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IEEE 802.11ba: Low-Power Wake-Up Radio for Green IoT

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The authors offer substantial insights of IEEE 802.11ba, including the deployment scenarios, PHY operations, and MAC operations. Their insights facilitate further research and implementation of IEEE 802.11ba WUR to empower the next generation green IoT.

Abstract

Low-power devices have manifested their crucial roles in manifold green Internet of Things (IoT) applications, including healthcare, smart home, industrial sensors, and wearable apparatuses. However, to prolong the operation time of these devices, significantly enhancing the battery capacity turns out to be an intractable challenge due to the mandatory constraint of limited form factors. Achieving this goal thus inevitably relies on new designs of physical-layer (PHY)and medium access control (MAC) schemes. This desire has driven IEEE 802.11 Task Group "ba" (TGba) to launch the normative work of wake-up radios (WURs) since 2017. To comprehend essential knowledge of this new technical feature, in this article, we consequently offer substantial insights of IEEE 802.11ba, including the deployment scenarios, PHY operations (waveform, modulation, data rate selection, and synchronization design), and MAC operations (radio wake-up procedure, WUR duty cycle, WUR mode, channel access scheme, and the format of a MAC packet data unit). The provided insights facilitate further research and implementation of IEEE 802.11ba WUR to empower the next generation green IoT.

Introduction

The next generation wireless paradigms, such as machine-type communications (MTC), machine-to-machine (M2M) communications, and/or the Internet of Things (IoT) are projected to sustain a variety of applications. These applications may involve industrial operations in places unreachable by humans, require a large number of low-cost/power devices to collect environmental data [1, 2], or facilitate unmanned automation such as smart home/city/factory [3, 4]. In these applications, devices are generally powered by batteries, and frequently replacing batteries is practically infeasible due to potentially unaffordable cost. As a result, low power consumption has been regarded as one of the most crucial requirements for devices to sustain the next generation IoT paradigms [5].

Although orthogonal frequency-division multiplex (OFDM), enjoying low-cost implementation of equalization, has been widely applied to state-of-the-art mobile networks such as IEEE 802.11a/g/n/ac/ax, LTE/LTE-A, and New Radio, such a multi-carrier transmission scheme is not efficient in terms of energy consumption. In practice, a typical OFDM receiver may consume tens to hundreds of milliwatts, and the power consumption at a transmitter could double that at a receiver [6, 7]. To reuse OFDM so as to harmonize with state-of-the-art mobile networks, one feasible scheme is to allow a device to transmit data using a single tone waveform (a single OFDM subcarrier) as adopted in Third Generation Partnership Project (3GPP) narrowband IoT (NB-IoT). A more efficient alternative is to permit a device to switch to the sleep state if there is no data to be uploaded/downloaded. In light of the power saving mode operation in IEEE 802.11, a device switching to the sleep state should periodically wake up to receive control information from an access point (AP). Based on the indication carried in control information, a device is aware of whether there is downlink data from an AP. If a device stays in the sleep mode for a longer time, a device can enjoy lower power consumption but at the expense of increased latency in data reception. To develop an effective mechanism for battery-driven devices to achieve balance between power efficiency and data reception latency, IEEE 802.11 TGba was formed to develop draft 0.1 (D0.1) of IEEE 802.11ba (also known as wake-up radio, WUR) in 2017, and D2.0 has been released in 2019 [8]. The timeline of the IEEE 802.11ba standardization progress is illustrated in Fig. 1.

The target of IEEE 802.11ba WUR is to enable an active device with power consumption less than 1 mW. For this purpose, a device is equipped with two radio chains known as the *primary* connectivity radio (PCR) and the *companion* connectivity radio (i.e., WUR) [8-9]. This two-radio-chain framework has also recently received considerable attention in the design of low-power IoT devices [10-15]. The PCR supports complete operations of legacy IEEE 802.11, which is expected to switch to the sleep mode for as long a duration as possible to significantly reduce power consumption. On the other hand, a new frame called "wake-up frame" is introduced, and the WUR monitors wake-up frames transmitted from an AP. If wake-up frames are received by the WUR, this event triggers the PCR to transition from the sleep mode to the active mode. To monitor wake-up frames, a WUR should coexist with legacy IEEE 802.11 AP/devices in the same bands (i.e., 2.4 GHz or 5 GHz) to meet the same bandwidth requirement of the PCR.

