WHITE PAPER

Key Considerations for Wi-Fi 6 Multi-User OFDMA Testing

Introduction

Wi-Fi 6 refers to the IEEE 802.11 standard based Wireless Local Area Network (WLAN) technology that introduces several new enhancements and features over previous generations of Wi-Fi solutions. Wi-Fi 6E is also a part of IEEE 802.11ax standard. As an extension of Wi-Fi 6, it enables the operation of features in the unlicensed 6 GHz band, in addition to the currently supported 2.4 GHz and 5 GHz bands. It provides networks the capacity, efficiency, and performance required to support next-generation applications.

New Wi-Fi 6/6E test tools and methodologies are needed to meet the industry need for comprehensive testing strategies covering the expanded range of test cases without significantly increasing investment and test time.

Orthogonal Frequency-Division Multiple Access (OFDMA) introduced in 802.11ax standard is a large step beyond OFDM, which is used by previous generation 802.11 standards. OFDMA is a feature that has been used in wireless communication systems such as LTE for many years to improve frequency efficiency. However, in LTE, OFDMA is time-based such that various subcarriers correspond to different user equipment during one Transmission Time Interval (TTI).

In 802.11ax, OFDMA is frame-based. With OFDMA support in 802.11ax, multiple users simultaneously share a full channel bandwidth for channeling data sessions more effectively. The combination of the frequency section and the transmission time for each user is a bandwidth segment called a Resource Unit (RU). A wide range of test coverage is now required to validate new 802.11ax features such as OFDMA and multi-user MIMO scale and performance. Those test cases require a testbed with many independent client station (STA) radio interfaces in order to achieve repeatable testing results and emulate various realistic use cases with different types of RUs assignments managed by an AP for possible OFDMA operations defined under IEEE 802.11ax standard.

This white paper provides an overview of Wi-Fi 6 OFDMA fundamentals based on the IEEE 802.11ax standard. It offers an in-depth look into how DL and UL OFDMA protocols between AP and STAs operate, including the basics of OFDMA scheduling, trigger frames, MU-BAR and MU-STA BA frames, RU types, possibility RU allocations, etc.

The paper also explores the testing challenges and solutions for MU-OFDMA with a special focus on traffic throughput and timing performance and covers the tri-band frequencies of 2.4GHz, 5GHz, and the new 6GHz to 7GHz spectrum. The testbed details, methodologies, test cases, and results were based on Spirent Wi-Fi 6 testing solutions.

SOLUTION

New Wi-Fi 6/6E test tools and methodologies are needed to meet the industry need for comprehensive testing strategies covering the expanded range of test cases without significantly increasing investment and test time.

Wi-Fi 6 (IEEE 802.11AX) Overview

IEEE 802.11ax standard is intended to address the following enhancements and improvements over the previous generation of IEEE 802.11ac

- Enhance operation in 2.4GHz, 5 GHz, and new 6GHz bands
- Increase average throughput per station by at least 4x in a dense deployment scenario
- Environments include indoor AND outdoor
- Scenarios include dense public area, corporate office, outdoor hotspot, dense residential apartments, and stadiums
- Maintain or improve power efficiency of the stations
- Support new 6GHz spectrum (IEEE 802.11AX D6.0, WFA-AX R2 Certification)

IEEE 802.11ax D3.0 was the first draft standard approved in July 2018. The major improvements introduced in this new WLAN standard are summarized but not limited to those in Figure 1, including:

- Higher order modulation with 1024QAM support for ~20% higher rates
- Downlink and uplink OFDMA
- Downlink and uplink MU-MIMO
- Longer OFDM symbol with symbol duration increases by 4x
- Target Wake Time (TWT)
- Tri-band support introduced in IEEE 802.11ax D6.0 Draft
- BSS color for Spatial re-use
- Support of 8 Spatial streams

802.11ax HE PPDU Format

Before 802.11ax, AP and STAs were treated equally in PHY layer, therefore it has used the same type of PHY Protocol Data Unit (PPDU) format between AP and STAs. While 802.11ax starts adopting the concept of Downlink (AP to non-AP STA) and Uplink (non-AP STA to AP) in multi-user cases, it introduces four types of PPDU formats for various transmissions. The four types of HE PPDUs discussed below share the same baseline structure with only slight differences in the extended HE portions.

