Guard-Time Design for Symmetric Synchronization in IEEE 802.15.4 Time-Slotted Channel Hopping

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***Abstract*—Time-Slotted Channel Hopping (TSCH) is considered as one of the most reliable MAC solutions for low-power wireless networking. In order to establish time-slotted communications, this technique requires all nodes to remain synchronized. The synchronization is continuously done through normal communications to compensate the clock drift between different nodes. In this paper, we present a detailed look into the behavior of the IEEE 802.15.4 PHY and MAC in terms of the synchronization task. We show that the relation between timeslot offsets provided by the standard leads to different synchronization error margins for positive and negative relative clock drifts. This is due to the time required for detection of ongoing transmissions at receivers. This may lead to the situation that two nodes are able to communicate in only one direction. Depending on which node is the source node, the available margin to compensate the relative clock drift is different. Accordingly, we provide new values for timeslot offsets to compensate positive and negative relative clock drifts equally. Simulation results confirm that the standard offsets reduce the performance of TSCH due to asymmetric synchronization error handling. The results also show that this negative effect is mitigated by using the new offsets provided in this paper.**

I. Introduction

The Time-Slotted Channel Hopping (TSCH) mode of IEEE 802.15.4 [1] offers a reliable solution for low-power wireless sensor networks. It employs time division multiplexing as well as channel diversity to reduce internal and external interference. TSCH divides time into timeslots; each timeslot is meant for transmission of a maximum size packet and its acknowledgement, following a predefined timing diagram for communications. Using an appropriate node synchronization mechanism, the beginning of each timeslot should be aligned in all communicating nodes.

Each wireless sensor node uses a crystal clock source to keep track of time. Different parameters such as temperature, supply voltage, and manufacturing variances may cause a deviation from the nominal clock frequency. The relative clock drift between two wireless nodes leads to timeslot synchronization drift, that can eventually lead to communication failure. Because of such clock drift, the synchronization process needs to be periodically repeated to avoid long timeslot misalignment. The IEEE 802.15.4 [1] standard proposes techniques for node-to-node timeslot synchronization using normal communications. To compensate small drifts of the timeslot boundaries between the communicating nodes, guard times are introduced in the beginning of each timeslot. The full guard time or part of it is used to handle a maximum relative timeslot synchronisation error (SE^{max} (in seconds)). Considering a given SE^{max}, the maximum time period for which two nodes are still able to communicate without synchronization is

$$T_{sync}^{max} = \frac{SE^{max}}{Drift} \tag{1}$$

where *Drift* is the maximum relative clock frequency deviation between two nodes in parts per million (ppm). In a communication, the sender may be ahead of the receiver or behind, and thus there is need for a backward guard time as well as a forward guard time.

The IEEE 802.15.4 [1] standard defines some offsets to control packet communications in a timeslot. The relation between these offsets is defined so that equal forward and backward guard times are provided. However, it is not possible to use the whole backward guard time for overcoming the synchronization error. This is due to the fact that a frame can be detected at a receiver node only after the complete reception of its Synchronization Header (SHR). Thus, the receiver should always start listening at least an SHR duration before the transmission of the start symbol of the frame by the transmitter. This decreases the usable backward guard time for synchronization by one SHR duration and leads to asymmetric SE^{max} for forward and backward synchronization errors.

In this paper we analyze in detail the unequal handling of forward and backward synchronization error caused by the defined timeslot offsets in the IEEE 802.15.4 [1] standard. Then, we extract the proper value of different timeslot offsets, to have a symmetric synchronization error handling in TSCH. We assume a given maximum synchronization error (SE^{max}) as input. We also perform a set of simulations using the COOJA [2] simulator and Contiki [3] operating system to study the effect of symmetric and asymmetric synchronization error handling on the performance of TSCH.

The paper is organized as follows. Section II gives a short overview of TSCH timeslot timing that is defined in the IEEE 802.15.4 [1] standard. The guard time analysis to extract different timeslot offsets for symmetric synchronization error handling is presented in Section III. The simulation results achieved are discussed in Section IV. Section V concludes.

