802.11 Alternate PHYs

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Modern 802.11 Amendments

Today, we live in the IoT (Internet-of-things) world where everything needs to be connected in a fast, reliable and secure manner. Different devices and applications have different requirements of the network in terms of data rates, range, and power. For example, while some devices require connectivity with very high throughput for a short range (less than 10m), other devices might require low throughput over a long range. The common 2.4GHz and 5 GHz Wi-Fi protocols (802.11a/b/g/n/ac) do not always provide the optimum connectivity method for these requirements. For this reason, several new 802.11 standards have been developed in the last several years to provide better connectivity solutions catering to these unique requirements.

In this paper, we will address the traditional 802.11 2.4/5GHz standards. Then, we will discuss briefly three newer Wi-Fi amendments which are 802.11ad, 802.11af and 802.11ah and explain how they can provide better solutions to meet the new requirements.

Traditional PHYs Review (2.4 GHz and 5 GHz PHYs)

IEEE 802.11 Wireless Local Area Networks (WLANs), operating in 2.4 GHz and 5 GHz bands, are the most popular wireless technology in indoor environments. Today, they provide ubiquitous access with very high data rates and are easy to deploy at a low cost. IEEE 802.11 standards operating in these bands have evolved in the past 20 years from the original 802.11 standard to the latest 802.11ac, with 802.11ax on the horizon.

The original 802.11-1997 standard offered 1 or 2 Mbps data rates using Frequency-Hopping Spread Spectrum (FHSS) and Direct-Sequence Spread Spectrum (DSSS) technologies. In 1999, 802.11b was introduced and it offered 11 Mbps data rates using High Rate –DSSS (HR/DSSS) technologies in the 2.4GHz band and also introduced a data rate of 5.5 Mbps. In 1999, the 802.11a amendment was ratified as well. Unlike 802.11b, this amendment worked in the 5 GHz band and it offered a maximum data rate of 54 Mbps by leveraging Orthogonal Frequency-Division Multiplexing (OFDM) modulation. In 2003, 802.11g was introduced and it enabled 54 Mbps maximum data rates in the 2.4 GHz band using OFDM modulation. It was also backwards compatible with 802.11b and supported DSSS modulation, because it operated in the 2.4 GHz frequency band. In 2009, 802.11n introduced major enhancements that improved the WLAN throughput, range, and reliability and remained backwards compatible with legacy 802.11a/b/g devices as it operated in both the 2.4 GHz and 5 GHz frequency bands. Wider 40 MHz channels were introduced in 802.11n and the use of multiple-input-multiple-output (MIMO) antennas with multiple spatial streams was also added. With 802.11n, the maximum data rate reached 600 Mbps (in the standard) with a 4 spatial stream connection using a 40 MHz channel. In 2013, 802.11ac was ratified and the available channel bandwidth was increased further to reach 160 MHz, the number of supported spatial streams was increased to 8 (in the standard) and Multi-User MIMO (MU-MIMO) was introduced as well as a higher modulation rate (256-QAM). The maximum theoretical data rate with

802.11ac is now 6.933 Mbps. Table 1 summarizes this evolution of the IEEE 802.11 WLAN protocols operating in the 2.4 and 5 GHz bands.

Release Date	Standard	Frequency Band	Bandwidth	Modulation Techniques	Advanced Antenna Technology	Maximum Data Rate (Theoretical)
1997	802.11	2.4 GHz	20 MHz	DSSS,FHSS		2 Mbps
1999	802.11b	2.4 GHz	20 MHz	HR-DSSS		11 Mbps
1999	802.11a	5 GHz	20 MHz	OFDM		54 Mbps
2003	802.11g	2.4 GHz	20 MHz	DSSS,OFDM		54 Mbps
2009	802.11n	2.4 GHz,				
5 GHz	20/40 MHz	OFDM	MIMO, Max 4 Spatial Streams	600 Mbps		
2013	802.11ac	5 GHz	20/40/80/160 MHz	OFDM	MIMO, MU-MIMO, Max 8 Spatial Streams	6,933Mbps

Table 1: Evolution of the IEEE 802.11 WLAN Protocols

Even with these improvements happening in the 802.11 amendments operating in the 2.4 and 5 GHz bands, many challenges remain. The 2.4 GHz band is a congested band and the number of truly non-overlapping channels is limited to 3. The 5 GHz band, which has a larger number of non-overlapping channels, suffers from lower client support densities, unusual channel regulations that vary by region, and lack of range for low power scenarios.