- **HE SU PPDU:** [DL/UL] Normal Single User PPDU between an AP and an STA
- **HE ER SU PPDU:** [DL/DU] Enhanced Range SU PPDU, Training fields are boosted by 3dB to extend range. Packet structure is same as HE SU PPDU, except for the HE-SIG-A field which is repeated.
- **HE MU PPDU:** [DL] Multi-user PPDU from AP to multiple STAs to enable simultaneous transmission via OFDMA and/or MU-MIMO. The new HE-SIG-B introduced is to indicate RU and spatial stream info for MU operation.
- **HE TB PPDU:** [UL] Trigger-based PPDU for UL MU (OFDMA, MU-MIMO) operation from STAs. Compared with HE MU PPDU, this format does not have HE-SIG-B because AP indicates the RU allocation information in the trigger frame.

Compared with HE SU PPDU, this format has 8us HE-STF vs only 4us in HE SU PPDU.

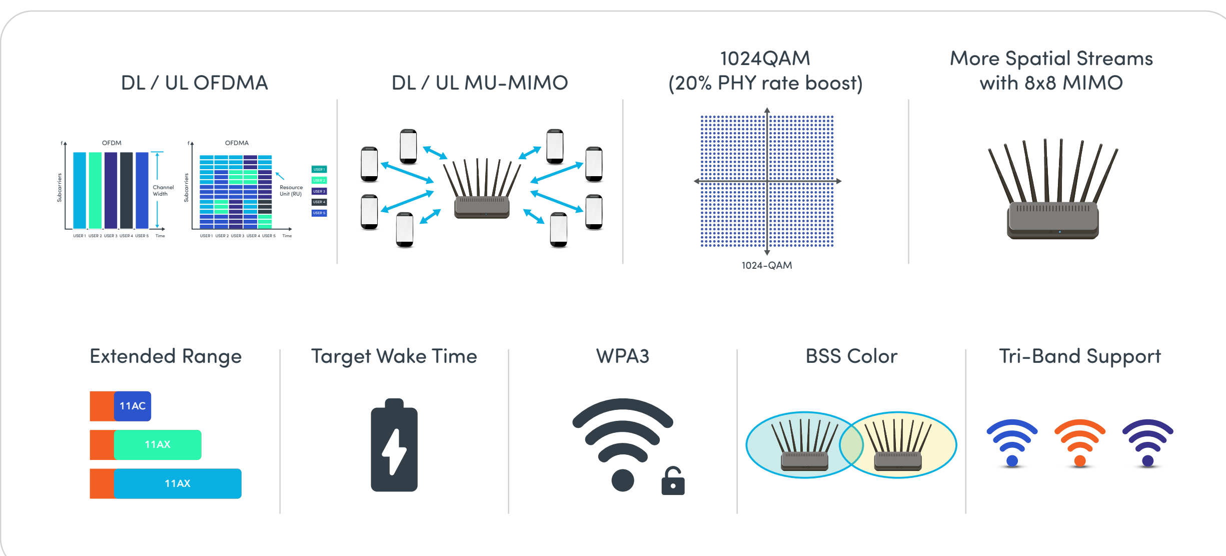


Figure 1. Major Features Introduced in IEEE 802.11ax Standard

Each type of PPDU consists of Legacy portion and HE portion. The Legacy portion consists of L-STF, L-LTF and L-SIG, which is for backward compatibility. In terms of modulation, there is a Pre-HE modulation part which is modulated and encoded in legacy OFDM. The Legacy portion and Pre-HE part do not match. RL-SIG is the repeated legacy SIG field, which helps the recipient STA to interpret the packet. HE-SIG-A is important for the new HE PPDU, with the following parameters included, followed by an optional HE-SIG-B section.

