ATP: A Fast Joining Technique for IEEE802.15. 4-TSCH Networks

Conference Paper · June 2018

DOI: 10.1109/WoWMoM.2018.8449759

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ATP: A Fast Joining Technique for IEEE802.15.4-TSCH Networks

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***Abstract*—IEEE802.15.4-TSCH (Time-Slotted Channel Hopping) is an emerging MAC protocol for low-rate wireless personal area networks (LR-WPANs). It combines time-division multiple access with channel-hopping to provide high reliability and ultra-low power consumption. The formation of an IEEE802.15.4-TSCH network relies on the periodic transmission of Enhanced Beacons (EBs). The transmission frequency of the EBs affects the joining time of nodes. An increase of this frequency reduces their joining time. In this paper, we present an Advertisement Timeslot Partitioning technique (ATP) which can be used to increase the EB rate without the need of allocating more timeslots. The key idea behind ATP is that it compacts multiple EBs in a single timeslot while it uses a different channel for each EB. Since a joining node listens to a random channel, increasing the number of frequencies per timeslot, we increase the probability of receiving an EB. Our evaluation shows that ATP improves the average joining time by up to 65% in the tested scenarios.**

I. Introduction

LR-WPANs as specified in the IEEE802.15.4 standard [1] are optimized for low-rate data transmission and low-power consumption. Applications of LR-WPANs include but not limited to industrial control and monitoring, wireless sensor networks, and asset and inventory tracking. One of the most widespread MAC protocols for industrial LR-WPANs is the IEEE802.15.4-TSCH [2]. This protocol aims to provide high reliability and ultra-low power consumption which are desirable features for industrial applications of LR-WPANs. In order to achieve these objectives, it uses a channel access method that combines timeslots and channel-hopping.

The formation of an IEEE802.15.4-TSCH network relies on the Enhanced Beacons (EBs), which are MAC frames that are periodically sent by nodes joined to the network so as to advertise it. A node desiring to join the network must receive an EB. For this purpose, it must turn its radio on and scan the available channels for an EB. Because of the use of multiple channels and the channel-hopping mechanism, finding an EB may require considerable amount of time. The longer the time it takes the node to receive an EB, the higher the energy it consumes. Tuning the transmission frequency of EBs, allows a trade-off between the joining time and the energy consumption [3]. Also, the increase of the EB send rate, typically requires the allocation of more timeslots and hence reduces the number of timeslots available for data transmission or reception.

In this paper we propose ATP; an Advertisement Timeslot Partitioning technique, which optimizes the use of an advertisement timeslot; that is a timeslot used for the transmission of EBs. The contributions of this paper are the followings:

1) We show that an advertisement timeslot can be used for sending more than one EBs.
2) We propose an optimization technique that can be used by an EB scheduling method to allow the nodes to send multiple EBs at different channels in an advertisement timeslot. We must note here that the various proposed EB scheduling methods [4], [5], [6], [7] use the default one EB per timeslot, thus, they would significantly benefit from the proposed technique.
3) Our evaluation demonstrates the capability of this technique to decrease the average joining time of nodes.

II. The IEEE 802.15.4-TSCH protocol

A. Timeslot template standard

In a timeslot, a node can send one frame and receive the related acknowledgment. As shown in Fig. 1, the duration of a timeslot is $macTsTimeslotLength$. The transmission of the frame starts exactly after $macTsTxOffset$ μs from the beginning of the timeslot. During this waiting period, the node can perform a Clear Channel Assessment (CCA). The CCA should start exactly after $macTsCcaOffset$ μs as compared to the beginning of the timeslot and lasts $macTsCca$ μs. When a CCA is performed, the node has at most $macTsRxTx$ μs, after the CCA, to switch from the *receive* (listening) state to the *transmit* state. The available transmission time is $macTsMaxTx$ μs, which is equal to the transmission time of a maximum length of a MAC frame, together with the physical layer header; that is a 127 bytes MAC frame and 6 bytes of the fixed-size physical layer header. If an acknowledgement is expected, the node waits $macTsRxAckDelay$ μs before starting to listen for the acknowledgement. After this time, it waits at least $macTsAckWait$ μs for the start of the acknowledgment.

On the other side, when a node expects to receive a frame in a specific timeslot, it starts to listen exactly after $macTsRxOffset$ μs from the beginning of the timeslot. The node waits at most $macTsRxWait$ μs for the start of the frame, and if no frame is detected in this time, it turns off its radio to save energy. When a valid frame is received, and an acknowledgement is required, the node waits $macTsTxAckDelay$ μs before starting to send the acknowledgment. The maximum transmission time of an acknowledgment is $macTsMaxAck$ μs.

