An Efficient Joining Scheme in IEEE 802.15.4e

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***Abstract*— Time Slotted Channel Hopping (TSCH) is one of main features of IEEE 802.15.4e standard designed for wireless sensor networks. It improves energy efficiency, network capacity and communication reliability in industrial applications. However, in the joining phase of TSCH network formation, sensor nodes have to remain awake status for a long time till they can reach synchronization. This is the reason which consumes a significant amount of energy. In this paper, we therefore propose a reliable lightweight joining scheme for TSCH network formation to speed up joining operation. The scheme is present in detail through analysis models as well as implementation result in real sensor nodes. Moreover, the comparison with other approaches is also mentioned to show the potential efficiency and better performance of our proposal.**

Keywords— Industrial Internet of Things, IEEE 802.15.4e, TSCH, Network formation.

I. Introduction

Nowadays Internet of Thing (IoT) becomes popular with people and it is applied in various areas such as human life, environment monitoring, especially, industrial sector, etc. The term "Industrial Internet of Things" (IIoT) arises as new trend of industrial process control, intelligent building control and automation technologies. In IoT ecosystem, the low power wireless network like wireless sensor network plays a very importance role because of its low operation cost, pervasive communication and energy efficient.

To meet strict requirements of industrial market, several wireless standards such as ISA100.11a [1] and Wireless HART [2], are developed to provide reliable and efficient communication for industrial automation. In 2012 IEEE released the new IEEE 802.15.4e-amendment [3] standard which extends the features of original IEEE 802.15.4 Medium Access Control (MAC) to address the emerging needs for industrial applications. IEEE 802.15.4e introduces the Time Slotted Channel Hopping (TSCH) mode, which facilitates multi-hop operation and overcomes fading and interference issue in wireless environment. The core of the TSCH is a medium access technique using time synchronization to achieve ultra-low power operation and channel hopping to enable high reliability [4]. Due to need of interconnecting to the internet, the Internet Engineering Task Force (IETF) "6TiSCH-IPv6 over the TSCH mode of IEEE 802.15.4e" working group has been established to enable the usage of IEEE 802.15.4e TSCH in IPv6 networks as well as IIoT environment.

In an IEEE802.15.4e network, all sensor nodes are synchronized, and time is organized into time slots. In each 15ms slot, the sensor can sleeps, transmits or receive data. Repetitive patterns of timeslots are group into slotframes, which continuously repeats over time. One of the main phases in TSCH operation is joining phase for synchronization at network bootstrap. When a new node wishes to join the network, it will listen to the advertisement packet (ADV) which is sent by motes being already part of network as synchronizers. The initial synchronization should be reached by electing at least one synchronizer node, normally being sink node (coordinator node). Once a joining node receives this ADV, it shall have same an Absolute Slot Number (ASN) value with other synchronizer nodes and thus synchronizes to network following action schedule on slotframe. After becoming a synchronizer node, it continuously broadcasts ADV to other new nodes for extending network.

Due to using channel hopping mechanism of IEEE 802.15.4e, frequency channel always changes at each timeslot. This affects the synchronization between synchronizers and new joining nodes because they can not negotiate for sending and receiving advertisement packet on the same frequency. It means that when an ADV is sent by the synchronizer on a given channel, the nodes not yet synchronized could be listening another channel. Besides, to wait for a valid ADV, joining node has to keep radio always on. If the synchronization does not reach for long time, it will consume a significant amount of energy and reduce overall energy efficiency of the network. To overcome these problems, De Guglielmo et al [5] reveals the Random-based Advertisement (*RbADV*) algorithm. According to their work, each synchronizer node sends advertisement packet and repeat periodically with a period time (expressed in number of slots). This operation is carried out at a scheduled link, with optimal probability value to reduce the collision. Elvis Vogli et al [6] introduces two novel advertisement broadcast scheduling mechanisms (Random Vertical filling – *RV* and Random Horizontal filling – *RH* algorithm) to speed up joining phase. In RV, each synchronizer node only sends ADVs on a random channelOffset (representable element for communication frequency in the TSCH schedule) and at the first slot of the periodical multiple of slotframes. Otherwise, with RH, each synchronizer node will send ADVs at a random slot of the periodical multiple of slotframes with channelOffset = 0. The performance of two above solutions is same. However, in these approaches, the joining time is affected significantly by number of synchronizer nodes in TSCH network. Once total of synchronizer nodes is low, the joining time still keeps long and network can not dynamically adjust to speech up.