- **HE-SIG-A:** duplicated on each 20MHz which contains PHY information of the packet such as DL/UL, BSS Color, CP(GI)+LTF size, Spatial Reuse, Duration, MCS, BW, etc.
- **HE-SIG-B:** separately encoded on each 20MHz which contains multi-user information. This field is only needed in DL MU PPDU.

IEEE 802.11AX OFDMA

IEEE 802.11 standard is a packet-based protocol. Each PPDU contains preamble and data fields. An MU OFDMA frame has data to/from different STAs with various subcarriers or tones that are allocated to the clients for the entire frame duration. It works by dividing an allocated RF channel into many sub-sections to share with multiple users concurrently in both receive and transmission directions. With OFDMA support, multiple users simultaneously share a full channel bandwidth for channeling data sessions more effectively. The combination of the frequency section and the transmission time for each user is a bandwidth segment called a Resource Unit (RU). With OFDMA, different transmit powers may be applied to different RUs. This will be discussed later in the paper.

In downlink operation from an AP to many clients, OFDMA allows a single transmission to be split by sub-sections of frequency within a channel for multiple concurrent users. Different sections grouped with OFDM subcarriers of the channel are used by different clients. The difference between OFDM and OFDMA is illustrated in Figure 3. In OFDM mode, one of 4 users always occupies the entire frequency channel bandwidth at a time. OFDMA employs multiple subcarriers, but the subcarriers are divided into several groups and each group is referred to as an RU. So, several of the 4 users or all 4 users can share the entire channel bandwidth at the same time, to utilize spectrum more effectively. Equivalently in uplink, multiple client devices can transmit simultaneously on a different section of the channel, but those transmissions among multiple clients must be coordinated by an AP. It is important to note that in both downlink and uplink operations different users occupy different sub-sections of a channel for either receive or transmission.

