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IEEE 802.11

IEEE 802.11 is part of the IEEE 802 set of local area network (LAN) technical standards, and specifies the set of media access control (MAC) and physical layer (PHY) protocols for implementing wireless local area network (WLAN) computer communication. The standard and amendments provide the basis for wireless network products using the Wi-Fi brand and are the world's most widely used wireless computer networking standards. IEEE 802.11 is used in most home and office networks to allow laptops, printers, smartphones, and other devices to communicate with each other and access the Internet without connecting wires. IEEE 802.11 is also a basis for vehicle-based communication networks with IEEE 802.11p.

The standards are created and maintained by the Institute of Electrical and Electronics Engineers (IEEE) LAN/MAN Standards Committee (IEEE 802). The base version of the standard was released in 1997 and has had subsequent amendments. While each amendment is officially revoked when it is incorporated in the latest version of the standard, the corporate world tends to market to the revisions because they concisely denote the capabilities of their products. As a result, in the marketplace, each revision tends to become its own standard.

IEEE 802.11 uses various frequencies including, but not limited to, 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz frequency bands. Although IEEE 802.11 specifications list channels that might be used, the radio frequency spectrum availability allowed varies significantly by regulatory domain.

The protocols are typically used in conjunction with IEEE 802.2, and are designed to interwork seamlessly with Ethernet, and are very often used to carry Internet Protocol traffic.

This Linksys WRT54GS, a combined router and Wi-Fi access point, operates using the 802.11g standard in the 2.4 GHz ISM band using signalling rates up to 54 Mbit/s.

For comparison, this Netgear product, a combined router and Wi-Fi access point from 2013, uses the 802.11ac standard in the 5 GHz band, with signalling rates up to 6933 Mbit/s.

General description

The 802.11 family consists of a series of half-duplex over-the-air modulation techniques that use the same basic protocol. The 802.11 protocol family employs carrier-sense multiple access with collision avoidance (CSMA/CA) whereby equipment listens to a channel for other users (including non 802.11 users) before transmitting each frame (some use the term "packet", which may be ambiguous: "frame" is more technically correct).

802.11-1997 was the first wireless networking standard in the family, but 802.11b was the first widely accepted one, followed by 802.11a, 802.11g, 802.11n, and 802.11ac. Other standards in the family (c–f, h, j) are service amendments that are used to extend the current scope of the existing standard, which amendments may also include corrections to a previous specification.[1]

802.11b and 802.11g use the 2.4-GHz ISM band, operating in the United States under Part 15 of the U.S. Federal Communications Commission Rules and Regulations. 802.11n can also use that 2.4-GHz band. Because of this choice of frequency band, 802.11b/g/n equipment may occasionally suffer interference in the 2.4-GHz band from microwave ovens, cordless telephones, and Bluetooth devices. 802.11b and 802.11g control their interference and susceptibility to interference by using direct-sequence spread spectrum (DSSS) and orthogonal frequency-division multiplexing (OFDM) signaling methods, respectively.

802.11a uses the 5 GHz U-NII band which, for much of the world, offers at least 23 non-overlapping, 20-MHz-wide channels. This is an advantage over the 2.4-GHz, ISM-frequency band, which offers only three non-overlapping, 20-MHz-wide channels where other adjacent channels overlap (see: list of WLAN channels). Better or worse performance with higher or lower frequencies (channels) may be realized, depending on the environment. 802.11n and 802.11ax can use either the 2.4 GHz or 5 GHz band; 802.11ac uses only the 5 GHz band.

The segment of the radio frequency spectrum used by 802.11 varies between countries. In the US, 802.11a and 802.11g devices may be operated without a license, as allowed in Part 15 of the FCC Rules and Regulations. Frequencies used by channels one through six of 802.11b and 802.11g fall within the 2.4 GHz amateur radio band. Licensed amateur radio operators may operate 802.11b/g devices under Part 97 of the FCC Rules and Regulations, allowing increased power output but not commercial content or encryption.[2]

Generations

In 2018, the Wi-Fi Alliance began using a consumer-friendly generation numbering scheme for the publicly used 802.11 protocols. Wi-Fi generations 1–6 refer to the 802.11b, 802.11a, 802.11g, 802.11n, 802.11ac, and 802.11ax protocols, in that order.[7][8]

History

802.11 technology has its origins in a 1985 ruling by the U.S. Federal Communications Commission that released the ISM band[1] for unlicensed use.[9]

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In 1991 NCR Corporation/AT&T (now Nokia Labs and LSI Corporation) invented a precursor to 802.11 in Nieuwegein, the Netherlands. The inventors initially intended to use the technology for cashier systems. The first wireless products were brought to the market under the name WaveLAN with raw data rates of 1 Mbit/s and 2 Mbit/s.

