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A rapid joining scheme based on fuzzy logic for highly dynamic IEEE 802.15.4e time-slotted channel hopping networks

Thang Phan Duy, Thanh Dinh and Younghan Kim

Abstract

The IEEE 802.15.4e standard is an amendment of the IEEE 802.15.4-2011 protocol by introducing time-slotted channel hopping access behavior mode. However, the IEEE 802.15.4e only defines time-slotted channel hopping link-layer mechanisms without an investigation of network formation and communication scheduling which are still open issues to the research community. This article investigates the network formation issue of the IEEE 802.15.4e time-slotted channel hopping networks. In time-slotted channel hopping networks, a joining node normally takes a long time period to join the network because the node has to wait until there is at least one enhanced beacon message advertised by synchronized nodes (synchronizers) in the network on its own synchronization channel. This leads to a long joining delay and high energy consumption during the network formation phase, especially so in highly dynamic networks in which nodes join or rejoin frequently. To enable a rapid time-slotted channel hopping network formation, this article proposes a new design for slotframe structure and a novel adaptive joining scheme based on fuzzy logic. Our proposed scheme enables a synchronizer to be able to adaptively determine an appropriate number of enhanced beacons it should advertise, based on the number of available synchronizers in the network, so that joining nodes can achieve a short joining time while energy consumption of enhanced beacon advertisement at the synchronizers is optimized. Through extensive mathematical analysis and experimental results, we show that the proposed scheme achieves a significant improvement in terms of joining delay compared to state-of-the-art studies.

Keywords

Industrial Internet of Things, IEEE 802.15.4e, time-slotted channel hopping, network formation, fuzzy logic

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Introduction

Nowadays, the Internet of Things (IoT)[1] has become more and more popular and has been applied in various areas such as human life, environmental monitoring, and industrial sector. The term *Industrial Internet of Things* (IIoT) arises as a new trend of industrial automation technologies. In IIoT ecosystem, low-power wireless sensor networks play a key role in providing sensing information for automation processes at low operational cost, pervasive communication, and energy efficiency.

To meet strict requirements of industrial applications, several wireless standards such as Wireless HART[2] and ISA100.11a-2008[3] are developed to provide reliable and efficient communication. In 2012, the

School of Electronic Engineering, Soongsil University, Seoul, Republic of Korea

Corresponding author:
Younghan Kim, School of Electronic Engineering, Soongsil University, Sangdo-Dong, Dongjak-Gu, Seoul 156-743, Republic of Korea.
Email: younghak@ssu.ac.kr

Institute of Electrical and Electronics Engineers (IEEE) released a new IEEE 802.15.4e-2012[4] amendment standard which extends features of the original IEEE 802.15.4-2011[5] medium access control (MAC). The IEEE 802.15.4e introduces time-slotted channel hopping (TSCH) mode to facilitate multi-hop operations and address fading and interference issues in wireless environments. The core of TSCH is a medium access technique using time synchronization and channel hopping to achieve ultra-low power operation and high reliability.[6] Due to a need of interconnecting to the Internet, the IETF 6TiSCH WG (IPv6 over the TSCH mode of IEEE 802.15.4e)[7,8] has been established to enable the further adoption of IPv6-enabled protocols such as CoAP,[9] 6LoWPAN,[10] and RPL[11] in IEEE 802.15.4e standard.

In TSCH networks, all sensor nodes are synchronized, and time is divided into timeslots. In each 15-ms slot, a sensor may sleep, transmit, or receive packets. Timeslots are grouped into a slotframe which continuously repeats over time. Communication channels and operations of nodes are guided by the TSCH mechanism.

One of the main phases in TSCH networks is the network formation phase, which is related to configuration and synchronization during the network bootstrapping as well as network extension period. The initial synchronization should be done through electing at least one node (e.g. sink node). When a joining node wishes to join a network, it should listen for enhanced beacons (EBs) advertised by nodes which have been already synchronized, called synchronizers, including sink node. Once the joining node receives an EB, it obtains the same absolute slot number (ASN) value with other synchronizers and synchronizes with the overall network through its scheduled slotframe. This node then becomes a synchronizer and continuously advertises EBs to other joining nodes for extending network as well as maintaining network synchronization.

According to the channel hopping mechanism of IEEE 802.15.4e, a node changes its frequency channel at each timeslot. This impacts synchronization processes between synchronizers and joining nodes in TSCH networks. In particular, synchronizers and joining nodes have to take a long time period to find the same frequency for sending and receiving EBs. The reason is that when a synchronizer sends EBs on a certain channel, a joining node may listen on a different channel. Therefore, the joining node may not receive any EB for synchronization. In addition, the joining node also has to remain active fully to listen for EBs on its own synchronization channel for a long period. These cause high joining overhead (i.e. long delay and high energy consumption) during network formation. Based on this observation, it is clear to see that using an inefficient joining scheme of network formation will compromise the performance of network, especially so in highly dynamic networks where nodes may join or rejoin frequently, and fast joining is a critical requirement. Dynamic networks may happen in many cases, and industrial environment is not an exception. For instance, the mobility scenarios in industrial environment have been widely studied in M Barcelo et al.,[12,13] where sensors are attached to mobile workers, robots, or industrial goods. According to movements, the sensors or robots may often change their connection points and leave or join to different networks due to their interactive tasks. As most tasks in such an environment require real-time or low-delay communication, a fast joining scheme is desirable to avoid data transmission or interaction interrupted. In another example, high interference scenario, which is also quite popular in industrial environments, may lead to intermittent or lossy connections at sensor nodes.[14] In TSCH networks, a node typically uses advertisement (ADV)-based and keep-alive (KA)-based scheme to advertise EB and KA packets, respectively, for maintaining synchronization.[15] Under a high interference environment, if these packets are lost, related nodes may suffer from de-synchronization. As a result, they are required to rejoin the network.

