Enhanced Beaconless Synchronization for Regulatory Domain Specific IEEE 802.15.4g Smart Utility Networks

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Abstract—**This paper proposes a generic enhanced beaconless synchronization mechanism for industrial standard IEEE 802.15.4g Smart Utility Networks (SUN) in multiple regulatory domains globally. IEEE 802.15.4g has specified different regulatory domains for SUN applications, each with a distinctive set of channelization and corresponding operating parameters such as center frequency, channel width and channel spacing. This has added new challenges not limited to, but particularly in beaconless synchronization mechanism supporting low energy consumption demands in conventional IEEE 802.15.4 low rate wireless personal area networks (WPANs). This paper first provides the updates in the SUN technical specification, identifies the challenges due to the effort of addressing multi-regional governing regulatory demands and then proposes a generic solution to tackle the problem. This simple but straightforward approach is preferable in industrial applications with strict energy efficiency requirement. The proposed beaconless synchronization mechanism has outlined two metrics with conflicting interest, namely required time to achieve synchronization and effective bandwidth for data communication. As a result, it is found that as the input radio resource increases, the effective communication bandwidth increases exponentially, while the required time for synchronization increases only linearly.**

Keywords: Beaconless synchronization, IEEE 802.15.4g, smart utility networks, regulatory domains, smart grid

I. Introduction

The Smart Grid Framework [1] is proposed for the ultimate objective to conserve and optimize electricity consumption. In order to realize this extremely huge and complicated framework, various entities of pervasive functions and characteristics are connected to form a super-structured framework, a system of systems. Among others, one essential component in the Smart Grid Framework responsible of establishing and maintaining connectivity among the entities, is the Smart Grid Information Network.

On par with the vision of the Smart Grid Information Network, an initiative to modernize the networking and communication systems in the next generation utility services is actively underway for the past few years. The primary target of the initiative is to establish Smart Utility Networks (SUN) to optimize the networking system in public utility services such as electricity, water and gas. Among other efforts mobilized in this direction, IEEE 802.15.4g is a standardization group developing a global standard for the low rate wireless personal area network (WPAN) system [2] for SUN. The IEEE 802.15.4 low rate WPAN standards family mainly targets the application domain requiring systems with low data rate, low power consumption and low complexity. Compared to its high and medium rate counterparts such as 802.15.3 high rate WPAN [3] and 802.11 wireless local area network (WLAN) systems [4], 802.15.4 has pronounced emphasis on many low energy consumption features tailored for low rate applications.

Inheriting the 802.15.4 base standard [5] along with all its functionalities, the 802.15.4g standard has all the low energy consumption features at its disposal. In the physical (PHY) layer design, the multi-rate frequency shift keying (MR-FSK) PHY is supported by many vendors and system integrators. In the medium access control (MAC) layer design, many low energy MAC functionalities such as low power MAC architecture, beaconless MAC architecture and power saving mechanisms are supported. From the system design point of view, 802.15.4g is a system built on top of the 802.15.4 platform with optimization for SUN industrial applications.

This paper highlights one potential problem encountered by the 802.15.4g SUN specification in inheriting the beaconless synchronization mechanism from [5]. The beaconless synchronization in [5] is a low energy consumption mechanism facilitating time synchronization between network devices and coordinators without having the coordinator to transmit periodic beacons. Devices wishing to associate to a network can simply send a request to the coordinator asking for a beacon, receive the beacon, perform the intended data exchange and go to sleep mode for the rest of the time. The idea of the mechanism is to reduce power-hungry channel scanning operations by network devices, thus reducing power consumption and prolonging battery lifespan. This effective and essential 802.15.4 MAC functionality, is however, facing some challenges due to the amendments specified by 802.15.4g, newly added to address global SUN regulatory and system demands.

Therefore, in this paper, we have proposed an improved mechanism for beaconless synchronization for 802.15.4g SUN systems with the diversified and more complicated channelization. The contribution of this paper is three-fold: (a) provided the latest updates on the 802.15.4g SUN specification, (b) addressed the potential challenges posed by the newly specified SUN channelization to conventional beaconless synchronization and, (c) proposed an improved method by modifying the existing mechanism.

