# IEEE 802.11ah: Sub-1-GHz License-Exempt Operation for the Internet of Things

*Minyoung Park*


## ABSTRACT

IEEE 802.11ah Task Group has been developing an amendment to the 802.11 standard to define sub-1-GHz license-exempt operation to support sensors and Internet of Things applications. This article presents an overview of major physical layer and MAC layer features of 802.11ah.


## INTRODUCTION

The IEEE 802.11 standard [1] is one of the most widely adopted wireless connectivity technologies for digital devices such as laptops, smartphones, tablets, digital TVs, DVD/Blu-ray players, gaming consoles, and portable music players. Since the introduction of IEEE 802.11b in 1999 with data rates up to 11 Mb/s, IEEE 802.11 has been evolving to support more and more use cases that require higher throughput. In 2003, 802.11g was introduced with the adoption of an orthogonal frequency-division multiplexing (OFDM) modulation technique, which increased the data rate to 54 Mb/s. In 2009, 802.11n was published, which supports data rates up to 600 Mb/s utilizing multiple-input multiple-output (MIMO) and doubling the channel width to 40 MHz. The latest amendment, 802.11ac, was published in 2013, which supports data rates up to 6.9 Gb/s in the 5 GHz band. The enhancement is achieved by increasing the channel widths to 80 and 160 MHz, and the maximum number of spatial streams to eight.

Most of the enhancements in the amendments have been optimized for a small number of high data rate devices such as laptops, tablets, and smartphones, but not for a large number of low data rate devices such as sensors and Internet of Things (IoT) devices. As an example, the use cases and requirements of 802.11ac are summarized in Table 1. The main usages of 802.11ac are wireless display, distribution of HDTV, and rapid upload/download of large files, which all require high data rates for streaming videos or large file transfers among small numbers of devices, mostly in indoor environments.

*Minyoung Park is with Intel Corporation.*

## 802.11AH USE CASES AND IOT APPLICATIONS

In 2010, the IEEE 802.11ah Task Group was formed in the IEEE 802.11 Working Group to define an amendment to the 802.11 standard that operates in the sub-1-GHz license-exempt frequency spectrum to support the following three use cases: sensors and meters, backhaul sensor and meter data, and extended range WiFi [2]. Among these use cases, the sensors and meters use case includes the following sub use cases, which all fall into IoT use cases: smart grid, environmental/agricultural monitoring, industrial process sensors, healthcare, home/building automation, and home sensors. As summarized in Table 1, these IoT use cases typically support a much larger number of devices per access point (AP) for both indoor and outdoor environments with a much longer transmission range but at a much lower data rate than the use cases and requirements of 802.11ac.

### SUB-1-GHZ LICENSE-EXEMPT OPERATION

Although sub-1-GHz bands have more limited frequency spectrum available (e.g., there is only a total of 26 MHz spectrum available in the 915 MHz industrial, scientific, and medical [ISM] band in the United States) than the 2.4 and 5 GHz ISM bands, as shown in Fig. 1, it is sufficient for low data rate applications such as IoT applications because such applications typically transmit small amounts of data infrequently. Moreover, since the 915 MHz ISM band (902–928 MHz) has 8.5 dB less free space propagation loss than the 2.4 GHz ISM band, this can be used to enhance the link budget between devices, and either enable long-range transmission for outdoor metering applications or reduce energy consumption of a device by lowering transmit power and supporting indoor sensor applications.

This article gives an overview of the major features adopted in the 802.11ah specification currently being developed in the IEEE 802.11 Working Group with details of how the features solve the challenges to support IoT use cases. In the following sections, the availability of sub-1-GHz spectrum, as well as channelization in key geographical locations, are described and then


0163-6804/15/$25.00 © 2015 IEEE

| | 802.11ac use cases and requirements [3, 4] | 802.11ah IoT use case and requirements [2] |
|---|---|---|
| Use cases | 1) Wireless display<br>2) Distribution of HDTV<br>3) Rapid upload/download | Sensors and meters |
| Data rate requirement | 20 Mb/s–3 Gb/s | 100 kb/s |
| Single frame packet size | Large (e.g., 1500 bytes) | Small (e.g., few 100 bytes) |
| Traffic type | Video streaming/large file transfer | Periodic packet transmisson every few to tens minutes |
| Distance between devices | 5–60 m | Up to 1 km |
| Number of stations | 3–20 | Up to 6000 |
| Location | Mostly indoor | Indoor and outdoor |

**Table 1.** Comparison of 802.11ac and 802.11ah.

the major physical (PHY) layer and medium access control (MAC) layer features of 802.11ah are explained.