To reduce joining overhead, De Guglielmo et al.[16] proposes random-based advertisement (RbADV) algorithm in which each synchronizer advertises EBs periodically after a time period (i.e. a number of slots). The advertisement operation is carried out at scheduled cells to reduce collision. E Vogli et al.[17] introduces two novel advertisement broadcast scheduling mechanisms including random vertical filling (RV) and random horizontal filling (RH) algorithms to speed up joining time. In RV, each synchronizer periodically sends only one EB on a random *channelOffset* and at the first timeslot in every multiple slotframes period. In RH, each synchronizer sends EBs at a random timeslot within multiple slotframes and on the *channelOffset* 0. The performance of the two mechanisms is comparable. However, we see that the joining time of the above mechanisms highly depends on the number of synchronizers in TSCH networks. To achieve a short joining time, those mechanisms require a great number of synchronizers which may not be available in many cases of real network deployment. In case of a small number of synchronizers, a node has to wait for a long time period to join the network, and the joining overhead is thus expensive. This is a considerable limitation of the existing studies. As network conditions such as network density may vary, an adaptive scheme is required to achieve a balance between joining time and energy consumption for network formation.

In this article, we propose a novel fast joining scheme which is extended from our previous work,[18] with a new design of slotframe in TSCH networks. A novel fuzzy-logic-based adaptive mechanism is also proposed to enable a synchronizer to be able to adaptively determine an appropriate number of EBs it should advertise based on the network density, that is, the number of available synchronizers in network, so that a joining node can achieve a short joining time at any case regardless of the number of synchronizers while energy consumption of EB advertisement at the synchronizer is optimized.

In summary, this article makes the following contributions:

1. We find out the limitation of existing schemes. Without ability of adapting to the network density, the existing schemes may perform inefficiently in case of a small number of synchronizers or dynamic networks.
2. We propose a novel joining scheme based on fuzzy logic, which allows a synchronizer to adapt its EB advertisement operation based on the number of available synchronizers in network to achieve a short joining time in all cases and optimize energy consumption.
3. Through extensive mathematical analysis and experimental results, we show that the proposed scheme achieves a significant improvement compared to the state-of-the-art schemes in terms of joining time.

The rest of this article is organized as follows: section "Related work" provides the background about IEEE 802.15.4e standard. Section "Proposed approach" presents our proposed approach for network formation in TSCH networks in detail. Section "Performance evaluation" reports the insight of performance evaluation, experimental results, and discussion. Finally, section "Conclusion" concludes this article.

Related work

TSCH mode in IEEE 802.15.4e

In IEEE 802.15.4e networks, all sensor nodes synchronize on a periodic slotframe made by a number of timeslots. Each timeslot is assigned a type value for sensor activity. TSCH defines three main types of non-idle slot: advertisement broadcast—ADV slot, transmission—Tx slot, and reception—Rx slot. The IEEE 802.15.4e uses channel hopping mechanism to timeslotted access, in which a sensor node changes its communication channel frequency at each timeslot with different instants. Therefore, fading and interference issues are mitigated efficiently.

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

$$f = F\{(ASN + channelOffset) \bmod N_{ch}\} \quad (1)$$

where N_{ch} is the number of available physical frequencies, and with IEEE 802.15.4-compliant radio at 2.4 GHz band, N_{ch} can be up to 16 channels. The function F includes a lookup-table mapping between real frequency value (in GHz) and physical channel number in the range [11–26]. ASN presents the total number of slots since the start of TSCH networks, and it is calculated as follows: $ASN = (n \cdot L_{slotframe} + slotOffset)$, where n defines the slotframe cycle and $L_{slotframe}$ is the slotframe length. Note that $0 \leq slotOffset \leq L_{slotframe} - 1$ and $0 \leq channelOffset \leq N_{ch} - 1$.[19]

TSCH network formation

When a TSCH network establishes, sink node first broadcasts EBs to advertise network presence. An EB provides enough information of the existing network, such as ASN value, channel hopping information, timeslot information, and slotframe information. Once a joining node wants to join the network, it listens for EBs on its own synchronization channel. After receiving an EB, the joining node synchronizes with sink node through ASN value and aligns its slotframe to that of the overall network. At the same time, its MAC layer notifies the higher layer to execute other tasks. Following scheduled cells in the slotframe, this node conducts the activities such as network topology configuration, routing setup, and authentication for network formation phase. Then, it becomes a synchronizer and continuously broadcasts EBs to extend the network as well as maintain network synchronization.