New 802.11 WLAN protocols were needed to cater to new requirements like having very high throughput requirements (1Gbps) for short ranges or having large coverage areas with lower throughput requirements. 802.11ad, 802.11af and 802.11ah protocols were thus introduced to cater to these new requirements.

802.11ad Directional Multi-Gigabit - DMG PHY

Frequency Band Used

The IEEE 802.11ad amendment was announced in 2009 by the Wireless Gigabit Alliance (WiGig). The official 802.11ad amendment (Enhancements for Very High Throughput in the 60 GHz Band) was published by IEEE in December 2012. This protocol is now part of the latest rollup of the IEEE Standard 802.11-2016. 802.11ad operates in the 60 GHz unlicensed frequency band (57.24 to 65.88 GHz).

This range allows for higher channel bandwidth and offers greater throughput. It uses short wavelengths (5mm) thus making it possible to use compact antennas or antenna arrays. Operating at 60 GHz results in increased signal attenuation as compared to 2.4 and 5GHz bands. 802.11ad signals are expected to have a short range of around 10 meters (sometimes more depending on the environment). So 802.11ad technology can be thought of as a very high speed ad-hoc point-to-point Wi-Fi technology (above 1 Gbps) but for a short range (usually less than 10 meters).

Channel Plans

802.11ad operates in and around the 60 GHz channel bands. The useful unlicensed bands around 60 GHz (57 to 66 GHz) are regulated differently in various countries/regions around the world. Although 802.11ad defines four channels, some of the channels are not available in different geographies. The center frequencies of channels 1 to 4 are 58.32 GHz, 60.48 GHz, 62.64 GHz and 64.80 GHz respectively. The channel bandwidth of each channel is 2.16 GHz. Channel 2 is the recommended default channel as it is globally available as shown in Figure 1 and Figure 2.

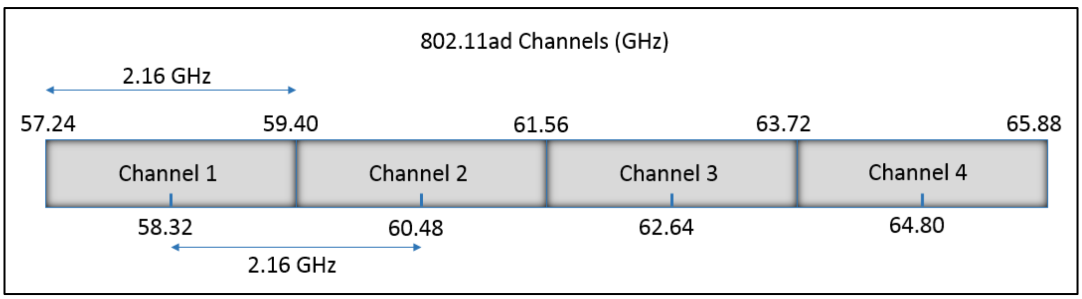

Figure 1: 802.11ad Channels

Modulation Methods and Data Rates

Three different modulation methods are specified with 802.11ad which are Control, Single Carrier PHY (SC PHY) and OFDM PHY. These different modulation modes offer a tradeoff between high throughput and robustness. The Control PHY, which is mandatory in any implementation, provides high levels of error correction and detection and thus has a relatively low throughput. The SC PHY uses a single carrier while OFDM uses multicarrier modulation and the OFDM PHY provides higher data throughput as compared to the SC PHY. Finally, a Low Power SC PHY is available for battery devices to minimize power consumption and extend battery lifetime.