## 802.11ah PHY Features

### Sub-1-GHz Frequency Spectrum and Channelization

The availabilities of frequency spectrum and channelization for key geographies are shown in Fig. 1. 802.11ah supports five frequency channel bandwidths ranging from 1 to 16 MHz. As shown in Fig. 1, there can be 26 1 MHz channels in the United States and fewer channels for the wider channel bandwidths.

Different countries have different rules for the allocated frequency bands in terms of maximum transmit power and channel width. For example, in the United States, an 802.11ah station can operate in the 915 MHz ISM band with the maximum transmit power of 1 W without any restrictions on channel bandwidth. On the other hand, Japan can use 915.9–929.7 MHz band for 802.11ah operation, but the signal frequency bandwidth is limited to 1 MHz and the maximum transmit power is limited to 250 mW (920.5–923.5 MHz). Please refer to [5, Annexes D and E] for more details.

### Basic PHY Designs of 802.11ah

The basic PHY parameters of 802.11ah are summarized in Table 2. In order to support the sensor and meter use case as well as the extended range WiFi use case [2], 802.11ah supports data rates ranging from 150 kb/s to 347 Mb/s. The basic PHY design of 802.11ah is mostly inherited from 802.11ac. The 802.11ac signal waveforms with 20 to 160 MHz channel bandwidths are scaled down by 10 times to 802.11ah signal waveforms with 2 to 16 MHz maintaining the same number of subcarriers. Therefore, the tone spacing between adjacent subcarriers is now 31.25 kHz for all bandwidths. This makes the inverse/discrete Fourier transform (IDFT/DFT) period of 802.11ah equal to 32 μs, which is 10 times longer than that of 802.11ac. The OFDM symbol period is now 40 μs with 8 μs guard interval.

The IEEE 802.15.4 standard supports sub-1-GHz operation at the following frequency bands: 779–787 MHz, 868–868.6 MHz, 902–928 MHz, and 950–956 MHz with the following PHY data rates: 20, 40, 100, and 250 kb/s [6].

### Transmission Range Enhancement

In order to meet a transmission range of 1 km at a minimum date rate of at least 100 kb/s for outdoor IoT applications [2], the transmission range of 802.11ah operating in the 900 MHz band is significantly enhanced compared to that of 802.11n operating in the 2.4 GHz band. The transmission range is enhanced by increased link budget between two devices based on the following design choices.

**Lower operation frequency spectrum:** 802.11ah operates in sub-1-GHz bands, which improves link budget significantly compared to 2.4 GHz operation. For example, a client device operating in the 2.4 GHz band experiences 8.5 dB more free space path loss than one operating in the 900 MHz band.

**Narrower channel bandwidth:** 802.11ah transmits a signal in a 10 times narrower channel bandwidth than 802.11n. This reduces its noise bandwidth by 10 times and thus can increase the signal-to-noise ratio (SNR) at a receiver by 10 dB.

**1 MHz channel bandwidth support:** In addition to 10 times narrower channel bandwidths, 802.11ah supports 1 MHz channel bandwidth, which can increase the SNR by 3 dB compared to using the 2 MHz channel bandwidth.

**Robust coding scheme:** 802.11ah supports the repetition coding scheme for 1 MHz channel bandwidth when binary phase shift keying (BPSK) modulation is used with 1/2 coding rate, and this adds another 3 dB to the SNR.

Table 3 summarizes the link budget enhancement of 900 MHz 802.11ah over 2.4 GHz 802.11n. 802.11ah operating in the 900 MHz band at 150 kb/s is expected to have approximately 24.5 dB better link budget than 802.11n operating in the 2.4 GHz band at 6.5 Mb/s.

### Low-Power and Low-Cost Support for Indoor Sensors

As shown in Table 3, the link budget can be enhanced by more than 24 dB compared to an 802.11n device operating in the 2.4 GHz band. Instead of increasing the transmission range, this enhancement can be used to lower transmit power of a sensor device. The transmit power can easily be reduced to 0 dBm considering that the nominal transmit power of a typical 802.11 device is around 15–17 dBm. This can reduce the transmit energy consumption and also lower the cost of an 802.11ah radio of a small sensor device.