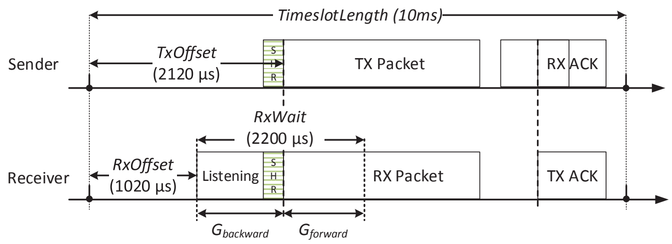


Fig. 1. TSCH timeslot diagram of acknowledged transmissions.

II. TSCH Timeslot Timing

The IEEE 802.15.4 [1] standard defines a timeslot diagram for TSCH communications. Fig. 1 shows this diagram with the default timings. A receiver node starts listening to the channel after *RxOffset* duration from the beginning of its timeslot with respect to its own timing. Listening for the start of an incoming packet continues at the receiver for *RxWait* duration. If packet reception is not started in this period, the receiver skips packet reception and goes to sleep. The sender transmits the data packet, timing the start symbol to be sent at time *TxOffset*, according to its own clock. In the IEEE 802.15.4 [1] standard, the relation between these parameters is defined as:

$$TxOffset = RxOffset + RxWait/2 \tag{2}$$

This puts the *TxOffset* exactly in the middle of the *RxWait* period. The listening periods before and after *TxOffset* at the receiver node are called backward guard time ($G_{backward}$) and forward guard time ($G_{forward}$), respectively. According to (2), the backward and forward guard times are equal. In the IEEE 802.15.4 [1] standard, it is assumed that two nodes can communicate if their synchronization error is less than the backward or forward guard time. Thus, SE^{max} is assumed to be equal to the defined guard times (i.e., $Nominal\ SE^{max} = G_{forward} = G_{backward} = TxOffset - RxOffset$).

A wireless node may transmit up to the end of a timeslot. The end of a node's timeslot may collide with the start of another node's timeslot. Therefore, if communication between two nodes starts from the beginning of a timeslot, it may fail due to a collision with the transmission of another node at the end of the previous timeslot. The *RxOffset* period is defined to overcome this internal interference due to synchronization loss.

A node can be a time-source node that is used as a time reference for timeslot synchronization of it's neighbors. A higher layer decides about time-source nodes in the network [1]. Each node in the network periodically re-synchronizes with one of its time-source neighbors. Synchronization is done by timestamping the ongoing packet communications between each pair of nodes. The TSCH standard defines two techniques to synchronize timeslots. In the first technique, if a receiver receives a packet from its time-source neighbor, it timestamps the start symbol of the frame. As the start symbol of a frame is supposed to be transmitted at *TxOffset* by the sender, the receiver shifts its timeslot with the computed error compared to the timestamp. In the second technique, if a node sends a packet to a time-source neighbor, the receiver timestamps the packet reception start time. Then it sends back the measured error with its expected packet reception time to the sender node, using the acknowledge packet. The sender node uses this data to re-synchronize with its time-source neighbor. These techniques require all nodes to use the same timeslot timing values.

PHY Protocol Data Unit (PPDU)			
Preamble Sequence	SFD	Frame Length	PHY Payload
5 octets Synchronization Header (SHR)		1 octet PHY Header (PHR)	127 octets (maximum) MAC Protocol Data Unit (MPDU)

Fig. 2. The IEEE 802.15.4 [1] Physical (PHY) layer frame structure.

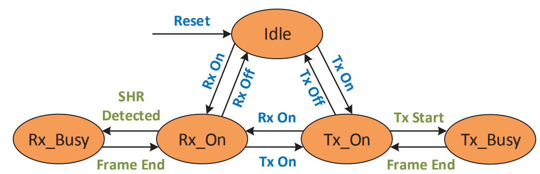


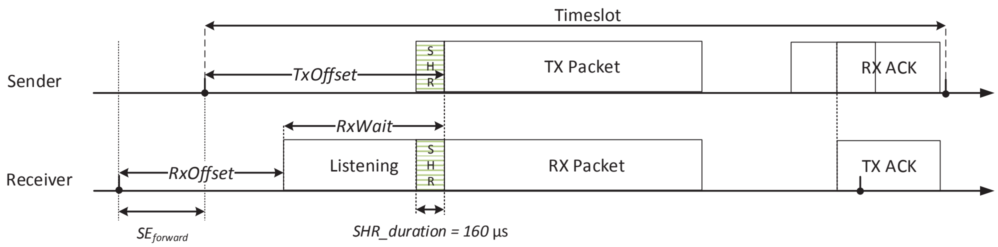
Fig. 3. State diagram of the basic operating modes of IEEE 802.15.4 transceiver.