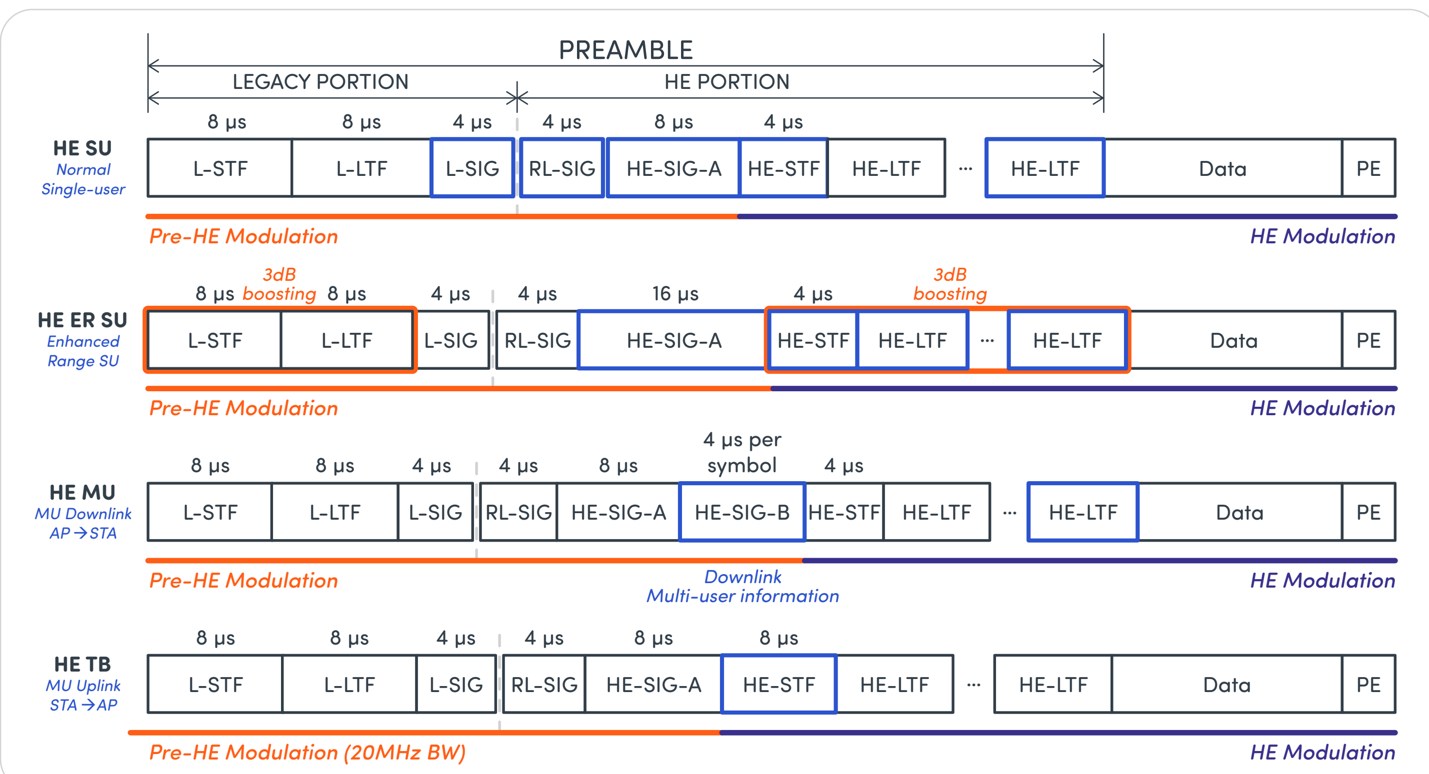


Figure 2. Four HE PPDU types - HE SU, HE ER SU, HE MU, and HE TB

An OFDM symbol is constructed of subcarriers, the number of which is a function of the PPDU bandwidth. There are several subcarrier types:

- Data subcarriers for data transmission
- Pilot subcarriers for phase information and parameter tracking
- Unused subcarriers for either data or pilot transmission. The unused subcarriers are the DC subcarriers, the Guard band subcarriers at the band edges, and the Null subcarriers

OFDM transmission among multiple clients are completely sequential in terms of time, otherwise, RF collision can happen while multiple transmissions are occurring simultaneously. Carrier-sense multiple access with **collision avoidance** (CSMA/CA) is a mechanism to help in those cases with an overhead cost of airtime utilization due to RF contention. However, when number of clients in use is large, this mechanism is not very effective and airtime overhead due to RF collision can be significant such that the effective rate drops dramatically. The sequential transmission of OFDM ensures that each client takes its time slot for a window of possible transmission. The concurrent transmission scheme with OFDMA can be much more effective in terms of using an airtime with multiple clients sharing the medium in terms of both time and frequency.

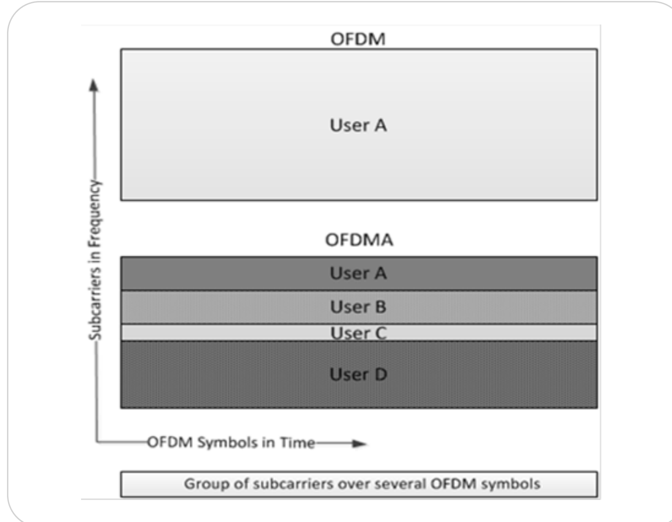


Figure 3. OFDM vs OFDMA in 802.11ax (from IEEE 802.11 Draft Standard)