Routing protocol in TSCH: RPL

RPL[11] is the IPv6 routing protocol for low-power and lossy networks standardized by the IETF ROLL WG. In particular, the IETF 6TiSCH WG proposes RPL on top of the TSCH mode of IEEE 802.15.4e to address challenging industrial scenarios such as industrial automation and deterministic control loops. In a network using RPL, sensor nodes are organized in a destination-oriented directed acyclic graph (DODAG) structure. DODAG is rooted at a sink or multiple sink nodes. Each node is attached a rank which is computed by an object function (OF) based on routing metric (e.g. link quality).

The DODAG construction begins to be built from sink node. The sink node periodically broadcasts a DODAG information object (DIO), a signaling message containing its rank and other configuration parameters. In 6TiSCH network, when a joining node receives an EB and becomes a synchronizer, it is permitted to receive DIOs. Based on received DIOs, this node inserts transmitters's address in its *NeighborList* for selecting a preferable parent.[20] After using OF to compute its own rank, it starts to broadcast DIOs to the network. Thanks to this mechanism, each node can know its number of neighbors based on the information of *NeighborList*, which is also the number of synchronizers the node recognizes in network. In this article, we use RPL as a principal routing protocol of network layer for discussing our proposal.

Proposed approach

In this section, we describe the design for our proposed joining scheme and fuzzy-logic-based adaptive EB advertisement mechanism in detail.

Proposed joining scheme in TSCH networks

Typically, the IEEE 802.15.4e does not define any specific structure for slotframes. For designing an efficient joining scheme, we propose to separate a slotframe into two parts including an advertisement plane highlighted by yellow color and a communication plane, as revealed in Figure 1. The advertisement plane consists of ADV slots which are reserved for broadcasting EBs. The communication plane is only used to exchange data packets. The separation is to eliminate the impact of EB advertisement on data transmission in TSCH networks. In the advertisement plane, the scheduling for EB advertisement specifies which ADV slots and channels or which ADV cells a synchronizer broadcasts EBs in a multiple slotframes ($multi-slotframe$). Figure 1 also shows an example about the scheduled ADV cells (i.e. red cells) in the advertisement plane. Instead of using ($slotOffset, channelOffset$) to identify a cell, ($slotOffset, physicalChannel$) is used, where *physicalChannel* is translated by equation (1). In the figure, each multi-slotframe includes three slotframes, and the advertisement plane can contain up to five ADV slots. With four ADV slots of the scheduled ADV cells, synchronizers in network only broadcast EBs at these four available ADV slots of a multi-slotframe, and after three slotframes period, they repeat this action.

Based on the design, the joining scheme is proposed to reduce joining time as follows: each synchronizer uses random consecutive physical channels (e.g. channels 14, 15, 16, and 17 as illustrated in Figure 1) to broadcast EBs at consecutive ADV slots in the advertisement plane and repeats the EB advertisement periodically after a multi-slotframe period. The number of consecutive broadcast channels is equal to the number of scheduled ADV slots; with a joining node, it chooses a random available channel to listen for EBs. By exploiting multiple ADV slots with consecutive channels, the probability that a joining node listens on the same channel with one of synchronizers is increased. This increases a chance that a joining node may receive EBs at early stage to reduce joining time even when there is only a small number of available synchronizers.

Theoretical analysis

We now theoretically analyze the joining time of the proposed scheme in comparison with RV,[17] a recent study investigating on TSCH formation.

We assume that a joining node J starts to listen for EBs on a channel f_J at time t_0 to join a network with a set S of N synchronizers, $S = \{S_i\}$ and $i = 1, \ldots, N$.

Statement 1. The necessary condition that node J joins the network within a period T is $\exists S_i(\forall S_i \in S)$; S_i sends at least an EB packet on the same channel f_J at time $t_1(t_1 - t_0 \leq T)$; and at time t_1, $\forall S_k$ with $k = (1, \ldots, N)/i$, $f_k \neq f_J$. Moreover, we also consider two other conditions as follows: the first condition is to guarantee that there is at least one synchronizer using the same channel with J to send EB during the listening period of J; the second condition is necessary to ensure that the EB advertisement of S_i is not failed due to the collisions.

With a total number of N synchronizers, the first condition happens with the probability

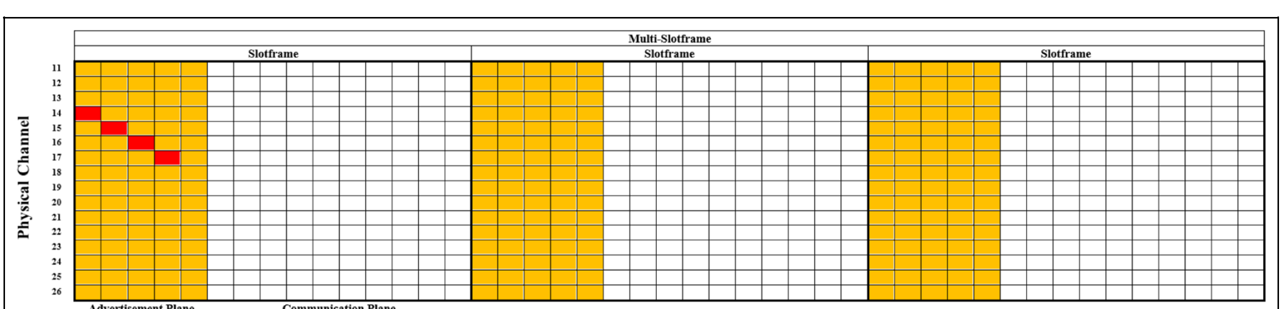

Figure 1. Slotframe structure of the proposed joining scheme.

