Wi-Fi 7: A Leap Towards Time-Sensitive Networking

Table of Contents

Wi-Fi 7 aims to deliver extremely high throughput (EHT) - three times higher peak throughput than its predecessor Wi-Fi 6E, along with better network efficiency, deterministic latency, and higher reliability.

Executive Summary

The latest Wi-Fi standard, 802.11be or Wi-Fi 7 aims to deliver extremely high throughput (EHT) - three times higher peak throughput than its predecessor Wi-Fi 6E, along with better network efficiency, deterministic latency, and higher reliability. The high throughput is envisaged to exploit the 6 GHz band which has a shorter propagation range, and is particularly suitable to provide Basic Service Set (BSS) isolation in dense and challenging environments like airports, sports arenas, and large retail complexes. The lower latency and higher reliability are aimed at enabling time-sensitive networking (TSN) use cases. Some TSN use cases are robotic surgery, augmented and virtual reality, online gaming, and cloud computing. Factory and process automation require high reliability, where Wi-Fi 7 needs to guarantee three or more 'nines' reliability and sub 10 ms deterministic latency to aim at replacing wired communications.

The 802.11be standard introduces several new features and enhancements to the PHY and MAC layers. The PHY layer is enhanced to support 320 MHz channels, 4096 QAM, 16 spatial streams in MU MIMO, and a forward compatible frame format. The OFDMA enhancements include multi-RU support with preamble puncturing of single user frames. A more efficient MAC architecture is introduced where the MAC layer is split into the upper MAC (U-MAC) and lower MAC (L-MAC) to support the use of multiple radio links. Referred to as Multi-link operation (MLO), this feature enables the AP/client to use multiple links of the same/different bands to improve throughput and reduce latency. Stream classification service (SCS) is introduced to prioritize latency sensitive applications such as real time voice and video. Another MAC feature that attempts to reduce latency is restricted TWT (R-TWT) with TID-to-link mapping.

This primer presents an overview of the above mentioned features in the 802.11be standard along with the benefits and challenges that these features offer. The new use cases that can be brought to reality with the ultra low latency, reliability and extremely high throughput offered by the 802.11be enhancements are elucidated.

Evolution from 6/6E to 7

From a data rate of 2Mbps in 802.11b to almost 7 Gbps in Wi-Fi 5 (Wave 2), the focus of successive generations of Wi-Fi standards has been to achieve better and better data rates. The higher data rates are achieved by wider channel bandwidths, new spectrum bands (5 GHz, 6 GHz), higher order MCS and more MIMO spatial streams (see Figure 1).

