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Guard Time Optimisation and Adaptation for Energy Efficient Multi-hop TSCH Networks

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Abstract—In the IEEE 802.15.4-2015 standard, Time Slotted Channel Hopping (TSCH) aims to guarantee high-level network reliability by keeping nodes time-synchronised. 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 paper, we investigate the impact of the guard time on network performance. We identify that, when using the 6tisch minimal schedule, the most significant cause of energy consumption is idle listening during guard time. Therefore, we first perform mathematical modelling on a TSCH link to identify the guard time that maximises the energy-efficiency of the TSCH network in single hop topology. We then continue in multi-hop network, where we empirically adapt the guard time locally at each node depending its distance, in terms of hops, from the sink. Our performance evaluation results, conducted using the Contiki OS, demonstrate that the proposed decentralised guard time adaptation can reduce the energy consumption by up to 40%, without compromising network reliability.

Index Terms—Internet of Things, IEEE 802.15.4-2015, TSCH, Synchronisation, Guard Time, 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 Control (MAC) protocol for low-power and reliable networking solutions in Low-Power Lossy Networks (LLNs). Although there is a vast literature of unstandardised MAC protocols that are optimised for different scenarios [2], [3], the standardised TSCH offers interoperability between IoT devices. Indeed, at its core, TSCH implements a channel hopping scheme to avoid interference, and consequently to enable high reliability [4], while it employs time synchronisation to achieve low-power operation, see Fig. 1. 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:

\[ \text{frequency} = F((ASN + \text{channelOffset}) \mod nFreq), \]

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) [5].

Continuously re-synchronizing the network may prevent the loss of synchronisation. Thus, to account for loss of synchronisation, under TSCH scheme, a receiver maintains its radio on receiving mode for an extended period of time, named Guard Time. More specifically, the receiver turns its radio on slightly before the scheduled transmission to guarantee the successful packet reception, see Fig. 2. In [6], [7], we highlighted the effect of guard time on single hop network. Indeed, we identified that, when employing the 6tisch minimal schedule in point to point link, most of the energy consumed is wasted in idle listening, due to the guard time.
In this paper, we further investigate the importance of guard
time in a multi-hop network. In multi-hop TSCH networks,
the guard time is typically configured statically and, therefore,
needs to account for the worst case scenario, not only in terms
of clock drift, but also in terms of network size (see, for ex-
ample, the Contiki OS\textsuperscript{1} \cite{8} and OpenWSN \cite{9} implementations
of the TSCH protocol). Instead, in this work, we demonstrate that
TSCH could significantly improve their energy-efficiency by
adapting their guard time in an independent and decentralised
manner. To this aim, we first study the optimal guard time
values as a function of the clock drift, using both an ana-
lytical model and simulations. We then present our thorough
empirical study for decentralised guard time adaptation for
energy-efficient multi-hop TSCH networks. Our performance
evaluation results on top of COOJA (a simulator for Contiki
OS), demonstrate that fine-tuning the guard time on each node
can significantly improve the energy efficiency of a TSCH
multi-hop network without compromising its reliability.

The remainder of our paper is organised as follows. Sec-
tion II provides an overview of the TSCH mechanics and
summarises the related work. We then detail our problem for-
mulation and we present guard time optimisations in Section II
proposing a mechanics for adaptive guard time adaptation
in multi-hop TSCH networks. We implement our solutions on
top of the Contiki OS and then demonstrate their performance
in Section IV, focusing on the following metrics: energy
consumption and reliability. Finally, Section V provides the
concluding remarks and future perspectives for our work.

II. TSCH MECHANICS AND RELATED WORK

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, ASN is initialised
to 0. Fig. 2 illustrates a typical TSCH-based communication
between two nodes.