As the clocks of the nodes drift from perfect time and have different drift rates, the transmitter and the receiver of

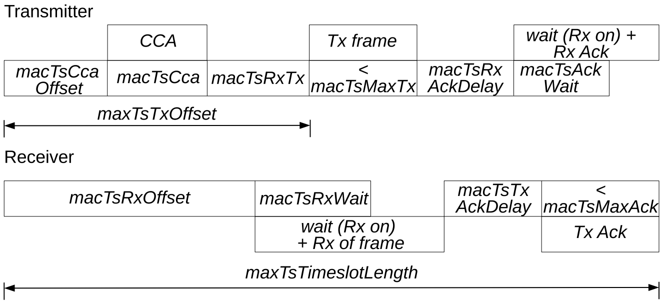


Fig. 1. The IEEE802.15.4-TSCH timeslot template.

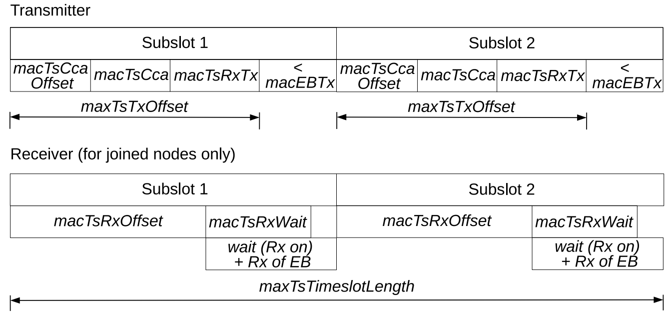


Fig. 2. Advertisement Timeslot structure with ATP using 2 subslots.

a frame do not have the same perception of time. This means that the transmitter, may start transmitting before or after the expected transmission start time on the recipient's side, leading to a failure. To be flexible with this slight desynchronization, the receiver starts listening $macTsRxWait/2$ μs before the expected transmission start time, which means that $macTsRxOffset$ is $macTsRxWait/2$ μs less than $macTsTxOffset$, and waits $macTsRxWait/2$ μs after this time. This mechanism requires the clocks of nodes to never differ more than $macTsRxWait/2$ μs, so as to be able to communicate. As a result, the nodes should periodically synchronize their clocks.

B. Channel hopping and Scheduling

In IEEE 802.15.4-TSCH networks, the communication between neighboring nodes takes place according to a schedule. The schedule instructs a node what to do at each timeslot of the slotframe: transmit, receive, or sleep [3]. In addition, it assigns a channel offset for each of the timeslots that the node is active (transmit or receive). The channel offset is a number utilized for the calculation of the channel to be used. There are as many channel offsets as there are channels available. The calculation of the channel is made according to the following formula [2]:

$$channel = F((ASN + channelOffset)\%C) \tag{1}$$

where ASN is the Absolute Slot Number, defined as the total number of timeslots elapsed since the start of the network, C the number of available channels (e.g., 16 when using radios that are compliant with IEEE 802.15.4 at 2.4 GHz, when all channels are used), and F is a bijective function mapping an integer comprised between 0 and $C-1$ into a channel. Eq. (1) implements the channel hopping mechanism. Considering that the number of timeslots in the slotframe is not multiple of C, Eq. (1) returns a different channel for the same timeslot and channel offset at each slotframe cycle.

III. The Advertisement Timeslot Partitioning

In this section, we present ATP. The idea of this technique is based on the following two features of an EB: (a) Its size can be significantly reduced. For example, using the recommended settings defined in the minimal 6TiSCH (IPv6 over IEEE802.15.4-TSCH) configuration [3], the size of an EB can be limited to as little as 40 bytes. (b) It is sent to the link-layer broadcast address and is not acknowledged [3]. Consequently, there is a considerable amount of unexploited time in an advertisement slot.

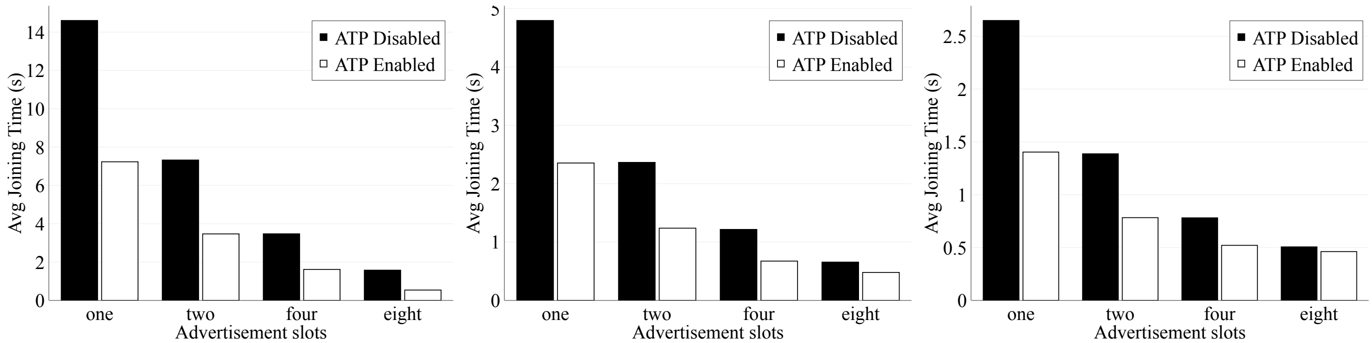
According to ATP, an advertisement slot is partitioned into smaller parts called subslots. A subslot is a compressed slot version that is used for the transmission of one EB. The only differences between slot and subslot are as follows: (a) The subslot does not contain the intervals of the slot that are related to frame acknowledgement. (b) The available transmission time in a subslot is not $macTsMaxTx$ but $macEBTx$, which is defined as the maximum transmission time of an EB.