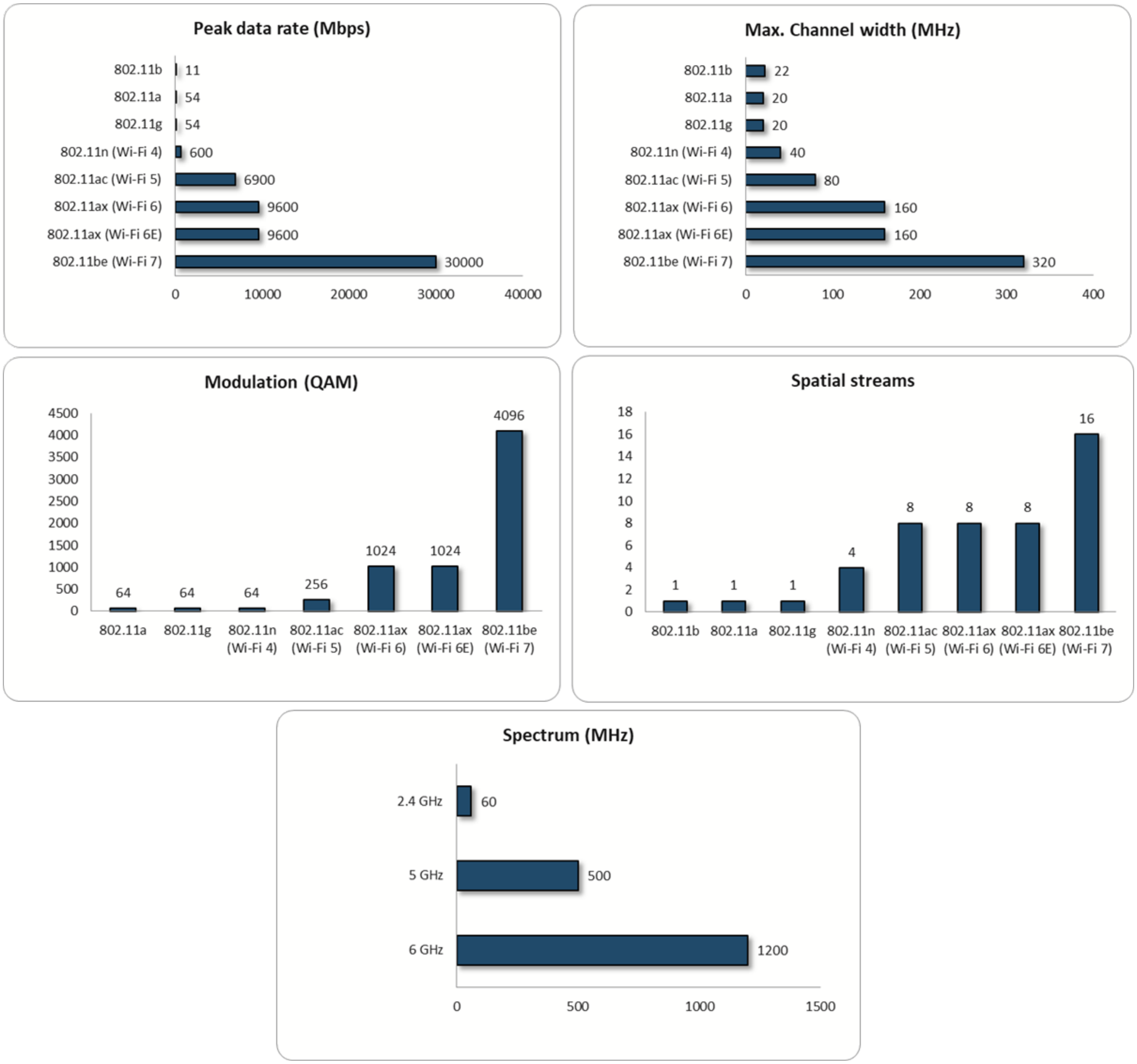


Figure 1

The focus of Wi-Fi 6/6E was to bring in efficiency in spectrum use, specifically in dense 2.4 GHz and 5 GHz deployments. It introduces uplink (UL) MU MIMO and OFDMA transmissions and introduces more flexible rules for channel bonding and carrier sense. Wi-Fi 7 brings in significant PHY and MAC improvements over Wi-Fi 6/6E, as tabulated below.

Table 1: Comparison of Wi-Fi 6/6E and Wi-Fi 7			
	Feature	**Wi-Fi 6/6E**	**Wi-Fi 7**
PHY	OFDMA	Single resource unit (RU) per STA	Multiple RUs per STA
	MU MIMO	8 spatial streams	16 spatial streams
	MCS	1024 QAM	4096 QAM
	Maximum channel width	160 MHz	320 MHz
	Preamble puncturing	No support for puncturing single user frames	Support for puncturing single user frames Support for puncturing 320 MHz channels
	Access Categories	VO, VI, BE, BK	VI, VO, BE, BK, R_VO, R_VI
	Multi-link Operation	Not supported	Synchronous use of multiple radio links of different /same bands supported
Performance	Maximum data rate	9.6 Gbps	46 Gbps
	Latency	With OFDMA [12] DL: 25 ms UL: 54 ms	Target < 10 ms
	Reliability		Target: 99.99%-99.999%

PHY Enhancements

The data rates supported by Wi-Fi 6/6E are accelerated by Wi-Fi 7 exploiting three PHY enhancements - higher channel width (320 MHZ), higher order MCS (4K QAM), and higher number of MIMO spatial streams (16). Another progressive improvement in Wi-Fi 7 is the introduction of forward compatible frame format, which simplifies the support for different PHY formats in the same network and introduction of new PHYs in the future.

320 MHz channels

The full potential of the 6 GHz band is exploited in Wi-Fi 7 with increasing the maximum channel bandwidth to 320 MHz. Furthermore, the support for 160 + 160 MHz and 240/160 + 80 MHz channels provides high bandwidth even when no contiguous spectrum is available. Such high bandwidths enable AR/VR, 8K streaming video and online gaming applications which require extremely high throughput and low latency.

Since wide channels are prone to frequency selective fading, these are inefficient for use in high density deployments such as sports stadiums. Wider channels also result in OBSS interference in the network and higher power consumption.

4K QAM

4096 QAM in Wi-Fi 7 provides for a 20% improvement in data rate as compared to 1024 QAM in Wi-Fi 6/6E [2]. This marginal gain in data rate needs to be weighed against the complexity in its implementation. Decoding symbols in 4096 QAM requires a very high SNR of about 38 dB at the receiver [3], limiting its use in several practical applications. The best use of this feature is probably in the 6 GHz band for high volume file/video exchange over short distances such as proximity advertising in retail.

MU MIMO with 16 spatial streams
A doubling of data rate is expected to be achieved with the support for 16 spatial streams in Wi-Fi 7 as compared to 8 spatial streams in Wi-Fi 6/6E. Dense deployments such as sports stadiums, coverage in trains, and conference events can benefit from a higher number of spatial streams.

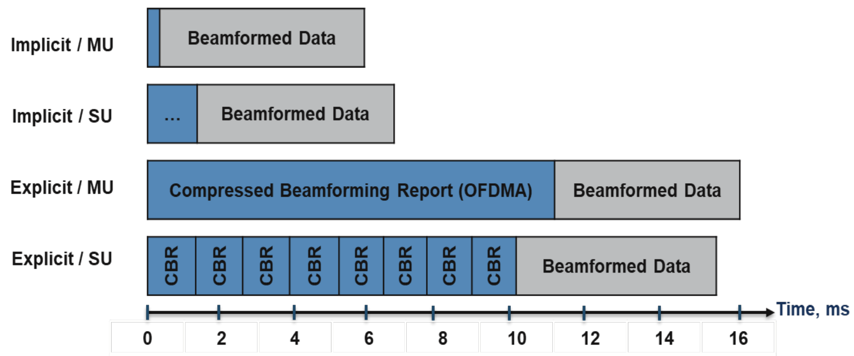
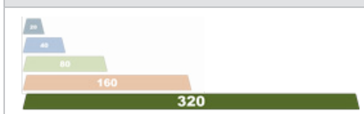
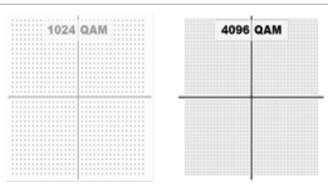
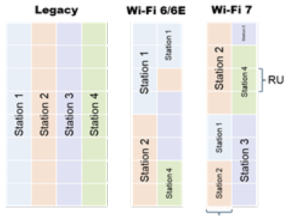
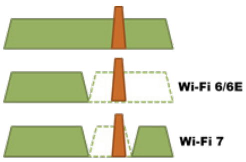
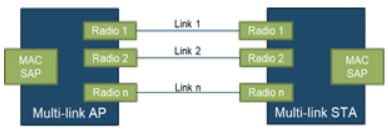