Since the clock of each node drifts relative to its neigh-
bours\textsuperscript{1}, nodes periodically exchange Enhanced Beacon (EB)
packets to periodically re-synchronise, and thus, to remain
time-synchronised throughout the deployment’s lifetime. Syn-
chronisation does not need explicit EB exchange, data packets
may also be utilised to compute clock drifts \cite{10}. Typically,
an EB contains the current ASN 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. In TSCH, there are two ways for two nodes to
re-synchronise, frame-based and acknowledgment-based syn-
chronisation, respectively \cite{11}. During the re-synchronisation

\textsuperscript{1}Contiki OS - www.contiki-os.org

![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.](image-url)
III. Guard Time Adaptation

In this paper, we propose the decentralised adaptation of the guard time for reducing the energy-consumption of a TSCH network. To this end, we begin with the analysis of a TSCH link, demonstrating that there is a guard time that maximises its energy-efficiency.

A. Guard Time Optimisation in a TSCH link

A node transmits a data packet at the beginning of each timeslot, exactly after the TxOffset. TSCH incorporates a Guard Time to account for clock drift. Indeed, 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 $\tau$ seconds or until a frame preamble is received. The guard time $\tau$ is equally spaced around the end of the TxOffset. Thus, for a certain guard time, $\tau$, the maximum synchronisation error, $\epsilon_T$, that can be tolerated is:

$$\epsilon_T = \frac{\tau}{2} - \tau_p,$$

where $\tau_p$ is the time required for the reception of the frame preamble. Let us consider the use of clocks with an error of $\pm \epsilon_f$. 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:

$$\epsilon_T = T \left( \frac{1}{1 - \epsilon_f} - \frac{1}{1 + \epsilon_f} \right),$$

where $T$ is the period of synchronisation events. By equating (2) and (3), we calculate a minimum guard time required to achieve zero packet loss due to loss of synchronisation ($\tau_m$):

$$\tau_m = 2T \left( \frac{1}{1 - \epsilon_f} - \frac{1}{1 + \epsilon_f} \right) + 2\tau_p.$$

Observe that in the ideal case where the clock error is $\epsilon_f = 0$ ppm, the minimum acceptable guard time is $\tau_m = 2\tau_p$.

The minimum guard time, given by (4), constitutes the optimum value for achieving the highest energy-efficiency in the TSCH link. Indeed, longer guard times would lead in unnecessary time spent in idle listening, whilst shorter guard time would lead into packet loss due to loss of synchronisation, i.e., energy wasted for the transmission of packets that do not reach their destination.

B. Guard Time Adaptation in Multi-Hop TSCH Networks

In a multi-hop context, the clock drift increases with the width of the network. As a result, a longer guard time is required to maintain synchronisation. Similarly to a single-hop link, there is a network-wide optimum guard time configuration, that is the minimum guard time that keeps the network synchronised. Yet, as we show in the simulations that follow, the network-wide optimum guard time, is not necessarily the optimum value for each individual node. Hence, the energy consumption of the TSCH network can be further improved by adapting the guard time in a decentralised manner.

<table>
<thead>
<tr>
<th>Simulation Setup.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology</td>
<td>1-hop</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>1-hop: 2 (a transmitter and receiver)</td>
</tr>
<tr>
<td>Node spacing</td>
<td>1-hop: 20 m in line</td>
</tr>
<tr>
<td>TSCM</td>
<td>1-hop: 20 m in line</td>
</tr>
<tr>
<td>Duration</td>
<td>60 minutes</td>
</tr>
<tr>
<td>Traffic Pattern</td>
<td>1 pkt/60 sec</td>
</tr>
<tr>
<td>Data packet size</td>
<td>102 bytes (77 bytes payload)</td>
</tr>
<tr>
<td>Routing model</td>
<td>RPL [14]</td>
</tr>
<tr>
<td>MAC model</td>
<td>TSCH (6TiSCH minimal schedule)</td>
</tr>
</tbody>
</table>

We follow a heuristic approach to investigate the network behaviour under various guard times. As shown in the simulations that follow, our exhausted study demonstrates that the optimum guard time essentially depends on the number of hops away from the sink. Hence, the performance of the TSCH network can be improved by adapting each individual node’s guard time to its hop-distance from the sink node. To this aim, we begin by empirically identifying and constructing a look-up table of the minimum guard times that maintain synchronisation in various hop-distances from the sink. In runtime, each node then adapts its guard time using the look-up table and information obtained from the routing protocol regarding its hop-distance to the sink.

