUCTION

In 2016 the IEEE 802.15.4-2015 standard [1] was published to offer a certain quality of service for deterministic industrial-type applications. Among the operating modes defined in this standard, Time-Slotted Channel Hopping (TSCH) is a medium access scheme for lower-power and reliable networking solutions in Low-Power Lossy Networks (LLNs). Indeed, it is adopted by major industrial-oriented standards such as WirelessHART and ISA100.11a.

In Fig. 1, a TSCH schedule is illustrated. At its core, TSCH implements a channel hopping scheme to defeat noise and interference, and consequently to enable high reliability [2], while it employs time synchronisation to achieve low-power operation. More specifically, TSCH presents a deterministic scheduling approach where each cell consists a pair of timeslot and `channel offset` for collision avoidance purposes. Each channel offset is translated into a frequency as follows:

$$frequency = F\{(ASN + channelOffset)\ \%\ nFreq\} \tag{1}$$

where ASN is the Absolute Sequence Number, while $nFreq$ is the number of available frequencies (*e.g.*, 16 when using IEEE 802.15.4-compliant radios at 2.4 GHz with all channels in use) [3].



Channel offset	0	1	2	3	4
4		A > D			
3			C > D		
2					D > E
1				B > D	
0	ADV				

Fig. 1: An example of a TSCH scheduling for node D. $A > D$ stands for "node A transmits to node D", while ADV cells are used for broadcast and advertising control packets (*e.g.*, DIO).

To account for loss of synchronisation, a TSCH receiver maintains its radio on receiving mode for an extended period of time, named `Guard Time`. In this work, we investigate the effect of guard time duration on network performance. Through an analytical model and simulations, we show that most of the energy consumed is wasted by idle listening, due to the guard time. Hence, we demonstrate that fine-tuning guard time significantly improves the energy-efficiency of TSCH without compromising its reliability.

II. OVERVIEW

TSCH relies on scheduling, therefore nodes must remain time synchronised throughout the network deployment's lifetime. To this end, nodes periodically exchange Enhanced Beacon (EB) packets. Synchronisation does not need explicit EB exchange, data packets may also be utilised to compute clock drifts [4]. Typically, an EB contains time and channel frequency information, as well as information about the initial link and slotframe for new nodes to join the network. New nodes may join a TSCH network by "hearing" an EB frame from another node.

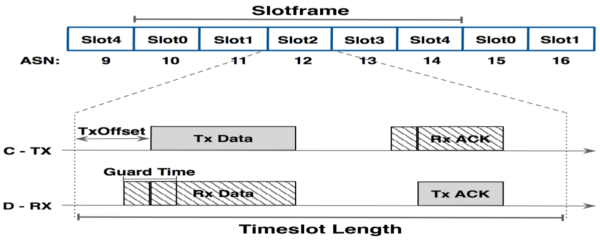


Fig. 2: A typical TSCH timeslot template for a transmitter (top) and receiver node (bottom): node C, transmits its data packet after `TxOffset`, while the receiver D, uses a `Guard Time` to avoid missing the incoming packet by turning its radio ON slightly before the packet arrival.

A. Scheduling in TSCH Network

Figure 2 illustrates a typical TSCH-based communication between two nodes. In TSCH networks, time is divided into timeslots of equal length, large enough to transmit a frame and to receive an acknowledgement, while a set of timeslots construct a slotframe. At each timeslot, a node may transmit or receive a frame, or it may turn its radio OFF for saving energy. Each timeslot can be either dedicated (contention-free) or shared (contention-based approach). Finally, each timeslot is labelled with `ASN`, a variable which counts the number of timeslots since the network was established.