Figure 2: Data transmission vs. sounding and feedback overhead comparison. 16 spatial streams, 8 users, 2 streams per user [6]

The full potential of MU MIMO can be realized only when accurate channel state information is available for all the spatial streams. As the channel parameters keep varying over time, the STAs have to provide channel state information (CSI) feedback (channel sounding) to the AP frequently. The increased number of spatial streams in Wi-Fi 7 coupled with wider channel width will introduce significant channel sounding overhead, as depicted in the figure below. In order to mitigate this sounding overhead, the 802.11be standard suggests enhanced explicit and implicit channel sounding schemes. The enhancements for explicit sounding involve improvements in codebook design, quantization/ compression processing to reduce sounding overhead. The implicit channel sounding procedure exploits uplink/downlink channel reciprocity to estimate channel state information (CSI) at the receiver by using CSI at the transmitter [6]. However, implicit sounding requires careful calibration at the APs to compensate for non-reciprocal impairments in the RF-to-baseband and baseband-to-RF chains .

Table 2: Benefits, challenges and applications of key Wi-Fi 7 features

Feature	Benefits	Challenges	Application
 320 MHz Channels	• Extremely high throughput • Low latency	• More interference • Higher power consumption • High channel variability • Filtering characteristics	
 4096 QAM	• High throughput • Spectral efficiency	• 38 dB SNR • Requires beamforming • Difficult in NLOS conditions	
 16 Spatial Streams	• High throughput • Spectral efficiency	• Channel sounding overhead • Advanced scheduling algorithms • Lower power per stream	

Feature	Benefits	Challenges	Application
 M-RU allocations	• High channel utilization • High throughput	• Implementation and scheduling complexity	
 Improved Preamble Puncturing	• Improved channel utilization		
 Multi-link Operations	• Extremely high throughput • Low latency • High reliability	• Tight coordination between links • High power consumption • Implementation complexity	

OFDMA Enhancements

The 802.11be standard provides enhancements to OFDMA to improve performance in outdoor scenarios and add more flexibility for channel utilization in dense deployments. The number of OFDMA tones is increased by 4 times compared to 11ax, allowing more flexibility in resource utilization.

Preamble Puncturing

Preamble puncturing was introduced in 11ac to enable STAs to adaptively change bandwidth for each transmitted frame. However, until 11ax, the number of modes for puncturing is restricted to only some of the secondary subchannels in OFDMA. Wi-Fi 7 extends the puncturing to single user frames, thereby improving channel utilization.

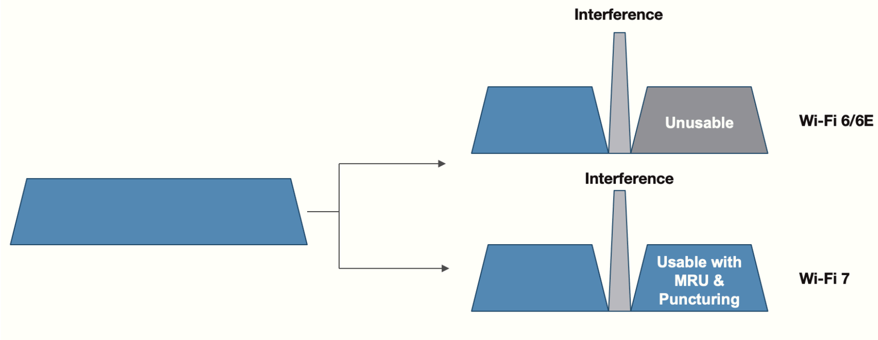


Figure 3: Improved channel utilization in Wi-Fi 7 with MRU+Preamble puncturing

Multi-RU

In 11ax, only one OFDMA resource unit (RU) was allowed to be allocated to an STA. Such restricted allocation of resources leads to sub-optimal utilization, especially when the number of STAs is small. This limitation is overcome in Wi-Fi 7 by allowing for allocation of multiple RUs per STA.

The large number of OFDMA tones available in Wi-Fi 7 result in several possible RU combinations. To establish a trade-off between combination complexity and spectral efficiency, only limited multi-RU combinations are allowed. Small size RUs (26-tone, 52-tone, 106-tone) can be combined only with small size RUs, while large size RUs (more than 242-tone) can be combined with only large size RUs. Combinations of small size and large size RUs are not allowed. A maximum of 3 RUs can be allocated to a single user [7].

The benefits of multi-RU allocation can be realized only when clients support this feature, thus might take some time until the Wi-Fi 7 client ecosystem is mature.