The organization of this paper is given in the following:

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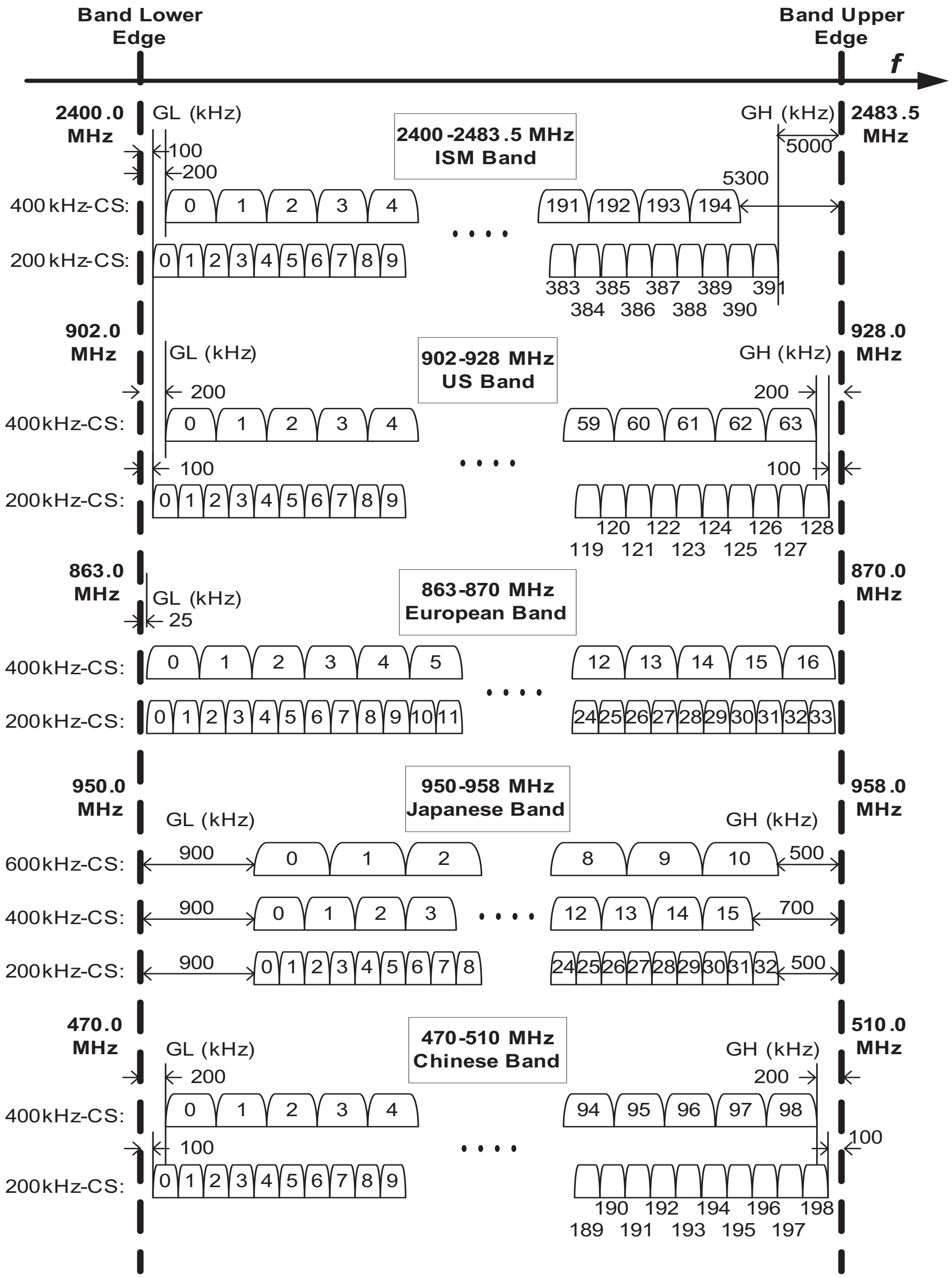

Fig. 1. Channelization of Major Regulatory Domains for SUN Frequency Bands. CS: channel spacing. GL: lower guard band. GH: higher guard band. ISM: Industry-Science-Medical.

