SETTING NEW PERFORMANCE STANDARDS WITH IEEE 802.11bn

In-depth overview of Wi-Fi 8

White paper | Version 02.00 | Lisa Ward, Jörg Köpp

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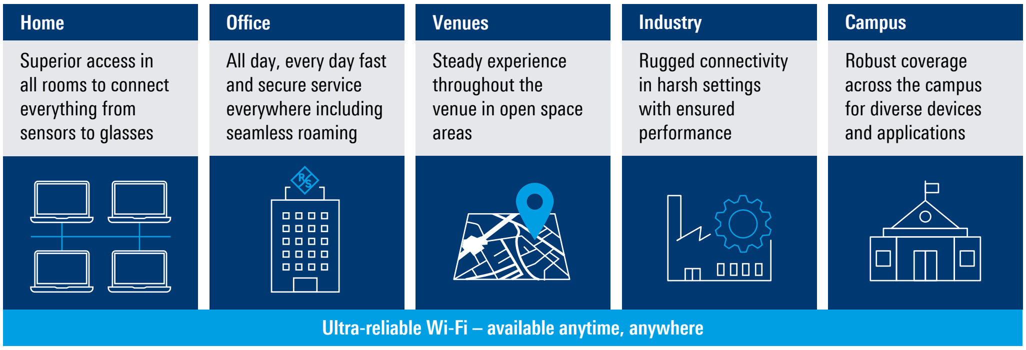
1 WI-FI 8 FOR ULTRA-HIGH RELIABILITY

Wi-Fi, also known as IEEE 802.11, has become an indispensable and widely embraced technology. Its versatility spans an expanding array of products and applications, including video conferencing, augmented and virtual reality (AR/XR), the internet of things (IoT), content sharing, web browsing and streaming video. Notably, most internet traffic on mobile devices is transmitted via Wi-Fi, particularly in homes, offices and public spaces.

Unlike previous generations of Wi-Fi that primarily focused on throughput improvements, IEEE 802.11bn is introducing and enhancing features to improve user experience by providing stable performance, spectrum efficiency, reduced latency, seamless connectivity, power efficiency and smart coexistence.

Figure 1: Providing ultra-high reliable Wi-Fi – applications and challenges



Home	Office	Venues	Industry	Campus
Superior access in all rooms to connect everything from sensors to glasses	All day, every day fast and secure service everywhere including seamless roaming	Steady experience throughout the venue in open space areas	Rugged connectivity in harsh settings with ensured performance	Robust coverage across the campus for diverse devices and applications

Ultra-reliable Wi-Fi – available anytime, anywhere

The new IEEE 802.11bn draft amendment [1] introduces enhancements for ultra-high reliability (UHR) and will serve as the foundation for Wi-Fi 8, as specified by the Wi-Fi Alliance. (Both the terms IEEE 802.11bn and UHR are utilized throughout this white paper.)

Overall, the primary physical layer parameters of Wi-Fi 7 – including frequency range of 1 GHz to 7.25 GHz, maximum channel bandwidth of 320 MHz, maximum number of spatial streams of 8, subcarrier spacing of 78.125 MHz and highest modulation scheme of 4096QAM will stay as they are, which also implies that the maximum physical layer data rate will stay the same with around 23 GHz on a single 320 MHz 8x8 MIMO link.

Table 1: Comparison of key physical layer parameters of last three generations

	IEEE 802.11ax, high efficiency	IEEE 802.11be, extreme high throughput	IEEE 802.11bn, ultra-high reliability
Frequency range	1.0 GHz to 7.125 GHz	1.0 GHz to 7.250 GHz	1.0 GHz to 7.250 GHz
Channel bandwidth	20 MHz to 160 MHz	20 MHz to 320 MHz	20 MHz to 320 MHz
OFDMA: resource units (RU)	regular RU (RRU)	▶ multiple RU (MRU) ▶ regular RU (RRU)	▶ distributed-tone RU (DRU) ▶ multiple RU (MRU) ▶ regular RU (RRU)
Subcarrier spacing	78.125 kHz	78.125 kHz	78.125 kHz
Symbol time	12.8 µs	12.8 µs	12.8 µs
Guard interval (GI)	0.8 µs, 1.6 µs, 3.2 µs	0.8 µs, 1.6 µs, 3.2 µs	0.8 µs, 1.6 µs, 3.2 µs
Modulation	up to 1024QAM	up to 4096QAM	up to 4096QAM
Spatial streams (N_{ss})	up to 8	up to 8	up to 8
Maximum PHY data rate per link	9.6 Gbps	23.1 Gbps	23.1 Gbps

This white paper will explore the new PHY and MAC features and enhancements including distributed-tone resource units (DRU), enhanced long range (ELR) capabilities, unequal modulation (UEQM), multi-access point (multi-AP) coordination, roaming, non-primary channel access (NPCA), dynamic subband operation (DSO) and more.

2 TACKLING REAL-WORLD WI-FI CHALLENGES

Today's and future applications in homes, enterprises, industries and public spaces demand high throughput, along with minimized and predictable worst-case delays and jitter, enhanced reliability and improved power efficiency.

Consequently, an IEEE study group has defined certain targets [2] for the enhancement for ultra-high reliability:
- Increasing throughput by 25% compared to IEEE 802.11be [3] under certain conditions (rate vs. range)
- Reducing latency by 25% for the 95th percentile of latency distribution
- Reducing packet loss probability by 25% for scenarios requiring seamless transition between basic service set (BSS)
- Reduce power consumption for access points (AP)
- Improved peer-to-peer (P2P) operation

Table 2 lists new PHY layer features and enhancements in IEEE 802.11bn. Many of them are focused on improving rate vs. range performance especially in the uplink.

Table 2: IEEE 802.11bn essential physical features

Feature	Benefit
Distributed-tone resource unit (DRU)	Improves uplink transmit power in UL OFDMA transmission by distributing tones over a wider bandwidth
Enhanced long range (ELR) PDDU	Overcomes the link budget imbalance between downlink and uplink in some regulatory requirements
Interference mitigation (IM)	Enables reliable reception of the PPDU in the presence of an interfering signal by adding additional pilots in the data section of the PPDU
Long LDPC codeword	Additional support of codeword length of 3888 bits
Modulation and coding schemes (MCS)	Additional combinations of existing coding rates and modulation schemes to close gaps
Unequal modulation (UEQM)	Improves performance for UHR MU PPDU with non-MU-MIMO beamformed transmission

IEEE 802.11bn contains several new MAC layer features and enhancements as well. Table 3 provides a list of more basic MAC features such as dynamic power save, which provides a straightforward mechanism to reduce power consumption while listening on a link. Table 4 lists the more advanced MAC layer features such as roaming and multi-AP coordination that require some amount of coordination between devices.

Table 3: Essential new MAC layer features

Feature	Benefit
Dynamic bandwidth expansion (DBE)	Allows AP to operate with an expanded operating bandwidth that is greater than its BSS operating bandwidth up to the AP's maximum supported bandwidth for DBE
Dynamic/periodic unavailability (DUO/PUO)	Allows STA to indicate unavailability to the AP to improve in-device coexistence
Dynamic power save (DPS)	Possibility to operate with lower capabilities to reduce power consumption when listening on the link
Dynamic subband operation (DSO)	Allows AP with a wider bandwidth than its associated STA to dynamically allocate frequency resources to the STA, extending beyond the STA's current operating bandwidth while remaining within the AP's BSS
Low-latency indication (LLI)	Enables a TXOP responder to inform the TXOP holder regarding its low-latency needs
Multi-link power management	Optimized power management signaling in multi-link operation (MLO)
Non-primary channel access (NPCA)	A mechanism to dynamically switch from a busy primary channel to an alternative primary channel
Prioritized EDCA (P-EDCA)	Improves ability for STAs with high priority traffic to access the channel
Adaptive operation mode (AOM)	STA can request to limit transmission parameters (MCS, N_{SS}, bandwidth (BW), punctured subchannels, etc.) to handle in-device interference issues

Table 4: Advanced MAC layer features with AP interaction

Feature	Benefit
Peer-to-peer (P2P) communications	Enables an AP to share a TXOP with multiple P2P non-AP STAs
Seamless mobility domain (SMD)	Seamless transition from current AP MLO device (MLD) to a target AP MLD without requiring reassociation
Multi-AP coordination (MAPC)	MAPC allows APs to coordinate transmission to associated STAs to optimize overall KPI such as latency, reliability or throughput. Supported schemes are coordinated beamforming (Co-BF), coordinated spatial reuse (Co-SR), coordinated TDMA (Co-TDMA), coordinated restricted target wait time (Co-RTWT) or coordinated channel recommendation (Co-CR)

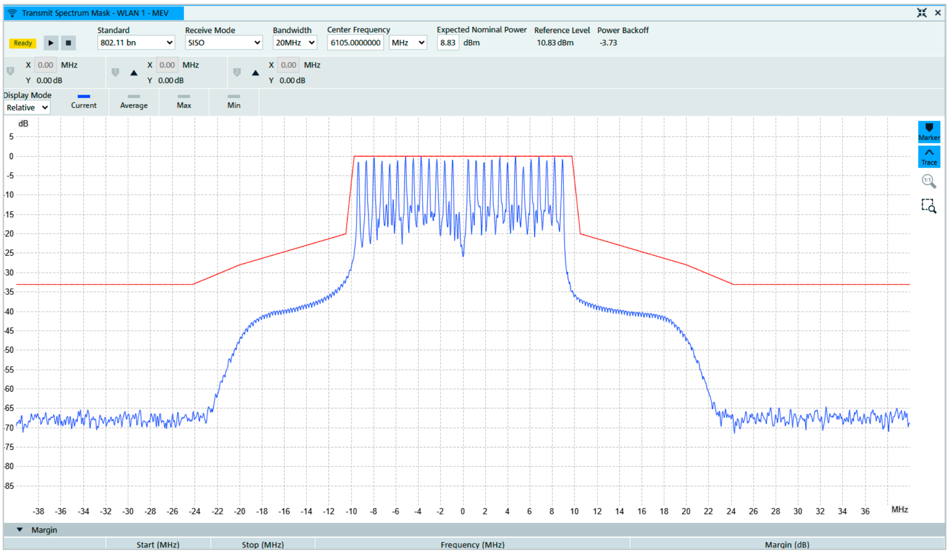
3 PHY FEATURES

In the physical layer, three principal enhancements are specified. Two of them, i.e. distributed-tone resource units (DRU) and enhanced long range (ELR) PPDU, primarily aim to improve the transmission power and reliability of device uplink transmissions. The third, i.e. modulation and coding enhancements, includes adding new MCS levels to close some SNR gaps and adding unequal modulation (UEQM) to improve beamforming (BF) performance.

3.1 Distributed-tone resource units (DRU)

Distributed-tone resource unit (DRU) is a clever physical layer enhancement in IEEE 802.11bn to overcome power spectral density (PSD) limitations in the uplink. PSD limits, defined per MHz, can be quite low for STAs. This limits the total power the STA can transmit even if the STA could easily meet the total transmit requirement. In the regular resource unit (RRU) defined in IEEE 802.11ax [4] as resource unit (RU), users are allocated a resource unit with adjacent tones separated by 78.125 kHz so that about 13 tones are transmitted per MHz. To meet the PSD limits, the tones need to be transmitted at relatively low power. DRUs solve this problem by distributing tones over a wider bandwidth (called the distribution bandwidth (DBW)). The tones for each STA become non-contiguous, and the STA transmits fewer tones per MHz so that each tone can be transmitted at higher power.

