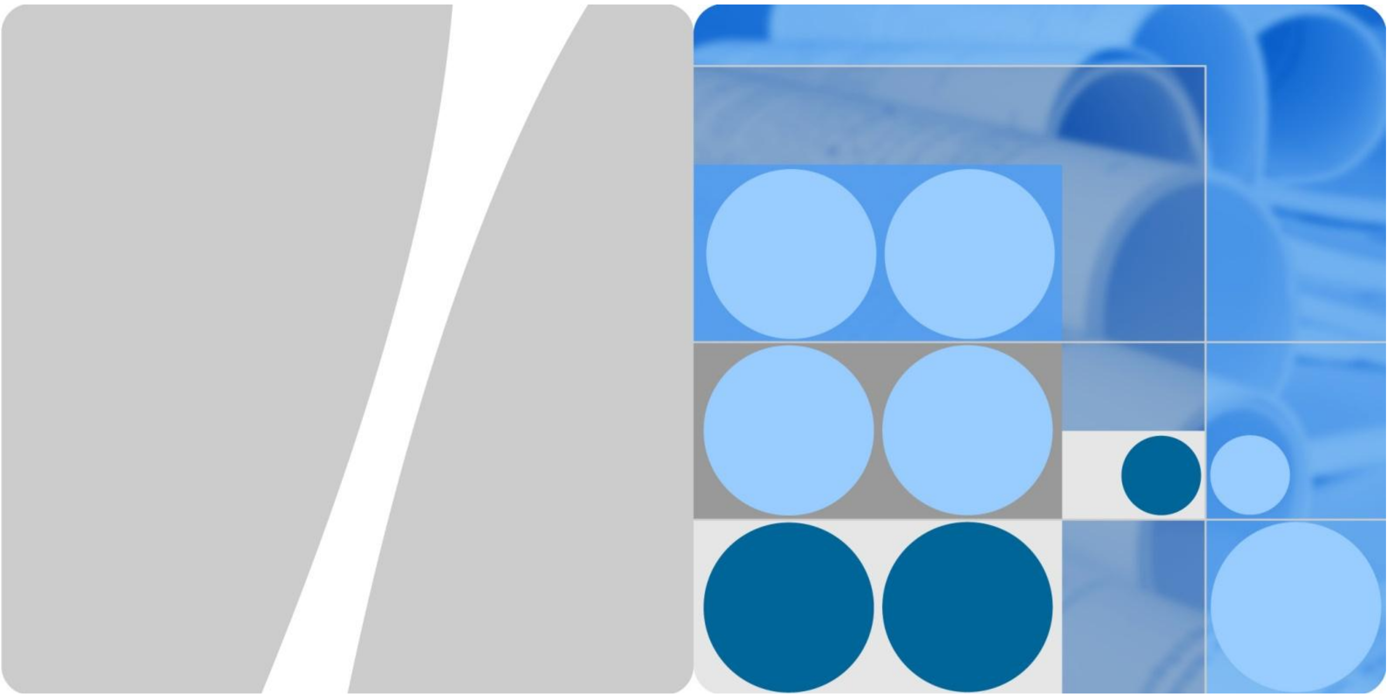

WLAN 802.11ac Technology White Paper

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Keywords

802.11ac, frequency band, channel bandwidth, MCS, MIMO, compatibility, A-MPDU

Abstract

Since the first-generation 802.11 standard was released in 1997, Wi-Fi achieves great developments and popularity in the past 16 years. Nowadays, 802.11ac further promotes 802.11 development. This document describes the background, advantages, and key technologies of 802.11ac.

Abbreviations

Acronym	Full Name
CSI	Channel State Information
TxBF	Tx Beamforming
STA	Station
AP	Access Point
MCS	Modulation and Coding Scheme
MIMO	Multi input, multiple output
NDP	Null Data Packet
RTS/CTS	Request-to-send/Clear-to-Send

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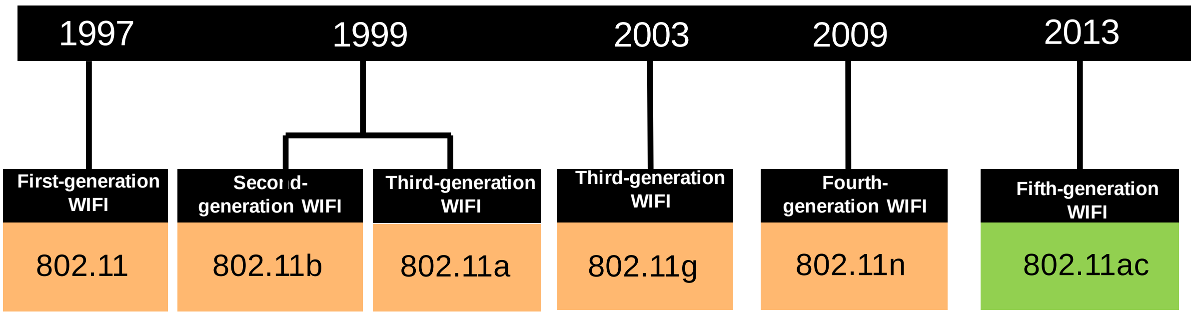
1 Background

Since the first-generation 802.11 standard was released in 1997, Wi-Fi achieves great developments and popularity in the past 16 years. Nowadays, Wi-Fi becomes the first choice for Internet access of increasing users, and tends to replace wired access gradually. To satisfy needs of new service applications and reduce the gap with wired network bandwidth, each generation of 802.11 standard among four generations of Wi-Fi systems (801.11, 802.11b, 802.11a/g, 802.11n) greatly improves the rate. In the fifth-generation 802.11 standard, the rate improvement is undoubtedly a highlight in industry.