The background and details of the problem are explained in Section II. The different regulatory and operating requirements for SUN are described in Section III. A brief introduction of the IEEE 802.15.4g network and the conventional beaconless synchronization method are given in Sections IV and V. The proposed solution to tackle the problem is detailed in Section VI. The evaluation of the proposed approach is given in Section VII. Finally Section VIII shows the corresponding text in [2] that enables the employment of this proposed mechanism.

II. Problem Background

The channelization for 802.15.4g PHY layer has been designed to support multi-channel-spacing, multi-rate and multi-PHY operations to address different regulatory domains, system demands and application segments. In particular, the specification with multiple center frequencies and channel spacing (CS), although capable of increasing flexibility in communication speed scalability, has presented new challenges to the synchronization process, especially when the beacon is absent.

Most conventional WPAN systems employ a single CS scheme for the same PHY layer design. This architecture is straightforward for discovery and synchronization between devices since there is only one center frequency and CS choice for an incoming device to attempt to discover an existing coordinator in a particular channel. On the other hand, when the channelization becomes more diversified (*i.e.* more alternative CS schemes among which the center frequencies are not consistently aligned), discovery and synchronization becomes difficult because newly powered-on devices do not know which CS scheme to use in order to discover the existing coordinator in an operating network.

An example can be given with reference to the 2400-2583 MHz band in Figure 1. First, assume that an incoming device with 200-kHz CS scheme is powered-on in channel #2 for the first time and is seeking to discover and synchronize with an existing coordinator. Secondly, assume that the existing coordinator is operating in channel #0 in the 400-kHz CS scheme. In this example, it is impossible for the incoming device to synchronize with the coordinator, and yet interference will be generated if the incoming device proceeds to occupy channel #2 in the 200-kHz CS scheme. To make the condition worse, beaconless synchronization further requires the incoming device to request the beacon from the coordinator, increasing the level of impossibility in the discovery process.

Generalizing from the example given above, the following generic conditions can be derived. In a system employing one common CS scheme for beaconless synchronization, both the device and the coordinator are constantly using the same format of signaling. On the other hand, if multiple CS parameters are allowed, beacon request frames and beacons may be blindly sent in multiple CS schemes by different devices, significantly reducing the effectiveness of the synchronization process. As a result, multiple networks may be deployed in close proximity, generating mutual interference. Therefore, there should be a control mechanism to ensure the alignment of the same CS and center frequencies during the commencement of discovery and synchronization. To our best knowledge, this control mechanism has not been addressed in existing literatures.

III. Channelization

There are a total of twelve regulatory-domain-specific frequency bands allocated for deployment of IEEE 802.15.4g SUN [2]. In this section, five of the major bands are listed for discussion:

- 2400-2483.5MHz (Worldwide)
- 902-928MHz (United States)
- 863-870MHz (Europe)
- 950-958MHz (Japan)
- 470-510MHz (China)

Figure 1 illustrates the channelization of the MR-FSK PHY in these regulatory domains. At the band lower edge of each channel plan, there are different values of guard bands denoted as GL to reduce out-of-band interference. The guard bands for upper edge are denoted as GH and are allocated for the same purpose.

One important parameter in the channelization is the channel spacing (CS). CS can be generally known as the amount of bandwidth allocated for communication of signals. In Figure 1, CS is defined as the occupied bandwidth between the center frequency of a particular channel to that of the adjacent channel. All five bands are employing CS of 200kHz and 400kHz, with an additional 600kHz CS in the 950-958MHz band. By referring to Figure 1, the total number of channels allocated for each frequency band with respective CS values can be determined.

Another essential parameter is the center frequency of each channel. Out of the five bands, the 2400-2483.5MHz band, 902-928MHz band and 470-510MHz band have aligned center frequency between the 200kHz and 400kHz CS, while the 863-870MHz and 950-958MHz bands have unaligned center frequencies between different CS.

The employment of multiple types of CS is the key issue to be discussed in the later sections.