Figure 2: Wi-Fi 8 DRU measurements on the CMP180



Transmit Spectrum Mask - WLAN 1 - MEV

Ready

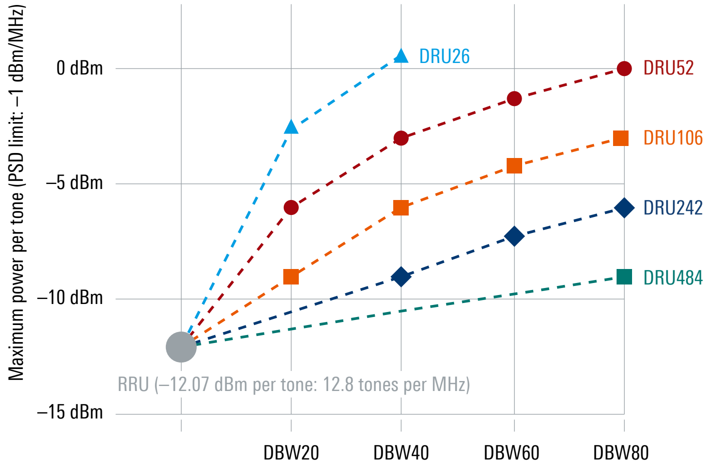
Standard: 802.11 bn
Receive Mode: SISO
Bandwidth: 20MHz
Center Frequency: 6105.0000000 MHz
Expected Nominal Power: 8.83 dBm
Reference Level: 10.83 dBm
Power Backoff: -3.73

X 0.00 MHz Y 0.00 dB
X 0.00 MHz Y 0.00 dB
X 0.00 MHz Y 0.00 dB

Display Mode: Relative

DRU will be particularly useful for low power indoor (LPI) devices operating in the 6 GHz band where PSD regulatory limits are quite strict (e.g. FCC LPI client: –1 dBm/MHz). Figure 3 shows the example calculation for an FCC LPI client and the potential spreading gain as a function of the DBW. The increased transmitting power will improve coverage range and allow for higher data rate at longer distances.

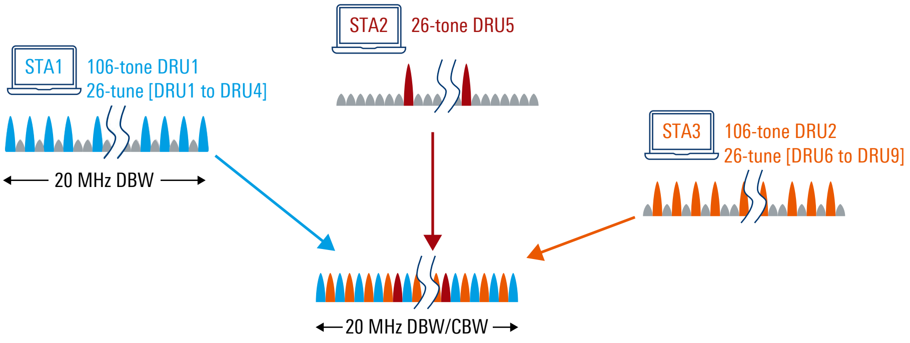
Figure 3: Maximum transmit power per single tone for different DBW and DRU spreading gain



DRU spreading gain				
	DBW20	**DBW40**	**DBW60**	**DBW80**
DRU26	9 dB	12 dB	–	–
DRU52	6 dB	9 dB	12 dB	12 dB
DRU106	3 dB	6 dB	9 dB	9 dB
DRU242	–	3 dB	6 dB	6 dB
DRU484	–	–	–	3 dB

To ensure spectral efficiency, DRUs will only be used in UL OFDMA transmissions where several users are triggered to transmit their PPDU at the same time. Figure 4 shows an example of an UL OFDMA transmission with three STAs transmitting DRUs in a 20 MHz DBW. In addition, DRU transmission is not permitted with more than two spatial streams. Furthermore, UL MU MIMO will not use DRU because it increases complexity and did not show significant performance gain in simulations. In addition, DRUs are not allowed for AP DL transmissions because the PSD limits for AP DL transmissions are less strict and typically the majority of tones will be used anyway in DL transmission.

Figure 4: Example UL OFDMA transmission with two 106-tone DRU and one 26-tone DRU in a 20 MHz DBW



3.1.1 DRU tone plan

While the DRU provides a clever way to improve uplink communications, it may not be used in all situations and needs to work with the RRU. For this reason, as well as limiting the changes needed at the PHY layer, the DRU will reuse many of the same concepts that were defined in legacy PHY. For example, the DRU tone plan will follow the hierarchical structure where larger RUs consist of smaller size RU tones. The number of tones in an RU is also the same as in legacy PHY, e.g. RU26 and RU52 have 26 and 52 tones, respectively. This structure makes RU assignment and scheduling simpler. Table 5 shows the data subcarrier range and pilot subcarrier indices for the DRUs in a 20 MHz distribution bandwidth (see the IEEE 802.11bn amendment [1] for DRU index, data subcarrier and pilot subcarrier indices for the 40 MHz, 60 MHz and 80 MHz distribution bandwidths).

Table 5: 20 MHz DRU index, subcarrier range and pilot subcarrier indices in '{}'

	20 MHz DRU index, subcarrier range and pilot subcarrier indices in '{}'								
26-tone	DRU1, –120:9:–12, 6:9:114 {–111, 15}	DRU2, –116:9:–8, 10:9:118 {–89, 37}	DRU3, –118:9:–10, 8:9:116 {–100,26}	DRU4, –114:9:–6, 12:9:120 {–78, 48}	DRU5, –112:9:–4, 5:9:113 {–67, 59}	DRU6, –119:9:–11, 7:9:115 {–56, 70}	DRU7, –115:9:–7, 11:9:119 {–34, 92}	DRU8, –117:9:–9, 9:9:117 {–45, 81}	DRU9, –113:9:–5, 4:9:112 {–23,103}
52-tone	DRU1, 26-tone [DRU1, DRU2] {–111, –89, 15, 37}		DRU2, 26-tone [DRU3, DRU4] {–100, –78, 26, 48}			DRU3, 26-tone [DRU6, DRU7] {–56, –34, 70, 92}		DRU4, 26-tone [DRU8, DRU9] {–45, –23, 81, 103}	
106-tone	DRU1, 26-tone [DRU1, DRU2, DRU3, DRU4] {–111, –78, 15, 48}					DRU2, 26-tone [DRU6, DRU7, DRU8, DRU9] {–56, –23, 70, 103}			

3.1.2 Transmission of DRU: DBW modes

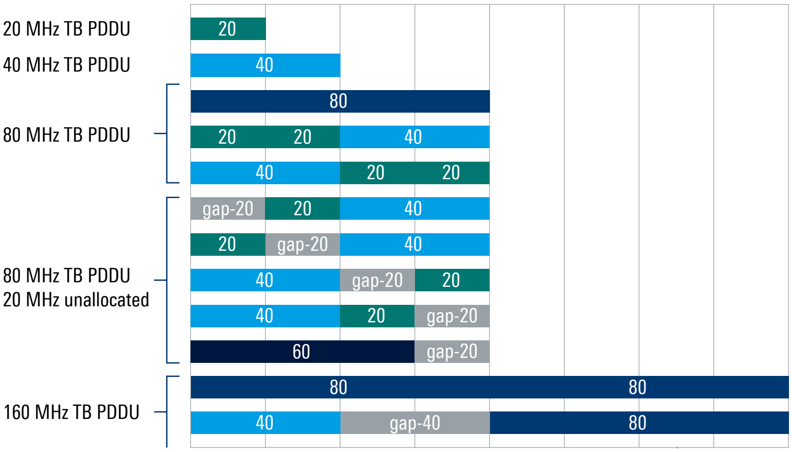
DBW modes are defined for DRU transmission in different PDDU sizes (i.e. 20 MHz, 40 MHz, 80 MHz, 160 MHz and 320 MHz PPDU bandwidths) to maximize the power boost of each DRU while also specifying restrictions to reduce transmission complexity.

Figure 5 shows the permitted DBW modes for the various PPDU sizes. For 20 MHz and 40 MHz PPDUs, the DBW can only be 20 MHz and 40 MHz, respectively. For an 80 MHz PPDU with all subchannels allocated, three DBW modes are possible: DBW20-DBW20-DBW40 or DBW40-DBW20-DBW20 or DBW80. If one of the 20 MHz subchannels in the 80 MHz PPDU is not allocated, five DBW modes are possible as shown on Figure 5. The 80 MHz subblock in a 160 MHz or 320 MHz TB PPDU uses the permitted configurations for the 80 MHz TB PPDU with two notes:

- The DBW20-DBW20-DBW40 and DBW40-DBW20-DBW20 modes are only allowed in the primary 80 MHz channel
- In case of two unallocated 20 MHz channels in an 80 MHz subblock of a 160 MHz or 320 MHz TB PPDU, the gap40-DBW40 or DBW40-gap40 modes are also possible

For 160 MHz and 320 MHz PPDU bandwidths, a hybrid mode is defined where DRU and RRU may both be used. In this case each 80 MHz subblock will use either RRU or DRU, i.e. DRU and RRU cannot both be used in the same 80 MHz subblock. In addition, the minimum RRU size is 242 in the hybrid mode. The hybrid mode provides a way to efficiently use the available bandwidth to leverage the benefits of DRUs or to accommodate RRUs depending on the requirements within different 80 MHz subblocks.

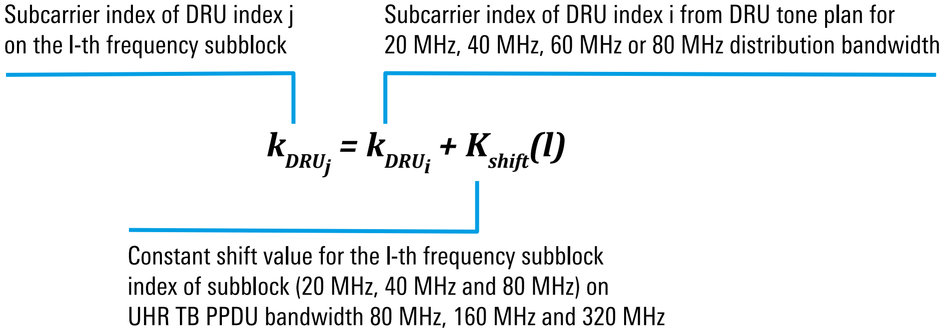
Figure 5: DBW modes for the 20 MHz TB PPDU, 40 MHz TB PPDU, 80 MHz TB PPDU and 160 MHz TB PPDU



3.1.3 DRU tone plan for DRUs transmitted in a wider bandwidth PPDU

The DRU tone plans are defined based on the DRU being distributed over a given DBW, e.g. the 20 MHz subcarrier and pilot indices (see Table 5) are defined assuming the DRU is transmitted in a 20 MHz PPDU. However, as illustrated in the transmission of DRU: DBW modes section, the 20 MHz DRU, e.g. can be transmitted as part of a wider PPDU bandwidth, e.g. 80 MHz. To determine the DRU subcarrier indices, k_{DRU_j}, in these cases, IEEE 802.11bn provides a straightforward formula as shown in Figure 6.