Therefore, in the paper, we firstly propose new structure of slotframe of TSCH network that can enable the dynamic adjustment of joining operation speed. Besides, we also introduce an efficient lightweight joining scheme with aim of continuously reducing joining time as well as influence of quantity of synchronizer nodes factor. To evaluate proposed approach, mathematic model as well as implementation result are present. Furthermore, a performance comparison with above other approaches is also mentioned to show advantage of our proposal.

Organization of the paper is as follows: The second section provides background knowledge about IEEE 802.15.4e standard. Section III presents our proposed approach for network formation in TSCH network in detail. Section IV reports insight of performance evaluation, experimental results and discussion. The last section concludes this paper.

II. IEEE 802.15.4E OVERVIEW

The IEEE 802.15.4e [3] standard is an amendment to the MAC protocol of the original IEEE 802.15.4 standard. TSCH mode plays an important role to achieve low-power operation and high reliability for industrial wireless network.

A. *TSCH Mode in IEEE 802.15.4e*

In IEEE 802.15.4e network, all sensor nodes synchronize on a periodic slotframe made by a number of timeslots. Each timeslot is assigned a type value for sensor activity. The TSCH defines three main types of non-idle slot: advertisement broadcast – ADV slot, transmission (Tx) – Tx slot and reception (Rx) – Rx slot. Furthermore, IEEE 802.15.4e uses channel hopping mechanism to time slotted access. This leads to changing communication channel frequency on each timeslot at different instants. Therefore, fading and interference issue are mitigated efficiently.

Another basic concept of TSCH is logical link. A link is defined as a single element in the TSCH schedule and identified by a *slotOffset* in slotframe and a *channelOffset* value for directed communication between two sensors. To translate channelOffset into physical frequency f, equation (1) is used.

$$f = F\{(ASN + channelOffset) \; mode \; N_{ch}\} \qquad (1)$$

Where N_{ch} is the number of available physical frequencies, with using IEEE 802.15.4-compliant radio at 2.4GHz band, N_{ch} reaches maximum being 16 channels. The function F includes a lookup-table mapping between real frequency value (under GHz unit) and ordering physical channels number in the range [11-26]. Absolute Slot Number (*ASN*) presents total number of slots since the start of TSCH network. It is calculated $ASN = (k \cdot S + slotOffset)$, where k defines the slotframe cycle and S is the slotframe size and note that, $0 \leq slotOffset \leq S - 1$, $0 \leq channelOffset \leq N_{ch} - 1$ [7].

B. *TSCH Network Formation*

When a TSCH network establishes, firstly, usually sink node will broadcast ADVs to advertise network presence. The ADV provides enough information of existing network such as ASN value, channel hopping information, timeslot information, slotframe information, etc. A new node wants to join the network, it shall listen the advertisement packet on one or all of available frequencies. After it receives ADV, joining node will synchronize with sink node through ASN value and align its slotframe to that of the overall network. At the same time, the MAC layer notifies the higher layer. Following scheduled links, it will execute communication activities like network topology configuration, routing setup and authentication in Network formation process. Once synchronized, joining node will become a synchronizer node. It means that it will continuously broadcast ADV to other new nodes for extending network.

III. PROPOSED APPROACH

In this section, the proposed idea for fast joining phase is revealed in the detail. It is developed with lightweight requirement to easily implement on sensor nodes which have limitation about memory as well as computation capacity.