Figure 1-1 802.11 standard evolution



The wired Ethernet and applications drive 802.11ac development. As wired Ethernet GE access gradually goes mainstream, WI-FIWi-Fi needs to provide good user and service experience. In practice, 802.11n products face the following challenges:

1. Large-bandwidth application

Large-bandwidth applications are widely used in Wi-Fi:

(1) Apple iCloud service synchronization

(2) Youtube video services

(3) Vine (Twitter) video shooting and sharing application services

(4) Video conference services transferred from fixed devices to mobile devices

(5) Video services for product and solution promotion by more and more enterprises

(6) …

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The applications propose high bandwidth for Wi-Fi. As predicted by Ericsson, video traffic on the mobile network will increase by 60% every year until the end of 2018 when video traffic will account for half of global mobile data traffic.

2. Large-scale terminal access
   (1) Facing the BYOD trend, each employee may have two or more Wi-Fi terminals. Each terminal consumes network resources.
   (2) In football fields, new product conference sites, or classrooms, concurrent access of many users poses a serious challenge to 802.11n products.
   (3) As there is more wireless access and fewer wired access, increasing terminals use Wi-Fi.
3. 3G/4G OFFLOAD

In the case of explosive increase of data services in the cellular system, more traffic is load balanced on the Wi-Fi network to reduce the load of the cellular system. Wi-Fi shoulders the crossbeam. The Wi-Fi network is required to provide larger capacity and more user access.

To meet the preceding requirements, the fifth-generation 802.11 standard is developed. The fifth-generation 802.11 standard 802.11ac is an improvement compared with 802.11n. The following table describes the differences between 802.11ac, 802.11n, and 802.11a working in the same frequency band.

Feature	**802.11a**	**802.11n**	**802.11ac**
Channel width	20 MHz	20 MHz	20/40/80 MHz
		40 MHz (option)	160 and 80+80 MHz (option)
OFDM	Y	Y	Y
SGI	N	Y	Y
MIMO	Single antenna	SU MMO Up to 4 antennas	SU and MU MIMO Up to 8 antennas
Preamble	Legacy	Mixed Format(MF)	Mixed Format(MF) only
		Green Field(GF)	
Modulation and coding schemes	Expressed as rates	76 MCS	9 MCS
Beamforming (option)	NA	Staggered and NDP	NDP
Feedback format	NA	Compressed and non-compressed V matrix	Compressed V Matrix
Link adaptation	N	Y	Y
Coding	BCC	BCC/LDPC (option)	BCC/LDPC (option)
Media Access Control (MAC)	CSMA/CA	CSMA/CA	CSMA/CA

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Feature	802.11a	802.11n	802.11ac
QoS (802.11E)	4 access categories TXOP support	4 access categories TXOP support	4 access categories TXOP support
MAC protection	RTS/CTS	RTS/CTS spoofing	RTS/CTS spoofing
TXOP sharing	NA	NA	Supported for MU-MIMO
Static/Dynamic BA operation	NA	N	Y
MSDU	2304B	2304B or 7920B	2304B or 7920B
MPDU	3895B	3895B or 7991B	3895B, 7991B, or 11454B
A-MSDU	N	3839B or 7396B	3839B or 7396B
A-MPDU	N	65 KB	1 MB
MAC Protocol Data Unit	MPDU only	MPDU or A-MPDU	A-MPDU only

At the PHY and MAC address layers, 802.11ac optimizes the channel bandwidth, multi-input multi-output (MIMO), modulation mode and uses new technologies. 802.11ac architecture is the same as 802.11n architecture. That is, 802.11ac is evolved from 802.11n.

802.11ac provides a maximum throughput of 6.93 Gbit/s, which is almost 10 times the maximum throughput of 802.11n. The initially launched Wave 1 802.11ac products provide the maximum throughput of up to 1.3 Gbit/s, meeting expectations of Gbit/s Wi-Fi. In addition to great increase of the maximum throughput, 802.11ac enhances the concurrent user access capability. 802.11ac can transmit data of four users simultaneously. It improves channel management when multiple channel bandwidths are used and enhances compatibility with 802.11a and 802.11n.

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2 Technology Implementation

Compared with 802.11n, 802.11ac has the following improvements:

1. Uses new technologies or extends original technologies to improve the maximum throughput or number of access users. The technologies include multi-stream MIMO, 256QAM, and multi-user MIMO.
2. Optimizes protocols to reduce complexity. For example, 802.11ac deletes implicit TXBF, and provides only one channel probe mode and one feedback mode.
3. Keeps compatible with old 802.11 protocols. 802.11ac improves the physical layer frame structure and channel management when different channel bandwidths are used. The following table describes the improvements.