$$P_1 = N \cdot \frac{1}{C} \tag{2}$$

The probability that a node $S_k (S_k \neq S_i)$ at time t_1 uses a channel f_k so that $f_k \neq f_J$ is $(1 - (1/C))$. Derive this probability for $(N-1)$ nodes (N nodes excluding node S_i), and we have the probability to happen the second condition, that is

$$P_2 = \left(1 - \frac{1}{C}\right)^{N-1} \tag{3}$$

From equations (2) and (3), the necessary condition occurs with the probability

$$P = N \cdot \frac{1}{C} \cdot \left(1 - \frac{1}{C}\right)^{N-1} \tag{4}$$

Node J has C options of f_J, and each option has a probability to occur the necessary condition, given in equation (4). We can calculate the number of channels, ∂, which J can select, so that the necessary condition happens as follows

$$\partial = C \cdot P = N \cdot \left(1 - \frac{1}{C}\right)^{N-1} \tag{5}$$

Now, considering a perfect network condition, the number of multi-slotframes, M_s (each multi-slotframe is a duration of T_M), that node J needs to join the network can be considered as a uniform discrete random variable with a range of $[1 - C]$ (the best case is 1 and the worst case is C). In each multi-slotframe, a node S_i may advertise N_{EBs} messages on different channels. Therefore, we calculate the expected M_s as follows

$$M_s = \frac{C+1}{2 \cdot \partial} = \frac{C+1}{2 \cdot N \cdot N_{EBs}} \cdot \left(1 - \frac{1}{C}\right)^{1-N} \tag{6}$$

However, the perfect condition is unrealistic. In fact, the transmission errors on channels may happen, depending on the network condition. As a result, packet delivery ratio, PDR, is normally smaller than 1. A node J can join the network if and only if a synchronizer S_i transmits EB packets on the same channel f_J successfully. By considering such a realistic network condition, M_s should be calculated as follows

$$M_s = \frac{C+1}{2 \cdot N \cdot N_{EBs} \cdot PDR} \cdot \left(1 - \frac{1}{C}\right)^{1-N} \tag{7}$$

Based on equation (7), the expected joining time $T_{join}^{propose}$ of the proposed scheme is then calculated as follows

$$T_{join}^{propose} = M_s \cdot T_M = \frac{(C+1) \cdot T_M}{2 \cdot N \cdot N_{EBs} \cdot PDR} \cdot \left(1 - \frac{1}{C}\right)^{1-N} \tag{8}$$

From equation (8), it is clear to recognize that the joining time of a node depends on not only the number of synchronizers but also the number of EBs it may advertise.

In RV, a node is permitted to advertise only once per multi-slotframe. Similarly, we obtain the joining time T_{joim}^{RV} as follows

$$T_{joim}^{RV} = M_s \cdot T_M = \frac{(C+1) \cdot T_M}{2 \cdot N \cdot PDR} \cdot \left(1 - \frac{1}{C}\right)^{1-N} \tag{9}$$

Discussion. By comparing equations (8) and (9), we can see that by designing an advertisement plane with multiple ADV slots, the proposed scheme can reduce the joining time by N_{EBs} folds compared to RV. The proposed scheme achieves a short joining time even when the number of synchronizers is low, by adjusting the number of EBs. Therefore, the proposed scheme helps cut off a significant delay and overhead for the network formation, especially so in highly dynamic networks.

Practically, the number of ADV slots affects significantly the throughput of TSCH networks. In our implementation, we consider only a small number of slots for the advertisement plane (i.e. 5% of the total number of slots in a slotframe).[21]

Fuzzy-logic-based adaptive EB advertisement mechanism

In the above proposed scheme, synchronizers exploit all ADV slots for EB advertisement to achieve a short joining time. However, from equation (8), there is a trade-off between joining time and energy consumption when we increase the number of EBs. In order to reduce the joining time, synchronizers have to utilize more EBs, thus suffering higher energy consumption. In addition, equation (8) also indicates that the joining time of a joining node depends on not only the number of EBs that a synchronizer utilizes but also the number of available synchronizers in network. It means that when the number of synchronizers is high, only small number of advertised EBs is enough for EB advertisement of each synchronizer to achieve a short joining time, and utilizing a great number of advertised EBs is obviously unnecessary and inefficient. Inspired from this observation, we propose an adaptive EB advertisement mechanism based on fuzzy logic[22] for our joining scheme. The mechanism determines an appropriate number of EBs a synchronizer should advertise, based on the number of available synchronizers in network, so that a node joining the network can achieve a short joining time while the energy consumption of EB advertisement at the synchronizer is optimized. Note that a synchronizer can know the other available

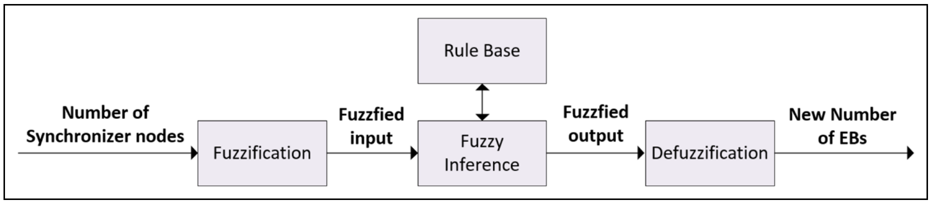

Figure 2. Model of fuzzy system for adaptive EB advertisement.