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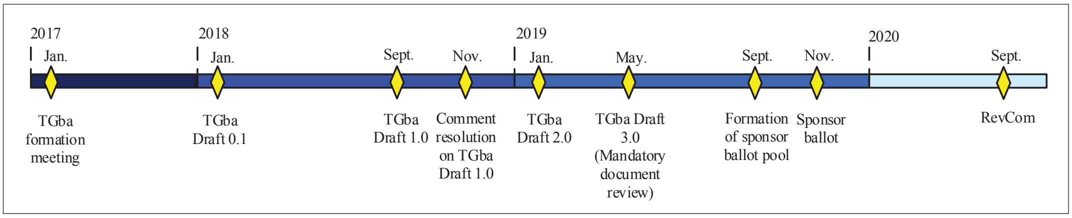

Figure 1. Timeline of IEEE 802.11ba standardization progress.

To fully comprehend this new technology in IEEE 802.11 to sustain applications of green IoT, in this article, a comprehensive overview of IEEE 802.11ba is provided. Beginning by introducing the deployment scenarios of WURs, knowledge of physical-layer (PHY) and medium access control (MAC) operations are provided, respectively, and this article is concluded with future research opportunities.

Deployment Scenarios of IEEE 802.11ba WUR

IEEE 802.11ba WURs can be applied to the scenarios of smart home/office, warehouse, outdoor cattle farms, synchronous wake-up of sensors, synchronous wake-up of wearable devices, reconnection of wearable devices, wake-up vehicle-to-pedestrian (V2P) radios, and smart scanning. Among all these potential scenarios, in this section, smart home/office and warehouse management are adopted as examples to elaborate the downlink and uplink transmissions using WURs, respectively.

Smart home/office (downlink transmissions): The smart home/office is a popular scenario with dozens of IoT devices. In a house/office, there can be manifold applications empowered by low-power devices, and we may take the control of a smart curtain as an instance. In this instance, a light sensor monitors the light condition and sends the sensed results to a cloud server through an AP deployed in a house/office. The cloud server determines whether to open or close the curtain based on the sensed results. As illustrated in use case 1 of Fig. 2, a cloud server sends the command to open/close the curtain to the AP based on the light condition, and the AP sends a wake-up frame to the curtain equipped with a WUR and a PCR. When this wake-up frame is successfully received by the WUR, the PCR is awake. Subsequently, the AP transmits the command to the PCR of the smart curtain to open or close the curtain. Alternatively, in use case 2 of Fig. 2, the house owner can remotely open/close the curtain through sending a command from a station (STA) to an AP; then an AP wakes up the curtain and relays the command to the curtain.

Warehouse (uplink transmissions): WURs can also be applied to an industrial scenario such as a warehouse. In this scenario, sensors responsible for monitoring storage conditions such as temperature and humidity are equipped with a WUR and a PCR. Due to the sporadic nature of traffic sent from a sensor (i.e., data is of a small size and is transmitted infrequently), a sensor does not have to be woken up periodically, but is only woken up when the WUR of a sensor receives a wake-up frame from an AP. In this case, the PCR

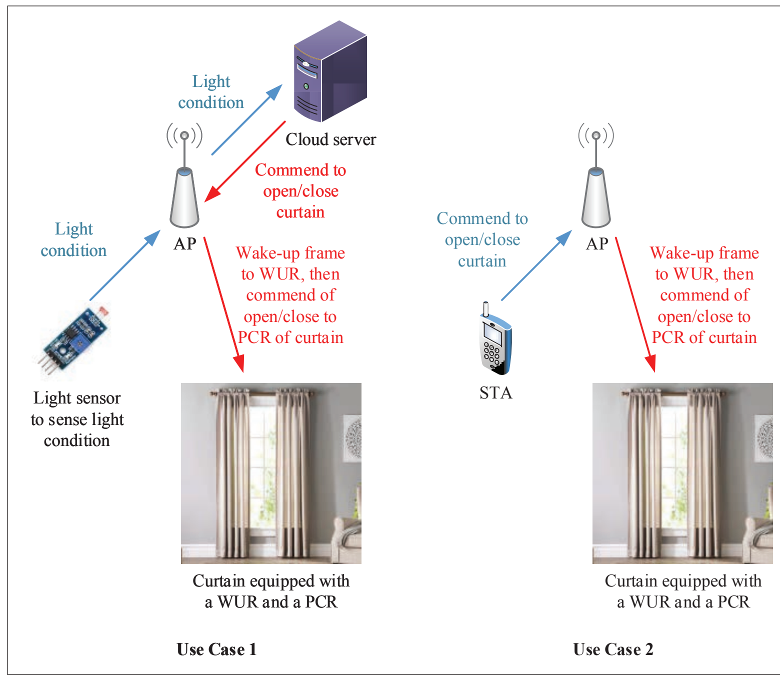

Figure 2. Two use cases to control curtains with WURs.

of a sensor is awake and sends the sensed results to an AP.