No.	Improvement	Description	Benefit
	Channel bandwidth	1. Adds 80M channel bandwidth. 2. Adds 160M channel bandwidth. 3. Integrates two non-adjacent 80M channel bandwidths into a 160M channel bandwidth.	Improved maximum throughput
	Working frequency	Works in the frequency band less than 6 GHz, excluding 2.4 GHz. The frequency band of 5 GHz is mainly used.	1. Abundant spectrum resources 2. Less interference
	MIMO	1. Improves single-user MIMO, and supports a maximum of eight streams. 2. Uses multi-user MIMO, and transmits data of four users simultaneously.	1. Improved maximum throughput 2. Increased number of users 3. Enhanced link reliability

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No.	Improvement	Description	Benefit
	TXBF	1. Supports only explicit Beamforming (implicit Beamforming is not supported). 2. Improves channel probe and feedback modes. 802.11ac sends Null Data Packets (NDPs) to probe channels, and uses feedback with the compressed V matrix. Originally, multiple channel probe and feedback modes are used.	Simplified design
	MCS	1. Uses 256QAM (256QAM bit rates 3/4 and 5/6). 2. Provides 10 MCS modes. Originally, the MCS mode is provided based on MIMO.	Improved maximum throughput
	Compatibility	1. Abandons Greenfield preamble and supports only Mixed preamble. 2. Improves the physical layer frame structure to be compatible with original 802.11 standards.	Enhanced compatibility with earlier Wi-Fi standards
	Channel management	1. Enhances channel management when 20M, 40M, 80M, and 160M channel bandwidths are used simultaneously.	1. Improved channel use efficiency 2. Reduced channel interference 3. Improved maximum throughput 4. Enhanced compatibility
	Frame aggregation	1. Improves frame aggregation. 2. Supports only A-MAC Protocol Data Unit Aggregation (MPDU).	Improved MAC layer efficiency and maximum throughput

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2.1 Frequency Band

Original Wi-Fi systems define 2.4 GHz or 5 GHz frequency band. 802.11n supports both 2.4 GHz and 5 GHz frequency bands. There are obvious problems at the 2.4 GHz frequency band as Wi-Fi applications are increasingly used.

1. Congested frequencies: A large number of non-Wi-Fi devices such as baby monitors, microwave ovens, and cordless telephones also work at the 2.4 GHz frequency band. Interferences from these devices affect Wi-Fi performance, and Wi-Fi cannot effectively solve these problems.
2. Fewer frequency resources: The 2.4 GHz frequency band has only 83.5 MHz frequency resources. Fewer frequency resources indicate more frequency multiplexing and interferences. In addition, high-channel-bandwidth networking is limited, and the Wi-Fi maximum throughput cannot be fully used.

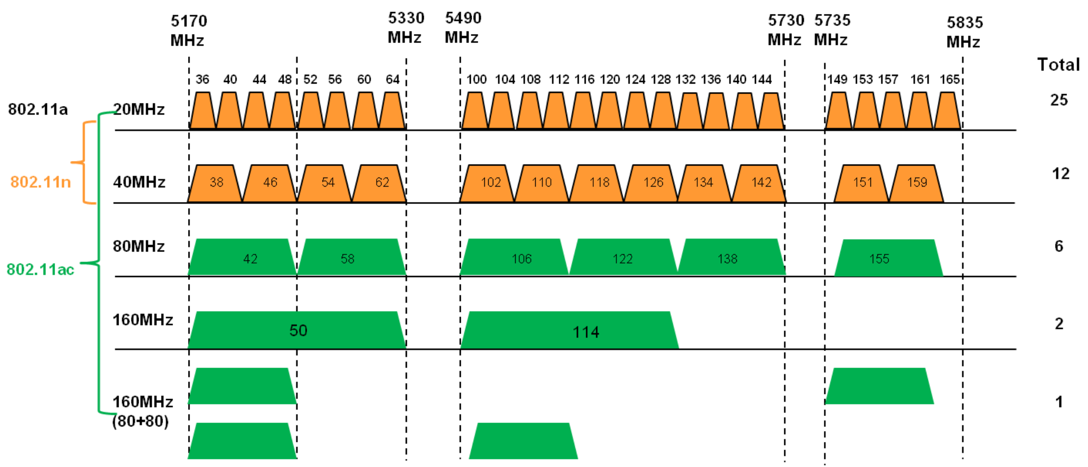
802.11ac does not support the 2.4 GHz frequency band. It prevents interferences at the 2.4 GHz frequency band and promotes popularity of terminals at the5 GHz frequency band. In the 802.11n era, over half of terminals on the live network support only the 2.4 GHz frequency band.

Although 802.11ac defines the frequency band less than 6 GHz frequency band (excluding 2.4 GHz frequency band), the mainstream frequency band is still 5 GHz. 802.11ac is also called 5G Wi-Fi.