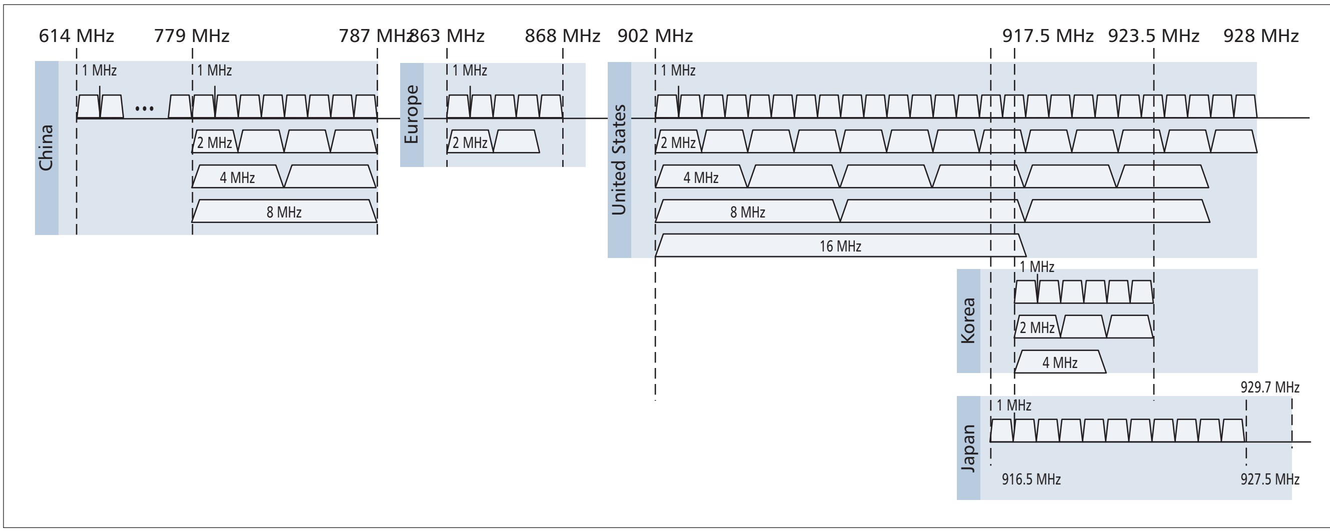


**Figure 1.** Frequency spectrum availabilities in sub-1-GHz and channelization in key geographies.

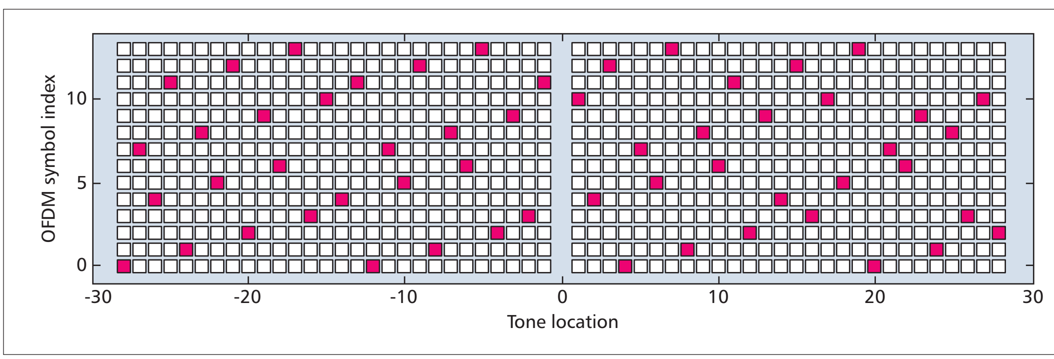


**Figure 2.** Traveling pilot positions for a signal transmitted in 2 MHz channel width and the number of space-time stream (STS) is 1 (red square = pilot tone, white square = data tone).

### Selective Subchannel Transmission

Although the 1 or 2 MHz channel bandwidth can enhance transmission range or reduce transmit power for IoT and sensor applications by reducing noise bandwidth, such a narrow bandwidth signal becomes more susceptible to flat fading than a 20 MHz 802.11ac signal. Considering that the 1 MHz channel width is approximately just 3 tones of the 20 MHz 802.11ac signal, the 1 MHz signal can easily be in a deep fade for an indoor environment with a short delay spread.