In fact, WURs can be implemented not only at the STA side, but also on the AP side. However, due to the tight schedule of the standardization of IEEE 802.11ba, the primary task of the TGba emphasizes the procedure for an AP to wake up a device (i.e., only devices equipped with WURs). Nevertheless, to be forward compatible to use cases not supported at this stage, a vender specific field is provided in the type of wake-up frames (which will be elaborated later). This vendor-specific field leaves more room for vendors to develop more use cases in their own implementation or in the Wi-Fi Alliance (WFA) for further interoperability.

PHY Operations of IEEE 802.11ba

Waveform and Modulation of Wake-Up Frames

The transmitter of IEEE 802.11ba (i.e., an AP) reuses the existing OFDM transmitter architecture adopted by IEEE 802.11a/g/n/ac/ax with 312.5 kHz subcarrier spacing. Since narrowband waveform reception can significantly reduce the power consumption at the receiver (i.e., device) side, the narrowband OFDM waveform is generated by populating a contiguous 13 out of 64 subcarriers including a null center subcarrier to occupy a 4 MHz band. To further reduce power consumption, the wake-up frame does not carry any data

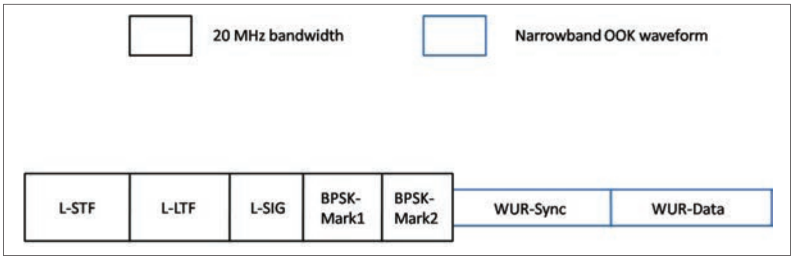

Figure 3. The PPDU format of the wake-up frame for WURs.

information, and an AP only utilizes the OFDM waveform as a transmission medium to transmit wake-up frames.

For the WUR, information bits are modulated into on-off keying (OOK) symbols, and the transmitter of wake-up frames uses these OOK symbols to mask the generated narrowband OFDM waveform (which is known as the OOK waveform). To further optimize the OOK waveform, OOK symbols are carried over 13 tones (subcarriers), which is known as multi-carrier OOK (MC-OOK) in IEEE 802.11ba.

At the receiver side, OOK demodulation does not require any channel equalization in the frequency and time domains, and therefore a non-coherent detection, such as envelope detection, is sufficient. Using non-coherent detection, the receiver does not need to maintain/track a highly accurate oscillation rate. As a result, a phase-locked loop (PLL) can be avoided to further reduce the power consumption at the receiver side.

Physical Layer Convergence Procedure Protocol Data Unit of Wake-Up Frames

To coexist with legacy IEEE 802.11 devices in the same bands, a 20 MHz non-high-throughput (non-HT) preamble is prepended in any WUR physical layer convergence procedure (PLCP) protocol data unit (PPDU). The PPDU format for WURs is illustrated in Fig. 3, which includes the legacy short-training field (L-STF), legacy long-training field (L-LTF) legacy long-training field (L-LTF), legacy signal (L-SIG), BPSK Mark 1, and BPSK Mark 2. Please note that the symbols from L-STF to BPSK Mark 2 are not modulated on 13 tones, and a WUR PPDU relies on the LSIG field to silence the legacy IEEE 802.11 devices in the same band (i.e., 20 MHz) up to 5.6 ms to avoid collisions. BPSK Mark 1 and Mark 2 are used to spoof legacy devices. However, this 20 MHz preamble cannot be recognized and decoded by a WUR receiver due to the narrowband reception capacity. Nevertheless, the 20 MHz preamble can be used for coarse automatic gain controller (AGC) setting. On the contrary, the synchronization (SYNC) and data fields are modulated using OOK waveform on 13 tones, and these two fields are introduced later.