IV. Network Management in IEEE 802.15.4g SUN

An IEEE 802.15.4g network consists of at least two devices, one of which is the coordinator. The coordinator is responsible of controlling the timing of the network, and manage the radio resources among devices operating within the network. The coordinator is a full function device (FFD) which contains the complete set of specified MAC services. The coordinator is assumed to be connected to power source and thus able to perform a higher level of power-hungry operations. The reduced function device (RFD) is a device that contains a reduced set of MAC services. The RFDs are normally end nodes performing only a specific set of functionalities, *e.g.* wireless meters.

There are two types of network management modes specified in SUN, the beacon-enabled mode and the non-beacon-enabled mode. A network in the beacon-enabled mode requires the coordinator transmitting beacons to surrounding devices periodically. The devices are required to scan for the beacon, and may associate with the coordinator to form communication links upon receiving the beacons. This is known as passive scanning. On the other hand, a network in non-beacon-enabled mode requires the devices intending to join the network to send a beacon request to the coordinator. Only upon receiving the beacon request, the coordinator sends out the beacon. This is known as active scanning.

Both passive and active scanning mechanisms are employed to facilitate synchronization between devices in the network. Synchronization is important to establish time reference between the coordinator and the devices. Additionally, information on the network management such as PHY and MAC parameters are distributed to devices in the process of synchronization.

Synchronization in the beacon-enabled mode is fairly straightforward. Since beacons are sent periodically, the coordinator can include relevant network management information into the beacons and inform the associated devices. Once the devices scan and receive the first beacon, they have knowledge of the network and can proceed accordingly. This paper focuses discussions on beaconless synchronization in following sections.

V. Beaconless Synchronization for IEEE 802.15.4 Low Rate WPAN

In conventional non-beacon-enabled network mode in low rate WPAN [5], a typical procedure of beaconless synchronization is illustrated in Figure 2(a). The coordinator is constantly in receive mode scanning to detect beacon request from devices. When the coordinator receives a beacon request (BReq) frame, it switches from receive mode to transmit mode in order to send the beacon to the requesting device. Likewise, the requesting device, after sending the BReq, changes to receive mode to receive the beacon from the coordinator. After receiving the beacon, the device goes to sleep mode to preserve battery lifespan. Since coordinator is an FFD, most of the power-hungry scanning operation is conducted by the coordinator to reduce power consumption of other RFDs. Besides beacon request, this procedure can also be used for data request by devices.

It is important to note that the procedure in Figure 2(a) assumes that both the coordinator and the device are transmitting and receiving with the same data rate mode all the time. In the context of this paper, the CS used for transmitting and receiving is constantly the same. From [5], it can be observed that each PHY is employing one particular CS value at all times.

On the other hand, in Figure 2(b), it is assumed that there are multiple allowable choices of PHY parameters such as CS. In this case, the situation becomes more complicated and thus require more detailed procedures in order for the synchronization protocol to work. The example in Figure 2(b) uses the parameters following the SUN specifications. CS of 200kHz is employed by the coordinator in receive mode, while CS of 400kHz is used to transmit the BReq to the coordinator. It is clear that the coordinator will not be able to receive the BReq frame from the device. Synchronization becomes almost impossible. In certain regulatory domains, besides difference in CS, even the center frequencies are not aligned between 200kHz CS and 400kHz CS. This adds difficulty in synchronizing the device and the coordinator in SUN.

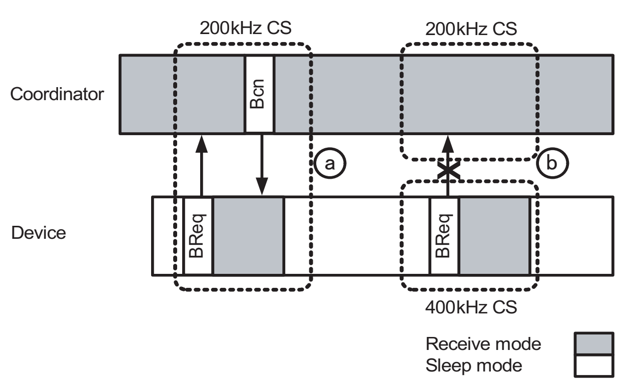

Fig. 2. Illustration of Beaconless Synchronization in Conventional Low Rate WPAN. Case (a): Same CS for both transmitter and receiver. Case (b): Different CS for transmitter and receiver. CS: channel spacing. Bcn: beacon. BReq: beacon request.