<table>
<tr><th>Channel Number</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>Center Frequency (GHz)</td><td>58.32</td><td>60.48</td><td>62.64</td><td>64.80</td></tr>
<tr><td rowspan="5">Region/Country</td><td colspan="3">U.S.A, Canada, Korea</td><td></td></tr>
<tr><td colspan="4">European Union</td></tr>
<tr><td></td><td colspan="2">China</td><td></td></tr>
<tr><td></td><td colspan="3">Japan</td></tr>
<tr><td></td><td>Australia</td><td></td><td></td></tr>
<tr><td colspan="5">Note: Available Channels are marked in Blue</td></tr>
</table>

Figure 2: 802.11ad Channels Availability across Regions/Countries

There are 32 modulation and coding scheme (MCS) entries defined in 802.11ad (MCS 0 to 31). The data rates associated with each MCS index are listed in Table 2.

All 802.11ad frames use the same packet structure consisting of Preamble, header and data. There is an optional training field for beamforming. Different PHYs vary in the definition of the individual fields and in the modulations and coding scheme used.

Use Cases

Typical use cases for 802.11ad include:

- Multimedia Sharing and Streaming: Wireless Display, TV (For example wireless streaming of 4K HD video from a mobile phone to a TV screen)
- Wireless Docking Stations
- Distribution of HDTV (For example transmission of lightly compressed or uncompressed video from a computer or digital camera to an HDTV, monitor or projector
- Wireless Peripheral Devices (Wireless Hard Drives, Memory Sticks)
- High Speed multi-gigabit Wireless Connectivity to upload/download large files without fixed network infrastructure
- Automatic Sync Applications (For example Wireless Uploading Images/ Videos from Cameras)

PHY	MCS	Modulation	Code Rate	Data Rate Mbps
Control PHY	0	DBPSK	1/2	27.50
Single Carrier PHY (SC PHY)	1	π/2 BPSK	1/2	385.00
	2	π/2 BPSK	1/2	770.00
	3	π/2 BPSK	5/8	962.50
	4	π/2 BPSK	3/4	1155.00
	5	π/2 BPSK	13/16	1251.25
	6	π/2 QPSK	1/2	1540.00
	7	π/2 QPSK	5/8	1925.00
	8	π/2 QPSK	3/4	2310.00
	9	π/2 QPSK	13/16	2502.50
	10	π/2 16 QAM	1/2	3080.00
	11	π/2 16 QAM	5/8	3850.00
	12	π/2 16 QAM	3/4	4620.00
OFDM PHY	13	SQPSK	1/2	693.00
	14	SQPSK	5/8	866.25
	15	QPSK	1/2	1386.00
	16	QPSK	5/8	1732.50
	17	QPSK	3/4	2079.00
	18	16-QAM	1/2	2772.00
	19	16-QAM	5/8	3465.00
	20	16-QAM	3/4	4158.00
	21	16-QAM	13/16	4504.50
	22	64-QAM	5/8	5197.50
	23	64-QAM	3/4	6237.00
	24	64-QAM	13/16	6756.75
Low Power Single Carrier PHY (SC PHY)	25	π/2 BPSK	13/28	626.00
	26	π/2 BPSK	13/21	834.00
	27	π/2 BPSK	52/63	1112.00
	28	π/2 QPSK	13/28	1251.00
	29	π/2 QPSK	13/21	1668.00
	30	π/2 QPSK	52/63	2224.00
	31	π/2 QPSK	13/14	2503.00

Table 2: 802.11ad Data Rates

802.11af TV High Throughput (TVHT) PHY

IEEE 802.11af standard, commonly known as White-Fi or Super-Wi-Fi, is a WLAN standard that utilizes the spare radio spectrum or white spaces in the sub 1GHz television bands. The standard was accepted in 2014. The 802.11af physical (PHY) layer is based on the (OFDM) scheme specified in 802.11ac. Operating below 1GHz, these frequencies will provide a greater range when compared to 2.4 or 5 GHz bands.

Frequency Band Used

IEEE 802.11af defines the TV High throughput (TVHT) physical layer for White Space Devices (WSD) to use and operate in TV White Space (TVWS) frequency bands. Depending on the regulatory domain, 802.11af works in the 470 to 790 MHz range in Europe and in the 54 to 698 MHz range in U.S.A.

Because IEEE 802.11af channels operate over a wide frequency range, the propagation characteristics for the various channels differ. IEEE 802.11af signal coverage may vary from several hundred meters up to 1 kilometer in range.

