WHITE PAPER

The Wi-Fi Evolution

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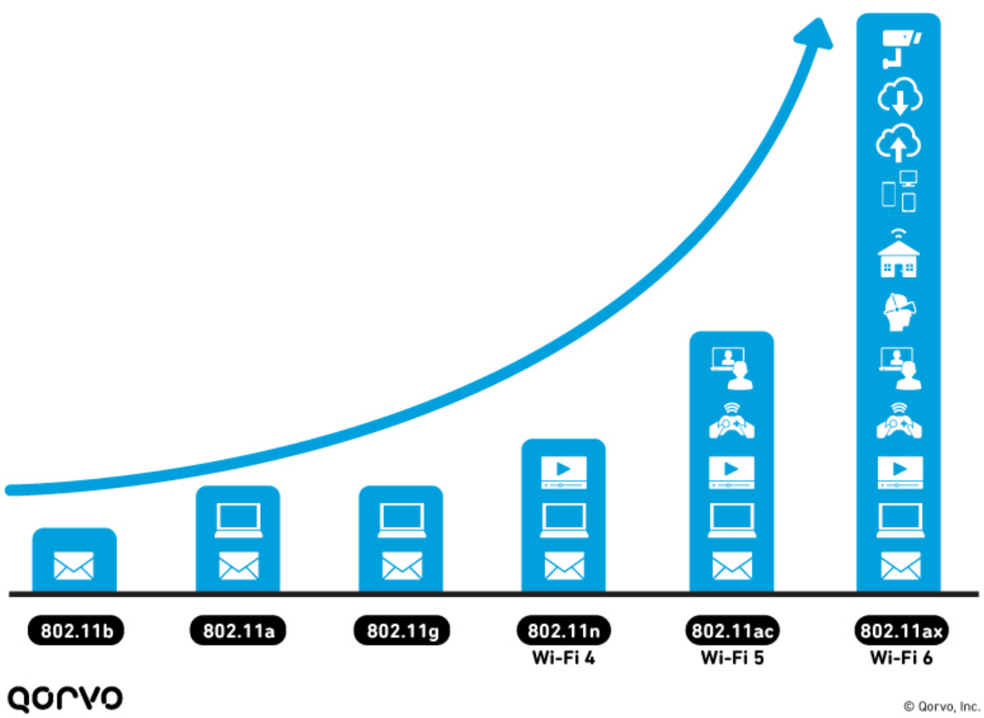
Introduction

Over the past 20 years, IEEE 802.11 commonly referred to as Wi-Fi has evolved from 2 Mbps to over gigabit speeds, a 1000-fold increase in throughput. The standard has continuously advanced itself by introducing new protocols such as 802.11n, 802.11ac and 802.11ax (Wi-Fi 6). The new standards support higher order of modulation schemes such as 64 QAM, 256 QAM and 1024 QAM. These new standards also support transmission of multiple streams to a single client or multiple clients simultaneously. In addition to increasing peak data rates, efforts have been made to improve spectral efficiency which characterizes how well the system uses the available spectrum. Multi-user techniques such as multi-user multiple-input-multiple-output (MU-MIMO) and orthogonal frequency division multiple access (OFDMA) have been introduced to improve network efficiency and network capacity. Once Wi-Fi (802.11) standards have been released and implemented, the world began to transform as markets opened and new technology emerged. Each new standard is built on previous standard with improvement in speed and reliability.



Wi-Fi Standards

IEEE 802.11 Protocol	Release Date	Frequency Band(s)	Bandwidth	Max Throughput
802.11-1997	1997	2.4	22	2 Mbps
11b	1999	2.4	22	11 Mbps
11a	1999	5	20	54 Mbps
11g	2003	2.4	20	54 Mbps
11n (Wi-Fi 4)	2009	2.4/5	20/40	600 Mbps
11ac (Wi-Fi 5)	2013	2.4/5	20/40/ 80/160	6.8 Gbps
11ax (Wi-Fi 6)	2019	2.5/5	20/40/ 80/160	10 Gbps

If you are looking to buy a new wireless networking gear or a mobile device, you are overwhelmed by too many choices and abbreviations. Since Wi-Fi was first released to consumers in 1997, its standards have been continually evolving – typically resulting in faster speeds and network/spectrum efficiency. As capabilities are added to the original 802.11 standard, they become known by their amendment (802.11b, 802.11g, etc.). Table 1 lists different standards and max theoretical data rates achieved with those standards. Typical rates are lower than theoretical based on several factors, including the signal degradation with distance, modulation rate and forward error correction coding, bandwidth, MIMO multiplier, guard interval and typical error rates. The 802.11 family consists of a series of half-duplex over the air modulation techniques that use the same basic protocol. In this paper, we will discuss the basics of each Wi-Fi standard.