Vic Hayes, who held the chair of IEEE 802.11 for 10 years, and has been called the "father of Wi-Fi", was involved in designing the initial 802.11b and 802.11a standards within the IEEE.[10] He, along with Bell Labs Engineer Bruce Tuch, approached IEEE to create a standard.[11]

In 1999, the Wi-Fi Alliance was formed as a trade association to hold the Wi-Fi trademark under which most products are sold.[12]

Wi-Fi generations

Generation	IEEE standard	First Approved	Maximum link rate (Mbit/s)	Radio frequency (GHz)		
Wi-Fi 7	802.11be	2019-03-21	1376 to 46120	2.4	5	6
Wi-Fi 6/6E	802.11ax	2014-03-27	574 to 9608	2.4	5	6[3]
Wi-Fi 5	802.11ac	2008-09-26	433 to 6933	↓[4]	5	
Wi-Fi 4	802.11n	2003-09-11	72 to 600	2.4	5	
(***Wi-Fi 3***)*	802.11g	2000-09-21	6 to 54	2.4		
(***Wi-Fi 2***)*	802.11a	1997-09-16			5	
(***Wi-Fi 1***)*	802.11b	1997-12-09	1 to 11	2.4		
(***Wi-Fi 0***)*	802.11	1991-03-21	1 to 2	2.4		

**Wi-Fi 0*, *1*, *2*, and *3* are unbranded common usage.[5][6]

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The major commercial breakthrough came with Apple's adoption of Wi-Fi for their iBook series of laptops in 1999. It was the first mass consumer product to offer Wi-Fi network connectivity, which was then branded by Apple as AirPort.[13][14][15] One year later IBM followed with its ThinkPad 1300 series in 2000.[16]

Protocol

802.11 network standards [hide]

Frequency range, or type	PHY	Protocol	Release date [17]	Frequency (GHz)	Bandwidth (MHz)	Stream data rate [18] (Mbit/s)	Allowable MIMO streams	Modulation	Approximate range	
									Indoor	Outdoor
1–7⅛ GHz	DSSS[19], ~~FHSS~~[A]	802.11-1997	June 1997	2.4	22	1, 2	—	DSSS, ~~FHSS~~[A]	20 m (66 ft)	100 m (330 ft)
	HR/DSSS [19]	802.11b	September 1999	2.4	22	1, 2, 5.5, 11	—	CCK, DSSS	35 m (115 ft)	140 m (460 ft)
	OFDM	802.11a	September 1999	5	5/10/20	6, 9, 12, 18, 24, 36, 48, 54 (for 20 MHz bandwidth, divide by 2 and 4 for 10 and 5 MHz)	—	OFDM	35 m (115 ft)	120 m (390 ft)
		802.11j	November 2004	4.9/5.0 [B][20]					?	?
		802.11y	November 2008	3.7 [C]					?	5,000 m (16,000 ft)[C]
		802.11p	July 2010	5.9					200 m (https://ieeexplore.ieee.org/document/8723326)	1,000 m (3,300 ft)[21]
		802.11bd	December 2022	5.9/60					500 m (https://ieeexplore.ieee.org/document/8723326)	1,000 m (3,300 ft)
	ERP-OFDM	802.11g	June 2003	2.4					38 m (125 ft)	140 m (460 ft)
	HT-OFDM [22]	802.11n (Wi-Fi 4)	October 2009	2.4/5	20	Up to 288.8[D]	4	MIMO-OFDM (64-QAM)	70 m (230 ft)	250 m (820 ft)[23]
					40	Up to 600[D]				
	VHT-OFDM [22]	802.11ac (Wi-Fi 5)	December 2013	5	20	Up to 693[D]	8	DL MU-MIMO OFDM (256-QAM)	35 m (115 ft)[24]	?
					40	Up to 1600[D]				
					80	Up to 3467[D]				
					160	Up to 6933[D]				
	HE-OFDMA	802.11ax (Wi-Fi 6, Wi-Fi 6E)	May 2021	2.4/5/6	20	Up to 1147[E]	8	UL/DL MU-MIMO OFDMA (1024-QAM)	30 m (98 ft)	120 m (390 ft) [F]
					40	Up to 2294[E]				
					80	Up to 4804[E]				
					80+80	Up to 9608[E]				
	EHT-OFDMA	802.11be (Wi-Fi 7)	*May 2024* (est. (https://groupe r.ieee.org/groups/802/11/Reports/802.11_Timelines.htm#tgbe))	2.4/5/6	80	Up to 11.5 Gbit/s[E]	16	UL/DL MU-MIMO OFDMA (4096-QAM)	30 m (98 ft)	120 m (390 ft) [F]
					160 (80+80)	Up to 23 Gbit/s[E]				
					240 (160+80)	Up to 35 Gbit/s[E]				
					320 (160+160)	Up to 46.1 Gbit/s[E]				
	WUR [G]	802.11ba	October 2021	2.4/5	4/20	0.0625, 0.25 (62.5 kbit/s	—	OOK (multi-carrier OOK)	?	?