Channel Plans

A TVHT device has support for single-channel bandwidth or basic channel unit (BCU) or W of 6, 7, and 8 MHz depending on the regulatory domain. Moreover, additional bonded or non-contiguous bandwidths of 2W, 4W, W+W, and 2W+2W are possible, as shown in the below figure. Only single-channel bandwidth W and a single spatial stream is mandatory, although multiple-input multiple-output (MIMO) transmissions with 4x space-time block coding (STBC) and 4x multi-user (MU) diversity can be supported.

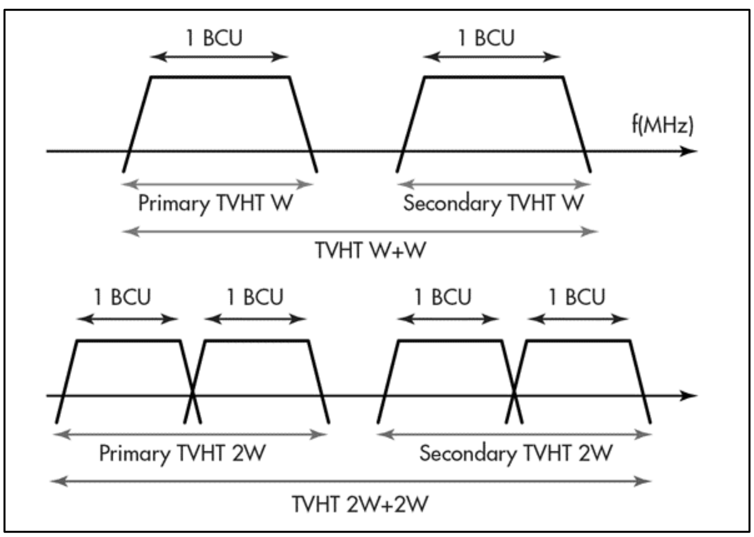

Figure 4: 802.11af Channels

In the U.S. for example, only 6 MHz channels are allowed in TV channels 2, 5, 6, 14-35, 38-51. In Europe.

TV White Space Channel	Lower Frequency	Upper Frequency	Channel Width	Spectrum
2	54 MHz	60 MHz	6 MHz	VHF Low-Band
5	76 MHz	82 MHz	6 MHz	VHF Low-Band
6	82 MHz	88 MHz	6 MHz	VHF Low Band
14 – 35	476 – 602 MHz	476 – 602 MHz	6 MHz	UHF
38 - 51	612 – 692 MHz	620 – 698 MHz	6 MHz	UHF

Figure 5: 802.11af U.S. 6 MHz Channels

Modulation Methods and Data Rates

The maximum achievable data rate per spatial stream is 26.7 Mbps for 6 and 7 MHz channels and 35.6 Mbps for 8 MHz channels. With four spatial streams and four bonded channels, the maximum data rate is 426.7 Mbps for 6 and 7 MHz channels and 568.9 Mbps for 8 MHz channels.

Use Cases

Typical use cases for 802.11af include:

- Rural Broadband Deployment:
    - For example, areas which are poorly served with cellular or broadband can utilize 802.11af to provide long-range internet services with Internet speeds more than 100 Mbps.

802.11ah - Sub 1 GHz (S1G) PHY

The S1G PHY operates below 1 GHz and is covered in this section.

Frequency Band Used

The IEEE 802.11ah PHY (commonly known as Wi-Fi Halow) was ratified in 2016. It uses the less congested 900MHz ISM license-free band to provide improved transmission range as compared to traditional 2.4 GHz and 5 GHz Wi-Fi PHYs. This PHY was developed to address the range and power constraints of new IoT devices so it can offer a larger range with lower power requirements from the client devices. 802.11ah signals have good propagation and penetration capabilities and it will be used for many IoT and M2M applications. As shown below, different countries have different sub 1GHz ISM bands that are available for 802.11ah.