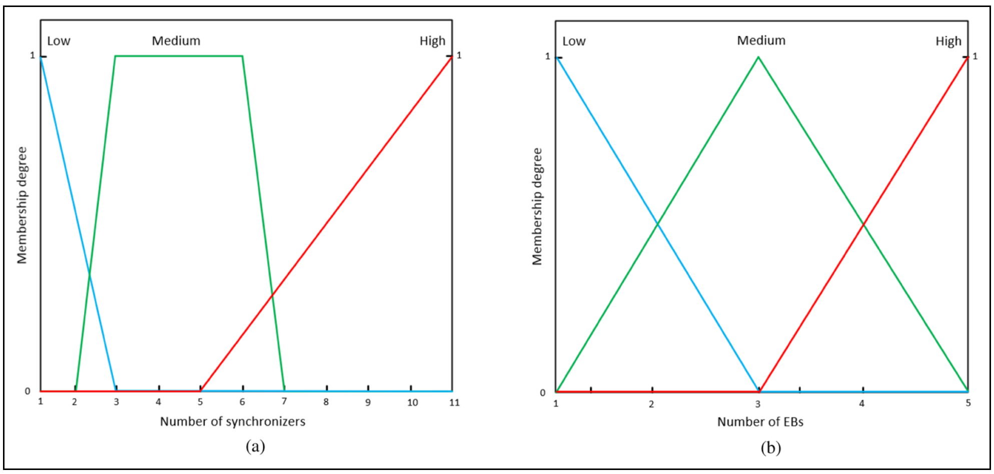

Figure 3. Mamdani membership functions of (a) input variable (number of synchronizers) and (b) output variable (new number of EBs).

synchronizers in network based on the *NeighborList* information available at its network layer.

Figure 2 presents our fuzzy system model of the adaptive EB advertisement mechanism. The input variable (i.e. number of synchronizers) is initially in a numerical format, called crisp input. Fuzzification maps each crisp input value to the corresponding three fuzzy sets characterized by Mamdani membership functions (Low, Medium, High).[23] In detail, the input value is assigned a membership degree for each fuzzy set as shown in Figure 3(a). The fuzzified input is processed by inference mechanism based on the IF-THEN construct of computer programming which is defined as rules in Table 1. For example, at rule 1, if current number of synchronizers is *Low*, the number of EBs will change to be *High*. The number of EBs in form of fuzzified output, represented by membership functions as shown in Figure 3(b), will be defuzzified by deffuzzification through the first-of-maximum (FOM) algorithm and then converted to a crisp output value. This crisp output value is also a new number of EBs a synchronizer should advertise to network. From mathematic model in N Nedjah and M Maurelle,[22] the crisp output is the smallest value which has the highest membership degree in the obtained fuzzy set. Therefore, new number of EBs, N_{EBs}^{Fuzzy}, is given by

Table 1. Interference rules for fuzzy system.

Rule	IF number of synchronizers is	THEN number of EBs is
1	Low	High
2	Medium	Medium
3	High	Low

$$N_{EBs}^{Fuzzy} = \{x|\mu(x) = max(x_i) \wedge \forall x_i, x < x_i\} \tag{10}$$

where x_i is the crisp output value of membership function i, and $\mu(x)$ is the membership degree of crisp output value x.

Energy consumption model of EB advertisement

We model energy consumption of EB advertisement based on the previous work.[15] Let Q be the energy consumption of EB advertisement in single multi-slotframe at a node. Q is given by

$$Q = N_{EBs} \times \left(\frac{PktSz}{MaxPktSz} \times Q_{ADV}\right) \tag{11}$$

For adaptive EB advertisement

Table 2. Measured and calculated charge drawn of TelosB and OpenMote-STM32 for each packet size, one ADV slot, in μC.

Size	TelosB		OpenMote-STM	
	Measured	Calculated	Measured	Calculated
30 bytes	16.4	18.1	28.1	29.1
60 bytes	32.9	36.2	56.3	58.1
90 bytes	49.3	54.3	84.5	87.2
127 bytes	69.6	76.7	119.2	123.1

$$Q^{fuzzy} = N_{EBs}^{fuzzy} \times \left(\frac{PktSz}{MaxPktSz} \times Q_{ADV} \right) \quad (12)$$

where $PktSz$ is the packet size of an EB; $MaxPktSz$ is the maximum size of a packet in TSCH networks, typically equal to 127 bytes; and Q_{ADV} is the energy consumption during an ADV slot when advertising an EB having $MaxPktSz$. Usually, an EB consists of an ASN value, initial link, and slotframe information for joining nodes to join a network. Therefore, the packet size of each EB is configured depending on the number of links and options encoded as information elements (IE) in the advertisement (26–127 bytes). Table 2 presents the energy consumption of an ADV slot with various packet sizes of the EB, under measurement, and model calculation based on results from X Vilajosana et al.[15,24]