In 802.11ah, this problem is mitigated by selective subchannel transmission, which selects the best subchannel from a wider channel bandwidth. For example, the best 1 MHz subchannel can be selected from a 4 MHz channel bandwidth. This can improve signal power by approximately 7 dB for an indoor channel model with 50 ns root mean square (rms) delay spread as shown in [7].

### Traveling Pilots for the Outdoor Environment

Since 802.11ah is designed for outdoor IoT usage as well as indoor usage, it has to cope with a high Doppler case where a signal is reflected from a moving car. This means that channel estimation has to be updated throughout a packet. The previous 802.11 amendments such as 802.11n and 802.11ac use the long training field in the preamble of a packet for channel estimation and rely on the initial channel estimation throughout the packet [8]. Although a 20 MHz OFDM symbol has 4 pilot tones out of 64 subcarriers, their locations are fixed and thus cannot cover the other 52 data tone locations for the channel estimation throughout a packet for a large delay spread in outdoor usage.

In order to update channel estimation throughout a packet for all 52 data tone locations, 802.11ah supports a traveling pilot scheme that shifts pilot tones every OFDM symbol such that the traveling pilot tones over multiple OFDM symbols can cover all data tone locations. Figure 2 illustrates the traveling pilot positions for a 2 MHz channel width signal when the number of space-time streams (NSTS) is 1. In this case, the traveling pilot pattern repeats every 14 OFDM symbols. The details of other traveling patterns are described in [5, 8].

## 802.11ah MAC Features

802.11ah MAC features are mainly designed to enhance the efficiency of MAC protocols and MAC frame formats to reduce energy consumption of a client device, and to support a large number of clients for sensor and IoT applications for both indoor and outdoor environments.

## Mitigating Contention and Reducing Channel Access Delay

Supporting a transmission range of up to 1 km introduces a new challenge for an 802.11 station. As shown in Fig. 3, in a typical outdoor environment, an access point (AP) is installed at a much higher elevation, such as a rooftop, than client stations, which are mostly located near the ground. This creates much higher path loss between client stations than that between a client station and the AP because there are more building structures obstructing signal propagation between client stations than between a client station and the AP [9]. This makes the hidden node problem worse because it becomes harder for a station to hear transmissions from other stations to the AP, and this causes more collisions among transmissions from the stations to the AP. More collisions increase energy consumption of a station because the station needs to stay active longer for retransmissions to successfully deliver a data packet to the AP.

| PHY parameters | Supported values |
|---|---|
| Channel bandwidths | 1 MHz, 2 MHz, 4 MHz, 8 MHz, 16 MHz |
| Modulation schemes | BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM |
| Code rates | 1/2 with 2 times repetition, 1/2, 2/3, 3/4, 5/6 in either convolutional or low-density parity check (LDPC) |
| Maximum number of spatial streams | Four spatial streams |
| Data rates | 150 kb/s (1 MHz channel bandwidth, 1 spatial stream, BPSK, 1/2 coding rate, repetition coding) to 347 Mb/s (16 MHz channel bandwidth, 4 spatial streams, 256 QAM, 5/6 coding rate) |

**Table 2.** 802.11ah PHY parameters.

| Parameters | Link budget enhancements of 900 MHz 802.11ah over 2.4 GHz 802.11n |
|---|---|
| Free space path loss | +8.5 dB |
| Noise bandwidth | +10 dB |
| Sub-total link budget gain | +18.5 dB |
| 1 MHz channel width | +3 dB |
| Repetition coding | +3 dB |
| Total link budget gain | +24.5 dB |

**Table 3.** Link budget parameters between 900 MHz and 2.4 GHz.

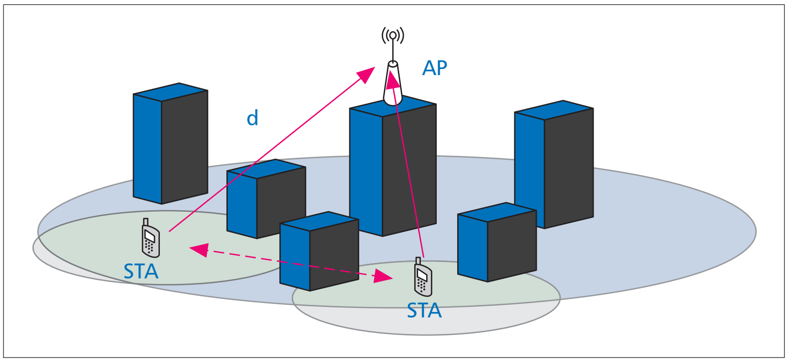


**Figure 3.** Illustration of an outdoor environment where an AP is installed at a rooftop and client stations are located near the ground. The path loss between STAs is much higher than the path loss between the AP and a STA.