Due to the power spectral density (PSD) regulation in some geographical regions, narrowband OOK waveform has to be transmitted at lower power. This operation leads to a sharp power drop between the legacy preamble and the OOK portion contained in a WUR PPDU. Such a power drop is called signal/carrier loss, which may degrade the performance of protection from being interfered by other legacy IEEE 802.11 devices. On the other hand, if the power level of the legacy preamble is lowered to the power level of the OOK portion, the LSIG protection region could be harmed. To bridge the power gap between 20 MHz non-HT preamble and the narrowband OOK portion, an additional 20 MHz OFDM symbol with 312.5 kHz subcarrier spacing and binary phase shift keying (BPSK) is added in the middle of a PPDU.

Data Field in PPDU

Since a wake-up frame carries control information only, the data field in a WUR PPDU is used to carry control information instead of data. In a WUR PPDU, both SYNC field and data field are OOK waveforms. The SYNC field is used to help the WUR receiver synchronize with this wake-up frame and know the position of the data field. For the SYNC field, the lowest data rate is applied to facilitate the robustness. For the data field, multiple data rates can be applied to achieve either better spectrum efficiency or better coverage (reliability). For the sake of simplicity, two data rates are supported by WURs for the data field: 250 kb/s and 62.5 kb/s. The higher (i.e., 250 kb/s) data rate can be accommodated for short-range communications to enhance the spectrum efficiency. From simulation studies, the crosspoints of the link margins using the 250 kb/s data rate are 105 m and 70 m at the carrier frequencies 2.4 GHz and 5 GHz, respectively. The lower (i.e., 62.5 kb/s) data rate facilitates coverage extension, especially in the outdoor environment, to achieve the same level of coverage as that of legacy IEEE 802.11.

SYNC Field in PPDU and Synchronization Using Wake-Up Frames

To differentiate the two data rates in the data field through using the SYNC field under the constraint of only one correlator at the WUR receiver, two schemes can be adopted. The first scheme is to have different synchronization sequences with different durations, and the duration of the SYNC field depends on the data rate of the data field. When the low data rate is used for the data field, the duration of the SYNC field is 128 μs (denoted as SYNC1). When the high data rate is used for the data field, the duration of the SYNC field is 64 μs (denoted as SYNC2). The purpose of using a longer SYNC duration (SYNC1) for a lower data rate is to achieve better reliability performance, while a shorter SYNC duration (SYNC2) associated with a higher data rate achieves better spectrum efficiency. For example, suppose that WUR data has a 48-bit payload. If SYNC2 for the high data rate reduces from 128 μs (as compared to SYNC1) to 64 μs, the packet duration is reduced by 20 percent. Since the wake-up frame does not carry data, the wake-up frame may be regarded as overhead. Therefore, for better spectrum efficiency, the overall length of a WUR PPDU should be as short as possible.

MAC Operations of IEEE 802.11ba

Basic Wake-Up Operations

The basic unicast wake-up procedure is illustrated in Fig. 4, in which the wake-up procedure starts from an AP transmitting a wake-up frame, followed by a response from a STA. Note that the WUR does not have the ability to transmit; hence, the response frame from the STA must be transmitted by its PCR. Upon receiving a wake-up frame, a STA may not send the response frame promptly, which is referred to as wake-up delay. Wake-up delay is mainly due to the STA's PCR being completely turned off. As a result, when the PCR is required to be turned on again, a period of time is needed to boot the PCR. The wake-up delay can be several milliseconds, depending on the capability of the PCR. The existence of the wake-up delay and the relatively slow reply of the response frame from the STA result in a slow error recovery procedure (i.e., it takes the AP several milliseconds to check whether the wake-up frame is successfully received by the STA or not). Consequently, the retransmission of the wake-up frame may also take place a little bit late if the AP does not receive any response frame from a STA. Fortunately, WUR-equipped STAs are usually IoT devices, which emphasize extremely low power consumption, while delay is not a key performance factor.

WUR Duty Cycle

In IEEE 802.11 systems without WURs, power saving mainly relies on properly designating a duty cycle. A STA only needs to periodically wake up to receive the Beacon frame to obtain the traffic indication map (TIM) and check whether there is downlink data to receive. If the TIM indicates that there is no downlink data, a STA can go back to the doze state; otherwise, a STA can initiate a downlink data reception procedure by sending a power saving poll (PS-Poll) frame to the AP, after which the STA can go back to the doze state. In IEEE 802.11ba, the WUR can reuse the concept of duty cycles to further reduce the power consumption. A STA and an AP can exploit a negotiation procedure (typically a request/response frame exchange) to decide four major duty cycle parameters:

1. The **duty cycle period**
2. The **starting point of the "on" duration** (in which the WUR of a STA should turn on)
3. The **length of the "on" duration**
4. The **minimum wake-up duration**

Therefore, the power consumption of the duty cycle WUR of a STA is determined by the duty cycle period and the length of the "on" duration.