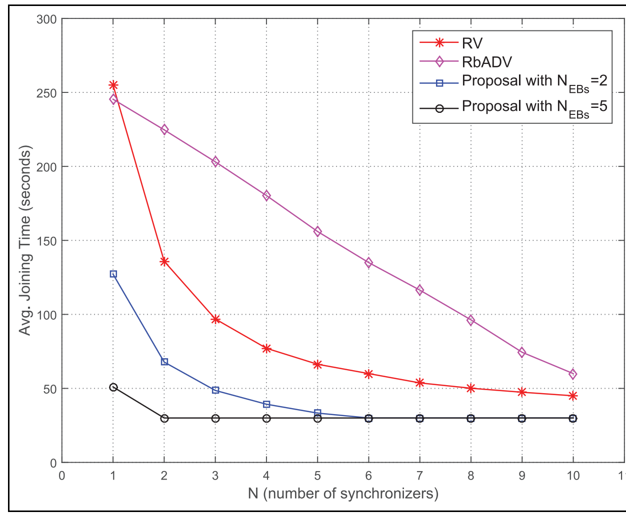

Figure 4. Average joining time under various number of synchronizers.

Performance evaluation

We now move to evaluate performance of the proposed scheme in comparison with the state-of-the-art schemes, based on both mathematical model and experimental results. We use two metrics as follows:

1. *Average joining time* (s): it is the mean time a joining node needs to join a TSCH network.
2. *Average power consumption* (μC/s): this metric indicates the average energy consumption of EB advertisement for network formation in a TSCH network.

Theoretical results

We assume that a multi-slotframe consists of 20 slotframes. A slotframe contains 101 timeslots, and each slot is 15 ms long. In addition, $PDR = 1$, $C = 16$, and $N_{EBs} = 2$ and 5. Results obtained through the theoretical model presented in section "Theoretical analysis" are plotted in Figure 4. The figure presents the average joining time under various number of synchronizers. The results indicate that the proposed scheme helps reduce the joining time significantly in all cases including a low and a high number of synchronizers, compared to RbADV algorithm[16] and RV algorithm.[17] In detail, at low network density (i.e. the low number of synchronizers), the joining time of the proposed scheme is much shorter than the two state-of-the-art schemes. The difference between them becomes smaller when the density is higher. By using more EBs, the proposed scheme with $N_{EBs} = 5$ achieves a significantly shorter joining time than that with $N_{EBs} = 2$ at low network density. However, when the density is high with a greater number of synchronizers, the results of the two graphs are similar. Based on this finding, an adaptive mechanism is thus necessary, which is evaluated in the next part.

Implementation and experimental results

Implementation. We implement the proposed scheme using OpenWSN stack—an open-source implementation of a fully standards-based protocol stack for capillary networks, rooted in the new IEEE 802.15.4e TSCH standard[25]—to evaluate the performance in real environments. The main language of OpenWSN is pure C. Experiments are conducted on TelosB motes with MSP430 microcontroller, 10k RAM, and 48k Flash. In our setting, all available 16 channels are used for communication. Similar to the theoretical model, we configure 20 slotframes for a multi-slotframe. Each slotframe has 101 timeslots with 15 ms long for a slot. Moreover,

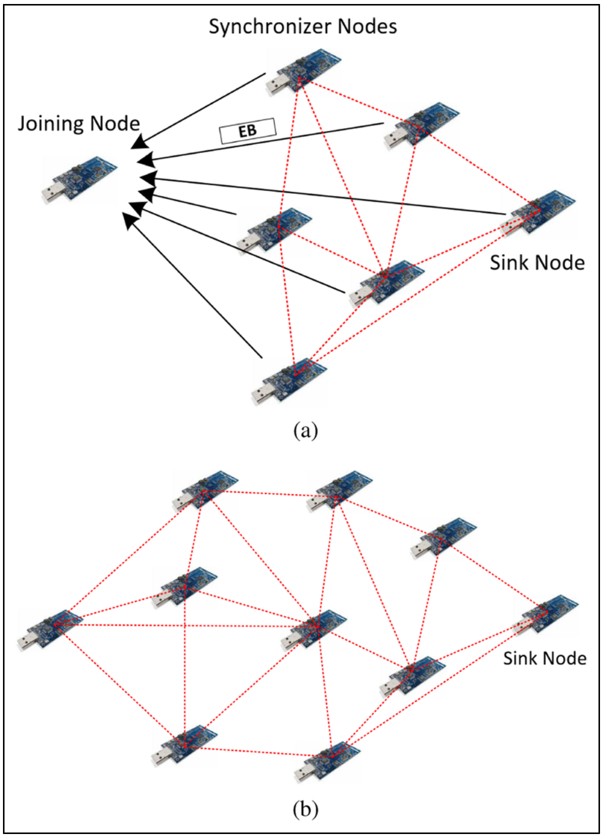

Figure 5. Network model used in experiments of (a) joining time and (b) power consumption.