***Restricted Access Window:*** 802.11ah mitigates the hidden node problem by restricting the time at which a station can start to contend for the medium so that packet transmissions from stations do not overlap with each other. 802.11ah defines a time window called a restricted access window (RAW) during which only a group of stations that are associated with an AP are allowed to access the medium. The structure of a RAW is illustrated in Fig. 4a. A RAW is divided into RAW slots, and each RAW slot is typically allocated to one station. The maximum number of slots in a RAW is 64. A RAW slot may also be allocated to more than one station to achieve statistical multiplexing among the stations in the RAW slot. A station in the group is allowed to contend for the medium at the beginning of the allocated RAW slot. Although the RAW slot is allocated to the station by the AP, the station still needs to perform the contention-based channel access because stations associated with other APs do not have the information about the RAW slot allocation and may still contend for the medium. The RAW parameter set (RPS) element contains information of one or more RAWs such as the RAW start time, RAW slot duration, and number of slots. The details of the RAW parameter set element are defined in [5]. The simulation results in [10] show that collisions among hidden nodes can be mitigated significantly using the RAW scheme.

***Synchronization Frame:*** In 802.11, a station is allowed to start to contend for the medium only if it has valid information of the medium so that it does not interrupt packet transmissions and receptions of other stations in the network. The station obtains the information of the medium from the duration field of a packet that was received correctly; otherwise, it has to wait for a time duration called ProbeDelay to expire to avoid collision with a packet transmission of other station [1]. For example, if a station just woke up from sleep and has not received a packet, it has to either wait for a packet or wait until the ProbeDelay timer expires, which adds additional energy consumption to the station. The ProbeDelay problem is described in [10] in more detail.

In 802.11ah, the medium access delay due to

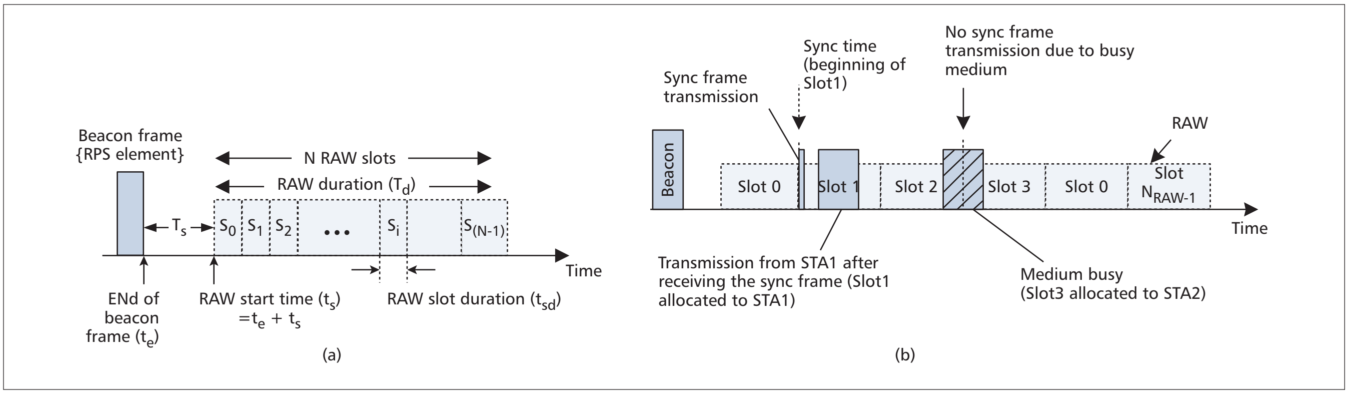


**Figure 4.** Illustration of a) a RAW; b) synchronization frame operation.

the ProbeDelay is reduced with help from an AP. As illustrated in Fig. 4b, the AP transmits a synchronization (sync) frame at the beginning of a RAW slot when the medium is idle so that a station can obtain the information of the medium from the sync frame and access the medium right after the end of the sync frame reception instead of waiting for the ProbeDelay time to expire. If the medium is busy at the AP, the sync frame is not transmitted, and the station waits for the ProbeDelay time to expire to prevent possible collision at the AP. The simulation results in [10] show that the sync frame technique can increase the battery life of a station by up to 31 percent when the ProbeDelay time is set to 5 ms.