2.2 Channel Bandwidth

802.11ac adds 80 MHz and 160 MHz bandwidths. 802.11n supports 20 MHz and 40 MHz bandwidths, where 20 MHz bandwidth is mandatory and 40 MHz bandwidth is optional. 802.11ac supports 20 MHz, 40 MHz, 80 MHz, 80+80 MHz (incontinuous, non-overlapping), and 160 MHz, where 20 MHz, 40 MHz, and 80 MHz bandwidths are mandatory, and 80+80 MHz and 160 MHz bandwidths are optional. The following figure uses North American spectrum as an example and illustrates the differences between 802.11ac, 802.11n, and 802.11a. For 160 MHz bandwidth, 802.11ac supports 2 continuous or incontinuous 80 MHz channels.

Figure 2-1 802.11ac channel bandwidth



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The variable bandwidth design reserves compatibility with small channel bandwidth. In addition, increased bandwidth also improves the maximum throughput and brings better user experience.

Channel bandwidth scalability also causes the interference when multiple channels are used. 802.11ac needs to manage channel bandwidth management efficiently to reduce channel interference and make full use of spectrum bandwidth.

2.3 MCS

802.11n defines eight MCS modes for each MIMO combination. There are four modulation modes: BPSK, QPSK, 16QAM, and 64QAM.

MCS Index	Modulation Mode	Code Rate	802.11n	802.11ac
0	BPSK	1/2	Supported	Supported
1	QPSK	1/2	Supported	Supported
2	QPSK	3/4	Supported	Supported
3	16QAM	1/2	Supported	Supported
4	16QAM	3/4	Supported	Supported
5	64QAM	2/3	Supported	Supported
6	64QAM	3/4	Supported	Supported
7	64QAM	5/6	Supported	Supported
8	**256QAM**	**3/4**	**Not supported**	**Not supported**
9	**256QAM**	**5/6**	**Not supported**	**Not supported**

To improve the maximum throughput, 802.11ac uses higher-order modulation 256Q-AM with improved modulation efficiency. 802.11ac supports code rates 3/4 and 5/6 and 10 MCS modes. Original 802.11 standards provide MCS coding for each MIMO combination, which is abandoned by 802.11ac. Therefore, there are only 10 MCS coding modes in 802.11ac. A higher MCS value indicates higher maximum throughput. This is because different modulation coding modes use different numbers of bits in each sub-carrier. Each sub-carrier represents 2 bits in BPSK mode, 4 bits in 16QAM mode, 6 bits in 64QAM mode, and 8 bits in 256QAM mode. The following constellation figure shows BPSK, QPSK, 16QAM, 64QAM, and 256QAM. A higher order modulation mode achieves a higher modulation efficiency. The modulation efficiency is not improved linearly. The modulation efficiency in latter modulation modes is slightly improved.

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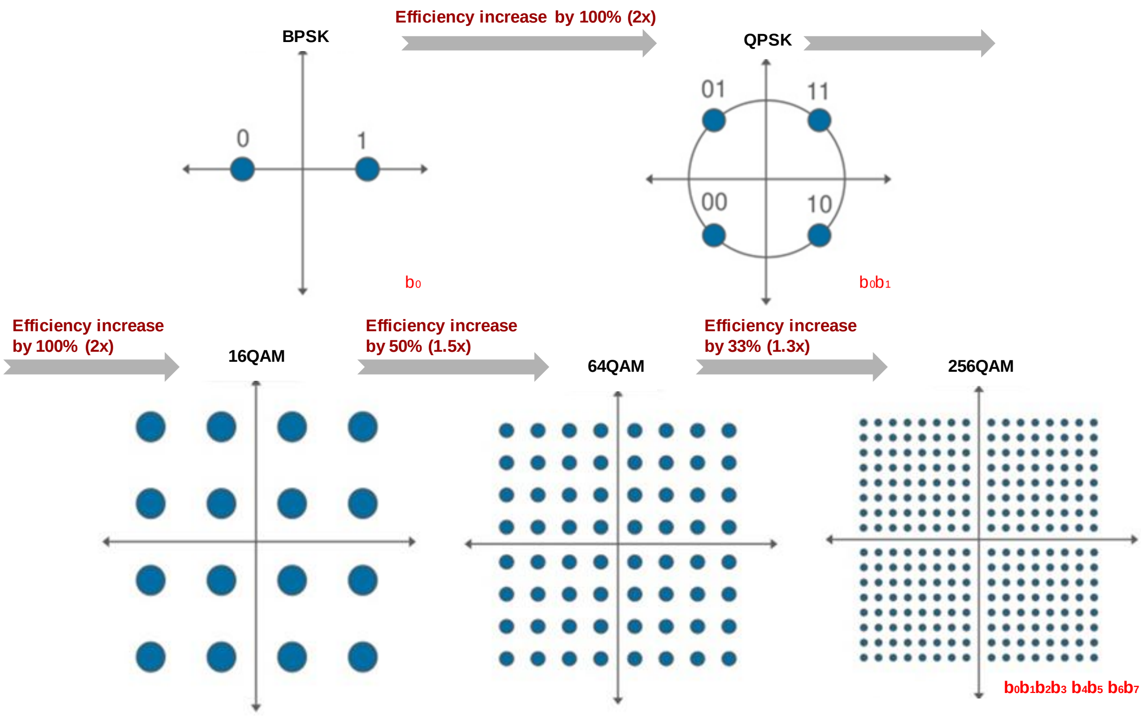
Figure 2-2 Different modulation modes



256QAM improves efficiency, but has strict requirements for the wireless environment and demands higher SNR than 64QAM. Therefore, MCS8 and MCS9 are often applicable to scenarios where STAs are close to APs. In the scenarios, serviceable signals are strong and interference signals are weak, meeting SNR (SNR = Useful signals/Interference signals) requirements.