MRU Type	Tones	Allowed combinations	
Small-size RU	26-tone, 52-tone, 106-tone	20/40 MHz: 20/40/80 MHz:	26-tone RU + 106-tone RU 26-tone RU + 52-tone RU
Large-size RU	242-tone, 484-tone, 996-tone, 2 × 996-tone, 3 × 996-tone	80 MHz:	242-tone RU + 484-tone RU
		160 MHz:	484-tone RU + 996-tone RU 242-tone RU + 484-tone RU + 996-tone RU
		240 MHz:	484-tone RU + 2 × 996-tone RU 2 × 996-tone RU
		320 MHz:	484-tone RU + 3 × 996-tone RU 3 × 996-tone RU

Figure 4: Applicable MRU combinations for different bandwidth modes in EHT

Forward Compatible PHY Frame Format

One of the drawbacks of supporting legacy in Wi-Fi has been the lack of an explicit way to indicate the PHY protocol version in the frames. In all Wi-Fi versions beyond 11n, the protocol version is indirectly derived either from the MCS of the HT-SIG1 (in 11n) and VHT-SIG1 (in 11ac) or from the repetition of the L-SIG (in 11ax) (see Figure 3). 802.11be introduces the U-SIG field which circumvents auto-detection of preamble and makes the 11be frame format forward compatible. The U-SIG field includes 5 version independent fields, i.e., PHY Version Identifier, Bandwidth, UL/DL, BSS Color, and TXOP, followed by the version dependent fields, and version independent CRC and Tail fields at the end (see Figure 4). The purpose of the PHY Version Identifier field is to identify the exact PHY version starting with EHT, thus paving the way for supporting explicit identification of all future protocol versions.

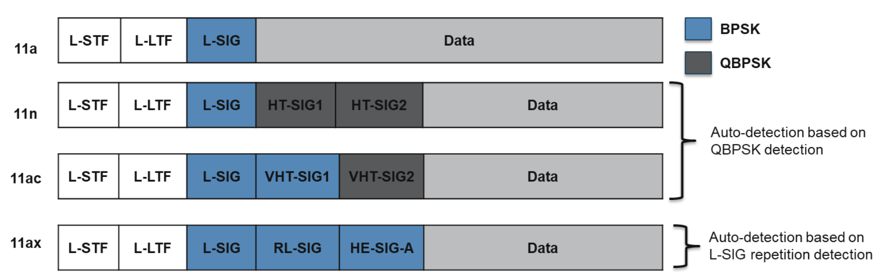


Figure 5: Preamble auto-detection in legacy frames

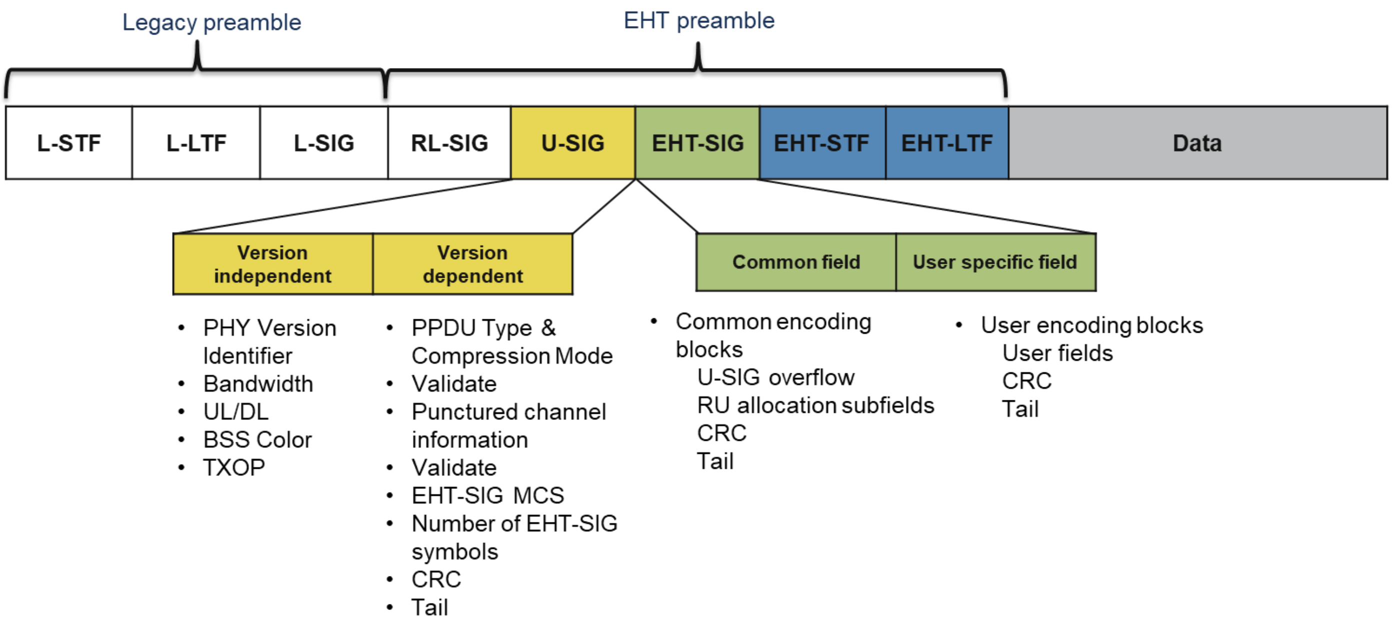


Figure 6: EHT frame format

MAC Enhancements

Multi-link Operation

One of the most promising new features introduced in 802.11be is the multi-link operation. Multi-link operation refers to sending/receiving packets concurrently on multiple channels which can be either in the same band or different bands. It is designed to provide:

- High spectrum efficiency
- Low latency
- Load balancing
- High reliability

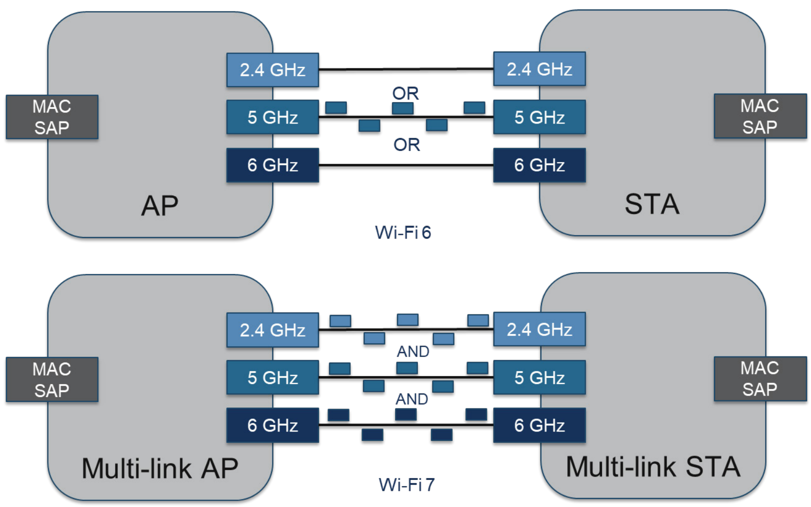


Figure 7: Difference between non-Multi-link and Multi-link operation

MAC Architecture

The ability to transmit/receive synchronously on different bands calls for architectural changes to the MAC layer. 802.11be redefines the APs and STAs as multi-link devices (MLDs), where an MLD refers to an AP/STA with multiple wireless interfaces. The MAC layer functionality is divided into two sublayers (see Figure 8):

- Upper MAC (U-MAC): The upper MAC is common to all wireless interfaces of an MLD and carries out link agnostic functions - sequence number assignment, MSDU aggregation/de-aggregation, MPDU encryption/decryption, setup, association and authentication.
- Lower MAC (L-MAC): The lower MAC is independent for each wireless interface and carries out link specific functions - channel access, channel parameter estimation, EDCA queue maintenance, management and control frame generation, and MAC header creation and validation.

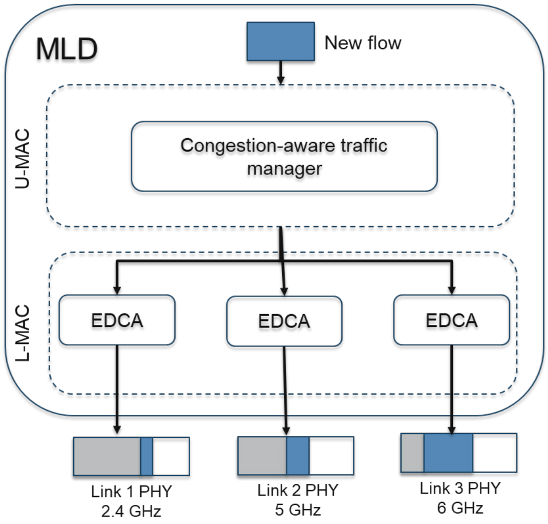


Figure 8: MAC data plane architecture (MLO) for unicast data frames [8]

The two-tier architecture facilitates seamless balancing of traffic load between multiple PHY links, improving spectrum efficiency.

Multi-link Channel Access and Transmission

MLO allows channel contention and access independently on each link, via a single association. The transmissions on multiple links in an MLD can happen asynchronously on all the links, or in a synchronous manner. A MLD can function with a single radio or multiple radios, the link usage being dependent on the mode of MLO deployed.

Multi-link Single Radio

MLSR enables a single-radio device to function as a multi-link device (MLD) by splitting its multiple antennas amongst multiple links, saving the cost of multiple radios. An MLSR MLD can perform clear channel assessment, control frame reception and data transmission/reception only on one channel at a time.

Enhanced Multi-link Single Radio

EMLSR enables the MLD to listen to two links simultaneously, and use links opportunistically. Improved throughput can be achieved this way, as compared to the single link operation (SLO). Due to its simplicity and low cost, EMLSR is best suited for use in client devices.

Non-Simultaneous Transmit and Receive Enhanced Multi-link Multi Radio

In NSTR-EMLMR, one of the links is designated as the primary link. Channel access over all the links is dependent on the primary link, with only one backoff counter for all the links. Simultaneous transmission and reception is not allowed over a pair of links in order to prevent self interference at the MLD. This requires alignment in the end time of physical layer protocol data units (PPDUs) that are simultaneously transmitted, so as to avoid overlapping of incoming responses on one link, e.g., ACKs, with the remaining transmission on another link. Due to dependency on the primary link for channel access, packets might experience higher latency in NSTR-EMLMR.