### Efficient Bidirectional Packet Exchanges

802.11ah introduced the target wake time and bidirectional transmission opportunity (TXOP; BDT) schemes to enhance bidirectional packet exchanges between two stations by eliminating overheads between uplink and downlink transmissions, thereby minimizing energy consumption of sensor devices.

***Target Wake Time:*** An AP buffers data destined for a station while the station is in a sleep state. The station periodically wakes up at beacon transmission times and receives a beacon to see if there is any buffered data at the AP based on the information in the traffic indication map (TIM) element contained in the received beacon. If the TIM element indicates that there is buffered data for the station, the station first sends a PS-Poll frame to the AP to indicate that the station is awake and is ready to receive the buffered data. The AP, however, needs processing time to find the buffered data for the station from its memory, and then has to contend for the medium and transmit the data to the station. This indefinite latency makes the station consume energy waiting for the buffered data.

Target wake time (TWT) addresses this problem by having an AP and a station schedule a future wake-up time (i.e., a TWT) of the station so that the AP knows when the station will be awake. The AP fetches buffered data from its memory before the TWT so that when a PS-Poll frame or a trigger frame is received from the station, the AP can transmit the buffered data without the processing time and the medium access latency. The time information of the next TWT can be delivered explicitly to the station during the frame exchange in the current TWT or calculated implicitly by adding a fixed time interval to the current TWT.

***Bidirectional TXOP:*** For a sensor device with a small battery, it is critical to minimize energy consumption of the device. A sensor device can minimize its energy consumption by coalescing transmit and receive activities in a single TXOP to increase its time in a sleep state.

BDT allows an AP and a station to exchange one or more uplink and downlink packets separated by a short inter frame space (SIFS) in a TXOP duration. In the BDT procedure, a station uses the More Data bit in the SIGNAL field of the PHY preamble to signal whether the station has more data to transmit following the current packet transmission.

802.11ah also added the Response Indication field in the SIGNAL field of the PHY preamble of a packet to better protect a response packet. The Response Indication field in the transmitted packet indicates one of the four different lengths of a response packet that will follow the transmitted packet so that the third party stations near the transmitter can defer until the end of the response packet. Since the Response Indication field is in the SIGNAL field, it uses the most robust modulation and coding scheme, and the third party stations can defer correctly as long as they decode the SIGNAL field correctly.

### Null Data Packet Carrying MAC Frame

In 802.11, a Control frame such as the ACK frame, which is 14 bytes long, has not been considered to be a large overhead for email or file transfer that transmits large packets (e.g., 1500 bytes). For sensor and IoT applications, however, the ACK frame can be a large overhead considering that those applications typically transmit much shorter data packets (e.g., 100 bytes [2]).

Control frames are transmitted with the lowest modulation and coding scheme, and for the 802.11ah 2 MHz channel width, it takes 440 µs to transmit an ACK packet (240 µs for the PHY

The new Short MAC header of a Short QoS Data frame is reduced to 12 bytes. In order to differentiate the new short MAC header format from the legacy MAC frame format, the protocol version field of the frame control field in the short MAC header is increased from 0 to 1 for the first time in 802.11 history.