Figure 6: DRU index calculation for DRUs with channel bandwidth wider than 80 MHz



Subcarrier index of DRU index j on the l-th frequency subblock

Subcarrier index of DRU index i from DRU tone plan for 20 MHz, 40 MHz, 60 MHz or 80 MHz distribution bandwidth

$$k_{DRU_j} = k_{DRU_i} + K_{shift}(l)$$

Constant shift value for the l-th frequency subblock index of subblock (20 MHz, 40 MHz and 80 MHz) on UHR TB PPDU bandwidth 80 MHz, 160 MHz and 320 MHz

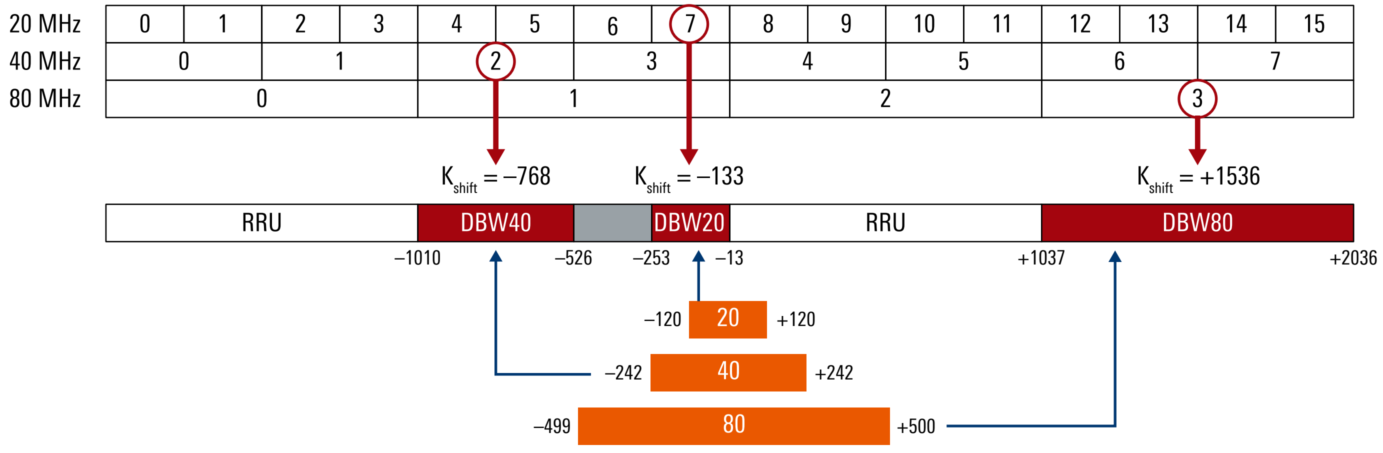
The constant shift, $K_{shift}(l)$, is given in the IEEE 802.11bn amendment and depends on the DBW and the channel bandwidth as shown in Table 6.

Table 6: Constant shift value K_{shift} for DRU on a frequency subblock of channel bandwidth of 80 MHz, 160 MHz and 320 MHz

Subblock size	CBW80		CBW160		CBW320	
	Subblock (l)	K_{shift}	Subblock (l)	K_{shift}	Subblock (l)	K_{shift}
20 MHz (DBW20)					0	–1916
					1	–1669
					2	–1404
					3	–1157
			0	–892	4	–892
			1	–645	5	–645
	0	–380	2	–380	6	–380
	1	–133	3	–133	7	–133
	2	+132	4	+132	8	+132
	3	+379	5	+379	9	+379
			6	+644	10	+644
			7	+891	11	+891
					12	+1156
					13	+1403
					14	+1668
					15	+1915
40 MHz (DBW40)					0	–1792
					1	–1280
			0	–768	2	–768
	0	–256	1	–256	3	–256
	1	+256	2	+256	4	+256
			3	+768	5	+768
					6	+1280
					7	+ 1792
80 MHz (for DBW80 and DBW60)					0	–1536
			0	–512	1	–512
			1	+512	2	+512
					3	+1536

Figure 7 shows an example for a 320 MHz PPDU in hybrid mode with three parts supporting DRUs in DBW 20 MHz, 40 MHz and 80 MHz.

Figure 7: Example for DRUs on a frequency subblock of 20 MHz, 40 MHz and 80 MHz in channel bandwidth of 320 MHz

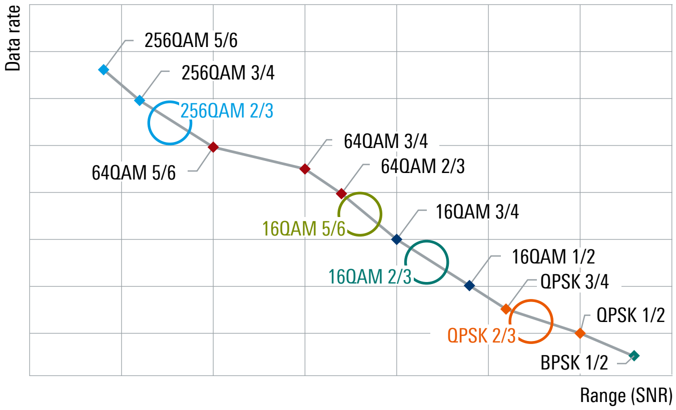


3.2 New modulation and coding schemes used for unequal modulation

3.2.1 IEEE 802.11bn modulation and coding schemes (MCS)

Legacy IEEE 802.11 standards support seven modulations and four code rates, but not all combinations are used. In some cases, the SNR sensitivity gap between legacy MCS levels can be more than 3 dB. This leads to less accurate rate adaptation and poor spectral efficiency. Therefore, four new MCS are introduced to fill in some of the SNR sensitivity gaps, improve link adaptation accuracy and improve throughput performance. The new modulation and coding schemes are QPSK 2/3, 16QAM 2/3, 256QAM 2/3 and 16QAM 5/6. Figure 8 illustrates how the new MCS levels provide finer tuning for the data rate versus the range.

Figure 8: IEEE 802.11bn rate vs. range



In the past the IEEE 802.11 PHY amendments introduced higher order MCS and the MCS index was increased. The new IEEE 802.11bn MCS fall between existing MCS. IEEE 802.11be had 16 MCS levels and changing the MCS index numbers to accommodate the new MCS could lead to increased specification work and potential backwards compatibility issues. Therefore, the new MCS are given index 17, 19, 20 and 23 but are inserted in the MCS table based on the effective MCS level. For signaling, a 5th bit is added to the four bits that signal the legacy MCS level. If the MSB bit 5 is 0, then the 4-bit MCS value is the same as in legacy. If the MSB bit 5 is 1, then it is a new IEEE 802.11bn MCS level, and the four bits refer to the previous MCS rate. Table 7 provides the IEEE 802.11bn MCS with the new MCS rates shown in color and the 5-bit MCS signaling information shown in square brackets.

Table 7: IEEE 802.11bn modulation and coding schemes

Modulation	Coding rate			
	1/2	2/3	3/4	5/6
BPSK	MCS0: [00000]			
QPSK	MCS1: [00001]	MCS17: [10001]	MCS2: [00010]	
16QAM	MCS3: [00011]	MCS19: [10011]	MCS4: [00100]	MCS20: [10100]
64QAM		MCS5: [00101]	MCS6: [00110]	MCS7: [00111]
256QAM		MCS23: [10111]	MCS8: [01000]	MCS9: [01001]
1024QAM			MCS10: [01010]	MCS11: [01011]
4096QAM			MCS12: [01100]	MCS13 [01101]

3.2.2 Unequal modulation (UEQM)

UEQM is used to improve beamforming performance by adapting the modulation scheme used on each spatial stream based on its channel quality. UEQM was first introduced in IEEE 802.11n. However, at the time beamforming was not adopted in most implementations due to hardware complexity. Now, though, beamforming technology has matured and is used in modern communications systems including IEEE 802.11. Therefore, IEEE 802.11bn reintroduces UEQM to further enhance IEEE 802.11 beamforming.

To keep signaling overhead and implementation complexity low, IEEE 802.11bn has defined a limited set of UEQM combinations. Despite the limited set, the combinations provide the needed flexibility for beamformed transmissions. Table 8 shows the possible combinations which depend on the number of spatial streams and a UEQM pattern. The S in the table represents the constellation index (i.e. the QAM level). S-1 is the constellation order that is one order lower than S, and S-2 is the constellation order that is two orders lower than S. It should be noted that the coding rate is not mentioned because while the modulation is different for each stream, the coding rate used is the same for all streams; this also simplifies UEQM implementation. Because UEQM is used to improve beamforming performance, it is only used for non-MU-MIMO beamformed transmissions.

Table 8: IEEE 802.11bn supported UEQM combinations

N_{ss}	UEQM pattern	1st stream	2nd stream	3rd stream	4th stream
2	0	S	S-1	–	–
	1	S	S-2	–	–
3	0	S	S	S-1	–
	1	S	S	S-2	–
	2	S	S-1	S-2	–
4	0	S	S	S	S-1
	1	S	S	S	S-2
	2	S	S	S-1	S-2
	3	S	S-1	S-1	S-2

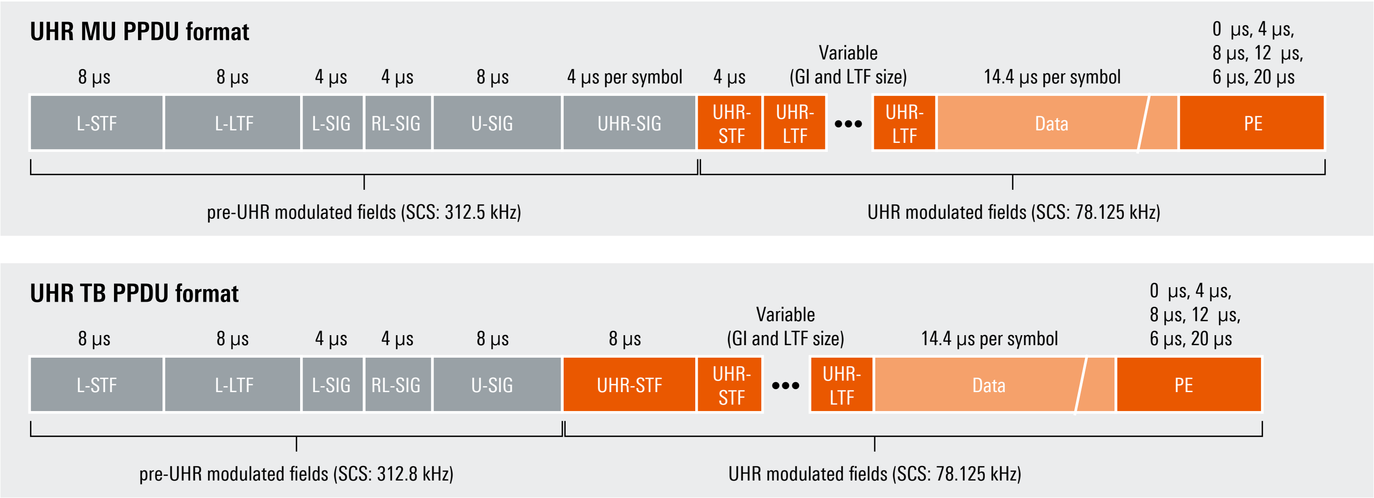
S	Modulation
1	QPSK
2	16QAM
3	64QAM
4	256QAM
5	1024QAM
6	4096QAM

3.3 UHR PPDU formats

The IEEE 802.11bn physical layer signaling design is being developed with a strong focus on incorporating new features while maintaining compatibility with legacy IEEE 802.11 devices. Similar to IEEE 802.11be, IEEE 802.11bn defines an MU PPDU format and a TB PPDU format. The UHR MU PPDU is used for transmission to one or more users, and the UHR TB PPDU is used for a transmission that is a response to a triggering frame. IEEE 802.11bn also introduces a new PPDU type, i.e. the enhanced long range (ELR) PPDU, to improve communications at longer ranges especially in the uplink. More information about ELR can be found in Section 3.4.

Figure 9 shows the UHR MU PPDU and UHR TB PPDU formats, respectively.