Simultaneous Transmit and Receive Enhanced Multi-link Multi Radio

STR-EMLMRis the most advanced form of MLO modes, with independent channel access on all the links. Since packets can be transmitted and received independently and simultaneously on all the links, latency is reduced and throughput is enhanced. When two links transmit and receive simultaneously, it results in uplink-to-downlink in-device coexistence interference. Hence, sufficient frequency separation is required between the links.

MLO paves the way for congestion-aware traffic management schemes, where the incoming traffic load can be distributed across the links based on the existing loads.

The performance gains of the multi-link transmissions may be hindered by legacy devices that still use single link. Just as other advanced features of 802.11be, the capabilities of client devices will limit the full benefits of MLO.

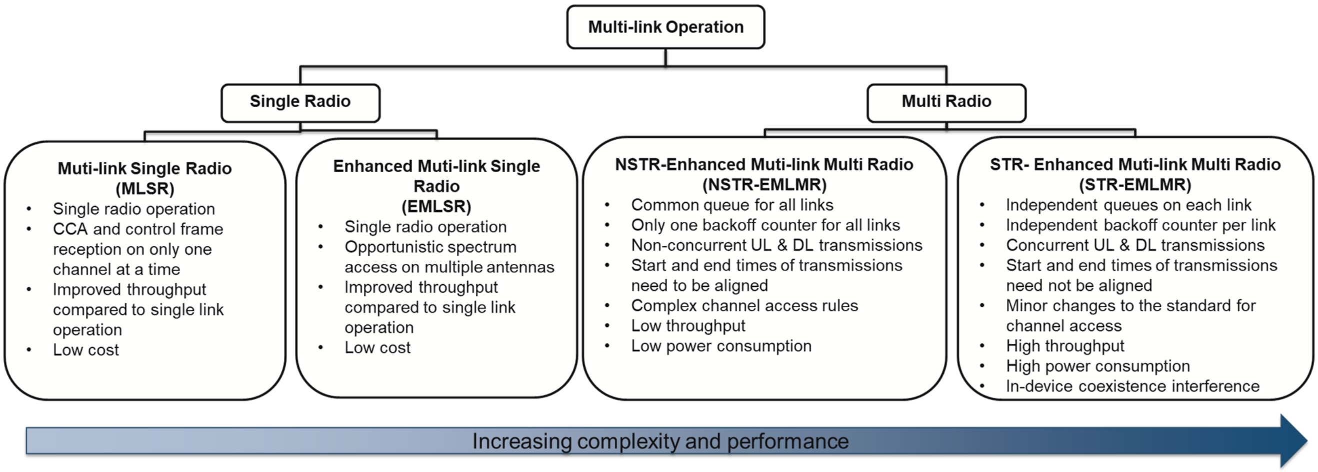


Figure 9: Modes of MLO channel access and transmission

Improved EDCA for Time Sensitive Networking

The 802.11e specification introduced Enhanced Distributed Channel Access (EDCA) with Access Categories (ACs) for different types of traffic: video (VI), voice (VO), background (BK), and best effort (BE). While ACs provide QoS differentiation by using different inter-frame spacing for different application types, the underlying CSMA-CA with random backoff medium access makes it difficult to satisfy deterministic latency requirements.

A key consideration in Wi-Fi 7 is to serve Time Sensitive Networks (TSN). A variety of approaches were considered to satisfy TSN requirements [3]. The approaches that 802.11be adopts are described below.

Real-Time Applications and Stream Classification Service (SCS)

A key consideration in serving TSNs is the ability to identify real-time applications (RTAs) and reorder the MAC Service Data Units (MSDUs) in the queue, so as to prioritize RTAs over other video and voice (VI, VO) access categories.

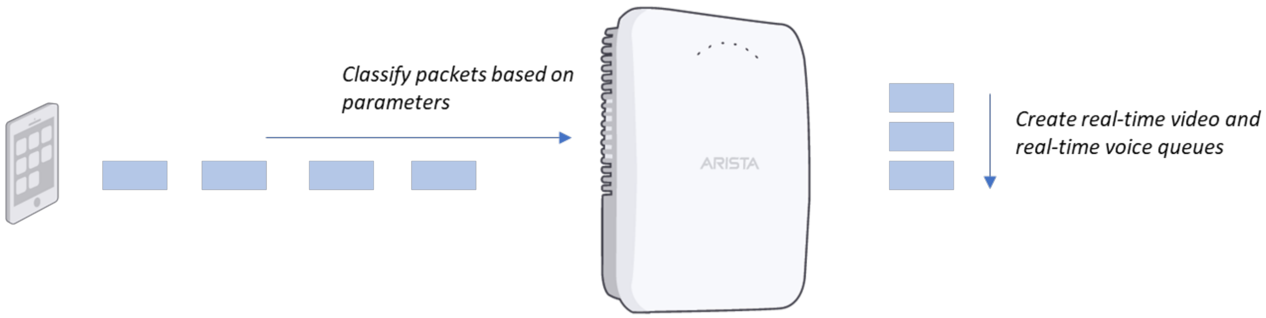


Figure 10: Stream Classification Service (SCS)

To identify real-time applications, Wi-Fi 7 introduces Stream Classification Service(SCS). With SCS, an AP classifies individual incoming MSDUs based on parameters provided by the client. SCS allows the user priority (UP), drop eligibility, and EDCA transmit queue to be selected based on the MSDU classification. A related feature in Wi-Fi 7 APs is mirrored stream classification (MSCS), where an AP infers the DL QoS to be used from higher-layer fields (e.g. DSCP, port, IP) in the UL packet; the AP then generates DL QoS rules based on the UL information. This could be especially useful if the client does not support SCS, forcing the AP to rely on higher layer information.