The IEEE 802.15.4 [1] standard only provides node-to-node synchronization techniques that work for single-hop communications. However, for multi-hop networks, the synchronization error adds up at each hop. Thus the synchronization period needs to be shorter to have a connected multi-hop network. Several articles address adaptive synchronization in multi-hop TSCH networks to increase synchronization accuracy and reduce its overhead for the network [4]–[6]. These mechanisms usually help a node to learn and predict the relative clock drift with other communicating nodes. By using software-based drift correction techniques, each node can adaptively change the synchronization intervals or adapt the used *GuardTime*. This increases synchronization accuracy for multi-hop communications as well.

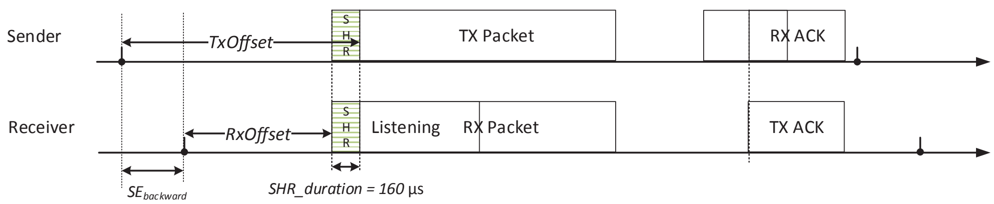
III. Guard Time Analysis

The IEEE 802.15.4 standard document defines some guard times to enable communication of two nodes in presence of a predefined SE^{max}. Here we have a look into the behavior of the IEEE 802.15.4 physical layer and the defined guard times in the protocol. We show that these guard times do not provide symmetric forward and backward synchronization error handling. Therefore the actual provided SE^{max} is not equal to the $Nominal\ SE^{max}$. Thus, different values are needed for the guard times.

Fig. 2 shows the IEEE 802.15.4 PHY frame format, also called Physical Protocol Data Unit (PPDU). The PPDU consists of 3 main parts, namely Synchronization Header (SHR), Physical layer Header (PHR), and payload. SHR is an automatically generated field by the PHY before a packet transmission, and includes a four-octets preamble followed by one byte Start-of-Frame Delimiter (SFD), indicating the end of SHR and the start of the packet data [1]. SHR follows by a single octet of PHY header which shows the PHY payload length.



(a) Receiver's timeslot ahead of that of the sender



(b) Receiver's timeslot behind that of the sender

Fig. 4. Maximum forward and backward synchronization error between a couple of sender and receiver nodes to have successful transmissions.

As defined in the IEEE 802.15.4 [1] standard document, a receiver keeps listening for duration *RxWait*. If the start of a frame is not detected by that time, the receiver goes to idle mode and skips packet reception. To check if a frame reception has been started by the end of the Rx guard time, the transceiver state should be checked. An IEEE 802.15.4 transceiver normally operates in five basic operating mode states, namely idle, Tx_On, Tx_Busy, Rx_On, and Rx_Busy (Fig. 3). To perform a packet reception, the radio should be in Rx_On state and listening. After detecting a valid SHR, the transceiver state automatically changes to Rx_Busy. The transmission of the SHR requires 160 μs (10 symbols). This leads to 160 μs delay in a receiver to go to the Rx_Busy state from the start of a PHY frame.

Considering the SHR detection delay and the timeslot timings defined in the IEEE 802.15.4 [1] standard document, Fig. 4 shows communication between two nodes in presence of forward and backward synchronization error. Fig. 4(a) shows the situation that the receiver's timeslot starts earlier than the sender's timeslot. For a successful packet transmission in this case, the receiver should detect the packet on air before the end of the *RxWait* period. As the sender transmits the start symbol of the frame at the time *TxOffset* and SHR is finished by that time, the transmission would be successful if *TxOffset* is before or tangent to the end of the *RxWait* period. Accordingly, based on Fig. 4(a), the actual maximum forward synchronization error is given by (3), which is also equal to $G_{forward}$.