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802.11 network standards										
Frequency range, or type	PHY	Protocol	Release date [17]	Frequency	Bandwidth	Stream data rate [18]	Allowable MIMO streams	Modulation	Approximate range	
				(GHz)	(MHz)	(Mbit/s)			Indoor	Outdoor
						250 kbit/s)				
mmWave (WiGig)	DMG [25]	802.11ad	December 2012	60	2160 (2.16 GHz)	Up to 8085[26] (8 Gbit/s)	—	~~OFDM~~[A], single carrier, low-power single carrier[A]	3.3 m (11 ft)[27]	?
		802.11aj	April 2018	60 [H]	1080[28]	Up to 3754 (3.75 Gbit/s)	—	single carrier, low-power single carrier[A]	?	?
	CMMG	802.11aj	April 2018	45 [H]	540/ 1080	Up to 15015[29] (15 Gbit/s)	4[30]	OFDM, single carrier	?	?
	EDMG [31]	802.11ay	July 2021	60	Up to 8640 (8.64 GHz)	Up to 303336[32] (303 Gbit/s)	8	OFDM, single carrier	10 m (33 ft)	100 m (328 ft)
Sub 1 GHz (IoT)	TVHT [33]	802.11af	February 2014	0.054 -0.79	6, 7, 8	Up to 568.9[34]	4	MIMO-OFDM	?	?
	S1G [33]	802.11ah	May 2017	0.7/0.8 /0.9	1–16	Up to 8.67[35] (@2 MHz)	4		?	?
Light (Li-Fi)	LC (VLC/OWC)	802.11bb	*December 2023* (est. (https://groupe r.ieee.org/ groups/802/11/Reports/tgbb_update.htm))	800–1000 nm	20	Up to 9.6 Gbit/s	—	O-OFDM	?	?
	~~IR~~[A] (IrDA)	802.11-1997	June 1997	850–900 nm	?	1, 2	—	~~PPM~~[A]	?	?
802.11 Standard rollups										
		802.11-2007 (802.11ma)	March 2007	2.4, 5		Up to 54		DSSS, OFDM		
		802.11-2012 (802.11mb)	March 2012	2.4, 5		Up to 150[D]		DSSS, OFDM		
		802.11-2016 (802.11mc)	December 2016	2.4, 5, 60		Up to 866.7 or 6757[D]		DSSS, OFDM		
		802.11-2020 (802.11md)	December 2020	2.4, 5, 60		Up to 866.7 or 6757[D]		DSSS, OFDM		
		802.11me	*September 2024* (est. (https://groupe r.ieee.org/ groups/802/11/Reports/802.11_Timelines.htm#tgme))	2.4, 5, 6, 60		Up to 9608 or 303336		DSSS, OFDM		

A. This is obsolete, and support for this might be subject to removal in a future revision of the standard

B. For Japanese regulation.

C. IEEE 802.11y-2008 extended operation of 802.11a to the licensed 3.7 GHz band. Increased power limits allow a range up to 5,000 m. As of 2009, it is only being licensed in the United States by the FCC.

D. Based on short guard interval; standard guard interval is ~10% slower. Rates vary widely based on distance, obstructions, and interference.

E. For single-user cases only, based on default guard interval which is 0.8 micro seconds. Since multi-user via OFDMA has become available for 802.11ax, these may decrease. Also, these theoretical values depend on the link distance, whether the link is line-of-sight or not, interferences and the multi-path components in the environment.