2.4 Single-user MIMO

MIMO falls into single-user MIMO and multi-user MIMO. MIMO uses spatial diversity and multiplexing. Although spatial diversity cannot directly improve the maximum throughput, the spatial diversity gain can increase the SNR so that a link can improve the capacity using a higher order modulation mode. Spatial multiplexing transmits multiple data streams of a single user or data streams of multiple users simultaneously without changing the channel bandwidth.

In Wi-Fi applications, Transmit Beamforming (TxBF) gains much attention. TxBF definition in 802.11n is complex, so TxBF is not well recognized in markets. 802.11ac simplifies the design.

1. 802.11n defines explicit and implicit Beamforming modes, but 802.11ac supports only explicit Beamforming.

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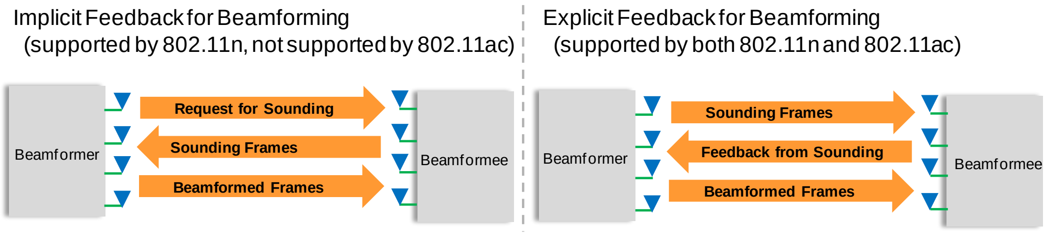
Figure 2-3 Explicit and implicit Beamforming



2. 802.11ac improves channel probe and feedback mechanisms. 802.11n uses the following modes to probe channels: Null Data Packets (NDPs) and staggered preamble. 802.11n defines three feedback formats: CSI, noncompressed, and compressed. It also defines immediate and delayed feedback modes. 802.11ac uses only NDPs to probe channels and supports only the compressed V matrix format and immediate mode.

	Sounding		**Feedback Methods and Formats**						
	NDP	Staggered Preamble	Implicit	Explicit					
				Immediate			Delayed		
				CSI	Noncompressed	Compressed	CSI	Noncompressed	Compressed
11n	x	x	x	x	x	x	x	x	x
11ac	x				x				

802.11n supports spatial multiplexing for multiple streams. 802.11n was the first to introduce MIMO technology to WiFi. It supports a maximum of four streams and provides the maximum throughput of up to 600 Mbit/s, which is a qualitative leap compared with 802.11a/b/g. 802.11ac supports a maximum of eight streams and provides the maximum throughput of 7 Gbit/s for a single user.

Spatial diversity and multiplexing use the multi-antenna system. To support eight streams, APs and STAs require eight antennas, which is a great challenge to both APs and STAs. More antennas increase device complexity, dimensions, and costs. This is also the reason why the mainstream 802.11n APs use dual antennas and STAs use single antenna although 802.11n can support four streams.

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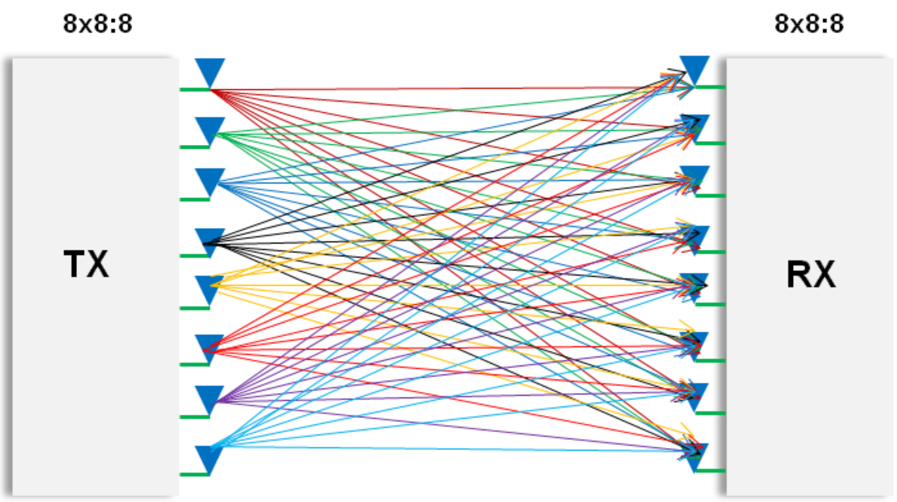
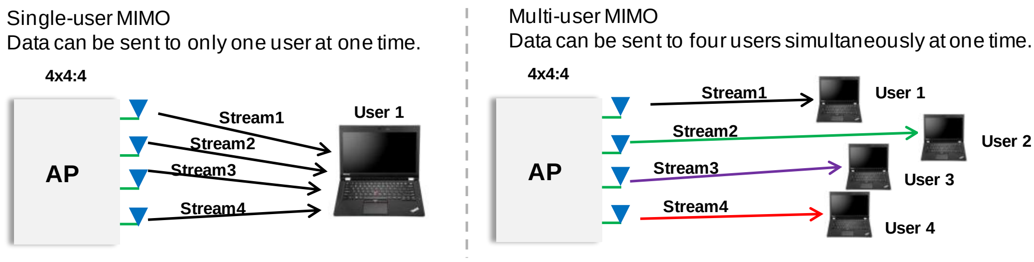
Figure 2-4 8*8 MIMO