$$SE^{max}_{forward} = (RxOffset + RxWait) - TxOffset \tag{3}$$

In the case that the receiver's timeslot starts with a delay of $SE_{backward}$ after the sender's timeslot (Fig. 4(b)), the receiver should detect the packet on the air before receiving the frame. As mentioned, the transceiver goes to the Rx_Busy state after detecting a valid SHR. Thus, listening for the incoming packet should be started at least an SHR duration before transmission of the start symbol of the frame by the sender. The start time of the frame at the sender is defined to be precisely at *TxOffset*. Accordingly, based on Fig. 4(b), the actual maximum backward synchronization error is given by (4).

$$SE^{max}_{backward} = TxOffset - RxOffset - SHR\_length \tag{4}$$

Thus, $SE^{max}_{forward}$ and $SE^{max}_{backward}$ are different for the defined offsets in the IEEE 802.15.4 [1] standard. As a couple of sender and receiver nodes may switch roles and use both forward and backward guard times over time, SE^{max} would practically be the minimum of the $SE^{max}_{forward}$ and $SE^{max}_{backward}$. Accordingly, the actual SE^{max} value for the offsets defined in the IEEE 802.15.4 standard is given by (5).

$$SE^{max}(802.15.4) = Nominal\ SE^{max} - SHR\_length \tag{5}$$

Next, we aim to define new timeslot offsets so that the synchronization error handling become symmetric. This leads to optimal use of guard times and provides equal nominal and actual SE^{max}. The maximum tolerable forward and backward synchronization errors should be equal to compensate synchronization lag symmetrically.

$$SE^{max}_{forward} = SE^{max}_{backward} = SE^{max} \tag{6}$$

Accordingly, the synchronization technique should guarantee that the synchronization error between each couple of communicating nodes does not exceed SE^{max}. By replacing $SE^{max}_{forward}$ and $SE^{max}_{backward}$ values in (6) by (3) and (4), the relation between timeslot offsets is given in (7).

$$TxOffset = RxOffset + (RxWait + SHR\_length)/2 \tag{7}$$

Equation (7) is proposed as a replacement for (2) to design TSCH timeslot offsets.

As it is shown in Fig. 4(a), the previous timeslot of the sender node (or other nodes with the same synchronization loss) overlaps the offset of the receiver node for the $SE_{forward}$ period. As the sender node may be transmitting at the end of the previous timeslot, the $SE_{forward}$ period should not overlap

TABLE I
TIMESLOT OFFSET VALUES BASED ON A GIVEN MAXIMUM SYNCHRONIZATION ERROR

Attribute	Value	SE^{max}	
		$200\mu s$	$1100\mu s$
RxOffset	SE^{max}	$200\mu s$	$1100\mu s$
TxOffset	$2 \times SE^{max} + SHR\_length$	$560\mu s$	$2360\mu s$
RxWait	$2 \times SE^{max} + SHR\_length$	$560\mu s$	$2360\mu s$
$G_{backward}$	$SE^{max} + SHR\_length$	$360\mu s$	$1260\mu s$
$G_{forward}$	SE^{max}	$200\mu s$	$1100\mu s$

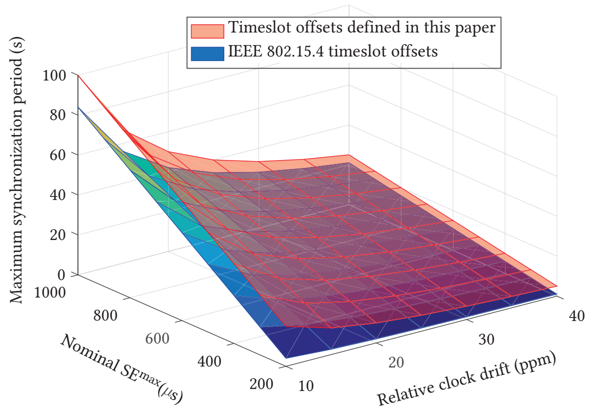


Fig. 5. The maximum period that can be used for TSCH synchronization to prevent communication errors, as a function of nominal maximum timeslot synchronization error (SE^{max}) and the maximum relative clock drift of sensor nodes.

with the listening phase at the receiver node. Thus, $SE_{forward} \leq RxOffset$ or

$$SE^{max}_{forward} = RxOffset \tag{8}$$

Considering (4), (6), and (8), *TxOffset* can be extracted as:

$$\begin{aligned} &RxOffset = SE^{max} = TxOffset - RxOffset - SHR\_length \\ &\Rightarrow TxOffset = 2 \times RxOffset + SHR\_length \\ &\Rightarrow TxOffset = 2 \times SE^{max} + SHR\_length \end{aligned} \tag{9}$$