VI. Beaconless Synchronization in SUN

As described in Section III, in the IEEE802.15.4g SUN specification [2], there are multiple choices of CS. Therefore, for beaconless synchronization in SUN, additional procedures to [5] are necessary to ensure reliable discovery between devices.

Figure 3 presents the proposed idea for beaconless synchronization between SUN devices. First of all, among the specified data rate modes, one, normally the most robust mode, *i.e.* the mode with the lowest data rate and best error performance, is chosen as the *base rate mode* (BRM). The BRM is the mode for exchanging command and control messages for purposes of synchronization, *i.e.* the beacon and beacon request frames. The coordinator will periodically allocate a portion of its operation time as receive mode in BRM, while other portions can be allocated to other higher speed communication modes. The device will then try to heuristically achieve synchronization with the coordinator by sending BReq frames and monitor the reply.

Figure 4 shows the flow chart of the internal operation of a device in the course of achieving beaconless synchronization with the coordinator. The following parameters are defined to facilitate the procedure in Figure 4:

- T_{scan} - duration of receiving mode in BRM of the coordinator
- T_{SI} - the interval between the start of one BRM to that of the next
- N_{scan} - T_{SI}/T_{scan}

The coordinator periodically switches to BRM receive mode, *e.g.* with 200kHz CS, for duration of T_{scan}. The interval between one T_{scan} period and the start of the next

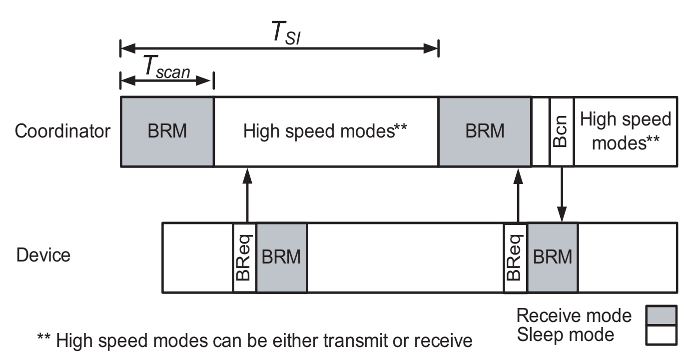

Fig. 3. Illustration of Beaconless Synchronization in IEEE 802.15.4g SUN. BRM: base rate mode. Bcn: beacon. BReq: beacon request.

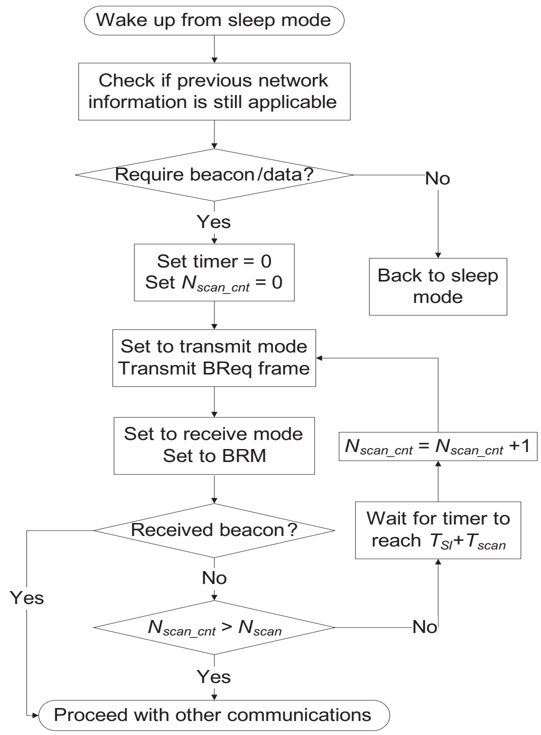

Fig. 4. Operational Flow Chart of a Device for Beaconless Synchronization

is T_{SI}. Other than the BRM receive mode, the coordinator may may conduct other high speed communications with other devices, *e.g.* with 400kHz and 600kHz CS, for an interval of $T_{SI} - T_{scan}$.