Figure 9: UHR MU PPDU and UHR TB PDDU formats



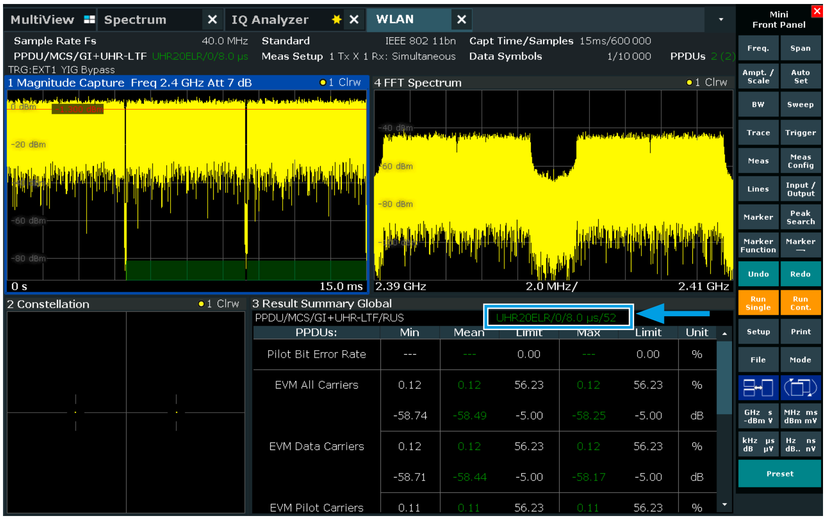
L-STF: non-HT short training field | L-LTF: non-HT long training field | L-SIG: non-HT signal field | RL-SIG: repeated non-HT signal field | U-SIG: universal signal field | UHR-SIG: UHR signal field | UHR-STF: UHR short training field | UHR-LTF: UHR long training field | Data: field carrying the PSDU(s) | PE: packet extension field

The legacy fields in the preamble are the L-STF, L-LTF, L-SIG, RL-SIG and U-SIG. The U-SIG was introduced in IEEE 802.11be to support forward compatibility, and IEEE 802.11bn makes minor changes to the U-SIG to support IEEE 802.11bn changes. For example, the PHY version identifier in the U-SIG is 0 for IEEE 802.11be and 1 for IEEE 802.11bn. Another example is using some of the bits that are reserved in the EHT U-SIG1 to provide the BSS color for the second AP when UHR multi-AP coordination is being used (see section 5.1); otherwise, that field is also reserved in UHR. The UHR-SIG field is similar to the EHT-SIG field. It contains information common to all users and user specific fields that contain resource allocation information for each STA. (See Rohde & Schwarz white paper [5] for more information on IEEE 802.11be and the U-SIG content.)

3.4 Enhanced long range (ELR) PPDU

Enhanced long range (ELR), as the name implies, is intended to extend the range and improve reliability of Wi-Fi transmissions. In the 2.4 GHz band, ELR may be used for uplink and downlink transmissions where, in addition to providing longer range for transmissions, it is expected to provide higher efficiency (e.g. improved coding, signaling, security methods) than legacy IEEE 802.11 used in this band. In the 5 GHz and 6 GHz bands, ELR is expected to overcome link budget imbalances that are common at a longer range or in challenging RF environments. This is because, as hinted in the DRU section, the STA transmit power can be significantly lower than the AP's. At longer ranges, the STA can hear the AP, but the AP cannot hear the STA. Because the intention is to improve this link budget imbalance, ELR is allowed only in the uplink in the 5 GHz and 6 GHz bands. Since the motivation for using ELR is longer range and not higher throughput, ELR is restricted to a 20 MHz bandwidth, a single spatial stream and two modulation and coding schemes, BPSK 1/2 or QPSK 1/2. This results in a data rate of 1.67 Mbit/s for BPSK 1/2 and 3.33 Mbit/s for QPSK 1/2.

Figure 10: UHR ELR PPDU measurements on the FSW signal and spectrum analyzer



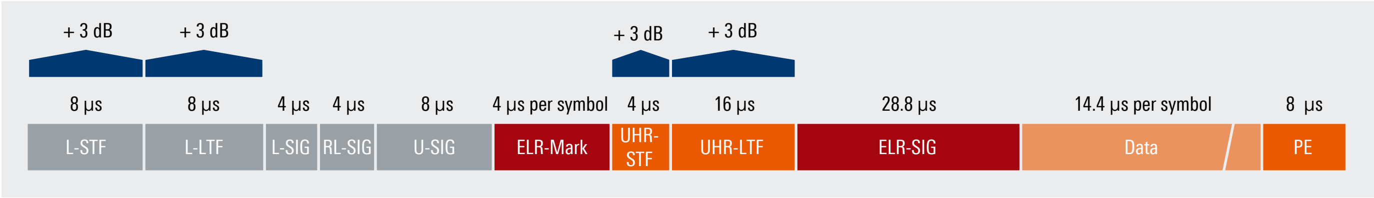
Sample Rate Fs 40.0 MHz
Standard IEEE 802 11bn
Capt Time/Samples 15ms/600 000
PPDU/MCS/GI+UHR-LTF UHR20ELR/0/8.0 µs
Meas Setup 1 Tx X 1 Rx: Simultaneous
Data Symbols 1/10 000
PPDUs 2 (2)
TRG:EXT1 YIG Bypass

3 Result Summary Global
PPDU/MCS/GI+UHR-LTF/RUS UHR20ELR/0/8.0 µs/52

PPDUs:	Min	Mean	Limit	Max	Limit	Unit
Pilot Bit Error Rate	---	---	0.00	---	0.00	%
EVM All Carriers	0.12	0.12	56.23	0.12	56.23	%
	-58.74	-58.49	-5.00	-58.25	-5.00	dB
EVM Data Carriers	0.12	0.12	56.23	0.12	56.23	%
	-58.71	-58.44	-5.00	-58.17	-5.00	dB
EVM Pilot Carriers	0.11	0.11	56.23	0.11	56.23	%

The ELR PPDU is similar to other UHR PPDU but has several differences to distinguish it from the MU or TB PPDU and to improve its reception at the receiver. Figure 11 shows the fields that make up the ELR PPDU. The fields in gray are legacy portions of the PPDU, the orange fields are UHR portions of the PPDU, and the red fields are fields used uniquely for ELR. Note that several fields are power boosted by 3 dB: the L-STF, L-LTF, UHR-STF and UHR-LTF. In the U-SIG field, the PHY version identifier (set to 1 for UHR) and the PPDU type and compression mode (set to binary 11) are used to indicate that the PPDU is for ELR. The ELR-SIG carries an ELR version identifier to allow for forward compatibility with future ELR enhancements. It also contains other information about the ELR PPDU such as MCS, coding and number of data symbols. The ELR-Mark field contains predefined tone patterns for cross-correlation to enable coherent combining at the receiver. The sequence used in the ELR-Mark symbols provides the BSS color so that the receiver can determine if the packet is from its BSS or from an OBSS.

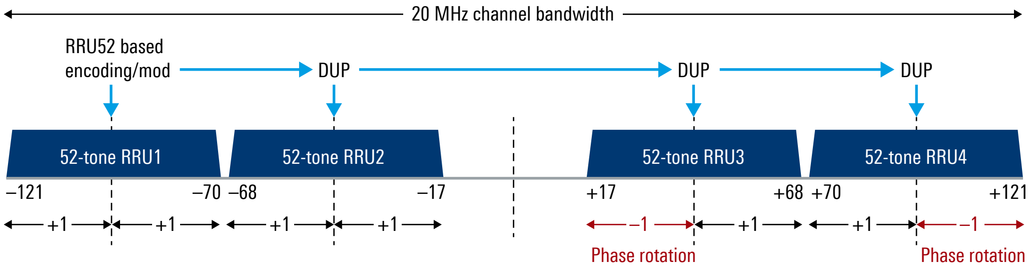
Figure 11: ELR PPDU format



L-STF: non-HT short training field | L-LTF: non-HT long training field | L-SIG: non-HT signal field | RL-SIG: repeated non-HT signal field | U-SIG: universal signal field | ELR-MARK: ELR mark field | UHR-STF: UHR short training field | UHR-LTF: UHR long training field | ELR-SIG: ELR signal field | Data: field carrying the PSDU(s) | PE: packet extension field

To achieve the range and reliability target, an ELR transmission in the frequency domain is made of four 52-tone RRUs (sent in a 20 MHz channel). The data transmitted in the first 52-tone RRU is repeated in the subsequent three 52-tone RRUs. This data duplication (DUP) within the 20 MHz bandwidth increases the reliability and range of the transmission. A drawback of this duplication is the higher resulting peak-to-average power ratio (PAPR). To reduce the PAPR, a phase rotation of –1 is applied to the first 24 data subcarriers of RRU3 and to the last 24 data subcarriers of RRU4 (see Figure 12).

Figure 12: ELR frequency domain duplication

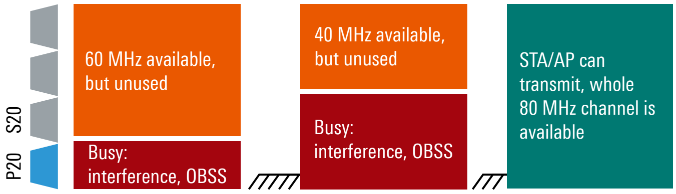


4 MAC ESSENTIALS

4.1 Non-primary channel access (NPCA)

In legacy IEEE 802.11 operation, a primary 20 MHz channel is used to determine if the basic service set (BSS) operating channel is available. If the primary channel is busy, a STA cannot transmit. The concept of the primary 20 MHz channel was introduced in IEEE 802.11a when only 20 MHz channels were used. Over time, IEEE 802.11 has introduced wider channels: 40 MHz, 80 MHz, 160 MHz and 320 MHz. However, the channel access rules have not changed; if the primary 20 MHz channel is busy, no transmissions are possible even if other/secondary 20 MHz channels are available. For example, if the primary 20 MHz channel of an 80 MHz BSS operating channel is busy but the other 20 MHz channels are available, 60 MHz of spectrum is unused. Figure 13 illustrates this inefficiency at a high level.

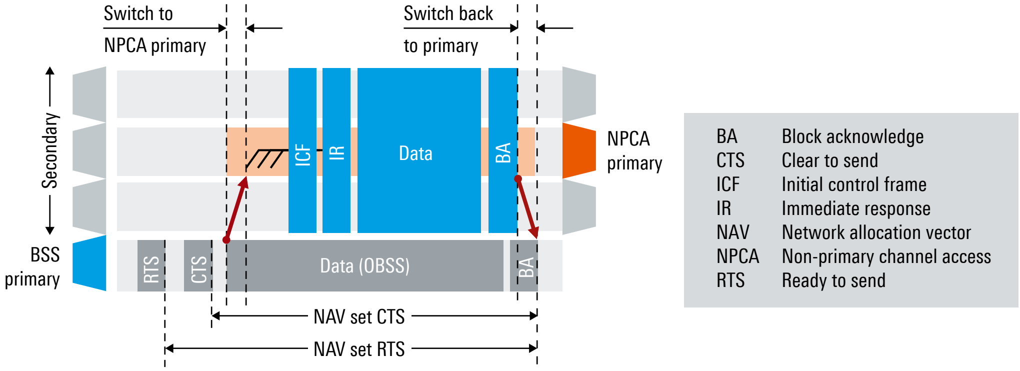
Figure 13: Channel access in case of busy primary or secondary channels without IEEE 802.11bn NPCA



To improve spectrum efficiency, mitigate congestion and increase network capacity, IEEE 802.11bn introduces the possibility to use a non-primary 20 MHz channel for channel access and transmission in an 80 MHz (or larger) PPDU when the primary 20 MHz channel is busy.

An AP announces its support for NPCA, the non-primary channel 20 MHz channel and other relevant information (such as channel switch time). Likewise, a STA will indicate its support for NPCA, the time it will take it to switch to the non-primary channel, and the time it will take to switch back to the primary channel. If the primary channel is busy and certain conditions are met such as receiving specific PPDU or control frames, the AP and STA can switch to the non-primary channel to initiate transmissions. It is still necessary to follow enhanced distributed channel access (EDCA) backoff procedures and TXOP initiation on the non-primary channel before transmitting data. In addition, the TXOP obtained on the non-primary channel should end before the network allocation vector (NAV) timer on the primary channel expires. An example of transmissions using NPCA is shown in Figure 14.