2.5 Multi-user MIMO

The use of multiple streams increases the maximum throughput of a single user. However, many terminals, especially mobile smart terminals, use a single stream. A single-stream terminal takes more time on the air interface to transmit data of the same size than a multi-stream terminal. Therefore, single-stream terminals become the bottleneck for increasing access users. Multi-user MIMO is a good choice. An AP can send different data to multiple users (a maximum of four users) simultaneously without changing the user bandwidth and frequency band.

Figure 2-5 Comparisons between single-user MIMO and multi-user MIMO



When an AP in the same frequency band sends data to multiple users simultaneously, signals of streams sent to a user cause interference to signals of streams sent to another user. Multi-user MIMO needs to work with TXBF to complete channel probe. The sender uses pre-coding technology to eliminate the interference according to the feedback matrix.

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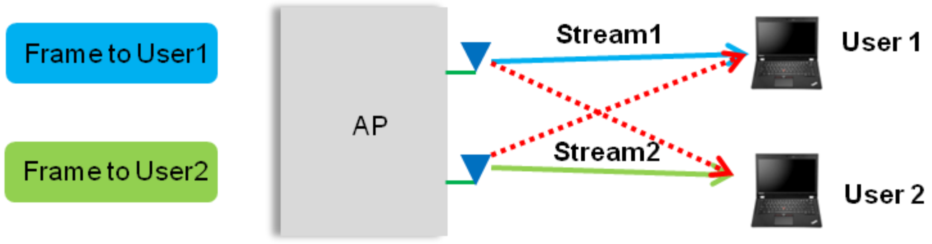
Figure 2-6 Interferences between multiple users



802.11ac supports only downlink multi-user MIMO and is able to transmit data to a maximum of four users. Uplink data is sent one by one, and cannot be sent simultaneously. When sizes of user packets to be transmitted simultaneously are different, frame padding is used. Scheduled BA mechanism is used to schedule ACK response messages of each user so that ACK messages are sent one by one.

When an AP supports Enhanced Distributed Channel Access (EDCA), priorities of different user services may be different. In this case, user service packets are sent to different AC queues. Multi-user MIMO uses the transmission opportunity (TXOP) to transmit packets with different priorities simultaneously.

Multi-user MIMO increases the number of concurrent users connected to a single AP. In scenarios using single-stream terminals, multi-user MIMO increases the number of concurrent users and an AP's downlink maximum throughput. When data streams are transmit to multiple users, interference between streams affects higher order modulation mode. For example, 256QAM cannot be used in this scenario.

2.6 Dynamic Channel Management

802.11ac supports wide channel bandwidths from 20 MHz to 160 MHz, which also brings challenges to channel management. When different channel bandwidths are used, proper management methods must be used to reduce interference between channels and fully use channels.

802.11ac defines an enhanced Request to Send/Clear to Send (RTS/CTS) mechanism to determine when channels are available. The mechanism is as follows:

1. An 802.11ac device sends an RTS. Basic 802.11a transmission, which is 20 MHz wide, is replicated another three times to fill the 80 MHz or another seven times to fill 160 MHz. Each nearby device, regardless of whether the primary channel is the 20 MHz channel over the 80 MHz or 160 MHz channel, can receive the RTS. Each device that receives the RTS sets virtual sub-channels in busy state.
2. The device that receives the RTS checks whether the primary channel or sub-channels of the 80 MHz channel are busy. If some channel bandwidth is used, the receiver replies with a CTS with available bandwidth and reports repeated bandwidth.
3. A CTS is sent over each available 20 MHz sub-channel.

The sender can learn available and unavailable channels. Then data is sent only over available sub-channels.

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Figure 2-7 Dynamic spectrum management