To exchange the above four parameters, an AP should advertise the minimum wake-up duration (8-bit field) and the **duty cycle period units** (16-bit field) in the WUR operation information element (IE) to STAs. The field of the minimum wake-up duration indicates the minimum length of the "on" period, and the field of the duty cycle period units indicates the time unit of the duty cycle period (in other words, the value of the duty cycle period should be a multiple of the value of the duty cycle period units). Then a STA can send the desired values of the length of the "on" duration (32-bit field) and the duty cycle period (16-bit field) to an AP (as a request). Subsequently, an AP indicates the starting point in the field of the starting time of the WUR duty cycle (in an enter WUR mode response) to complete the negotiation. The detailed procedure and information exchange are illustrated in Fig. 5.

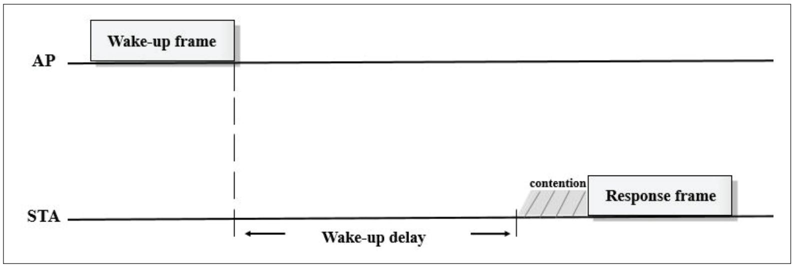

Figure 4. The wake-up procedure for an AP to wake up a STA.

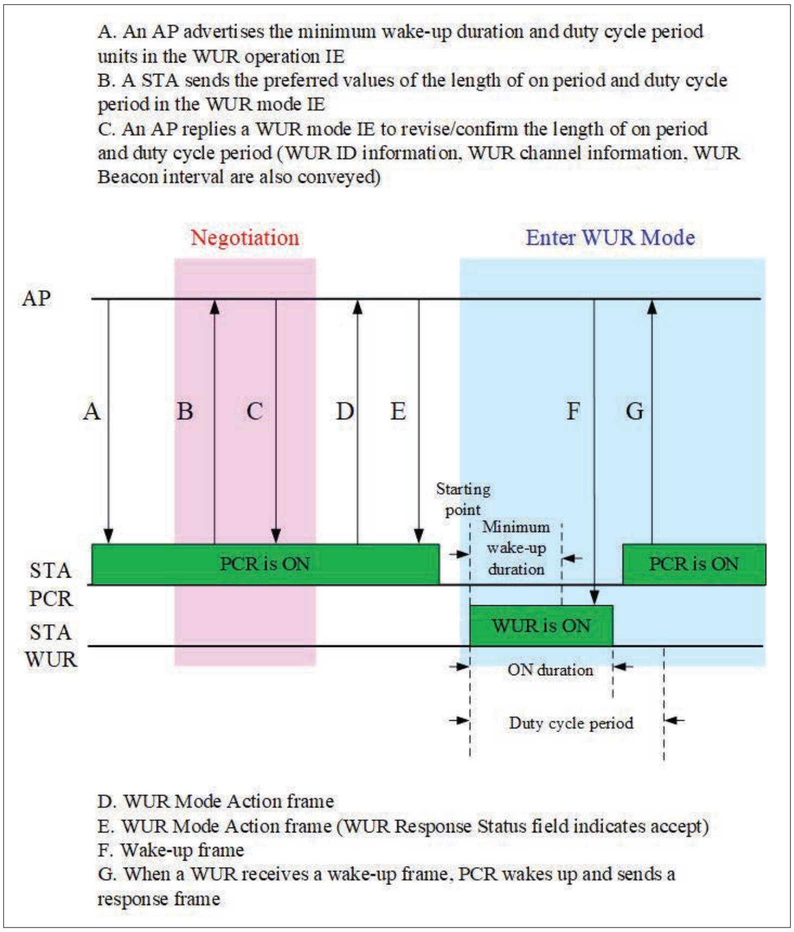

Figure 5. The negotiation procedure and information exchange to enter the WUR mode.