As for the device, as illustrated in Figure 4, when a device wakes up and requires synchronization beacon or communication data, it checks whether the network information obtained previously is still applicable. The mechanism to perform that is not within the scope of this paper. If the information is obsolete, it first sets the timer and operational parameters such as N_{scan_cnt} to respective initial values. Then the device will set to transmit mode and transmit a BReq frame. Next, the device will set to BRM receive mode to check whether the coordinator returns a beacon or data. If a beacon/data is received, the device may go back to sleep mode or perform other operations. If no beacon or data is received, the device will wait for a total duration of $T_{SI} + T_{scan}$ to transmit another BReq frame. Each repetition to wait for $T_{SI} + T_{scan}$ will increase operation counter N_{scan_cnt} by 1. If $N_{scan\_cnt} > N_{scan}$, *i.e.* the device has already scanned for a total of N_{scan} times, each for duration T_{scan} in different time positions across T_{SI}, the device will stop the synchronization process and proceed with other operations. Examples of other operations may be returning back to sleep mode, or starting its own network since no coordinator is detected.

It is worth to note that parameters T_{scan} and T_{SI} may be updated from time to time by the coordinator to suit instantaneous network demands. This indicates that every time the device wakes up, the synchronization procedure may have to be performed again.

The BRM periods and high speed modes periods in Figure 3 are two parameters with clash of interest. BRM period is mainly used for discovery messages exchange and is a factor that reduces the effective throughput of the system. On the other hand, the high speed modes period is used for actual data exchange that constructs the bandwidth efficiency. The analysis and evaluation on these factors are given in the next section.

VII. Performance Evaluation

The synchronization mechanism developed in Section VI is evaluated and discussed in this section. The performance evaluation in the beaconless synchronization can be quantified by two metrics, the bandwidth usage efficiency and the discovery time by device.

The maximum time required for the device to detect the coordinator is expressed as:

$$\max(T_{sync}) = T_{SI} \times \frac{T_{SI}}{T_{scan}} \tag{1}$$

Note that max(T_{sync}) is derived based on the assumption that the device has to perform all N_{scan} times of scanning periods. In other words, max(T_{sync}) is the worst case scenario.

The bandwidth efficiency of the system is defined as the ratio between the time available for actual data communications to the time for performing synchronization, *i.e.* scanning period in BRM. The bandwidth efficiency is expressed as:

$$E_{BW} = \frac{T_{SI} - T_{scan}}{T_{SI}} \times 100\% \tag{2}$$

Numerical analysis in this paper considers realistic parameters extracted from [5], [2]. For the non-beacon-mode network in [2], the timing unit is expressed in ms and the maximum value for one unit is approximately 300s considering a 50kbps data rate mode symbol duration (*i.e.* 20μs).

Figure 5 shows the relationship between the number of scanning period N_{scan} to maximum discovery time T_{sync}

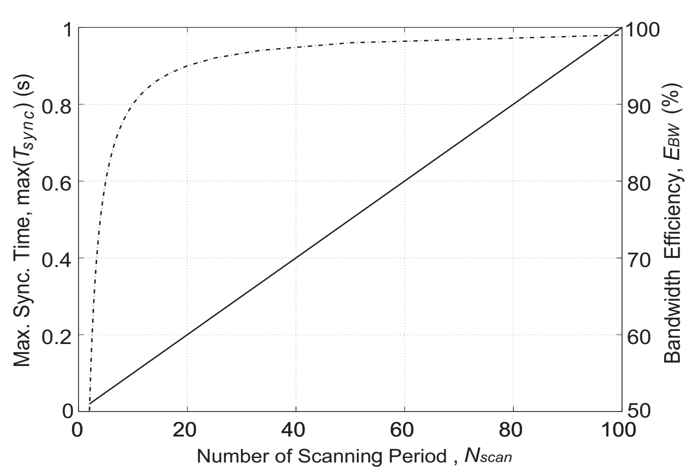

Fig. 5. Relationship between N_{scan} to T_{sync} and E_{BW}. Solid line: T_{sync}. Dotted line: E_{BW}.