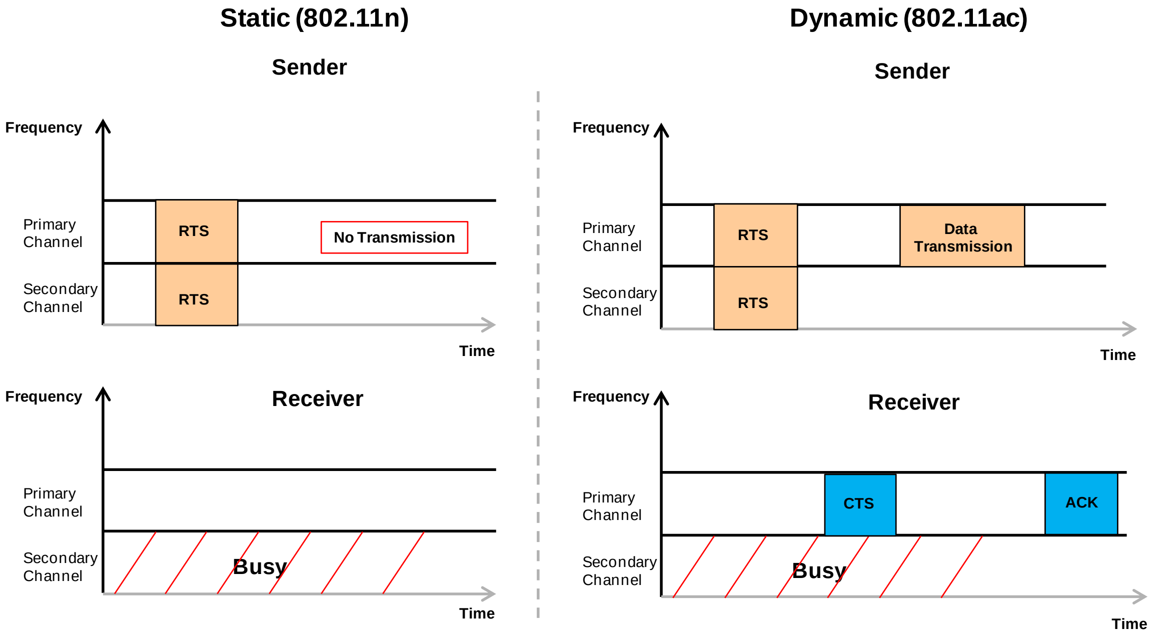
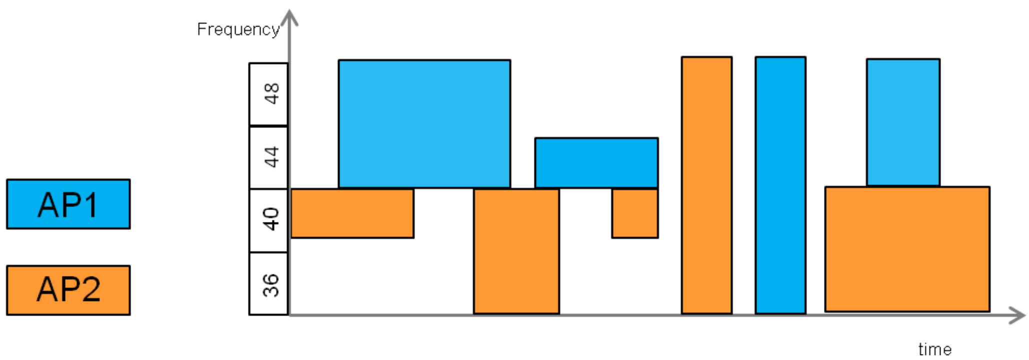


Figure 8 compares 802.11n and 802.11ac. In 802.11n, if a sub-channel is unavailable, the entire bandwidth is unavailable. In 802.11ac, if some sub-channels are unavailable, other sub-channels can still be used to send data.

Dynamic bandwidth management is designed for spectrum multiplexing. This function increases channel use efficiency and reduces interference between channels. Therefore, two APs can work in the same bandwidth channel.

Figure 2-8 Two APs over the same 80 MHz channel



2.7 Compatibility

802.11ac defines the following preamble formats: Greenfield and Mixed. Because Greenfield does not consider compatibility, 802.11ac does not use this format. 802.11ac improves the Mixed format to ensure compatibility with original 802.11 standards.

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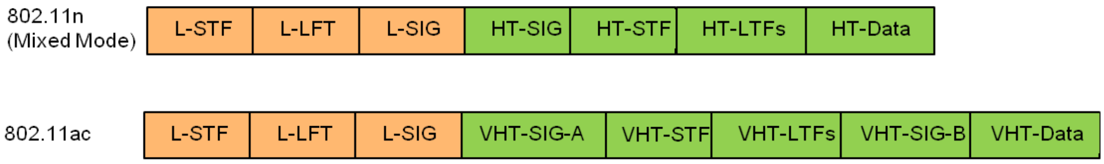
An 802.11ac device can detect the preamble and pilot in the frame format used by an access device to differentiate the 802.11 standard used by the access device and adapt to the access device. The following figure shows the formats of 802.11n and 802.11ac frames.

Figure 2-9 Formats of 802.11n and 802.11ac frames



The short training field (STF), long training field (LTF), and signal field (SIG) are used to ensure compatibility with 802.11a/b/g/n. The letter L indicates Legacy. The first symbol of VHT-SIG-A is BPSK modulated, and the second symbol is BPSK rotated by 90 degrees rotation (QBPSK) used to differentiate HT and VHT modes. VHT-STF in 802.11ac is used to enhance the automatic gain control in an MIMO transmission. VHT-LTF is used by the receiver to estimate the MIMO channel between the transmit and receive antennas. According to the total number of spatial streams, there can be 1, 2, 4, 6, or 8 VHT-LTFs. In 802.11ac, 1, 2, or 4 VHT-LTFs are used for mapping, and 6 or 8 VHT-LTFs are used for spatial streams. VHT-SIG-B indicates the length of data to be transmitted, modulation mode, and coding mode.