Fig. 2 shows an advertisement slot consisting of two subslots. To avoid confusion, it is noted that the recipient side described in Fig. 2 concerns only the joined nodes expecting to receive an EB from an other joined node of the network they belong to. On the contrary, a non-joined node willing to join the network, continuously scans the available channels for an EB derived from the same network.

$$N_{subslots} = \frac{macTsTimeslotLength}{macTsTxOffset + macEBTx} \tag{2}$$

It is obvious that the maximum number of subslots that an advertisement slot supports, can be calculated using Eq. (2). The creation of N subslots per advertisement slot, allows the maximum possible EB send rate of a node to be increased N times, without the need of allocating more timeslots. For example, if ATP is applied in a network where the default values of timeslot template for 2.4Ghz band is used, and the size of EBs is not greater than 84 bytes, then each advertisement slot can support two subslots and hence the maximum possible EB send rate can be doubled. When ATP is used, the EB transmission scheduling defines the subslots and the channel offset for each of these subslots that a node will use. The calculation of the channel used in a subslot, is done normally via Eq. (1), using the ASN of the slot to which the subslot belongs. As a consequence, using different channel offsets in the subslots of an advertisement slot, a node transmits on a different channel in each of them.

ATP causes a problem in the initial synchronization of a new node. Typically, a node initially synchronizes with the network by calculating the time deviation of its clock relative to that of the node from which it received the EB during the joining phase. The calculation is performed by comparing the expected arrival time of the EB and the actual arrival time. The



(a) N=1 (b) N=3 (c) N=5

Fig. 3. Average joining time with 1, 3, and 5 neighbors

expected arrival time is $macTsTxOffset$ in relation to the beginning of the timeslot the EB is received. However, when ATP is used, the expected arrival time must be calculated in relation to the start of the sublot in which the EB is received. To address this problem, we recommend adding an additional Information Element (IE) to EBs that will indicate the position of subslot (within the timeslot to which it belongs). If we use one byte to define the position of a subslot, then according to the standard the total length of the IE will be only 2 bytes. Therefore, we can solve the above problem with a very small increase in EB size.

IV. Evaluation & discussion of the results

We evaluate the performance of ATP by comparing the average joining time of a node when ATP is not used. For this purpose, we developed a simulator in Python. In the context of this simulator, we create a network where all nodes advertise EBs after joining, while they transmit these EBs in the first A timeslots of each slotframe. Each node allocates a channel offset for each advertisement slot assigned by a centralized and collision-free EB scheduling method. After all nodes join to the network, a particular node is disconnected multiple times and attempts to rejoin. The average joining time is calculated for different number of advertisement slots and neighbors. It is assumed that the nodes operate on the 2.4GHz band with 16 available channels and the network uses the default values of timeslot template for this band, combined with a slotframe size of 101 slots. In addition, the size of EBs is 50 bytes and, thus, when ATP is used each advertisement timeslot is partitioned into two subslots.

Fig. 3 shows the results when the numbers of neighbors N is equal to 1, 3, and 5 respectively. As expected, the average joining time decreases as the number of neighbors and advertisement slots increases. With the use of ATP, the average joining time decreases and the degree of reduction is dependent on the number of neighbors and advertisement slots. In the case where N is 1, ATP reduces the average joining time by 50% when A is 1, by 55% when A is 2 or 4, and by 65% when A is 8. When N is 3, with ATP, the average joining time is reduced by 50% when A is 1 or 2, by 45% when A is 4 and by 25% when A is 8. In the latter case, where N is 5, the reduction rate is 45% when A is 1 or 2, 35% when A is 4 and 10% when A is 8. It should be noted that all the above reduction rates have been calculated approximately. One last and very important observation is that the average joining time without ATP is the same as the average joining time when ATP is used with the half number of advertisement slots.

V. Conclusion & Future work

In this paper, we proposed a technique for IEEE802.15.4-TSCH networks that can be used by an EB scheduling method to allow sending multiple EBs at different channels in a timeslot, aiming to reduce the joining time of nodes. Our simulations demonstrate the capability of our technique to reduce the average joining time. Part of our future work is to evaluate our technique when used with the various EB scheduling methods proposed in the literature.

Acknowledgments

This work was supported by the General Secretariat for Research and Technology (GSRT) and the Hellenic Foundation for Research and Innovation (HFRI) in the context of the action "1st. Proclamation of Scholarships from HFRI for PhD Candidates".

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