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802.11 network standards										
Frequency range, or type	PHY	Protocol	Release date [17]	Frequency	Bandwidth	Stream data rate [18]	Allowable MIMO streams	Modulation	Approximate range	
				(GHz)	(MHz)	(Mbit/s)			Indoor	Outdoor
F. The default guard interval is 0.8 micro seconds. However, 802.11ax extended the maximum available guard interval to 3.2 micro seconds, in order to support Outdoor communications, where the maximum possible propagation delay is larger compared to Indoor environments.										
G. Wake-up Radio (WUR) Operation.										
H. For Chinese regulation.										

802.11-1997 (802.11 legacy)

The original version of the standard IEEE 802.11 was released in 1997 and clarified in 1999, but is now obsolete. It specified two net bit rates of 1 or 2 megabits per second (Mbit/s), plus forward error correction code. It specified three alternative physical layer technologies: diffuse infrared operating at 1 Mbit/s; frequency-hopping spread spectrum operating at 1 Mbit/s or 2 Mbit/s; and direct-sequence spread spectrum operating at 1 Mbit/s or 2 Mbit/s. The latter two radio technologies used microwave transmission over the Industrial Scientific Medical frequency band at 2.4 GHz. Some earlier WLAN technologies used lower frequencies, such as the U.S. 900 MHz ISM band.

Legacy 802.11 with direct-sequence spread spectrum was rapidly supplanted and popularized by 802.11b.

802.11a (OFDM waveform)

802.11a, published in 1999, uses the same data link layer protocol and frame format as the original standard, but an OFDM based air interface (physical layer) was added.

It operates in the 5 GHz band with a maximum net data rate of 54 Mbit/s, plus error correction code, which yields realistic net achievable throughput in the mid-20 Mbit/s.[36] It has seen widespread worldwide implementation, particularly within the corporate workspace.

Since the 2.4 GHz band is heavily used to the point of being crowded, using the relatively unused 5 GHz band gives 802.11a a significant advantage. However, this high carrier frequency also brings a disadvantage: the effective overall range of 802.11a is less than that of 802.11b/g. In theory, 802.11a signals are absorbed more readily by walls and other solid objects in their path due to their smaller wavelength, and, as a result, cannot penetrate as far as those of 802.11b. In practice, 802.11b typically has a higher range at low speeds (802.11b will reduce speed to 5.5 Mbit/s or even 1 Mbit/s at low signal strengths). 802.11a also suffers from interference,[37] but locally there may be fewer signals to interfere with, resulting in less interference and better throughput.

802.11b

The 802.11b standard has a maximum raw data rate of 11 Mbit/s (Megabits per second) and uses the same media access method defined in the original standard. 802.11b products appeared on the market in early 2000, since 802.11b is a direct extension of the modulation technique defined in the original standard. The dramatic increase in throughput of 802.11b (compared to the original standard) along with simultaneous substantial price reductions led to the rapid acceptance of 802.11b as the definitive wireless LAN technology.

Devices using 802.11b experience interference from other products operating in the 2.4 GHz band. Devices operating in the 2.4 GHz range include microwave ovens, Bluetooth devices, baby monitors, cordless telephones, and some amateur radio equipment. As unlicensed intentional radiators in this ISM band, they must not interfere with and must tolerate interference from primary or secondary allocations (users) of this band, such as amateur radio.

802.11g

In June 2003, a third modulation standard was ratified: 802.11g. This works in the 2.4 GHz band (like 802.11b), but uses the same OFDM based transmission scheme as 802.11a. It operates at a maximum physical layer bit rate of 54 Mbit/s exclusive of forward error correction codes, or about 22 Mbit/s average throughput.[38] 802.11g hardware is fully backward compatible with 802.11b hardware, and therefore is encumbered with legacy issues that reduce throughput by ~21% when compared to 802.11a.

The then-proposed 802.11g standard was rapidly adopted in the market starting in January 2003, well before ratification, due to the desire for higher data rates as well as reductions in manufacturing costs. By summer 2003, most dual-band 802.11a/b products became dual-band/tri-mode, supporting a and b/g in a single mobile adapter card or access point. Details of making b and g work well together occupied much of the lingering technical process; in an 802.11g network, however, the activity of an 802.11b participant will reduce the data rate of the overall 802.11g network.

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