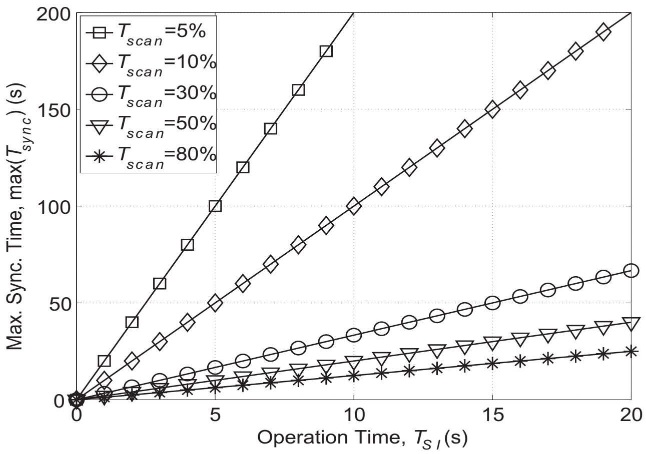

Fig. 6. Relationship between T_{SI} to T_{sync} in varying T_{scan}

and bandwidth efficiency E_{BW}. One important finding here is that as N_{scan} increases, T_{sync} increases linearly, whereas E_{BW} increases exponentially. This indicates that the proposed mechanism have the capability to provide more available bandwidth for actual data communication while preserving constant resources for beaconless synchronization.

Metric T_{sync} increases linearly as N_{scan} increases because $N_{scan} = T_{SI}/T_{scan}$ is the total number of T_{scan} periods that can fit into the total duration T_{SI}. Higher N_{scan} means that more rounds of T_{SI} duration is needed to complete the synchronization process, hence higher T_{sync}. It is also observed that metric E_{BW}, achieves approximately 90% at N_{scan}=20, beyond which, causes E_{BW} to gradually approach 100%. In other words, design to set N_{scan} beyond 20 is unnecessary.

Figure 6 shows the relationship between the operation time T_{SI} to the maximum required synchronization time T_{sync} in varying T_{scan} durations. A general observation reveals that the less time used for synchronization process, the higher T_{sync} becomes. For example, by allocating only 5% for T_{scan}, synchronization process requires 200s when operation time is 10s. This means that the coordinator has more resources for data communication with other devices, but the synchronization with the synchronizing device will take a longer time. Determining which parameter to employ depends greatly on the demands of the system.

Table I lists the required T_{scan} and achievable E_{BW} for several samples of T_{SI} instances, which is useful in designing the non-beacon-mode network to satisfy different system demands. For instance, reducing E_{BW} from 95% to 50% requires T_{SI} to be reduced 10 times.

TABLE I
COMPARISON BETWEEN T_{sync} AND E_{BW} VALUES

Parameters	Values				
T_{scan}	5%	10%	30%	50%	80%
E_{BW}	95%	90%	70%	50%	20%
T_{SI} (sampled at 5s)	100	50	17	10	7
T_{SI} (sampled at 10s)	200	100	33	20	13
T_{SI} (sampled at 15s)	300	150	50	30	18
T_{SI} (sampled at 20s)	400	200	65	40	25

VIII. CORRESPONDING SECTION IN DRAFT STANDARD 802.15.4G

The rules in [2] clause 5 define that a beacon frame can be obtained in an on-demand manner. In this case, the requester sends out a BReq frame to an existing coordinator, *i.e.* responder. The responder upon receiving the BReq frame may respond with a beacon frame. The requester should transmit the BReq frame at least once every T_{SI}. Additionally, in order to increase the probability of receiving the BReq, the responder should periodically allocate a fraction of operation time to scan for the BReq using a predefined common PHY signaling. These rules indicate the capability of devices employing the algorithm in proposed in this paper.

IX. CONCLUSION

This paper has proposed an improved beaconless synchronization mechanism to address the potential challenges posed by channelization specified in 802.15.4g SUN systems. Future works include implementation in prototype to verify the feasibility.

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