By replacing *RxOffset* and *TxOffset* in (3), based on the SE^{max} value, the *RxWait* duration can be expressed as:

$$\begin{aligned} &SE^{max} = (SE^{max} + RxWait) - (2 \times SE^{max} + SHR\_length) \\ &\Rightarrow RxWait = 2 \times SE^{max} + SHR\_length \end{aligned} \tag{10}$$

Table I provides different timeslot offset values based on a given SE^{max} as input. This table also provides numerical values for two SE^{max} samples. As *SHR_length* is a constant value equal to 160 μs, the difference in $G_{backward}$ and $G_{forward}$ values is more visible for smaller maximally allowed synchronization errors. This is necessary to tolerate the possible forward and backward synchronization error symmetrically.

Fig. 5 shows T^{max}_{sync} as a function of the nominal SE^{max} and the maximum relative clock drift between two nodes for the offsets defined in the IEEE 802.15.4 [1] standard and also in this paper. As shown in this plot, for any given relative clock drift, the T^{max}_{sync} that is provided by the offsets defined in this paper is higher than the values provided by the standard. This mean that the network is more stable and reliable. This difference is constant for all nominal SE^{max} values and a given clock drift. Accordingly, the effect of the timeslot offset design is more visible when shorter nominal SE^{max} is used (i.e., shorter guard times). On the other hand, when the maximum relative clock drift is lower for a given nominal SE^{max}, the difference in T^{max}_{sync} values for the two different timeslot offset designs is higher. This is because their SE^{max} values differ with a constant value of *SHR_length*. Thus, lower values of the relative clock drift lead to higher difference in their provided T^{max}_{sync}, according to (1).

IV. SIMULATIONS

In order to investigate the effect of symmetric and asymmetric timeslot offset design on the performance of TSCH, we perform a set of simulations using COOJA [2]. COOJA is part of the Contiki [3] operating system and emulates different types of motes to run the Contiki stack virtually. In our experiments, we use Sky motes that emulate the behavior of the TelosB/Tmote Sky platform. We deploy a scenario with one PAN Coordinator (node 1) and two nodes (node 2 and 3). All nodes are placed in the communication range of each other. Only the coordinator is a time-source node and nodes 2 and 3 can only synchronize to this node. We setup the coordinator to broadcast periodic Enhanced Beacons (EB). These EBs are used by nodes 2 and 3 for timeslot synchronization. A slotframe of size 3 is used. Each node has a dedicated TX timeslot in this slotframe, while others listen to that timeslot. Nodes 2 and 3 send a packet to the broadcast address every slotframe. With a clock drift of $\pm 50ppm$ for the crystal oscillator, we consider a clock drift of $+50ppm$ for node 2 and $-50ppm$ for node 3 to simulate the worst case relative clock drift of $100ppm$ between the two nodes. The coordinator runs with the reference clock so that each end node has a relative clock drift of $50ppm$ to it. In this setup, communications from node 2 to 3 use the backward guard time of the timeslot and communications from node 3 to 2 use the forward guard time.

The nominal $SE^{max} = 1100\mu s$ is used to setup the guard times. Accordingly, the default timeslot offsets that are defined in the IEEE 802.15.4 [1] standard are used for simulations with the protocol offsets. Timeslot offsets that are defined for $SE^{max} = 1100\mu s$ in Table I are used for the simulations with symmetric synchronization. We run each setup with different EB periods (synchronization periods) from 0.5 to 20 seconds, to extract the average Packet Reception Ratio (PRR) for the two links between nodes 2 and 3.

Fig. 6 shows the timeline of 3 consecutive timeslot communications in part of the simulation with protocol timeslot offsets. In the first timeslot, nodes 2 and 3 turn on their radios and listen to the medium to receive an EB. Due to the synchronization loss between them at that time, they start listening at different times. In the second timeslot, it can be seen that node 3 is not able to receive the packet transmitted by node 2, while in the third timeslot, node 2 is able to receive the packet sent by node 3. This clearly shows the