802.11-1997 Standard

802.11-1997 was the first wireless standard in the family, which was released in 1997, but is now obsolete. This standard defines the protocol and compatible interconnection of data communication equipment via the air in a local area network (LAN) using carrier sense multiple access protocol with collision avoidance (CSMA/CA). This protocol supported three physical layer technologies including infrared operating at 1 Mbps, a frequency hopping spread spectrum (FHSS) supporting 1 Mbps and an optional 2 Mbps data rate or a direct sequence spread spectrum (DSSS) supporting both 1 and 2 Mbps data rates. This protocol was not widely accepted because of interoperability issues, cost and lack of sufficient throughput.

802.11b Standard

802.11b products appeared on the market in mid-1999. It has a maximum theoretical data rate of 11 Mbps and uses the same CSMA/CA medium access method defined in the original standard. The dramatic increase in throughput of 802.11b along with substantial price reduction led to wide acceptance of 802.11b as a wireless technology. 802.11b uses the ISM unlicensed frequency band from 2400-2500 MHz. 802.11b is a direct extension of DSSS and uses complementary code keying (CCK) as its modulation technique. 802.11b is used in point-to-multipoint configuration where an access point communicates with mobile clients within the range of the access point.

This range depends of radio frequency environment, output power and sensitivity of the receiver. 802.11b has a channel bandwidth of 22 MHz, can operate at 11 Mbps but scale back to 5.5, then to 2, then to 1 Mbps (adaptive rate selection), in order to decrease the rate of re-broadcasts that results from errors.[1] The 802.11b standard shares the same frequency bandwidth of other wireless standards. Thus, within the home wireless devices such as microwave ovens, Bluetooth® devices, and cordless phones can cause interference with Wi-Fi.

802.11a Standard

The 802.11a uses the same core protocol as the original standard. It operates at 5 GHz and uses a 52-subcarrier orthogonal frequency division multiplexing (OFDM) with a maximum theoretical data rate of 54 Mbps. This achieves a practical throughput of mid 20 Mbps. Other data rates it supports includes 6, 9, 12, 18, 24, 36 and 48 Mbps. 802.11a is not interoperable with 802.11b as they operate in different unlicensed ISM frequency bands. The 5 GHz band gives 802.11a significant advantage since the 2.4 GHz is getting crowded, but because of high carrier frequency, the effective overall range is less than 802.11b/g.

802.11a products were not widely accepted initially because of cost, low range and incompatibility with 802.11b. Of the 52 OFDM subcarriers, 48 are for data and 4 are pilot subcarriers with a carrier separation of 312.5 kHz. Each of these subcarriers can be BPSK, QPSK, 16 QAM or 64 QAM. The bandwidth of channel is 20 MHz with occupied bandwidth of 16.6 MHz. Symbol duration is 4 μsec which includes a guard interval of 0.8 μsec. OFDM advantages include reduced multipath effects in reception and increased spectral efficiency.[2] Table 2 lists the different modulations supported by 11a and their respective theoretical data rate.

Table 2. 802.11a modulation rates and data rates for 20 MHz channel spacing.

Modulation Type (802.11a)	Coding Rate	Data Rate (Mbps)
BPSK	1/2	6
BPSK	3/4	9
QPSK	1/2	12
QPSK	3/4	18
16 QAM	1/2	24
16 QAM	3/4	36
64 QAM	2/3	48
64 QAM	3/4	54

802.11g Standard

802.11g became available in the summer of 2003. It uses the same OFDM technology introduced with 802.11a. Like 802.11a, it supports a maximum theoretical rate of 54 Mbps. But like 802.11b, it operates in the crowded 2.4 GHz and hence is susceptible to interference issues. 802.11g is backwards compatible with 802.11b (i.e. 802.11b devices can connect to an 802.11g access point). 802.11g was able to handle dual-band or dual-mode access points using 802.11a and 802.11b/g.

802.11n Standard

With 802.11n, Wi-Fi became even faster and more reliable. This is achieved by adding MIMO and 40 MHz channels to the physical layer (PHY) and frame aggregation to the MAC layer. MIMO is a method for multiplying the capacity of a radio link using multiple transmit and receive antennas to exploit multipath propagation. These antennas need to be spatially separated so that the signal from each transmit antenna to each receive antenna has a different spatial signature, so that on the receiver, it can separate these streams into parallel independent channels. Channels operating with a width of 40 MHz, doubles the channel width and provides twice the PHY data rate over a single 20 MHz channel. 802.11n draft allows up to 4 spatial streams with a maximum theoretical throughput of 600 Mbps.