Figure 14: Switching to the NPCA primary channel after a control frame exchange of an OBSS is detected on the primary channel



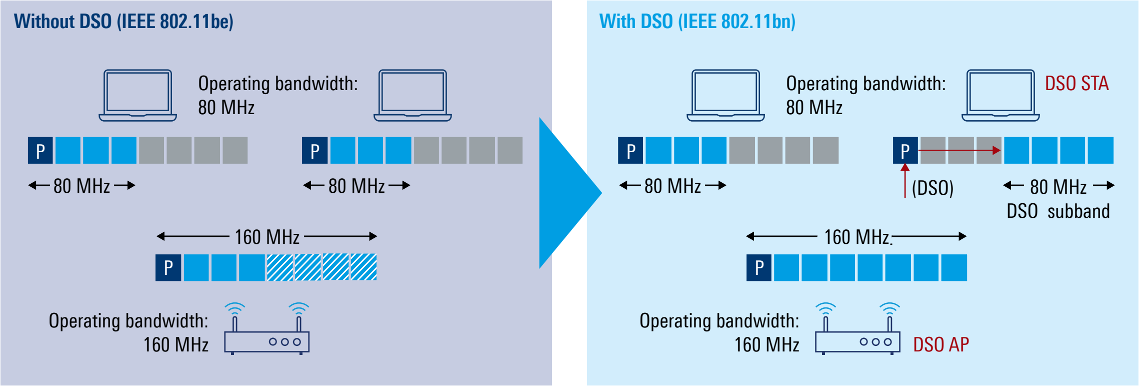
BA	Block acknowledge
CTS	Clear to send
ICF	Initial control frame
IR	Immediate response
NAV	Network allocation vector
NPCA	Non-primary channel access
RTS	Ready to send

4.2 Dynamic subband operation (DSO)

DSO is an IEEE 802.11bn feature designed to use spectrum more efficiently and flexibly. It addresses the common occurrence where the STA's operating bandwidth is narrower than the AP BSS bandwidth. If the AP and STA support DSO, an AP can dynamically allocate frequency resources to a STA that is outside the STA's current operating BW (but within the AP's BSS bandwidth).

The channel that includes the BSS primary channel with bandwidth equaling the STA's operating bandwidth is called the primary subband. The channel with bandwidth equal to the STA's operating bandwidth located outside the primary subband but within the BSS bandwidth is called the DSO subband. Figure 15 illustrates DSO operation and compares it to legacy (11be) operation without DSO. Note that without DSO, 80 MHz of the AP's spectrum is not used. However, with DSO the AP's full 160 MHz channel can be utilized.

Figure 15: Operation without DSO compared to IEEE 802.11bn operation with DSO



4.3 In-device coexistence

Many modern devices integrate multiple wireless technologies (e.g. Wi-Fi, Bluetooth®, UWB). For example, a user may use Wi-Fi for data connection on a smartphone or a tablet while using Bluetooth® to connect to a wireless headset. This can lead to in-device coexistence issues where use of one technology interferes with the other. The result is poor user experience and inefficient use of the wireless medium. For example, if an AP transmits a packet to a STA while the STA is exchanging transmissions with its Bluetooth® headset, the STA likely will not receive the packet from the AP. When the AP does not receive an ACK from the STA, it will assume the network conditions have deteriorated and will resend at a lower data rate.

IEEE 802.11bn introduces coexistence mechanisms that will enable Wi-Fi devices to communicate their unavailability to optimize scheduling and avoid collisions. Two primary modes of unavailability are specified: dynamic unavailability operation (DUO) and periodic unavailability operation (PUO). DUO is used when the STA needs to report impending short term unavailability to the AP. PUO is used when the STA informs its associated AP about recurring periods of unavailability. The AP may also use PUO to communicate periodic unavailability to its associated STAs.

4.4 Priority channel access for low-latency traffic

Existing enhanced distributed channel access (EDCA) delivers traffic based on differentiating user priorities (UP) and access priorities (AC). This differentiation is achieved by varying:

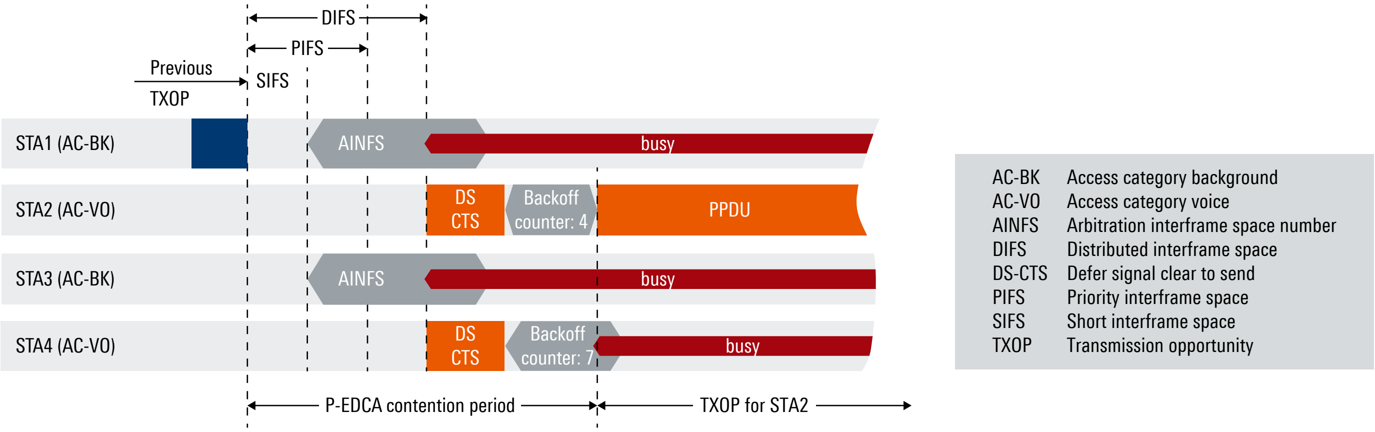
- Amount of time a STA senses the channel to be idle before backoff or transmission, or
- The length of the contention window to be used for the backoff, or
- The duration a STA transmits after it acquires the channel.

However, this mechanism cannot consistently guarantee low latency for time sensitive applications, especially as the number of STAs in a network increases.

Priority EDCA (P-EDCA) is introduced in IEEE 802.11bn to provide a mechanism for a device to access the medium earlier when it has high-priority, low-latency traffic to transmit. In IEEE 802.11 this type of traffic is given an access category of voice (AC_VO). When an AP has enabled P-EDCA, a device that supports P-EDCA may make use of this capability if it has buffered low-latency traffic and is experiencing contention failure. If this is the case, the device will send a "defer signal", which is a clear to send (CTS) frame (also called DS-CTS when used for P-EDCA). Other STAs will hear the DS and know that they cannot send their packets. This allows the device with high priority traffic to transmit its packet.

If more than one P-EDCA capable device needs to transmit a high priority packet, then those devices can contend for the medium. This is illustrated in Figure 16 where both STA2 and STA4 have AC-VO categorized data and requested deferred access to the medium by transmitting DS-CTS. STA2 wins the TXOP because its backoff counter was less than STA4's. Note that they only had to contend with each other for the medium and did not need to also contend with other STAs.

Figure 16: Example for P-EDCA used by STA2 and STA4



4.5 Power management

For many use cases, Wi-Fi devices spend a significant amount of time in listen mode. In legacy IEEE 802.11, the device listens over its full bandwidth and across all links. This consumes a significant amount of power and leads to shorter battery time between charges. Additionally, in some cases a STA does not need to use its full capabilities for frame exchanges.

Dynamic power save (DPS) will allow non-AP STAs and mobile APs to transition between a low capability mode for power saving and a high capability mode for full operation. DPS will significantly reduce power consumption in UHR devices because they can stay in the low capability mode until a higher performance mode is needed.

In low capability mode, a STA may use the default capabilities: 20 MHz, 1 SS, and 6 Mbit/s, 12 Mbit/s and 24 Mbit/s data rates. For flexibility, it is also possible for a STA to choose a low capability mode that is different than the default low capability mode. For example, it may choose to use two streams instead of one while in its low power listening state. In high capability mode, the STA will use a higher BW, more spatial streams and/or higher data rate than its low capability mode.

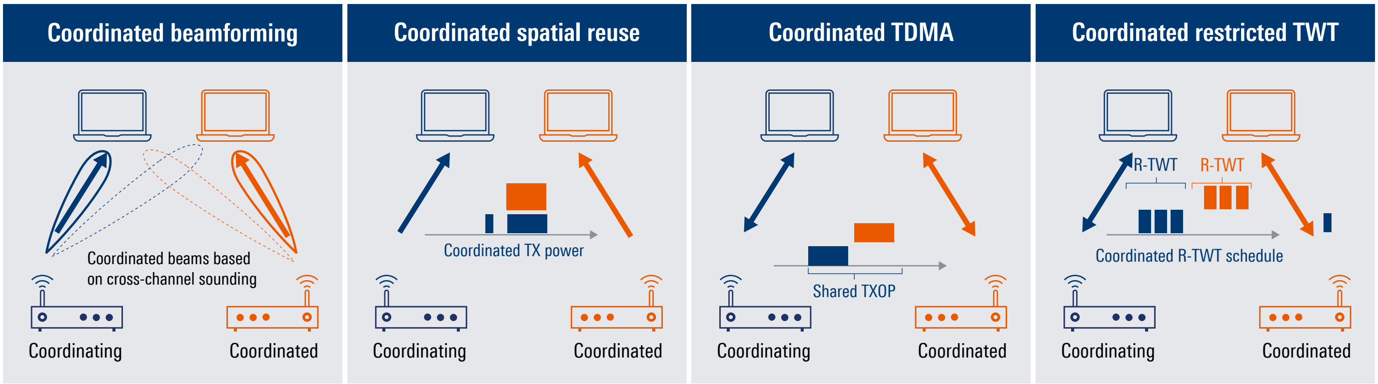
IEEE 802.11bn also adds multi-link power management (MLPM) enabling a multi-link device (MLD) to manage the power mode of its affiliated STAs across its different links so that a signaling frame sent on one link can indicate the power mode of its affiliated STAs on all links. MLPM enables a centralized and efficient way to control the STA power states.

5 ADVANCED MAC FEATURES

5.1 Multi-AP coordination (MAPC) framework

Multi-AP coordination (MAPC) is one of the new advanced features introduced in IEEE 802.11bn. In legacy IEEE 802.11, APs did little or no coordination with other APs. Depending on the scenario, this lack of coordination led to unfair use of the medium, long latency, and/or low throughput. The MAPC capabilities in IEEE 802.11bn will allow APs operating their BSSs on the same primary 20 MHz channel to coordinate/share resources to improve the overall network performance for both APs.

Figure 17: High-level view of MAPC schemes

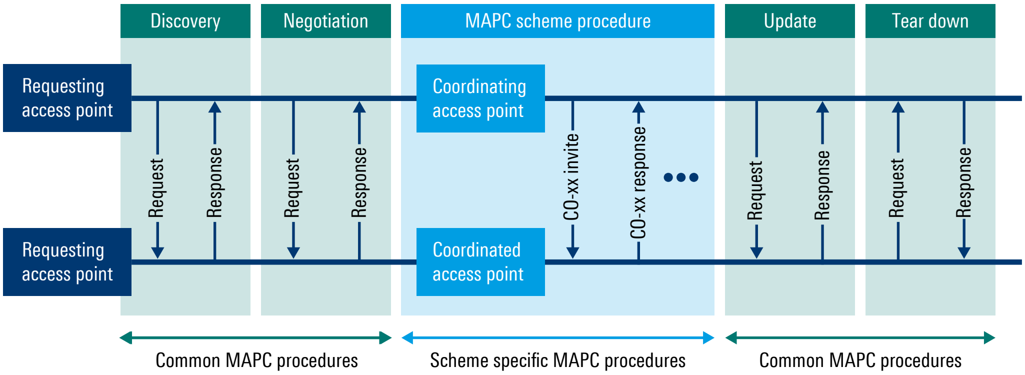


Several MAPC schemes are introduced to meet the challenges of different deployment types and scenarios. An AP may support multiple schemes:

- Coordinated beamforming (Co-BF)
- Coordinated spatial reuse (Co-SR)
- Coordinated time division multiple access (Co-TDMA)
- Coordinated restricted target wake time (Co-RTWT)

A common framework is used that can accommodate all the coordination schemes as illustrated in Figure 18. During the discovery procedure, an AP advertises its MAPC capabilities using a MAPC discovery request. An AP interested in participating in a coordination scheme with the requesting AP will respond with a MAPC discovery response. The APs will then negotiate per scheme parameters using MAPC negotiation frames. An AP can request to tear down an existing agreement at any time.