Once real-time applications are identified, they must be prioritized. To achieve this, Wi-Fi 7 adds two new high-priority queues to the EDCA queue system: real-time video (R_VI) with user priority (UP) 5, and real-time voice (R_VO) with user priority (UP) 6. These have higher priority than the basic VI and VO queues, ensuring that Wi-Fi 7 can meet the latency requirements for TSNs.

Real-Time Applications and R-TWT with TID-to-Link Mapping

To overcome the inherent limitations of the CSMA-CA with random backoff approach, Wi-Fi 7 introduces a Restricted Target Wake Time (R-TWT) mode. In conjunction with the mapping of Traffic-IDs (TIDs) to links in MLO, R-TWT basically works by reserving TWT service periods for latency-sensitive traffic. Thus, Wi-Fi 7 satisfies latency-sensitive applications by reserving resources for latency-sensitive TIDs in two dimensions: the TID to link mapping optimizes the resource selection in the frequency domain, and R-TWT allocates a dedicated service period (SP) in the time domain.

R-TWT is an enhancement of the Broadcast TWT function supported in 802.11ax such that:

- The procedure to set up an R-TWT group is the same as that for setting up a broadcast TWT group, except that the Restricted TWT Traffic Info field identifies the TIDs that carry the latency-sensitive traffic on the downlink and the uplink for the R-TWT group.
- A Wi-Fi 7 AP ensures that an R-TWT service period is used only for TIDs in the corresponding Broadcast TWT group. In other words, the AP ensures that only TXOPs serving the latency-sensitive TIDs are used in the R-TWT service period.
- Similarly, a Wi-Fi 7 client suspends the decrementing of its backoff counters for ACs that do not correspond to the TID for which the R-TWT Broadcast group was created.

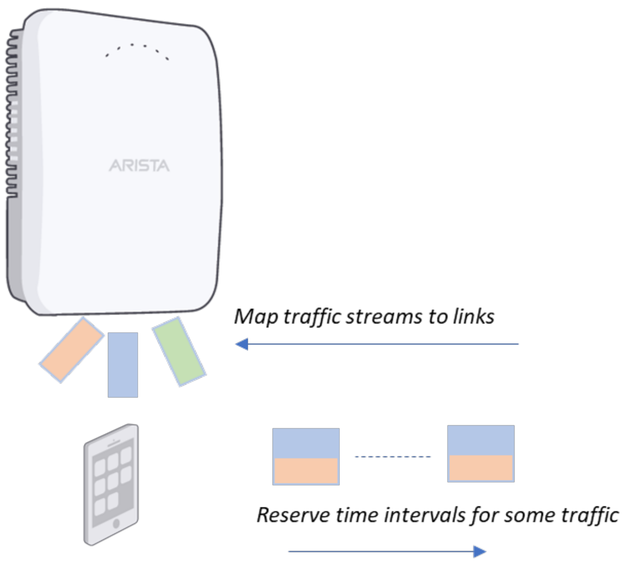


Figure 11: TID-to-Link Mapping and Restricted-TWT

Proposals that didn't make it to the standard

Multi-AP coordination

A low complexity multi-AP coordination, coordinated spatial reuse (CSR) is a part of the current 802.11be standard. Proposals for a tighter cooperation between nearby APs, which include coordinated scheduling, beamforming, and distributed MIMO systems will now be considered for Release 2.

Hybrid Automatic Repeat Request (HARQ)

Until 802.11ax, erroneous packets were dropped by the receiver and the transmitter had to retransmit the entire packet. Starting with 802.11be, HARQ was proposed, where the receiver does not discard the erroneous packet entirely, but combines the signals from several transmission attempts, thereby improving SNR and the ability to decode the packet correctly. However, HARQ places demand on memory consumption and computational speed. Hence, its implementation is still an open issue which may only be considered in Release 2.

Open Issues

Co-existence in the 6 GHz band

The benefits of the 320 MHz channel widths in the 6 GHz band can be realized only when the rules for co-existence with the incumbent technologies are well defined. As depicted below, the 6 GHz band is in use by several incumbent services viz., point-to-point microwave links, satellite services, mobile, TV and broadcast services.The FCC has laid down the rules of accessing the 6 GHz band for standard power APs and clients for outdoor/indoor operation via the Automated Frequency Coordination (AFC) system [13]. The upper portion of the 6 GHz spectrum (i.e., 6.425 to 7.125 GHz) is pending for consideration at the 2023 World Radiocommunication Conference (WRC-23) for supporting licensed 5G networks by the International Mobile Telecommunications (IMT) designation to support licensed 5G networks. The uncertainty of the pending WRC-23 decision is resulting in regulatory inaction that is hampering introduction of advanced 6 GHz Wi-Fi technology in several countries.

Power Management

A multilink device may consume significant power when it is in the listening mode, as it has to listen on multiple bands. Efficient energy saving mechanisms are required to manage this increased power consumption, especially in power-constrained client devices. Effective network traffic prediction methods to adaptively enable/disable links are required to manage the increased power consumption.