Typically, IEEE 802.15.4e does not define any structure for a slotframe. In our approach, we propose to divide slotframe into two parts: the advertisement plane and communication plane. The advertisement plane is reserved for sending ADVs and includes ADV slots. The communication plane is used to transport data. This separation help reduce effects of flexibly scheduling ADV broadcast on overall operation of TSCH network. Besides, based on network requirements, the number of ADV slots at advertisement plane can be tuned dynamically by either distributed or centralized scheduling method [4] in 6TiSCH.

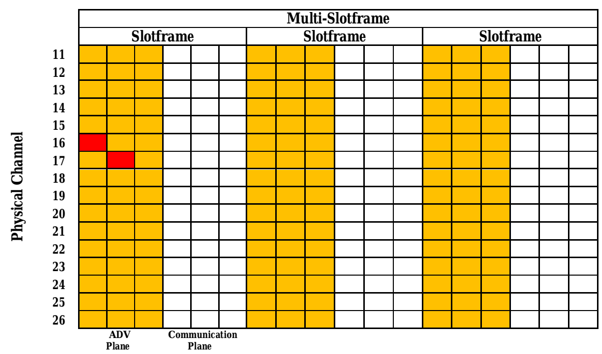

Figure 1. Scheduling structure of proposed approach

The scheduling of ADV broadcast consists of two aspects: (i) Number of ADV slots on advertisement plane; (ii) These ADV slots are repeated periodically with a period multiple of slotframes, known as a *multi-slotframe*. Figure 1 shows an example about scheduling architecture. Each cell is equivalent with a link in TSCH network. Instead of using *(slotOffset, channelOffset)* to identify the logical link, the table uses a corresponding pair *(physicalChannel, channelOffset*) with physicalChannel translated by (1). As it shows, multi-slotframe consists of three slotframes and advertisement plane can contain maximally three ADV slots. In case having two scheduled ADV slots (red cells), synchronizer nodes in network will send ADVs at only two available ADV slots of multi-slotframe and after three slotframes period, it will repeat again.

Based on proposed pre-configuration which is mentioned above, the following scheme is considered in this work to reduce joining time: Each synchronizer node uses random consecutive physical channels at ADV slots (consecutive red cells of table in figure 1) of advertisement plane to broadcast ADVs. The number of consecutive broadcast frequencies equals total scheduled ADV slots. A new node will choose a random available channel for listening ADV.

Here, we utilize theoretical model of Random Vertical filling algorithm in [6]. With condition that a synchronizer node is allowed to send ADVs in only one of available advertisement slots of multi-slotframe, the average joining time (T_S) is described as following:

$$T_S = T_M \cdot M_S = \frac{T_M\,(C+1)}{2N \cdot \Pi_D} \cdot \left(1 - \frac{1}{C}\right)^{1-N} \qquad (2)$$

Where T_M is multi-slotframe duration; M_S is mean number of T_M periods needed for synchronization; N represents number of synchronizer nodes existing in network; finally, Π_D and C are packet delivery ratio, number of channels in TSCH schedule, equivalently. According to our approach, if call N_{adv} being number of available ADV slots in advertisement plane using for sending ADVs in each multi-slotframe, the expectation of average joining time, denoted by T_{join}, will be formulated by equation:

$$T_{join} = T_M \cdot \frac{M_S}{N_{adv}} = \frac{T_M\,(C+1)}{N_{adv} \cdot 2N \cdot \Pi_D} \cdot \left(1 - \frac{1}{C}\right)^{1-N} \qquad (3)$$

Note that $\frac{T_{join}}{T_M} \geq 1$.