Figure 18: IEEE 802.11bn common multi-AP coordination framework



The next few subsections will describe each of the MAP schemes.

5.1.1 Coordinated beamforming (Co-BF)

Coordinated beamforming is a MAPC technique where two APs can coordinate transmissions to their respective STAs by acquiring the channel state information (CSI) from STAs associated with the other AP. This information can be used by each AP to beamform transmissions to their associated STAs while minimizing the interference to the STAs associated with the other AP (nulling). Co-BF provides a method to utilize the medium more efficiently. In IEEE 802.11bn, Co-BF is limited to coordination between two APs and used only in non-OFDMA MU MIMO transmissions with a maximum of two spatial streams.

Co-BF relies on accurate CSI. IEEE 802.11 uses null data packets (NDP) to sound channels and acquire the channel state information. IEEE 802.11bn Co-BF will reuse much of the EHT sounding principles, e.g. the EHT compressed beamforming/CQI report and sounding segmentation. In addition, the EHT TB PPDU is used to carry the Co-BF sounding feedback. A key difference, of course, is that sounding will now be performed for STAs associated with two APs. IEEE 802.11bn defines two types of sounding technique: sequential sounding and joint sounding.

5.1.2 Coordinated spatial reuse (Co-SR)

Operating in shared spectrum requires devices to perform medium sensing before transmission. When a device cannot reliably distinguish whether the medium is busy from its own BSS or from another, carrier spectrum use becomes inefficient. IEEE 802.11ax introduced "BSS color" to differentiate: If the signal comes from a different BSS color, then the threshold it uses to determine if it can transmit is lower than if it comes from the same BSS color. While BSS color was a step in the right direction, they do not require APs to consider the actual interference their transmissions will cause to the OBSS. This led to suboptimal performance and potentially unfair sharing of the channel from one AP. Co-SR in IEEE 802.11bn addresses this shortcoming by enabling APs to exchange transmit power and spatial reuse parameters. With this coordination, the APs can then use transmit power control to transmit simultaneously on the same channel without causing unnecessary interference to the other AP. The Co-SR transmission is initiated via a triggering frame by an AP that obtains a transmit opportunity (TXOP) and becomes the "coordinating AP". A DL MU PPDU format is used for transmitting the Co-SR and both APs start and end their transmission at the same time.

Two modes are defined to support different scenarios:

- Mode 1 is used to enable UHR+EHT or EHT+EHT Co-SR transmissions. In this case, the L-STF, L-LTF, L-SIG and RL-SIG fields in the preamble will have identical content for the transmissions of both APs.
- Mode 2 is intended for UHR+UHR transmissions. In this case, the L-STF, L-LTF, L-SIG, RL-SIG and U-SIG fields in the preamble will have identical content for the transmissions of both APs.

5.1.3 Coordinated time division multiple access (Co-TDMA)

Co-TDMA allows an AP that owns a TXOP (transmission opportunity) to share a portion of its TXOP time with one or more non-collocated AP(s). The coordinated AP, then, does not need to contend for the medium, which will be especially beneficial for low-latency traffic. In addition, this may improve overall system efficiencies by reducing contention time and/or collisions.

The Co-TDMA procedure can be described with three main phases:

- Polling: The coordinating AP announces its intention to share part of its TXOP with other APs. An AP with higher priority traffic (e.g. traffic with low latency) will respond to the coordinating AP that it wishes to take advantage of the sharing.
- Allocation: The coordinating AP allocates transmit time to the coordinated AP(s).
- (Potential) Return: The coordinated AP may return any unused portion of its time to the coordinating AP. The return of unused time may not be supported by all coordinated APs.

5.1.4 Coordinated restricted target wake time (Co-RTWT)

Target wake time (TWT) is a power saving feature introduced in IEEE 802.11ah/ax amendments that allows STAs to sleep for extended periods and wake up at specific intervals to transmit and/or receive data. Restricted TWT was introduced in IEEE 802.11be to reserve specific time slots for a STA running an application that requires low latency and high reliability. IEEE 802.11be only considered RTWT services within a BSS. For a STA at the edge of a BSS coverage, for example, interference from a neighboring AP can degrade the RTWT performance.

To reduce/prevent interference to STAs during their scheduled wake times, UHR introduces coordinated restricted target wake time (Co-RTWT) to enable APs to coordinate their restricted TWT (R-TWT) schedules. This will be particularly useful in overlapping basic service set (OBSS) environments to reduce/prevent interference to STAs during their scheduled wake times (TWT service periods).

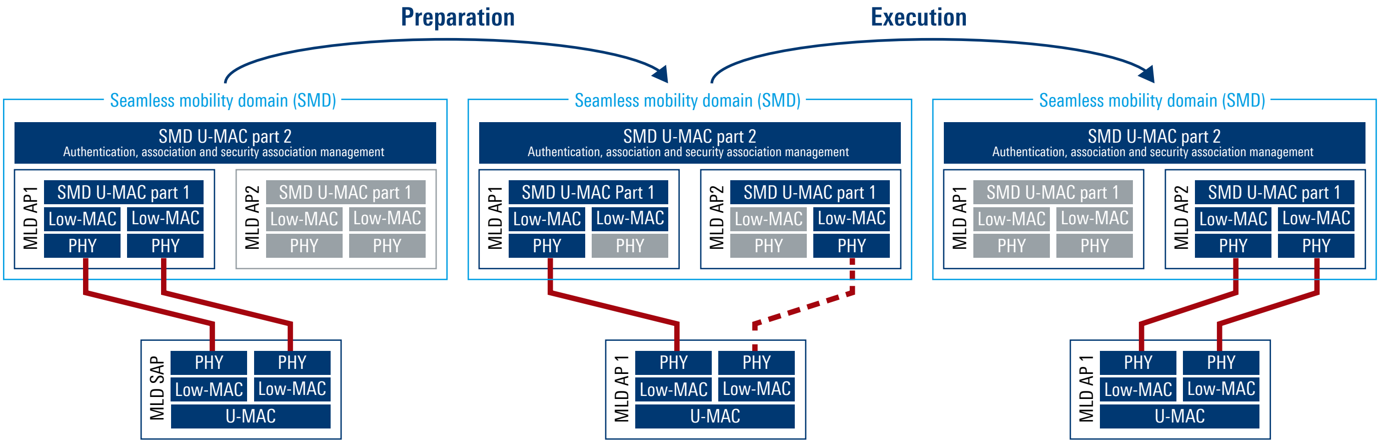
An AP requesting protection for its R-TWT schedules is called the requesting AP. The AP that extends the protection is called the coordinated AP. The requesting AP shares the R-TWT parameter set with the coordinated AP. The R-TWT parameter set includes important information such as the target wake time and TWT wake duration. The coordinated AP will ensure its TXOP ends before the protected RTWT service period starts. The coordinated AP will also advertise the schedule in its own beacon so its associated STAs supporting R-TWT can respect the protected schedule as well.

5.2 Seamless roaming

A main IEEE 802.11bn enhancement improves roaming for a STA multi-link device (MLD) transitioning to a different AP MLD in the same domain. The goal for seamless roaming, called SMD BSS transitioning, is to minimize the latency and packet loss that typically happens when STAs need to reassociate with a new AP.

The key to the enhancement is the introduction of a seamless mobility domain (SMD) that allows STAs to stay associated when transitioning between APs in the SMD. The concept is illustrated at a high level in Figure 19.

Figure 19: STA MLD roaming from AP MLD1 to AP MLD2



A STA obtains information about the SMD (such as its SMD ID) when it first associates with an AP that is part of the SMD. The STA is associated to the SMD via that AP. The association with the SMD enables the STA to maintain its association when it transitions to another AP in the SMD.

A STA sends a BSS transition management query frame to its current AP to request recommended target AP(s) for transition. The current AP responds with information about candidate target AP(s) such as the target AP address(es). In addition, the current AP may send unsolicited candidate target AP information. When the STA is ready to roam, it sends a link reconfiguration request that includes the target AP's address. The current AP sends context information (such as block acknowledge parameters and quality of service of established streams) for the STA to the target AP. The target AP adds links for the STA and informs the current AP. The current AP then sends a link reconfiguration response to the STA to indicate the transition preparation was successful.

The STA can execute the BSS transition by sending a link reconfiguration execution request to its current AP or to the target AP. Either way, the current AP may complete the transmission of buffered DL data frames to the STA, but the STA does not send uplink data during this time. Once the DL data from the current AP is completed or if a related timer expires, the STA and the target AP can begin exchanging uplink and downlink data frames.

A STA is not required to support SMD BSS transitioning to connect with an AP that is part of an SMD.

6 IEEE 802.11bn PHYSICAL LAYER TESTING

6.1 Transmitter requirements

The transmitter requirements for IEEE 802.11bn are based on requirements for IEEE 802.11be/EHT. Changes to the TX specification to include the four new MCS and reflect requirements for DRU or ELR usage will be highlighted in the following section. (For details on the IEEE 802.11be transmitter requirements, see [5]). Note that UEQM and 2xLDPC will not be used when performing the IEEE 802.11bn transmitter tests.

6.1.1 Transmitter constellation error

IEEE 802.11bn keeps the same IEEE 802.11be transmitter constellation error requirements for existing MCS and extends them to include the four new MCS levels. The TB PPDU constellation error requirement applies to both RRU and DRU. The constellation error requirements for the new MCS were determined based on simulations and selecting a target value that should result in a receiver degradation of less than or equal to 1 dB at a 10 % packet error rate. As expected, the EVM for the new MCS is within the range of the two existing MCS with the nearest higher and lower data rates. The resulting UHR constellation error requirements are shown in Table 9. For the ELR MCS, the requirements were relaxed because ELR is designed to be more robust for longer range transmissions and uses lower MCS levels that are less sensitive to noise and interference. The requirements for the ELR MCS are summarized in Table 10.