2.8 Frame Aggregation

On a Wi-Fi network, each frame is transmitted on an air interface in CSMA/CA mode. When many frames are transmitted, collisions reduce the air interface use efficiency. 802.11n starts to use frame aggregation at the MAC address layer. MSDUs or MPUDs are aggregated, and then encapsulated at the physical layer. This improves encapsulation efficiency and reduces usage and preemption on the air interface.

Figure 2-10 A-MSDU and A-MPDU

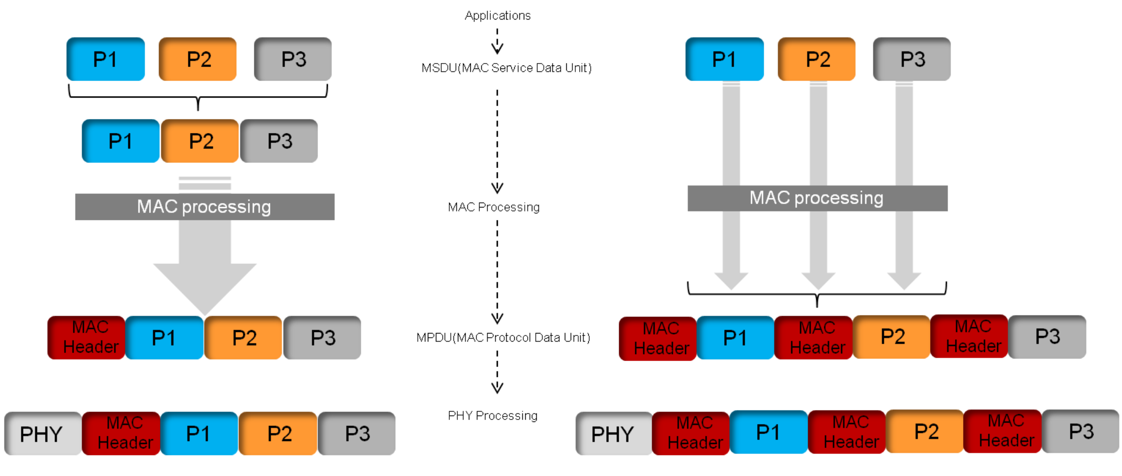


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Figure 11 shows A-MSDU and A-MPDU encapsulation. The two aggregation modes can improve encapsulation efficiency, but A-MPDU has the following advantage that A-MSDU does not have: When an error occurs during transmission, A-MSDU needs to retransmit the entire aggregated frame, while A-MPDU only needs to retransmit the error data packets because each MPDU has its MAC address header. Therefore, A-MPDU is used more frequently than A-MSDU.

To further improve efficiency and reliability, 802.11ac increases the MPDU size and A-MPDU frame size. 802.11ac supports only A-MPDU.

PHY	Aggregation	Max Bytes (Layer 2)	Max Bytes (Layer 1)	Max Data Rate	Throughput
11b	NO	2304	2336	11 Mbit/s	5-6 Mbit/s
11a/g	NO	2304	2336	54 Mbit/s	20-25 Mbit/s
11n	YES	7935	65535	450 Mbit/s	270 Mbit/s
11ac	YES	11454	1048575	1.3 Gbit/s	800 Mbit/s

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3 Benefits to Customers

802.11ac brings in the following benefits:

1. Higher maximum throughput

The earlier generations of Wi-Fi standards strive for the maximum throughput. 802.11 and 802.11g provide the maximum throughputs of 2 Mbit/s and 54 Mbit/s, whereas 802.11n and 802.11ac provide the maximum throughputs of 600 Mbit/s and 6.93 Gbit/s. With improved maximum throughput, 802.11ac can better cope with large-bandwidth requirements.

Standard	Channel Size	Max Modulation	Max Spatial Streams	Max Data Rate
802.11	20 MHz	DQPSK	1	2 Mbit/s
802.11b	20 MHz	CCK	1	11 Mbit/s
802.11g	20 MHz	64QAM	1	54 Mbit/s
802.11a	20 MHz	64QAM	1	54 Mbit/s
802.11n	20/40 MHz	64QAM	4	600 Mbit/s
802.11ac	20/40/80/160 MHz	256QA	8	6.93 Gbit/s

2. Lower interference

Although 802.11ac defines the frequency band less than 6 GHz frequency band (excluding 2.4 GHz frequency band), the mainstream frequency band is still 5 GHz. Compared with the 2.4 GHz frequency band that has only 83.5 MHz bandwidth, the 5 GHz frequency band used in some countries provides hundreds of MHz bandwidth. More frequency resources indicate reduced frequency multiplexing and interferences. Wi-Fi devices at the 2.4 GHz frequency band often suffer interferences from external devices. A large number of non-Wi-Fi devices such as baby monitors, microwave ovens, and cordless telephones also work at the 2.4 GHz frequency band. Interferences from these devices affect Wi-Fi performance, and Wi-Fi cannot effectively solve these problems.

3. More access users

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Though 802.11ac does not change Wi-Fi multi-address access, 802.11ac improves the maximum throughput and multi-user MIMO to enhance the concurrent user access capability. The improved maximum throughput indicates less time taken by each user on the air interface. That is, an AP can provide access services for more users at one time. Multi-user MIMO allows an AP to transmit data of multiple users at one time.

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