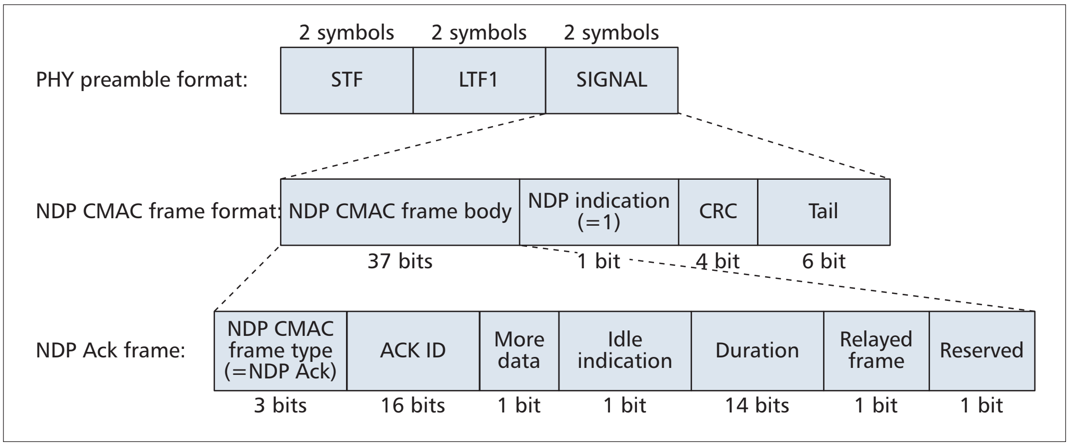


**Figure 5.** Illustration of the NDP CMAC frame format and the NDP Ack frame format in 2 MHz, 4 MHz, 8 MHz, and 16 MHz.

preamble and 200 μs for the ACK frame) at the 650 kb/s data rate. To transmit a 100-byte data packet at the same data rate, it takes 1480 μs (1240 μs for the data frame). In this case, the ratio between the ACK packet transmission time and the ACK and data packets transmission time is approximately 23 percent, which shows a large overhead of ACK frame transmission.

802.11ah mitigates this problem by defining a null data packet (NDP) carrying MAC (CMAC) frame format that consists of only the PHY preamble and no data field, as shown in Fig. 5. The SIGNAL field of the NDP CMAC frame is redefined to contain all the necessary information previously contained in a Control MAC frame. The length of an NDP CMAC frame is now fixed to the length of the PHY preamble, which is 240 μs (6 OFDM symbols) for a signal transmitted in a channel bandwidth larger than or equal to 2 MHz. For example, 802.11ah uses the NDP Ack frame shown in Fig. 5 instead of the ACK frame as a response to a data frame. The ratio between the NDP Ack frame transmission time and the NDP Ack frame and the data packet transmission time is now reduced to 14 percent. The details of the NDP CMAC frames are described in [5].

### Short MAC Frame

In 802.11n, the MAC header of a quality of service (QoS) Data frame can be 30 bytes long. For an IoT application that transmits a small packet (e.g., a temperature sensor with 50 bytes of data [2]) infrequently, the MAC header can be a big overhead.

802.11ah mitigates this problem by defining a new Short MAC frame format. The new Short MAC header of a Short QoS Data frame is reduced to 12 bytes. In order to differentiate the new short MAC header format from the legacy MAC frame format, the protocol version field of the frame control field in the short MAC header is increased from 0 to 1 for the first time in 802.11 history.

### Support of a Large Number of Stations

One of the use cases of 802.11ah is a smart grid use case where an AP has to support as many as 6000 stations within a 1 $km^2$ area [2, 11]. In order to support this use case, in 802.11ah, the number of stations that an AP can support is increased from 2007 to 8191. During an association process, a station is assigned with an association identifier chosen from 1 to 8191 by an AP. The AP maintains a traffic indication virtual bitmap where the $n$th bit is mapped to a station that has the association identifier value of $n$. When there is buffered data for the station with the association identifier value of $n$, the AP sets the $n$th bit of the bitmap to 1 and signals the information in the Partial Virtual Bitmap field of the TIM element in a beacon. Signaling such a large traffic indication virtual bitmap becomes challenging because in some cases the length of the Partial Virtual Bitmap field can be a couple of hundred bytes long.

In order to minimize the size of the TIM element, the traffic indication virtual bitmap is structured in a hierarchical fashion, and 802.11ah defines four encoding modes to compress the traffic indication virtual bitmap [5]. The simulation results in [12] show that the bitmap size can be compressed by 30–98 percent with the encoding schemes compared to the scheme defined in the baseline 802.11 standard [1].

### Increased Sleep Time

IEEE 802.11ah is designed to support a sensor device that sleeps for a very long period of time (e.g., a couple of days), waking up infrequently to transmit or receive a short data packet and going back to sleep. In the baseline 802.11 standard [1], however, a station cannot sleep for more than approximately 18 hours because the Max Idle Period field that contains the parameter BSSMaxIdlePeriod is an unsigned 16-bit value, and this parameter determines how long a station can stay idle (in seconds) before the station is disassociated from the AP. If the station wants to stay associated with the AP, it has to transmit a packet at least every BSSMaxIdlePeriod time.

In 802.11ah, the Max Idle Period field is redefined such that the two most significant bits of the Max Idle Period field is used as a scaling factor. When a scaling factor of 10,000 is used, a station can sleep for approximately 5.2 years without being disassociated from the AP.