Table 9: UHR transmit constellation error for non-ELR

UHR-MCS	Modulation	Coding	EVM of UHR MU PDDU	EVM of UHR TB PDDU transmit power larger than MCS7 maximum power	EVM of UHR TB PDDU transmit power equal or less than MCS7 maximum power
0	BPSK	1/2	–5 dB	–13 dB	–27 dB
1	QPSK	1/2	–10 dB	–13 dB	–27 dB
17		2/3	–12 dB	–13 dB	–27 dB
2		3/4	–13 dB	–13 dB	–27 dB
3	16QAM	1/2	–16 dB	–16 dB	–27 dB
18		2/3	–18 dB	–18 dB	–27 dB
4		3/4	–19 dB	–19 dB	–27 dB
19		5/6	–20 dB	–20 dB	–27 dB
5	64QAM	2/3	–22 dB	–22 dB	–27 dB
6		3/4	–25 dB	–25 dB	–27 dB
7		5/6	–27 dB	–27 dB	–27 dB
8	256QAM	2/3	–29 dB	–29 dB	–29 dB
23		3/4	–30 dB	–30 dB	–30 dB
9		5/6	–32 dB	–32 dB	–32 dB
10	1024QAM	3/4	–35 dB	–35 dB	–35 dB
11		5/6	–35 dB	–35 dB	–35 dB
12	4096QAM	3/4	–38 dB	–38 dB	–38 dB
13		5/6	–38 dB	–38 dB	–38 dB
14	BPSK-DCM-DUP	1/2	–5 dB	–	–
15	BPSK-DCM	1/2	–5 dB	–13 dB	–27 dB

Table 10: Transmitter constellation error for UHR-ELR

UHR-MCS	Modulation	Coding	EVM of UHR ELR PPDU
0	BPSK	1/2	–4 dB
1	QPSK	1/2	–5 dB

6.1.2 Unused tone error requirements for DRU

The primary objective of the unused tone error requirements is to manage interference and ensure coexistence with other users in an OFDMA transmission. IEEE 802.11be defined unused tone error requirements for RRU. IEEE 802.11bn adds the requirements for DRU. A DRU transmission may impact unused tones within its assigned distribution bandwidth creating interference that may impact other DRUs. A DRU may also impact tones outside its DBW. For example, multiple DBWs can exist in an 80 MHz PPDU, and a DRU in one DBW can create out of band emissions that affect DRUs in other DBWs. A DRU in a hybrid transmission may impact adjacent RRU transmissions in the neighboring 80 MHz subblock in addition to adjacent DRU in the DRU subblock. Therefore, there are two parts to the unused tone EVM requirement:

1. Unused tone error within the DBW and
2. Unused tone error outside the DBW

For the unused tone error **within a DBW**, the formula is:

$$UnusedToneError\,(\mathrm{i}_{DRU26/52}) \leq \max(\varepsilon - 1, -38\text{ dB})$$

Where

- ε is the used tone EVM (see Table 9)
- $\mathrm{i}_{DRU26/52}$ is the index of the other DRUs in the DBW

This measurement is performed over unused DRU26s for DBW20 and DBW40 and over unused DRU52s for DBW60 and DBW80.

For **tones outside the transmitting DRU's DBW**, IEEE 802.11bn adapts the mask from the IEEE 802.11be RRU unused tone error specification. The RRU unused tone error mask depended on the RU size and the measurement resolution (the error is measured and averaged in 26-tone RU blocks).

For IEEE 802.11bn, the measurement resolution is a 242-tone RRU and the step size is defined as the number of DBW20s. The DRU spreading gain (see table in Figure 3) is used to adjust the EVM to account for averaging over RRU242. The equation to calculate the unused tone EVM requirement for outside of the DBW is as follows:

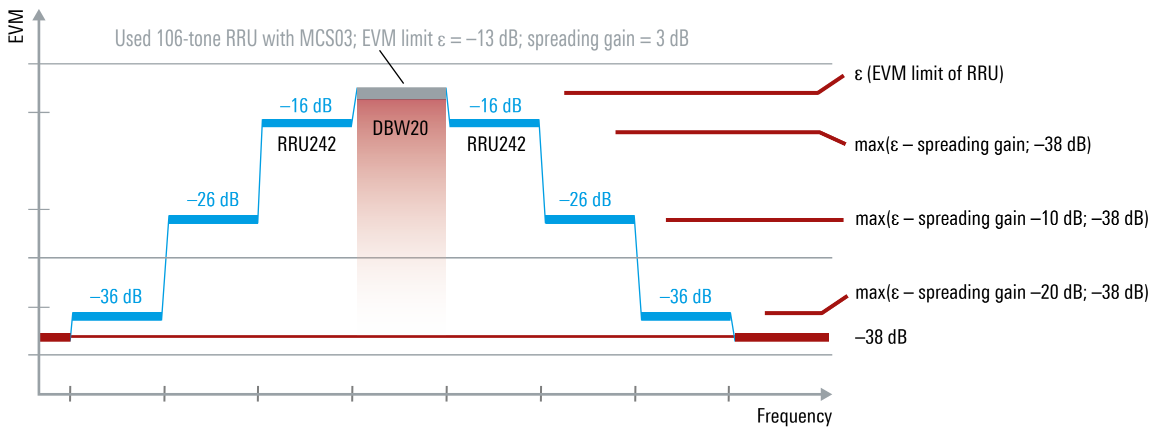
$$UnusedToneError\left(i_{RRU242,\,start} + m\right) \leq \begin{cases} \max(\varepsilon - \text{DRU spreading gain}, -38\text{ dB}), & \text{if} - r \leq m \leq -1 \\ \max(\varepsilon - 10 - \text{DRU spreading gain}, -38\text{ dB}), & \text{if} - 2r \leq m \leq -r-1 \\ \max(\varepsilon - 20 - \text{DRU spreading gain}, -38\text{ dB}), & \text{if} - 3r \leq m \leq -2r-1 \\ -38\text{ dB}, & \text{otherwise} \end{cases}$$

$$UnusedToneError\left(i_{RRU242,\,end} + m\right) \leq \begin{cases} \max(\varepsilon - \text{DRU spreading gain}, -38\text{ dB}), & \text{if } 1 \leq m \leq r \\ \max(\varepsilon - 10 - \text{DRU spreading gain}, -38\text{ dB}), & \text{if } r+1 \leq m \leq 2r \\ \max(\varepsilon - 20 - \text{DRU spreading gain}, -38\text{ dB}), & \text{if } 2r+1 \leq m \leq 3r \\ -38\text{ dB}, & \text{otherwise} \end{cases}$$

Where

- ε is the used tone EVM (see Table 9)
- r is the number of DBW20 in the transmitting DBW,
  $r = 1$ for DBW20, $r = 2$ for DBW40, and $r = 4$ for DBW80 and DBW60
- Spreading gain is given by the table in Figure 3

Figure 20: Example for DRU unused tone error outside the DBW (106-tone DRU, DBW20)



6.1.3 Transmitter pre-correction requirements

6.1.3.1 Trigger based PPDU

As in IEEE 802.11ax/802.11be, trigger based PPDUs are sent from multiple STAs in response to a triggering frame from an AP. The STAs perform pre-correction at the transmitter to ensure that the signals from the multiple STAs arrive at the AP with about the same power, center frequency offset (CFO) and timing. This ensures that the signals do not interfere with each other so that the AP can demodulate the signals and process the information from all the STAs easily. The IEEE 802.11bn pre-correction requirements for the TB PPDU are the same as IEEE 802.11be.

Table 11 provides the transmit power and RSSI requirements for the trigger based PPDUs. The absolute transmit power accuracy is applicable for the entire STA transmit power range. The RSSI is measured on the non-UHR portion of the UHR PPDU preamble to meet RSSI accuracy requirements. In the 2.4 GHz band, this is applicable for receive signals from –82 dBm to –20 dBm, and in the 5 GHz and 6 GHz bands for receive signals from –82 dBm to –30 dBm. Note that there are different requirements for high capability devices (device class A) and low-cost devices (device class B).

Table 11: Transmit power and RSSI measurement accuracy requirements for TB PPDU

Parameter	IEEE 802.11be minimum requirements		Comment
	class A devices	class B devices	
Absolute transmit power accuracy	±3 dB	±9 dB	accuracy of achieving a specified transmit power level
Relative transmit power accuracy	–	±3 dB	accuracy of the change in transmit power for consecutive EHT TB PDDU
RSSI measurement accuracy	±3 dB	±5 dB	difference between the measured RSSI and the received power

The STA compensates for CFO error compensation relative to the trigger frame frequency to reduce the amount of residual CFO at the AP during UL MU transmission. For the CFO requirement, the CFO error statistics are measured. At the 10% point of the CCDF curve, the CFO error must be less than 350 Hz. The measurement is made in the primary 20 MHz channel at –60 dBm received power. The CFO is measured after the U-SIG field.

For timing requirements, the STA needs to transmit within ±0.4 μs +16 μs from the end of the last OFDM symbol of the triggering PPDU sent by the AP to trigger the UL transmission.

6.1.3.2 Pre-correction for ELR PPDU

ELR transmission is intended for improving the link budget, especially for uplink transmissions in more challenging environments/longer ranges where SNR may be low. A receiver in this environment may use cross correlation to improve packet detection. However, cross correlation relies on the amount of phase difference across a sequence to be small. Therefore, IEEE 802.11bn requires an ELR uplink transmission responding to a soliciting frame from the AP to pre-correct its CFO. The STA needs to meet the following requirement after pre-correction: At the 10 % point of the CCDF curve, the CFO error must be less than 15 kHz.

The measurement is made in the primary 20 MHz channel at –82 dBm received power. The CFO is measured after the L-STF field. The symbol clock error is compensated by the same amount as the CFO error. For an ELR uplink transmission that is not in response to a soliciting frame, the STA should try to reduce its CFO error to meet the same target for better performance, but it is not a requirement to do so.

6.2 Receiver requirements

For the most part, IEEE 802.11bn reuses the receiver requirements specified in IEEE 802.11be. The requirements are updated to include the new MCS levels and ELR PPDU. In addition, IEEE 802.11bn adds a requirement for received channel power indication (RCPI) accuracy.

The PSDU length used for the receiver test cases is specified as follows:

- 512 octets for ELR-MCS0 and ELR-MCS1
- 2048 for UHR-MCS15
- 4096 for all other MCS

The non-ELR PPDUs used for the receiver tests should meet the following criteria:

- Guard interval: 0.8 µs
- Coding scheme:
  - BCC is used for 20 MHz PPDUs and the UHR-MCS is less than 10 or equal to 15, 17, 19, 20 or 23
  - LDPC is used in all other cases
- PPDU format: UHR MU PPDU without puncturing

6.2.1 Receiver minimum input sensitivity

Receiver minimum sensitivity measures the minimum signal strength the Wi-Fi receiver needs to decode the received signal with a packet error rate less than 10%. Table 12 provides the minimum sensitivity requirements for the UHR non-ELR MCS as a function of the PPDU bandwidth. Table 13 provides the minimum sensitivity requirements for the UHR ELR MCS.

Table 12: Receiver minimum input level sensitivity for UHR non-ELR PPDU

MCS	Modulation	Coding rate (R)	Minimum sensitivity (20 MHz PPDU)	Minimum sensitivity (40 MHz PPDU)	Minimum sensitivity (80 MHz PPDU)	Minimum sensitivity (160 MHz PPDU)	Minimum sensitivity (320 MHz PPDU)
0	BPSK	1/2	–82 dBm	–79 dBm	–76 dBm	–73 dBm	–70 dBm
1	QPSK	1/2	–79 dBm	–76 dBm	–73 dBm	–70 dBm	–67 dBm
17		1/2	–78 dBm	–75 dBm	–72 dBm	–69 dBm	–66 dBm
2		3/4	–77 dBm	–74 dBm	–71 dBm	–68 dBm	–65 dBm
3	16QAM	1/2	–74 dBm	–71 dBm	–68 dBm	–65 dBm	–62 dBm
19		2/3	–71 dBm	–68 dBm	–65 dBm	–62 dBm	–59 dBm
4		3/4	–70 dBm	–67 dBm	–64 dBm	–61 dBm	–58 dBm
20		5/6	–69 dBm	–66 dBm	–63 dBm	–60 dBm	–57 dBm
5	64QAM	2/3	–66 dBm	–63 dBm	–60 dBm	–57 dBm	–54 dBm
6		3/4	–65 dBm	–62 dBm	–59 dBm	–56 dBm	–53 dBm
7		5/6	–64 dBm	–61 dBm	–58 dBm	–55 dBm	–52 dBm
23	256QAM	2/3	–60 dBm	–57 dBm	–54 dBm	–51 dBm	–48 dBm
8		3/4	–59 dBm	–56 dBm	–53 dBm	–50 dBm	–47 dBm
9		5/6	–57 dBm	–54 dBm	–51 dBm	–48 dBm	–45 dBm
10	1024QAM	3/4	–54 dBm	–51 dBm	–48 dBm	–45 dBm	–42 dBm
11		5/6	–52 dBm	–49 dBm	–46 dBm	–43 dBm	–40 dBm
12	4096QAM	3/4	–49 dBm	–46 dBm	–43 dBm	–40 dBm	–37 dBm
13		5/6	–46 dBm	–43 dBm	–40 dBm	–37 dBm	–34 dBm
15	BPSK–DCM	1/2	–82 dBm	–79 dBm	–76 dBm	–73 dBm	–70 dBm

Table 13: Receiver minimum input level sensitivity for UHR ELR PPDU

Modulation	Rate (R)	RU tone and DUP	Minimum sensitivity (20 MHz PPDU)
ELR-MCS0	1/2	52-tone RRU with four times duplication	–82 dBm
ELR-MCS1	1/2	52-tone RRU with four times duplication	–82 dBm

6.2.2 Adjacent channel and nonadjacent rejection

Adjacent channel rejection tests are used to measure the ability of an IEEE 802.11bn receiver to detect and demodulate a signal in the presence of stronger signals in a nearby channel. The receiver demodulates the wanted IEEE 802.11bn signal at f_c with a bandwidth of W MHz (W = 20, 40, 80, 160 or 320) and power set 3 dB higher than the value of the minimum sensitivity level given in Table 12.