Table 3. 802.11n modulation and data rates for single stream.

MCS Index	Spatial Streams	Modulation Type	Coding Rate	Data Rate (Mbps) 20 MHz Channel 800nSGI	Data Rate (Mbps) 20 MHz Channel 400nSGI
0	1	BPSK	1/2	6.5	7.2
1	1	QPSK	1/2	13	14.4
2	1	QPSK	3/4	19.5	21.7
3	1	16 QAM	1/2	26	28.9
4	1	16 QAM	3/4	39	43.3
5	1	64 QAM	2/3	52	57.8
6	1	64 QAM	3/4	58.5	65
7	1	64 QAM	5/6	65	72.2

MCS Index	Spatial Streams	Modulation Type	Coding Rate	Data Rate (Mbps) 40 MHz Channel 800nSGI	Data Rate (Mbps) 40 MHz Channel 400nSGI
0	1	BPSK	1/2	13.5	15
1	1	QPSK	1/2	27	30
2	1	QPSK	3/4	40.5	45
3	1	16 QAM	1/2	54	60
4	1	16 QAM	3/4	81	90
5	1	64 QAM	2/3	108	120
6	1	64 QAM	3/4	121.5	135
7	1	64 QAM	5/6	135	150

20 MHz channels have 56 OFDM subcarriers, 52 are data and 4 are pilot tones with a carrier separation of 312.5 kHz. Each of these subcarriers can be a BPSK, QPSK, 16 QAM or 64 QAM. Total symbol duration is 3.6 or 4μSec, which includes a guard interval of 0.4 or 0.8μSec respectively. Table 3 lists different modulation and coding schemes for a single stream (for multiple streams, the data rate is multiple of number of streams). 802.11n supports frame aggregation where multiple MAC service data units (MSDUs) or MAC protocol data units (MPDUs) are packed together to reduce the overheads and average them over multiple frames, thereby increasing the user level data rate. Also, 802.11n is backward compatible to 802.11g, 11b and 11a.[3] Qorvo has been a leading provider of 802.11n components including power amplifiers, low noise amplifiers, switches and integrated front-end modules (FEMs).