Since the basic unit for the value of the duty cycle period units is 4 μs, the 16-bit value indicates the multiples of 4 μs. In other words, the maximum value of the duty cycle period units can be $4 \times 2^{16} = 2^{18}$ μs. As aforementioned, the value of the duty cycle period should be a multiple of the value of the duty cycle period units, and the exact value of multiples is decided by 16 bits. As a result, the maximum value of the duty cycle period can be $2^{16} \times 2^{18} = 2^{34}$ μs. Since the "on" duration could fully occupy the length of a duty cycle period, the maximum length of the "on" duration can thus be 2^{34} μs. On the other hand, since the minimum wake-up duration indicates the minimum length of the "on" duration, when a STA receives a value of the minimum wake-up duration sent from an AP, it is not adequate for a STA to set the length of the "on" duration to be smaller than the value of the minimum wake-up duration.

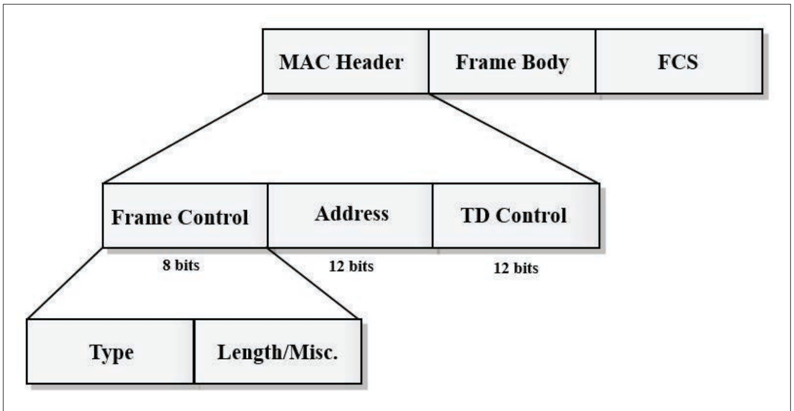

Figure 6. The MPDU format of a WUR frame of IEEE 802.11ba.

WUR Mode

Normally, a mode defines a state machine of a radio. In IEEE 802.11ba, two radios (PCR and WUR) are working together, and hence two state machines are running with mutual interaction under the WUR mode. For the PCR, it can be shut off before a STA receives any WUR frame, and it should be in the awake state after a STA receives a WUR frame. Moreover, the PCR shall send a response frame to an AP when the WUR frame is a wake-up frame, as illustrated in Fig. 5. Please note that there can be four types of WUR frames: WUR wake-up, WUR Beacon, WUR discovery, and WUR vendor-specific. Besides, a STA may not listen to a Beacon frame if a STA is in the power save mode. In this case, all the existing negotiated service periods between an AP and a STA for a STA's PCR schedules are suspended, which means that a STA's PCR is not required to wake up during the service period, and the parameters of the negotiated service periods for STA's PCR schedules are still reserved by an AP and a STA. For the WUR, it shall follow the duty cycle determined during the negotiation phase. During the "on" duration, the WUR shall stay awake, and the WUR can go into the doze state at other times. Note that the WUR can also be "always on," which can be treated as a special duty cycle, in which the "on" duration occupies the whole duty cycle period, as mentioned in the previous section. After receiving a wake-up frame, the WUR may turn off since the PCR is awake to work. However, the WUR can only be turned off after a successful frame exchange with an AP through a STA's PCR, which informs the AP that a STA is in the awake state, as illustrated in Fig. 5.

Before a STA enters the WUR mode, it should negotiate WUR parameters with an AP, as illustrated in Fig. 5. The WUR parameters are carried in a WUR mode IE, which can be transmitted by both an AP and a STA. A STA can include its preferred duty cycle parameters in WUR mode IE to inform an AP about its preference of the duty cycle; then an AP can reply a WUR mode IE to confirm or revise the duty cycle parameters. The replied WUR mode IE from an AP also carries information to notify a STA about the basic operating parameters, such as WUR ID information and WUR channel information. WUR ID information is used for a STA to determine whether a WUR frame is intended for it. WUR channel information specifies the channel that the WUR stays on, while the WUR Beacon interval facilitates the WUR to be awake at the specific time instants to receive WUR frames for the purpose of synchronization and alive check.

After the WUR parameters negotiation, a STA can enter the WUR mode by transmitting a WUR Mode Setup Action frame to an AP. Upon the reception of another WUR Mode Setup Action frame (in a reply from an AP) with a WUR Mode Response Status field indicating "Accept," a STA is in the WUR mode. A STA may also exit the WUR mode by transmitting a WUR Mode Teardown Action frame. For those STAs wishing to exit and enter the WUR mode frequently, the IEEE 802.11ba specification defines a special mode called "WUR mode suspend," in which the negotiated WUR parameters are still reserved by an AP and a STA, and a STA may turn off the WUR and use its PCR for communications. If a STA wishes to exit the WUR mode temporarily, a STA can enter the WUR mode suspend, and later, enter the WUR mode directly without a request/response procedure with an AP.