B. Clock Drift and Guard Time

A node transmits a data packet at the beginning of each timeslot, exactly after the `TxOffset`. TSCH incorporates a `Guard Time` to account for loss of synchronisation. To account for both positive and negative clock drift, the receiver wakes up before the expected end of the `TxOffset` and keeps the radio on for τ seconds or until a frame preamble is received. The Guard Time τ is equally spaced around the end of the `TxOffset`. Thus, for a certain guard time, τ, the maximum synchronisation error, ϵ_τ, that can be tolerated is:

$$\epsilon_\tau = \frac{\tau}{2} - \tau_p \ , \tag{2}$$

where τ_p is the time required for the reception of the frame preamble. Let us consider the use of clocks with an error of $\pm e_f$. The synchronisation error accumulates over time. The worst case scenario for synchronisation is right before a synchronisation event (*e.g.*, EB frame), when the error is:

$$\epsilon_T = T\Big(\frac{1}{1-e_f} - \frac{1}{1+e_f}\Big) \ , \tag{3}$$

where T is the period of synchronisation events. By equating (2) and (3), we calculate a minimum Guard Time required to achieve zero packet losses due to loss of synchronisation (τ_m):

$$\tau_m = 2T\Big(\frac{1}{1-e_f} - \frac{1}{1+e_f}\Big) + 2\tau_p \ . \tag{4}$$

It can be observed that in the ideal case where the clock error is $e_f = 0$ ppm, the minimum acceptable Guard Time is $\tau_m = 2\tau_p$. Fig. 3 plots minimum Guard Time for various clock drifts ($\tau_p = 160$ us, $T = 3.5$ s) demonstrating a linear behaviour.

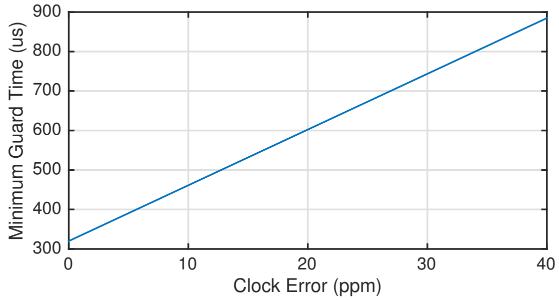


Fig. 3: Minimum guard time for operation without packet loss due to loss of synchronisation.

Topology parameters	**Value**
Topology	Line & Star
Number of nodes	2 (Line), 9 (Star)
Number of sources	1 (Line), 8 (Star)
Node spacing	20 m (Line), 16 m (Star)
Simulation parameters	**Value**
Duration	60 $minutes$
Traffic Pattern	0.6 $pkt/60\ sec$
Routing model	RPL [5]
Number of hops	1-hop
TSCH parameters	**Value**
MAC model	TSCH
EB frequency	$17/min$
Slotframe length	7
Timeslot length	15 ms
Guard Time	1200 us - 3200 us
Clock Drift	0 ppm
Hardware parameters	**Value**
Antenna model	CC2420
Radio propagation	2.4 GHz

TABLE I: Simulation setup.

III. PERFORMANCE EVALUATION

In order to assess the impact of Guard Time in the performance of TSCH, we ran a set of experiments using COOJA, the network simulator distributed as part of the Contiki Operating System[1]. In our experiments we emulated Z1 motes. We conducted a large number of simulations under various Guard Time configurations, ranging between 1200 us and 3200 us. We increase the Guard Time length by 200 us, while keeping the default values for the rest of parameters such as EB or data packet transmission frequency.

A. Setup

We deployed two scenarios; the first scenario is low contention in which two nodes, leaf transmitter and sink receiver, respectively, are positioned at a distance of 20 m. The second scenario (high contention) consists of 9 nodes, including the sink station, in a star topology. All 8 nodes are symmetrically distributed around the sink in an area of 20×20 m, and 1-hop communications take place among the sensor nodes and the sink. By employing the RPL protocol [5], each node is able to construct a Directed Acyclic Graph. Furthermore, we set our network to run with the Unit Disk Graph Medium (UDGM) for the sake of clarity. Finally, each simulation lasted 60 min. The details of the simulation setup are presented in Table I.