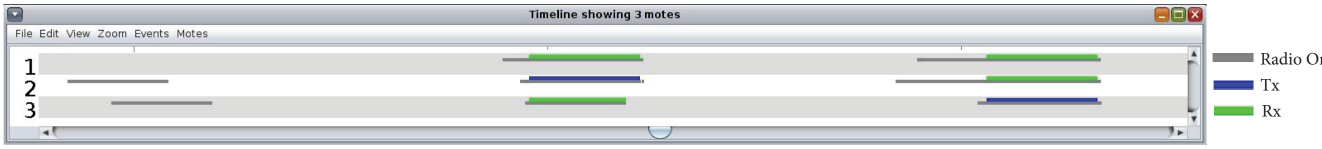
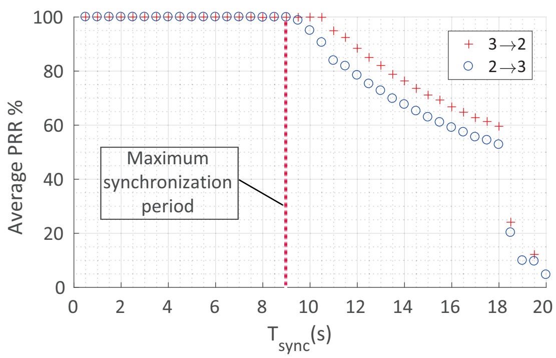
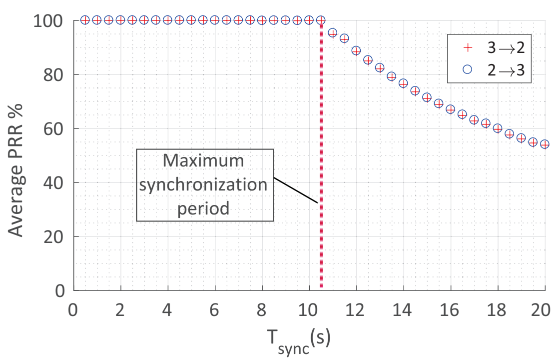


Fig. 6. The timeline of communications in 3 consecutive timeslots in the simulation with protocol timeslot offsets, in presence of synchronization loss.



(a) The IEEE 802.15.4 timeslot offsets



(b) Timeslot offsets defined in this paper.

Fig. 7. Average Packet Reception Ratio (PRR) of two directions of the link between two nodes, for different synchronization periods.

asymmetric synchronization error handling due to use of the protocol timeslot offsets.

Fig. 7 shows the simulation results for each timeslot offset design. For the timeslot offsets defined in the protocol, the link from node 2 to 3 starts experiencing packet drops earlier than the reverse link from node 3 to 2 (Fig. 7(a)). Thus, the maximum synchronization period to prevent packet errors due to synchronization error is lower than what was expected. This confirms the fact that the actual $SE^{max}_{backward}$ is lower than its nominal value. For the timeslot offsets proposed in this paper, Fig. 7(b) shows that both links between nodes 2 and 3 have the same performance. This shows that by adding a *SHR_length* to the backward guard time, the error handling is symmetric for forward and backward synchronization loss. The maximum synchronization period is also higher in this case. The symmetric synchronization also helps the nodes to stay synchronized with the coordinator for a longer time. When protocol timeslot offsets are used, node 3 is behind the coordinator and fail to receive EBs earlier. This leads to synchronization loss of node 3, so that it cannot communicate with other nodes. This brings the PRR of both links between nodes 2 and 3 close to zero, when synchronization periods longer than 18 seconds are used. On the other hand, by using the offsets proposed in this paper, node 3 stays connected to the network for a longer time.

V. Conclusion

The Time Slotted Channel Hopping (TSCH) mode of the IEEE 802.15.4 [1] standard defines a timeslot timing diagram to enable timeslot communications in presence of an amount of synchronization error between wireless nodes. In this paper, we showed that the provided relation between timeslot offsets in this diagram provides different synchronization error margins for positive and negative relative clock drifts. This is caused by the time that it takes for a receiver to detect the start of a packet. This leads to loss of packets for which the MAC frame is transmitted at the beginning of the receiver's guard time and the physical header is transmitted before start of listening at the receiver. Accordingly, we analyzed the TSCH timeslot offsets to provide new ones that tolerate the possible forward and backward synchronization error symmetrically. These offsets are parameterized based on a given maximum desired synchronization error as the input. We performed a set of simulations with the COOJA simulator. The results confirm the negative effect of asymmetric synchronization on the performance of the network, while they show that the new given offsets provide better performance.

Acknowledgment

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