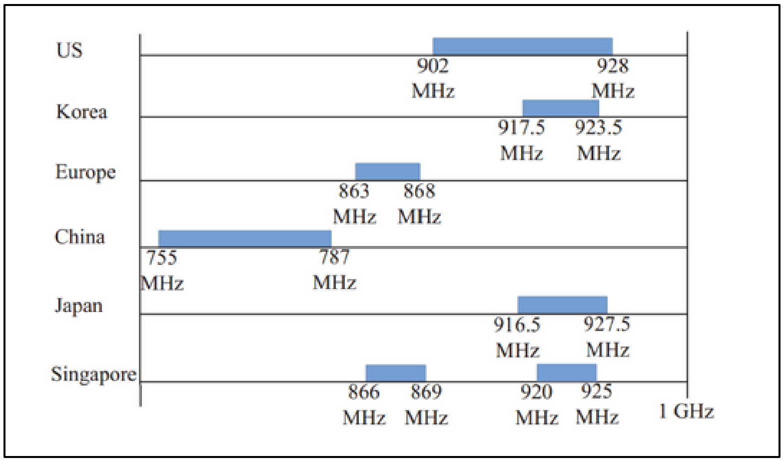

Figure 6: 802.11ah Frequency Bands across Regions

Channel Plans

IEEE 802.11ah defines the channels based upon the spectrum that is available in a given country. For example, for the U.S., the allocated band is from 902 to 928 MHz. The distribution of the channels for the U.S. is shown below. There are 26 1MHz channels, 13 2MHz channels, 6 4MHz channels, 3 8MHz channels and 1 16 MHz channel that can be used.

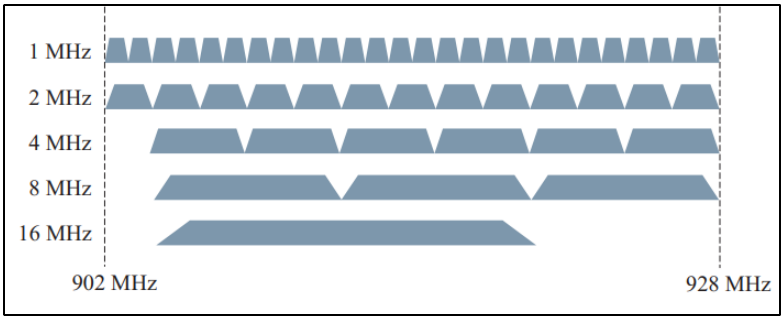

Figure 7: 802.11ah Channels in the U.S.

Modulation Methods and Data Rates

802.11ah uses OFDM and it supports MIMO and MU-MIMO with up to 4 spatial streams. It is a ten times down-clocked version of 802.11ac and it supports 2, 4, 8 and 16 MHz channels as compared to 20, 40, 80 and 160 MHz channels supported in 802.11ac. Moreover, 802.11ah supports 1MHz channels to provide extended range. The physical rates range from 150 Kbps to 347 Mbps (4 spatial streams 16 MHz & short guard interval).