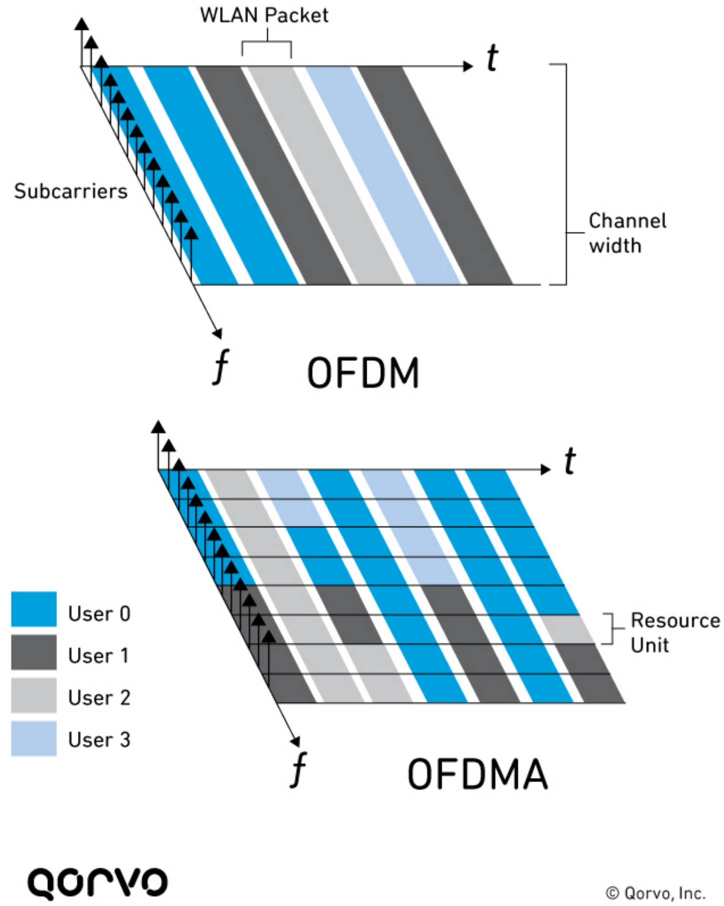
802.11ac Standard

802.11ac revved-up Wi-Fi by providing gigabit speeds per second and this is achieved by extending the 802.11n concepts which include wider bandwidth (up to 160 MHz), more MIMO spatial streams (up to 8), downlink multi-user MIMO (up to four clients) and high-density modulation (up to 256 QAM). 802.11ac supports 256 QAM at 3/4, 5/6 coding rate (MCS8/9) which required 6 dB tougher system level EVM (-34 dB) requirements. Qorvo 11ac components were able to easily satisfy those EVM requirements. 802.11ac works exclusively in the 5 GHz band, so dual-band access points and clients will continue to use 802.11n at 2.4 GHz. The first wave of 802.11ac released in 2013, supported only 80 MHz channels and up to 3 spatial streams delivering up to 1300 Mbps at physical layer. Second wave products, or 802.11ac wave 2 products were released in 2015, support more channel bonding, more spatial streams and MU-MIMO. MU-MIMO is a significant advancement of 802.11ac. While MIMO directs multiple streams to a single user, MU-MIMO can direct spatial streams to multiple clients simultaneously thus improving network efficiency. Also, 802.11ac uses a technology called beamforming. With beamforming, the antenna basically transmits the radio signals so they are directed at a specific device. 802.11ac routers are backwards compatible with 802.11b, 11g, 11a and 11n which means all the legacy clients just work fine with 802.11ac router.[4]

Wi-Fi 6 or 802.11ax Standard

802.11ax is the sixth generation of Wi-Fi, built on the strengths of 802.11ac, which provides more wireless capacity and reliability. 802.11ax achieves these benefits by using denser modulation (1024 QAM), (OFDMA), reduced subcarrier spacing (78.125 kHz) and using scheduled based resource allocation. Unlike 802.11ac, 802.11ax is a dual-band 2.4 and 5 GHz technology. 802.11ax was designed for maximum compatibility, coexisting efficiently with 802.11a/g/n/ac clients. 802.11ax uses OFDMA, which allows resource units (RUs) that divide the bandwidth according to the needs of the clients and provide multiple individuals with same user experience at faster speeds. With 802.11ac, the Wi-Fi channel was broken down into a collection of smaller OFDM sub-channels. At any given point in carriers in each PLCP protocol data unit (PPDU). However, with OFDMA (802.11ax), individual groups of subcarriers are individually allocated to clients as resource units on a per-PPDU basis (Figure 1).

Figure 1. OFDM vs OFDMA resource allocation.



Earlier 802.11 standards CSMA/CA method in which wireless clients first sense the channel and attempt to avoid collisions by transmitting only when they sense the channel to be idle. Although this clear assessment and collision avoidance serves well, its efficiency decreases when the number of clients grow very large. 802.11ax protocol solves this problem through OFDMA and schedule based resource allocation.[5] 802.11ax access points dictate when the device will operate, thus handling clients more efficiently. Resource scheduling also significantly reduces the power consumption during sleep time, which improves battery life of clients. Table 4, lists the differences between 802.11ac and 802.11ax protocols.

Table 4. 802.11ac vs 802.11ax.

	802.11ac (Wi-Fi 5)	802.11ax (Wi-Fi 6)
Bands	5 GHz	2.4, 5 GHz
Channel Bandwidth	20, 40, 80, 160 MHz	20, 40, 80, 160 MHz
FFT Sizes	64, 128, 256, 512	256, 512, 1024, 2048
Subcarrier Spacing	312.5 kHz	78.125 kHz
Symbol Duration	3.2μs + 0.8/0.4μs	12.8μs + 0.8/1.6/3.2μs
Highest Modulation	256 QAM	1024 QAM
Max Data Rate	6933 Mbps (160 MHz, 8 SS)	9607.8 Mbps (160 MHz, 8 SS)

Qorvo's broad 802.11ax portfolio includes 2.4 GHz and 5 GHz (FEMs) and bulk acoustic wave (BAW) filters. The portfolio's high energy-efficient FEMs reduce thermal issues associated with supporting MIMO in Wi-Fi equipment, allowing manufacturers to reduce product size and cost. Qorvo's bandedge and coexistence (BAW) filters improve Wi-Fi quality of service and prevent interference with adjacent LTE frequencies.

Summary

Qorvo is a leading provider of Wi-Fi connectivity solutions with a significant market share. Qorvo's portfolio of RF components provide efficient solutions with reliable coverage in smallest form factor that help improve the overall range, capacity and throughput.

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