Channel Access

Since the WUR needs to coexist with legacy IEEE 802.11 devices in the same band in order to meet the coexistence requirement and to avoid collisions with multiple WUR frames, an AP shall use the Enhanced Distributed Channel Access (EDCA) scheme to send WUR frames. EDCA is a carrier sensing multiple access with collision avoidance (CSMA/CA)-based channel access scheme, which requires an AP to monitor the status of the channel for a certain duration before transmitting a frame, and consequently to enable the coexistence of WUR frames and the legacy IEEE 802.11 frames.

EDCA is a quality of service (QoS)-enabled scheme through defining four access categories (ACs). Each AC has its own parameter set to access the channel, which decides the time duration for which a STA needs to monitor the channel before transmitting. The AC of higher priority has a shorter channel monitor time, resulting in a faster channel access opportunity. A WUR frame, considered as a kind of control frame, is expected to be granted higher priority. For the sake of simplicity, the IEEE 802.11ba specification reuses the existing four ACs, and allows an AP to use any AC to transmit multicast/broadcast WUR frames. To transmit unicast WUR frames, the corresponding AC is still not specified in the normative work of IEEE 802.11ba.

Moreover, due to the slow response after receiving the wake-up frame, an AP shall not update the contention window and counter under a particular AC when a failure or success for a unicast WUR frame transmission is identified. Since the time duration between the retransmission and the first transmission of the wake-up frame could be long, the channel condition may be totally different for the two transmissions.

MAC Protocol Data Unit Format of a WUR Frame

Due to the low transmission rate, a WUR frame cannot carry too many bits. Assuming a data rate of 62.5 kb/s, a 5 ms PPDU can only carry around 40 B. In this case, WUR frames do not adopt the conventional IEEE 802.11 MAC Protocol Data

Unit (MPDU) format with 48-bit address field. Instead, a new MPDU format is defined alternatively, as illustrated in Fig. 6.

Similar to the conventional IEEE 802.11 MPDU format, a WUR frame is composed of a MAC header, a frame body, and a frame check sequence (FCS). The frame body is optionally present depending on the type of WUR frame. Besides, it is also optional for a STA to support the reception of a frame with nonzero length frame body. The FCS carries the cyclic redundancy check (CRC) of the frame, and additionally embeds basic service set ID (BSSID) information.

The MAC header comprises a Frame Control field, an Address field, and a Type Depend (TD) Control field:

•The Frame Control field is 8 bits long, and further comprises a Type subfield and a Length/Miscellaneous (Misc.) subfield. The type field identifies different types of WUR frames, including wake-up frame, WUR Beacon frame, vendor-specific frame, WUR Discovery frame, and so on, where the vendor-specific frame is used for different purposes that different vendors wish to implement. The vendor-specific frame and the WUR Discovery frame are variable-length (VL) WUR frames, where the Length/Misc. subfield indicates the length of the frame body. The wake-up frame and the WUR Beacon frame are constant-length (CL) WUR frames, where the frame body is not present, and the Length/Misc. subfield indicates some other information.

•The Address field is 12 bits long, and the contents depend on the type of the WUR frame. For the unicast type of wake-up frame, the Address field carries a WUR ID (WID) assigned by an AP to a WUR STA to identify one WUR STA. For the type of multicast wake-up frame, the Address field carries a Group ID (GID) assigned by an AP to identify one or more WUR STAs. For the types of broadcast wake-up frame and WUR Beacon, the Address field carries the transmitter ID (TXID), as the frame is for all the WUR STAs. Note that the unicast wake-up frame, multicast wake-up frame, and broadcast wake-up frame all belong to the type of wake-up frame; thus, a further indication is needed in the Length/Misc. subfield to differentiate a broadcast wake-up frame and non-broadcast (multicast/unicast) wake-up frame. For the vendor-specific WUR frame, the Address field carries the 12 most significant bits of the organizationally unique identifier (OUI).

•The TD Control field in the MAC header carries type-dependent control information. For the WUR Beacon, the TD Control field carries a partial TSF for the purpose of synchronization. For other types of WUR frames, the TD Control field can be used for other types of enhancements.