802.11ah Modulation and Coding Schemes											
MCS index	Spatial Streams	Modulation Type	Coding rate	Data rate (in Mbps)							
				2 MHz channels		4 MHz channels		8 MHz channels		16 MHz channels	
				8 µs GI	4 µs GI	8 µs GI	4 µs GI	8 µs GI	4 µs GI	8 µs GI	4 µs GI
0	1	BPSK	1/2	0.65	0.72	1.35	1.5	2.93	3.25	5.85	6.5
1	1	QPSK	1/2	1.3	1.44	2.7	3	5.85	6.5	11.7	13
2	1	QPSK	3/4	1.95	2.17	4.05	4.5	8.78	9.75	17.6	19.5
3	1	16-QAM	1/2	2.6	2.89	5.4	6	11.7	13	23.4	26
4	1	16-QAM	3/4	3.9	4.33	8.1	9	17.6	19.5	35.1	39
5	1	64-QAM	2/3	5.2	5.78	10.8	12	23.4	26	46.8	52
6	1	64-QAM	3/4	5.85	6.5	12.2	13.5	26.3	29.3	52.7	58.5
7	1	64-QAM	5/6	6.5	7.22	13.5	15	29.3	32.5	58.5	65
8	1	256-QAM	3/4	7.8	8.67	16.2	18	35.1	39	70.2	78
9	1	256-QAM	5/6	N/A	N/A	18	20	39	43.3	78	86.7
0	2	BPSK	1/2	1.3	1.44	2.7	3	5.85	6.5	11.7	13
1	2	QPSK	1/2	2.6	2.89	5.4	6	11.7	13	23.4	26
2	2	QPSK	3/4	3.9	4.33	8.1	9	17.6	19.5	35.1	39
3	2	16-QAM	1/2	5.2	5.78	10.8	12	23.4	26	46.8	52
4	2	16-QAM	3/4	7.8	8.67	16.2	18	35.1	39	70.2	78
5	2	64-QAM	2/3	10.4	11.6	21.6	24	46.8	52	93.6	104
6	2	64-QAM	3/4	11.7	13	24.3	27	52.7	58.5	105	117
7	2	64-QAM	5/6	13	14.4	27	30	58.5	65	117	130
8	2	256-QAM	3/4	15.6	17.3	32.4	36	70.2	78	140	156
9	2	256-QAM	5/6	N/A	N/A	36	40	78	86.7	156	173
0	3	BPSK	1/2	1.95	2.17	4.05	4.5	8.78	9.75	17.6	19.5
1	3	QPSK	1/2	3.9	4.33	8.1	9	17.6	19.5	35.1	39
2	3	QPSK	3/4	5.85	6.5	12.2	13.5	26.3	29.3	52.7	58.5
3	3	16-QAM	1/2	7.8	8.67	16.2	18	35.1	39	70.2	78
4	3	16-QAM	3/4	11.7	13	24.3	27	52.7	58.5	105	117
5	3	64-QAM	2/3	15.6	17.3	32.4	36	70.2	78	140	156
6	3	64-QAM	3/4	17.6	19.5	36.5	40.5	N/A	N/A	158	176
7	3	64-QAM	5/6	19.5	21.7	40.5	45	87.8	97.5	176	195
8	3	256-QAM	3/4	23.4	26	48.6	54	105	117	211	234
9	3	256-QAM	5/6	26	28.9	54	60	117	130	N/A	N/A

Table 3: 802.11ah Data Rates

Use Cases

Typical use cases for 802.11ah include:

- Providing connectivity for large Scale Sensor Networks:
  - For example, to monitor the readings of multiple sensors and be able to provide real-time status of various utilities, 802.11ah APs can be deployed to provide the needed connectivity for a large number of sensors since it can offer a large transmission range of around 1km.
- Providing Backhaul Network for Sensors and Meter:
  - For example, outdoor low traffic (few kbps) sensors (potentially using IEEE 802.15.4g standard) can use IEEE 802.11ah/IEEE 802.15.4g Gateways as uplinks for these sensors. So the leaf sensors will use IEEE 802.15.4 protocol to send the data to the gateways. The gateways will use IEEE 802.11ah as a backhaul uplink network aggregating the data from multiple sensors.
- Providing Extended Range Wi-Fi with lower data rates (For example ranch, mountainous areas)

Summary

In this paper, we briefly described the new 802.11ad, 802.11af and 802.11ah protocols which belong to the 802.11 WLAN family of protocols and which were ratified in the last few years. These protocols were developed to meet new connectivity requirements that couldn't be achieved with the existing 2.4 GHz and 5 GHz wireless protocols including 802.11a/b/g/n/ac. The below table provides a quick summary of these protocols.

Standard	Frequency Band	Bandwidth	Maximum Data Rate (Theoretical)	Main Use Cases
802.11ad	60 GHz Band 57.24-63.72 (U.S.) 57.24-65.88 (Europe)	2.16 GHz	6756.75 Mbps	Short Range (less than 10m) Very High Throughput Connectivity (>1Gbps) for multimedia sharing, streaming, distribution of HDTV, Wireless Upload/Download etc.
802.11af	54-790 MHz (U.S.) 470-790 (Europe) Licensed Band	6 to 8MHz	568.9 Mbps (4 Spatial Steams, 4 Bonded 8 MHz Channels)	Provide Broadband in Rural Areas with reasonable speeds (above 100 Mbps)
802.11ah	Sub 1GHz Band 902-929 MHz (U.S.) 863 – 868 MHz (Europe) (License - Exempt Band)	1,2,4,8,16 MHz	347 Mbps (4 Spatial Streams / 16 MHz Channel / Short GI)	Provide Connectivity for Large Scale Sensor Networks Provide Backhaul Networks for Sensors and Meters

Table 4: Summary of 802.11ad, 802.11af and 802.11ah