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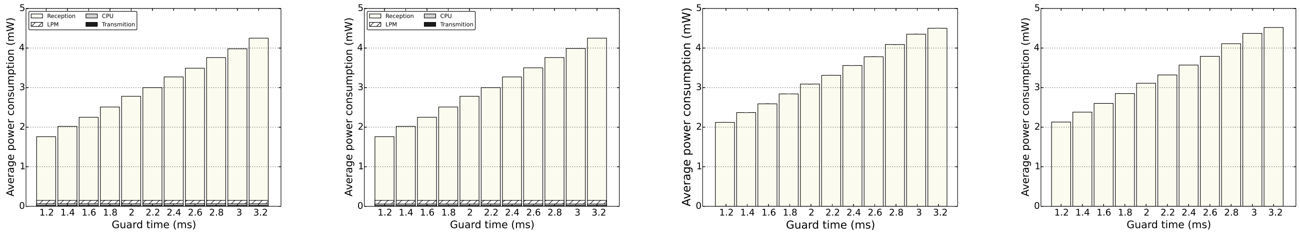
[1] Contiki OS - www.contiki-os.org



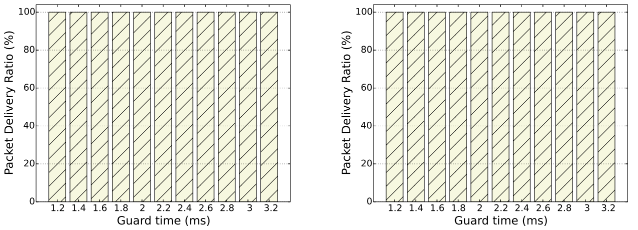
(a) Average power consumption for the single transmitter (leaf) node, in line topology.

(b) Average power consumption for the receiver (sink) node, in line topology.

(c) Average power consumption for the 8 transmitter (leaf) nodes, in star topology.

(d) Average power consumption for the receiver (sink) node, in star topology.

Fig. 4: A thorough power consumption analysis of the TSCH scheme both under the line and star topologies.



(a) PDR for low contention scenario (*i.e.*, line).

(b) PDR for high contention scenario (*i.e.*, star).

Fig. 5: Network reliability for line and star topologies.

IC	**Notes**	**Current Consumption**
CC2420	TX Mode @ 0 dBm	17.4 mA
	RX Mode	18.8 mA
MSP430f2617	Active Mode @ 8 MHz	4 mA
	Low-power Mode	0.5 uA

TABLE II: Approximate Current consumption of Z1 mote.

B. Simulation Results

The results hereinafter show the performance of the studied schemes in terms of reliability and energy consumption under line and star topologies. Note that in this set of simulations, the clock drift was configured at 0 ppm for the sake of clarity.

1) Network Reliability: For each scheme, we calculate Packet Delivery Ratio (PDR), in which packet loss is calculated as $1 - PDR$, and thus, packet loss 0% is the equivalent of 100% PDR. Our simulation results show that the evaluated Guard Time lengths, ranging from 1200 us to 3200 us, do not impact negatively the network reliability, see Figure 5 both for the line and star topologies. Indeed, in both scenarios, low and high contention, the PDR is kept at 100%.

2) Energy Consumption: To evaluate the energy consumption of each node in the network, we employed the Contiki's `Powertrace` and `Energest` power profile to estimate power consumption. This module monitors and logs in real-time the radio and Central Processing Unit (CPU) usage by saving the duration spent in each state (*i.e.*, transmitting, receiving, awaken, sleeping). Table II provides the current consumption levels at each of these states for Z1 mote[2] (3 V).

Here we present results with Guard Time configured between 1200 us and 3200 us. Our performance evaluation results show that Guard Time duration critically impacts energy consumption. More specifically, by reducing Guard Time length (*i.e.*, from 2200 us, default configuration of Contiki's TSCH implementation, to 1200 us), we can reduce average energy consumption per node per second by more than 30% (Fig. 4), without compromising network reliability. It is worth mentioning that the previously described trend is similar both for line and star topologies. Indeed, both leaf nodes and the sink node in both scenarios present similar behaviour.

IV. CONCLUSION

In this work, we investigated the behaviour of TSCH under different Guard Time configurations. More specifically, we analysed the the impact of the Guard Time duration to the network reliability and energy consumption. Our thorough performance evaluation results demonstrate that the Guard Time length has a straightforward impact on energy dissemination. It is shown that fine-tuning the Guard Time can result into significant savings in energy consumption without compromising the reliability of the network.

Our ongoing work consists of further investigating this lead under various realistic clock drift configurations (*e.g.*, 20 ppm, 30 ppm). Furthermore, we plan to perform a set of experimental studies over the FIT IoT-LAB testbed [6].

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