IV. PERFORMANCE EVALUATION

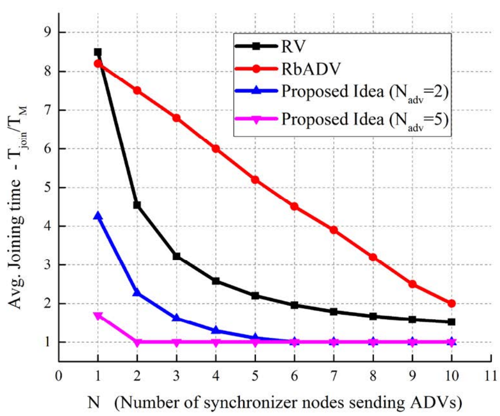

Figure 2. Avg. joining time comparison with other approaches

In this discussion, we will assume that all channels are available for communication (C=16). Transmission environment condition is idea (Π_D = 1). Figure 2 shows the average joining time represented by mean number of T_M periods (T_{join}/T_M) needed for synchronization, as a function of number of synchronizer nodes. As we can see, the joining time reduces very fast when number of synchronizer nodes in network increases. In addition, through comparison with other approaches (*RbADV algorithm* in [5] and *RV algorithm* in [6]), our proposal (with N_{adv}= 2 and 5) reaches better performance and reduction of joining time is directly proportional to the number of ADV slots in advertisement plane. With case having low total of synchronizer nodes, we can increase scheduled ADV slot to speed up joining operation.

Practically, the number of ADV slots affects significantly to throughput of TSCH network. We consider that the number of slots within the advertisement plane should be small (e.g. 5% of the total number of the slots in a slotframe). Moreover, with utilizing more ADV slots, synchronizer nodes also will spend more energy for sending ADVs. Therefore, the number of ADV slots can be tuned by trade-off between joining time speed and energy consumption requirement.

To demonstrate the feasibility, we implemented our approach in real sensor nodes and carried out measurements. We used OpenWSN stack (an open-source implementation of a fully standards-based protocol stack for capillary networks, rooted in the new IEEE802.15.4e Time Synchronized Channel Hopping standard [8]) and hardware platform – Tmote Sky motes.

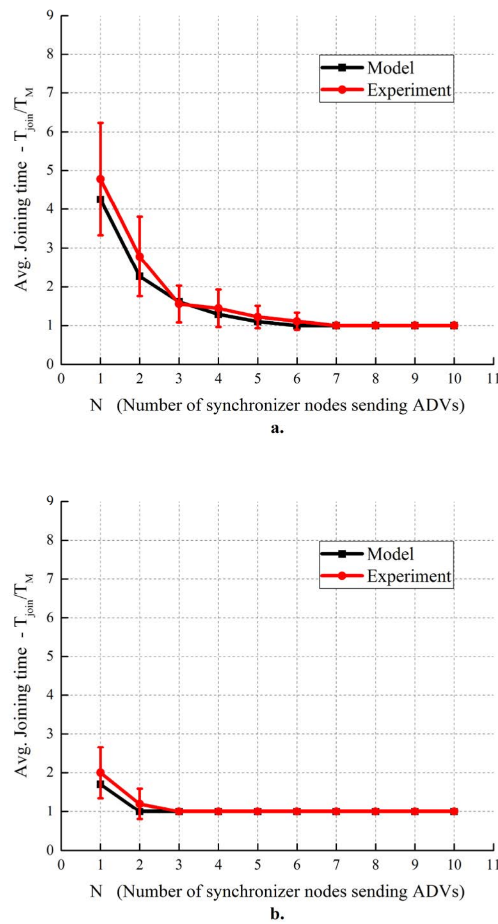

Figure 3. Measured avg. joining time with N_{adv}=2 (a), N_{adv}=5 (b)

The experimental scenarios were based on [6] with: multi-slotframe of 15 slotframes, each slotframe lasting 101 timeslots, $\Pi_D = 1$ and N value changing from 1 to 10. We performed measurements on two cases including $N_{adv} = 2$ and 5. The experimental results for each case were evaluated through 100 samples with confidence intervals at 95%. Figure 3 shows experimental results in comparison with theory function. It can be clearly recognized the similarity between them. This proves that theoretical model reflect relatively exactly practical result.

V. CONCLUSIONS

In this paper, we propose a fast node joining scheme to speed up joining phase in TSCH network formation. To demonstrate reliability of our proposal, theory model as well as implementation results are present in detail. In addition, the comparison with other works shows the potential efficiency and better performance of our approach and it is particularly suitable for implementing on constraint sensor nodes because of its light-weight specifications.

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