IV. Performance Evaluation

In order to evaluate the impact of guard time in the energy consumption of TSCH network and the benefits of guard time adaptation, we conducted a large set of simulations by employing COOJA, the network simulator distributed as part of the Contiki OS, and emulating the Z1 motes. Hereafter, we present a thorough performance evaluation for both statically configured and our adaptive scheme. The details of the simulation setup are presented in Table I.

A. Single-hop TSCH Links:

1) Setup: We first focused on single-hop TSCH links that employ the 6tisch minimum schedule. We studied the behaviour of TSCH links under various realistic clock drifts (i.e., $\pm 10$, $\pm 20$, $\pm 30$ and $\pm 40$ ppm). Indeed, we considered the worst case scenario TSCH link, thus, we configured the transmitter node to the maximum positive clock drift and the receiver at the maximum negative drift. For instance, in the case of the $\pm 20$ ppm configuration, we set the transmitter node at $+20$ ppm and the receiver at $-20$ ppm, resulting to
a relative drift of 40 ppm. Note that the clock drifts are constant throughout each simulation. Furthermore, we conducted simulations under various guard time (e.g., 400, 600, 800 µs) configurations, while keeping the default values for the rest of the parameters such as EB or data packet transmission frequency.

We have conducted a scenario with two nodes, leaf transmitter and sink receiver, respectively, positioned at a distance of 20 m. We choose the data packet size to be equal to 102 bytes that corresponds to all necessary information for MAC, routing and application operations. Furthermore, we set our network to run with the Unit Disk Graph Medium (UDGM) for the sake of clarity, where each node emits at 0 dBm transmission power. Finally, each simulation lasted 60 min.

In [6], we studied the impact of the idle listening during guard time on energy consumption. Hereinafter, we demonstrate the guard time optimisation that we performed, as well as the gains of the fine-tuning TSCH configurations in terms of reliability, goodput and energy consumption in single-hop communication.

2) **Guard Time:** We first investigate the minimum guard time that guarantees 100% Packet Delivery Ratio (PDR), under different clock drift values (i.e., 0, ±10, ±20, ±30 and ±40 ppm) using both the analytical model, presented in the previous Section, and a simulation campaign. Note that packet loss is calculated as 1 − PDR, and thus, packet loss 0% is the equivalent of 100% PDR. As can be observed from Fig. 3a, our model (i.e., Eq. (4)) approximates a linear behaviour between the guard time and clock error, when \( \tau_0 = 129 \mu \text{s} \) and \( T = 1.71 \text{s} \). Indeed, the larger is the clock drift, the longer the required minimum guard time for guaranteeing 100% of link reliability. It is important to mention that our simulation results validate our mathematical analysis, since they present almost a linear performance. Note that both nodes operate as EB transmitters and receivers; thus, the link is synchronised at half the EB period on average, \( T = 3.42/2 = 1.71 \text{s} \).

To further validate our empirical study, we here focus in the case of ±20 ppm, a typical worst-case clock drift in IoT devices [15]. Our performance evaluation results demonstrate that 390 µs is the minimum guard time length for efficient TSCH operation without compromising network reliability due

to loss of synchronisation. Indeed, as can be seen from Fig. 3b, only above 390 µs of guard time, both the reliability and the goodput, the application-level throughput (i.e., the number of actual data packets delivered to the sink), achieve 100% of performance.

3) **Energy Efficiency:** 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 tracking the time spent in each state (i.e., transmitting, receiving, awake, sleeping). Table II provides the current consumption levels at each of these states for Z1 mote2, considering that it is powered at 3 V.