Conclusion and Future Research

In this article, the essential knowledge for the next generation green IoT system, IEEE 802.11ba WUR, is comprehensively provided. The offered knowledge includes the deployment scenarios, the PHY operations, and the MAC operations of IEEE 802.11ba. For the PHY operations, the waveform and modulation schemes of wake-up frames, PPDU format of wake-up frames, supported data rates of wake-up frames, and synchronization sequence designs are intensively elaborated. For the MAC operations, the basic wake-up operations, WUR duty cycle, WUR mode, channel access scheme, and MPDU format are detailed as well.

The normative works of IEEE 802.11ba are just in the beginning stage, and a number of issues still remain open for further study. For example, as aforementioned, the performance of power saving in a STA depends on the duty-cycle period and the length of the "on" duration in the WUR mode. To adequately decide these two values, a STA needs to take the latency constraint in receiving downlink from an AP into consideration. A longer duty-cycle period with a shorter "on" duration improves the power saving performance. However, when packets arrive at an AP to be sent to a STA, an AP has to wait a longer time for the "on" duration, which thus extends the latency of packet transmissions. In addition, when there are multiple STAs with different latency constraints and/or priorities that need to be satisfied, how to adequately multiplex the duty cycle periods and handle the prioritized channel access also requires further studies.

The normative works of IEEE 802.11ba are just at the beginning stage, and a number of issues still remain open for further study. For example, as aforementioned, the performance of power saving in a STA depends on the duty-cycle period and the length of the "on" duration in the WUR mode.

References

[1] Z. Sheng *et al.*, "Lightweight Management of Resource-Constrained Sensor Devices in Internet of Things," *IEEE Internet of Things J.*, vol. 2, no. 5, Oct. 2015, pp. 402–11.

[2] E. Curry *et al.*, "Internet of Things Enhanced User Experience for Smart Water and Energy Management," *IEEE Internet Computing*, vol. 22, no. 1, Jan./Feb. 2018, pp. 18–28.

[3] E. Park *et al.*, "Comprehensive Approaches to User Acceptance of Internet of Things in a Smart Home Environment," *IEEE Internet of Things J.*, vol. 4, no. 6, Dec. 2017, pp. 2342–50.

[4] B. Chen *et al.*, "Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges," *IEEE Access*, vol. 6, 2018, pp. 6505–19.

[5] P. Le-Huy and S. Roy, "Low-Power Wake-Up Radio for Wireless Sensor Networks," *Mobile Network Appl.*, vol. 15, no. 2, Apr. 2010, pp. 226–36.

[6] K. Gomez *et al.*, "Achilles and Tortoise: Power Consumption in IEEE 802.11n and IEEE 802.11g Networks," *Proc. IEEE OnlineGreenComm*, Oct. 2013.

[7] D. Halperin *et al.*, "Demystifying 802.11n Power Consumption," *Proc. HotPower*, 2010.

[8] IEEE P802.11ba D1.0, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Wake-Up Radio Operation," 2019.

[9] D. K. McCormick, "IEEE Technology Report on Wake-Up Radio: An Application, Market, and Technology Impact Analysis of Low-Power/Low-Latency 802.11 Wireless LAN Interfaces," 802.11ba Battery Life Improvement: IEEE Tech. Rep. on Wake-Up Radio, Nov. 2017, pp. 1–56.

[10] R. Piyare *et al.*, "Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey," *IEEE Commun. Surveys & Tutorials*, vol. 19, no. 4, 4th qtr. 2017, pp. 2117–57.

[11] F. Z. Djiroun and D. Djenouri, "MAC Protocols with Wake-Up Radio for Wireless Sensor Networks: A Review," *IEEE Commun. Surveys & Tutorials*, vol. 19, no. 1, 1st qtr. 2017, pp. 587–618.

[12] X. Li, P. Baltus *et al.*, "A 60 GHz Ultra Low-Power Wake-Up Radio," *Proc. IEEE RWS*, 2011.

[13] V. Jelicic *et al.*, "Benefits of Wake-Up Radio in Energy-Efficient Multimodal Surveillance Wireless Sensor Network," *IEEE Sensors J.*, vol. 14, no. 9, Sept. 2014, pp. 3210–20.

[14] M. Magno *et al.*, "Design, Implementation, and Performance Evaluation of a Flexible Low-Latency Nanowatt Wake-Up Radio Receiver," *IEEE Trans. Industrial Informatics*, vol. 12, no. 2, Apr. 2016, pp. 633–44.

[15] M. Magno and L. Benini, "An Ultra Low Power High Sensitivity Wake-Up Radio Receiver with Addressing Capability," *Proc. IEEE WiMob*, 2014.

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