Guaranteed QoS

Offering guaranteed QoS in the form of deterministic latency, jitter and assured throughput has been challenging in Wi-Fi networks due to the inherent delays involved in the CSMA/CA mechanism. Intelligent use of features like TWT and multi-AP coordination is required in the future standards to deliver the stringent QoS requirements of time sensitive networking.

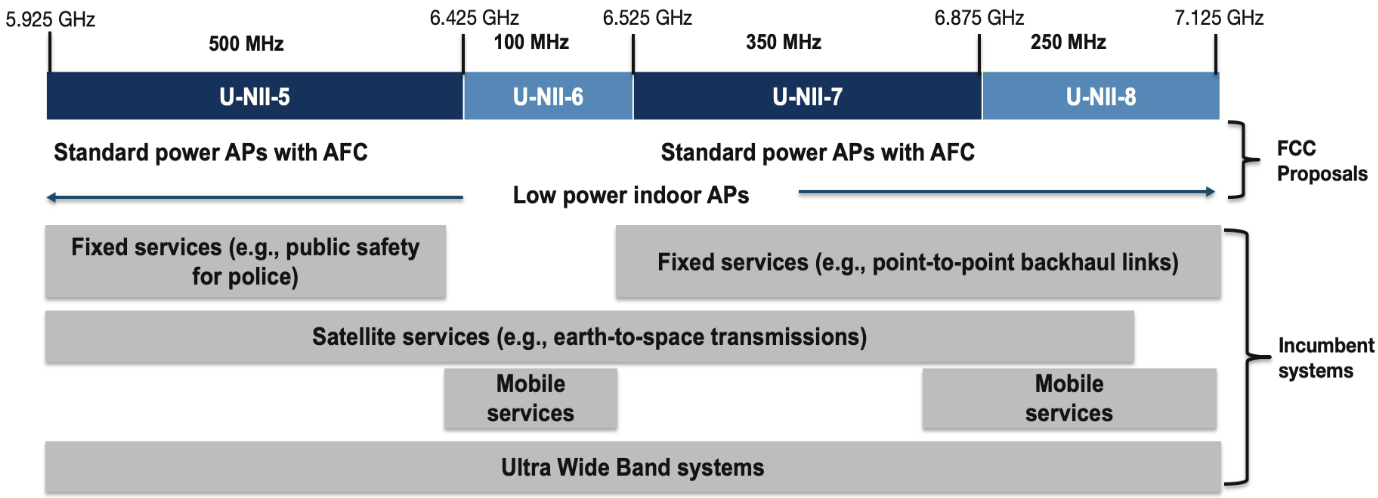


Figure 13: FCC frequency allocations in the 6 GHz band [11]

Conclusion

Wi-Fi 7 is a major advancement towards enabling time-sensitive networking that enables enterprise networks to support real time applications. It provides several features to utilize the 6 GHz band efficiently, paving the way for new use cases. 320 MHz channels, MRU, MLO and SCS are all features primed to reduce latency significantly and improve reliability and capacity of enterprise Wi-Fi networks. Arista is committed to support all these key features in the Wi-Fi 7 access points.

References

1. 6 GHz Spectrum Needs for Wi-Fi 7
2. Current Status and Directions of IEEE 802.11be, the Future Wi-Fi 7
3. IEEE 802.11be: Wi-Fi 7 Strikes Back
4. IEEE 802.11be – Wi-Fi 7: New Challenges and Opportunities
5. Understanding Multi-link Operation in Wi-Fi 7: Performance, Anomalies, and Solutions
6. Implicit Sounding Over- head Analysis
7. Multi-RU support for OFDMA
8. IEEE Draft 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 Amendment: Enhancements for Extremely High Throughput (EHT)," in IEEE P802.11be/D3.0, January 2023 , vol., no., pp.1-999, 1 March 2023
9. IEEE 802.11be Multi-Link Operation: When the Best Could Be to Use Only a Single Interface
10. Wi-Fi 7 : All you need to know
11. IEEE 802.11be Extremely High Throughput: The Next Generation of Wi-Fi Technology Beyond 802.11ax
12. Reduced latency benefits of Wi-Fi 6 OFDMA
13. Code of Federal Regulations Title 47

Santa Clara—Corporate Headquarters
5453 Great America Parkway,
Santa Clara, CA 95054

Phone: +1-408-547-5500
Fax: +1-408-538-8920
Email: info@arista.com

Ireland—International Headquarters
3130 Atlantic Avenue
Westpark Business Campus
Shannon, Co. Clare
Ireland

Vancouver—R&D Office
9200 Glenlyon Pkwy, Unit 300
Burnaby, British Columbia
Canada V5J 5J8

India—R&D Office
Global Tech Park, Tower A, 11th Floor
Marathahalli Outer Ring Road
Devarabeesanahalli Village, Varthur Hobli
Bangalore, India 560103

Singapore—APAC Administrative Office
9 Temasek Boulevard
#29-01, Suntec Tower Two
Singapore 038989

Copyright © 2024 Arista Networks, Inc. All rights reserved. CloudVision, and EOS are registered trademarks and Arista Networks is a trademark of Arista Networks, Inc. All other company names are trademarks of their respective holders. Information in this document is subject to change without notice. Certain features may not yet be available. Arista Networks, Inc. assumes no responsibility for any errors that may appear in this document. June 10, 2024