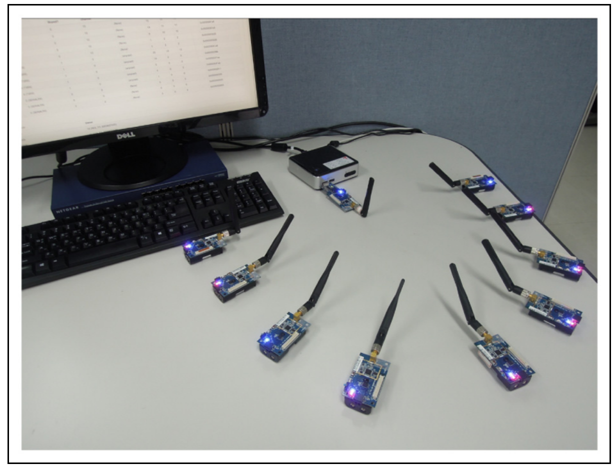

Figure 6. TelosB motes deployed for testbed.

the advertisement plane contains five ADV slots, and an EB has a length of 60 bytes. The experimental model and testbed deployment are shown in Figures 5 and 6, respectively. The random network topology is used for experiments. Each point on plots is the average of 10 measurements, and the error lines are minimum and maximum values.

In case of joining time, we set up experimental network model as shown in Figure 5(a). The network consists of N synchronizers (including sink node) which are in communication range of each other and with joining node. The joining time is measured from the time a joining node turned on to the time it receives the first valid EB. Different scenarios are created by varying N parameter from 1 to 10. In case of power consumption, we use a constant of 10 nodes as shown in Figure 5(b). Each experiment is conducted for 120 min. During experimental period, nodes join or rejoin randomly, so the number of available synchronizers varies dynamically. The power consumption of EB advertisement is obtained over the 10 nodes in the network.

Experimental results

Validation. First, we validate our analytical model by comparing theoretical results with testbed results. Figure 7(a) and (b) presents the correlation between analytical and experimental results in case of $N_{EBs} = 2$ and $N_{EBs} = 5$, respectively. The experimental results are slightly higher than the analytical results due to hardware delay in real motes. Importantly, the performance trend calculated by our model has strong coherence with testbed results, which shows that our analytical model is accurate enough to capture main behaviors of each protocol's performance. In detail, Figure 7(a) reveals that the joining time is reduced from 150 to 30s when the number of synchronizers increases from 1 to 6. After that it remains the same within 30s, which is the minimum joining time a node can obtain. In Figure 7(b), the number of EBs is increased to 5. In this case, the joining time in every case is shorter than two folds even when there is only one synchronizer. These results indicate that the higher the number of EBs, the shorter the joining time.

Figure 7(c) and (d) illustrates the power consumption of EB advertisement in the overall network with $N_{EBs} = 2$ and $N_{EBs} = 5$, respectively. The comparison between them shows that using more number of EBs helps shorten joining time, but consumes more energy.

We now compare the experimental results of the adaptive scheme using fuzzy logic with the original one ($N_{EBs} = 5$) and RV algorithm. The average joining time of the schemes under a dynamic scenario of the number of synchronizers is shown in Figure 8(a). In detail, the proposed adaptive and original schemes achieve similar joining time, and both of them have a better performance than RV. In terms of power consumption, Figure 8(b) reveals that the adaptive scheme helps reduce power consumption of EB advertisement in the network by 45% compared to the original one, thus reducing the trade-off between joining time and energy consumption while its joining time is much shorter than that of RV.