We here investigate the impact of the guard time on energy consumption, under ±20 ppm clock drift. To this aim, we first present energy consumption performance under various guard time configurations. Our results demonstrate that by reducing the guard time (i.e., from 2200 µs, default configuration of Contiki’s TSCH implementation, to 400 µs), we can decrease the average power consumption per node (i.e., receiver node in our scenario) by more than 40%, see Fig. 4a. Indeed the energy consumption is reduced further at guard times of less than 390 µs, yet at the cost of compromising the network reliability. To better visualise this trade-off, we define the energy-efficiency metric of TSCH as the average energy consumed for the successful reception of a single bit, and it is calculated as follows:

\[
\eta = \frac{E}{PDR \times T_{transmissions} \times P_{size} \times 8},
\]

where $E$ is the total energy consumed during the experiment, $T_{\text{transmissions}}$ is the total packet transmissions from the leaf to the sink node, while $P_{\text{size}}$ is the size of a data packet in bytes. Fig. 4b plots the energy efficiency of TSCH as a function of the guard time. It can be observed that there is an optimisation point for the guard time at $390 \mu s$. Below that optimal configuration the energy per correct bit increases rapidly, due to packet loss caused by loss of synchronisation. Above that optimal configuration the energy per correct bit increases again, as the energy consumed in idle listening increases with the guard time.

### B. Multi-Hop TSCH Networks

We next consider multi-hop TSCH networks that employ the 6tisch minimal schedule, and evaluate the proposed guard time adaptation. To this aim, we performed large set of simulations under different topologies. More specifically, we gradually increased the size of the multi-hop network, from single-hop up to 9 hops with 10 nodes that are positioned in line of 100 m. This topology is presented in Fig. 5. Furthermore, we configured each node to transmit one data packet every 60 seconds. By employing the RPL protocol [14], each node is able to construct a Directed Acyclic Graph (DAG). Similarly, to the single-hop scenario, we consider a worst case scenario for synchronisation, in which all odd nodes have positive clock drift and all even nodes have negative clock drift. Finally, each simulation lasted 60 min.

We first perform a large set of simulations for different topologies in order to estimate the minimum guard time that maintains 100% PDR. More specifically, we first set a single hop communication with two nodes to cross validate the previously presented mathematical analysis. Then we gradually extended our topology to multi-hop, from 2 to 9-hops in line, ending with the topology shown in Fig. 5. Our performance evaluation results demonstrate that nodes closer to the sink require less guard time, while from 7th hop this value is stabilised at $1200 \mu s$. The empirically-derived minimum required guard time for each hop is illustrated in Fig. 6, which is then used as a look-up table to adapt the guard time in run-time.

In this setup, the empirically-derived network-wide optimum guard time is $1200 \mu s$. We then compared our adaptive scheme against a statically and homogeneously configured (i.e., guard time at $1200 \mu s$) multi-hop network. Our performance evaluation results demonstrate that by fine-tuning the guard time at each node according to its hop-distance to the sink, yields significant energy savings for the TSCH network.
Indeed, our adaptive scheme essentially reduces the energy consumption for all the considered topologies by more than 12% in average, while up to 17% in 2-hop and 3-hop scenario, see Fig. 7a. Furthermore, as can be observed from Fig. 7b, the further away the nodes from the sink the less efficient is guard time adaptation approach in terms of energy consumption. Since the more away the node is from the sink, the more prone to packet losses, and thus, more retransmissions in the network are necessary.

V. CONCLUSIONS

In this work, we first investigated the impact of guard time on TSCH performance in terms of network reliability, goodput and energy consumption. We then performed empirical optimisations on guard time to maximise the energy-efficiency in a multi-hop TSCH network. Our performance evaluation results on top of COOJA (a simulator for Contiki OS), demonstrated that the guard time has a straightforward impact on reliability and on energy consumption. In particular, it is shown that adapting the guard time at each node according to its distance from the sink can result into significant savings in energy consumption without compromising the reliability of the network. Our ongoing work consists of further investigating this lead in random multi-hop topologies, where the clock drift and the large set of nodes may impact heavily the network synchronisation. Furthermore, we plan to study the behaviour of TSCH under realistic conditions by performing a set of experimental studies on FIT IoT-LAB testbed [16].

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Fig. 7. The gain of guard time adaptation evaluated under 9 multi-hop topologies (in line), from 2-hops to 9-hops with nodes positioned in distance of 100 m.