An interfering UHR-compliant signal with a duty cycle (on/off ratio) greater than 50% and the same bandwidth as the wanted signal is centered W MHz from the wanted signal (f_c + W MHz). The packet error rate is measured as the interferer signal power is increased. When the packet error rate reaches 10%, the delta between the interferer power and the wanted signal power is measured. This delta is called adjacent channel rejection. It must be greater than the value provided in Table 14. (If a 160 MHz or 320 MHz receiver is being tested but the regulatory domain does not allow an adjacent 160 MHz or 320 MHz channel, the adjacent channel rejection test can be skipped.)

The nonadjacent rejection test is performed in a similar manner, but the interfering signal is 2W MHz away from the desired signal. Table 14 provides the adjacent and nonadjacent channel power requirements for the IEEE 802.11bn non-ELR modulations. Table 15 provides the requirements for the UHR ELR modulations.

Table 14: Minimum required adjacent and nonadjacent channel rejection levels for non-ELR MCS

MCS	Modulation	Rate (R)	Adjacent channel rejection	Nonadjacent channel rejection
0	BPSK	1/2	16 dB	32 dB
1	QPSK	1/2	13 dB	29 dB
17		2/3	12 dB	28 dB
2		3/4	11 dB	27 dB
3	16QAM	1/2	8 dB	24 dB
19		2/3	5 dB	21 dB
4		3/4	4 dB	20 dB
20		5/6	3 dB	19 dB
5	64QAM	2/3	0 dB	16 dB
6		3/4	–1 dB	15 dB
7		5/6	–2 dB	14 dB
23	256QAM	2/3	–6 dB	10 dB
8		3/4	–7 dB	9 dB
9		5/6	–9 dB	7 dB
10	1024QAM	3/4	–12 dB	4 dB
11		5/6	–14 dB	2 dB
12	4096QAM	3/4	–17 dB	–1 dB
13		5/6	–20 dB	–4 dB
15	BPSK-DCM	1/2	16 dB	32 dB

Table 15: Minimum required adjacent and nonadjacent channel rejection levels for ELR MCS

Modulation	Rate (R)	RU tone and DUP	Adjacent channel rejection (20 MHz PPDU)	Nonadjacent channel rejection (20 MHz PPDU)
ELR-MCS0	1/2	52-tone RRU with four times duplication	16	32
ELR-MCS1	1/2	52-tone RRU with four times duplication	16	32

6.2.3 Receiver maximum input level

The receiver maximum input level tests the ability of a receiver to demodulate an IEEE 802.11be signal with an input level of –30 dBm operating in the 5 GHz and 6 GHz bands and –20 dBm operating in the 2.4 GHz band. The packet error rate (PER) is measured at each physical antenna port and must be below 10 %.

6.2.4 Received channel power indicator (RCPI) accuracy

RCPI is an indication of the received RF power on a channel. RCPI has been used in IEEE 802.11 for some time, but IEEE 802.11bn is the first to introduce a PHY receiver requirement to test the accuracy of the measurement by the STA. For this test, the PHY measures the received RF power over the UHR-STF or UHR-LTF and reports the average of the power measured across all active receive chains. For ELR PPDU, the reported value is 3 dB less than the measured power (because the UHR-LTF and UHR-STF are 3 dB higher than the data field). The RCPI value is reported in dBm and must be accurate within ±5 dB.

7 SMART TESTING FOR ULTRA-HIGH RELIABILITY

With each new generation of Wi-Fi, the radio designs were pushed to the next level. The same is true with Wi-Fi 8, but now with a strong focus on reliability, stable performance and user experience. As a result, even more accurate, efficient and smart test solutions are needed in every stage of the product lifecycle. Rohde & Schwarz is continuously developing its wireless test portfolio in order to empower the ecosystem at the forefront of this technology evolution. As the industry is constantly working on the next wireless standard like IEEE 802.11bn or IEEE 802.11bq (integrated mmWave) and beyond, engineers clearly want to have test solutions that already meet the requirements of tomorrow. With our high-end instruments like the R&S®SWM200A vector signal generator and the FSW signal and spectrum analyzer, we address exactly these types of needs.

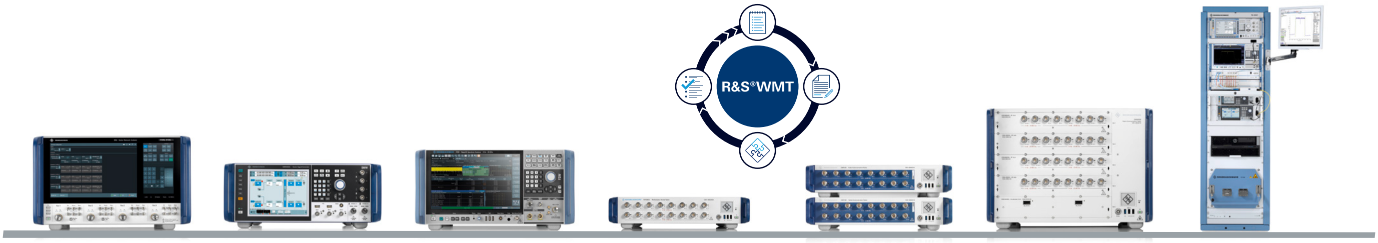
RF components like power amplifiers, filters and antennas are a crucial part of any RF design. These components have always required extremely low EVM. Now, with the support of features like multi-link operation over multiple bands and wider channels, the EVM requirements are becoming even more challenging. Rohde & Schwarz high-performance test solutions, like the R&S®ZNA vector network analyzer, R&S®SMW200A, FSW as well the PVT360 performance vector tester, make meeting this challenge easier.

In the phase of lab development of chipsets and modules, different aspects of standard and regulatory conformance as well as system performance become relevant. Besides traditional signal generators and analyzers, one box non-signaling testers like the CMP180 and CMX500 radio communication testers are extremely useful. Both support the RF performance and related features required for Wi-Fi 8. At a certain stage of product development (DVT), there is a need for extensive parametric testing under different conditions. Here, a high level of test automation together with high measurement speed and superior measurement accuracy, such as very low residual EVM, is of great importance. The CMP180 provides all that: up to 500 MHz bandwidth up to a frequency of 8 GHz in all bands with a fully automated non-signaling test framework based on R&S®WMT wireless automated testing.

Performing RF as well as end-to-end performance and quality testing of access points and stations is a wide, complex area that increasingly demands the capabilities of signaling test solutions like the CMX500. In addition to RF performance, OFDMA pre-correction and multi-link tests, the CMX500 can perform application testing, including Wi-Fi offloading, under real operating conditions (i.e. no test mode). Regulatory compliance is a must-have for any wireless device. However, it is becoming more and more complex with the introduction of receiver tests and region-specific requirements e.g. in the 6 GHz band for LPI, AFC, VLP etc. Efficient compliance testing would suggest pre-compliance testing by the vendor as supported with the CMX500 and require purpose-built conformance test systems like the R&S®TS8997 regulatory test system for wireless devices in the test labs.

Test and calibration in manufacturing represent a cornerstone of any quality assurance program, involving test automation, test speed, system integration as well as reliable and consistent measurements in a factory environment. These are the requirements the CMP180 was designed for. The CMP180 provides comprehensive chipset support through integration into vendor-specific tools or offered as the R&S®WMT wireless automated testing framework, which is optimized for high speed, parallel testing and full automation.

Figure 21: Committed to empowering the Wi-Fi ecosystem with superior test solutions: accurate – smart – efficient



R&S®ZNA vector network analyzer

R&S®SMW200A vector signal generator

FSW signal and spectrum analyzer

PVT360A performance vector tester

CMP180 radio communication tester

CMX500 radio communication tester

R&S®TS8997 regulatory test system for wireless devices

8 ABBREVIATIONS

Term	Explanation
AP	Access point
BPSK	Binary phase shift keying
BSS	Basic service set
BW	Bandwidth
CBW	Channel bandwidth
CCA	Clear channel assessment
CCDF	Complementary cumulative distribution function
CFO	Carrier frequency offset
Co-BF	Coordinated beamforming
Co-CR	Coordinated channel recommendation
Co-SR	Coordinated spatial reuse
Co-TDMA	Coordinated TDMA
Co-RTWT	Coordinated restricted target wait time
CRC	Cyclic redundancy check
DBE	Dynamic bandwidth expansion
DBW	Distribution bandwidth
DL	Downlink
DPS	Dynamic power save
DRU	Distributed-tone resource units
DSO	Dynamic subband operation
DUO	Dynamic unavailability operation
DUP	Duplicated transmission
EDCA	Enhanced distributed channel access
EHT	Extremely high throughput
EIRP	Equivalent isotopically radiated power
ELR	Extended long range DSO
EVM	Error vector magnitude
GI	Guard interval
HE	High efficiency
IEEE	Institute of Electrical and Electronics Engineers
IM	Interference mitigation
LDPC	Low density parity check
LLI	Low latency indication
L-LTF	Legacy long training field
L-STF	Legacy short training field
LO	Local oscillator
LPI	Low power indoor
LTF	Long training field
MAC	Medium access control layer
MAPC	Multi-AP coordination
MCS	Modulation and coding scheme
MIMO	Multiple input multiple output
MLD	Multi-link device
MLO	Multi-link operation
MRU	Multiple resource unit
MU	Multi user
MU-MIMO	Multi-user MIMO
NPCA	Non-primary channel access
N_{SS}	Number of spatial streams
OBSS	Overlapping BSS
OFDM	Orthogonal frequency division multiplexing

Term	Explanation
OFDMA	Orthogonal frequency division multiplexing access
PAPR	Peak to average power ratio
PE	Packet extension
PHY	Physical layer
PPDU	PHY protocol data unit
PSD	Power spectrum density
PSDU	PHY service data unit
P-EDCA	Priority EDCA
PUO	Periodic unavailability operation
P2P	Peer to peer
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RCPI	Received channel power indicator
RSSI	Receive signal strength indicator
RRU	Regular resource unit
SIG	Signal field
SNR	Signal to noise ratio
SMD	Seamless mobility domain
STA	Station
STF	Short training field
SU	Single user
TDMA	Time division multiple access
TG	Task group
TWT	Target wait time
TXOP	Transmission opportunity
UL	Uplink
UHR	Ultra-high reliability
U-SIG	Universal signal field
UEQM	Unequal modulation
VHT	Very high throughput
VLP	Very low power
WLAN	Wireless local area network

9 REFERENCES

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