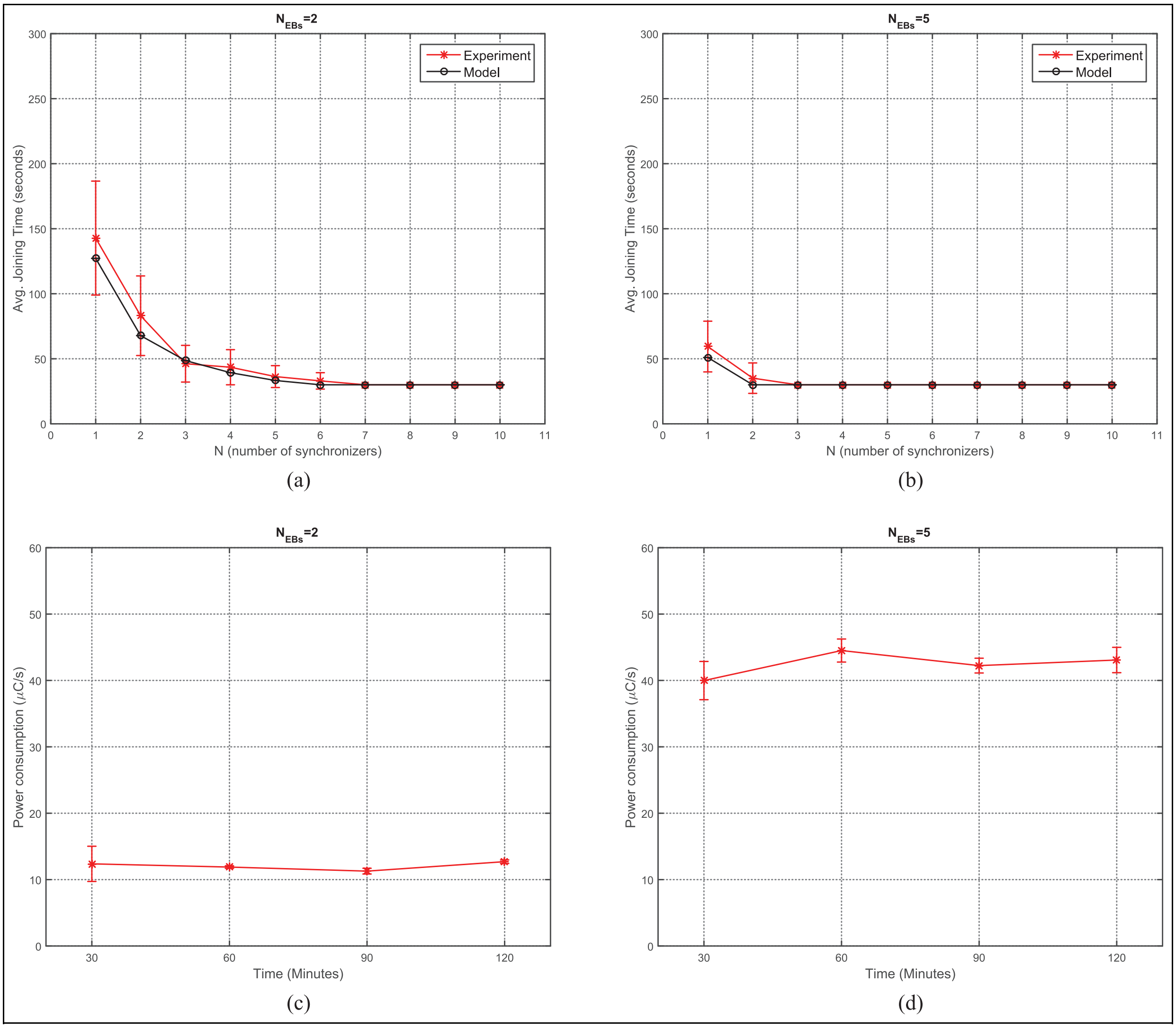

Figure 7. Average joining time under various number of synchronizers in case of (a) $N_{EBs} = 2$ and (b) $N_{EBs} = 5$, and power consumption versus time in case of (c) $N_{EBs} = 2$ and (d) $N_{EBs} = 5$.

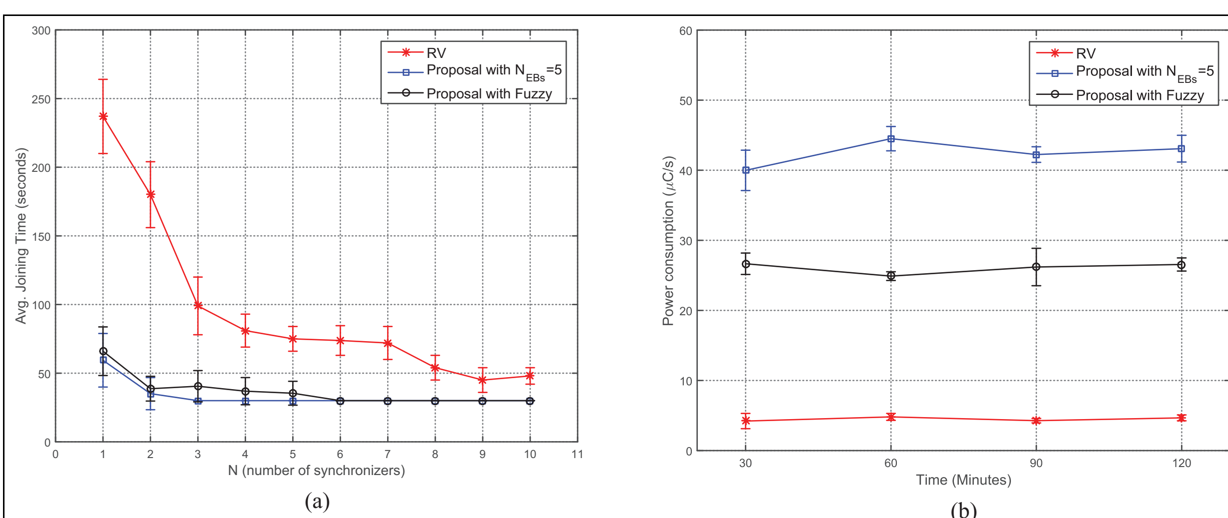

Figure 8. Comparison between the adaptive, non-adaptive scheme ($N_{EBs} = 5$) and RV in term of (a) average joining time and (b) power consumption.

Conclusion

In this article, we present a rapid joining scheme to speed up network formation through a new structure of slotframe in highly dynamic TSCH networks. Moreover, we also propose an adaptive mechanism to adjust the number of advertised EBs based on network density to optimize energy consumption. Through extensive mathematical analysis and experimental testbed on TelosB motes, the results show that the proposed scheme achieves a significant improvement in terms of joining time compared to other schemes.

Declaration of conflicting interests

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