## 802.11AH DEVELOPMENT TIMELINE

In 2010, the IEEE 802.11ah Task Group was formed. The task group developed the first 802.11ah draft amendment, D1.0, in October 2013. After going through four iterations of the letter ballot and comment resolution process, the task group developed the 802.11ah draft amendment, D5.0, in April 2015. The final 802.11ah amendment is expected to be published in 2016 [13]. The WiFi Alliance has also formed a task group named Extended Range ah to study requirements for an interoperability certification program [14].

## CONCLUSIONS

In this article, the major PHY and MAC features of IEEE 802.11ah are presented. 802.11ah is designed to support a wide range of applications in sub-1-GHz frequency spectrum: from sensors and Internet of Things applications to extended WiFi applications by providing data rates from 150 kb/s to 347 Mb/s. 802.11ah is designed to support an outdoor application that needs a transmission range up to 1 km at 150 kb/s. These are achieved by using the PHY parameters listed in Table 2. For an indoor application, the long-range capability can be used for energy-efficient communications for sensors by using a very low transmit power. As summarized in Table 4, 802.11ah provides energy-efficient MAC protocols and MAC frame formats that are optimized for sensors and IoT applications, which need to support a large number of stations and infrequent small packet transmissions.

| Functions for sensors and IoT | MAC features |
|---|---|
| Support for a large outdoor IoT network | RAW, synchronization frame, hierarchical TIM |
| Support for energy-efficient communications for sensors | TWT, BDT, NDP CMAC frame, short MAC frame, increased sleep time |

**Table 4.** Summary of 802.11ah MAC features.

### REFERENCES


[1] IEEE Std 802.11-2012, "IEEE Standard for Information Technology Telecommunications and Information Exchange between Systems — Local and Metropolitan Area Networks Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications."

[2] R. de Vegt, "Potential Compromise for 802.11ah Use Case Document," IEEE 802.11-11/0457r0, Mar. 2011.

[3] R. de Vegt, "802.11ac Usage Models Document," IEEE 802.11-09/0161r2, Jan. 2009.

[4] P. Loc and M. Cheong, "TGac Functional Requirements and Evaluation Methodology," IEEE 802.11-09/451r16, Jan. 2011.

[5] IEEE 802.11ah/D5.0, "Draft for Information Technology — Telecommunications and Information Exchange between Systems — Local and Metropolitan Area Networks — Specific Requirements — Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications — Amendment 6: Sub 1 GHz License Exempt Operation."

[6] IEEE Std 802.15.4-2011, "IEEE Standard for Local and Metropolitan Area Networks Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)."

[7] M. Fischer, *et al.*, "Frequency Selective Transmission," IEEE 11-12/1338r0, Nov. 2012.

[8] R. Porat *et al.*, "Traveling Pilots," IEEE 802.11-12/1322r0, Nov. 2012.

[9] R. Porat, S. Yong, and K. Doppler, "TGah Channel Model," IEEE 802.11-11/0968r3, Nov. 2011.

[10] M. Park, "IEEE 802.11ah: Energy Efficient MAC Protocols for Long Range Wireless LAN," *Proc. IEEE ICC*, 10–14 June 2014, pp. 2388–93.

[11] S. Kim *et al.*, "Association ID management for TGah," IEEE 802.11-11/88r1, Jan. 2011.

[12] M. Park, "TGah Efficient TIM Encoding," IEEE 802.11-12/388r2, May 2012.

[13] IEEE, "IEEE 802.11 Working Group Project Timelines," http://www.ieee802.org/11/Reports/802.11_Timelines.htm, accessed June 22, 2015.

[14] WiFi Alliance, "Current Work Areas," http://www.wi-fi.org/who-we-are/current-work-areas, accessed: June 22, 2015.


### BIOGRAPHY:


MINYOUNG PARK received B.S. and M.S. degrees from Yonsei University, Seoul, Korea, in 1993 and 1995, and his Ph.D. degree from the University of Texas at Austin in 2005, all in electrical engineering. From 1995 to 2001, he was a senior research engineer at LG Electronics Inc. He is currently a research scientist at Intel Labs. He has participated in various standards developments in IEEE 802.11 and the WiFi Alliance, and served as the Technical Editor of the IEEE 802.11ah Task Group. His research interests are focused on the physical and MAC layers of wireless communications systems.