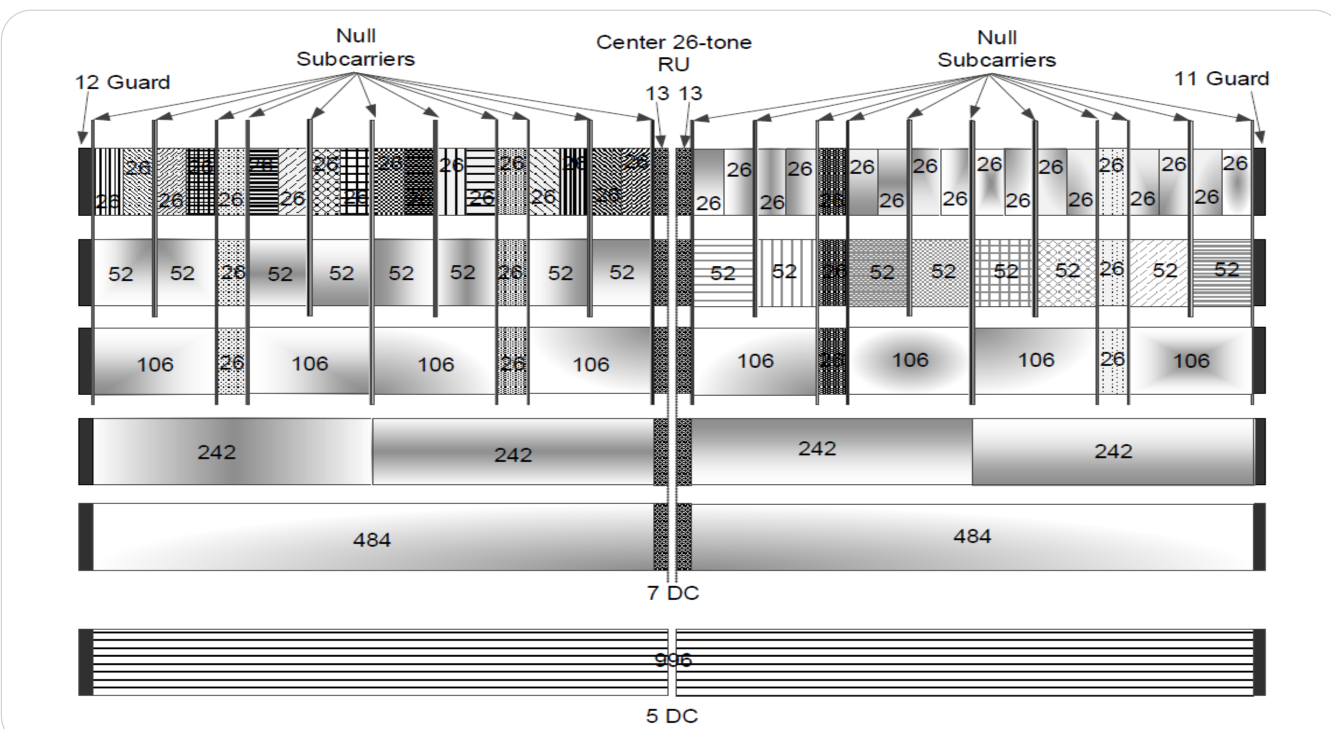


Figure 4. Possible RU Allocation on 80MHz Channel (from IEEE 802.11 Draft Standard)

Downlink OFDMA Transmission

HE DL MU operation allows an AP to transmit simultaneously to one or more STAs in DL OFDMA, DL MU-MIMO, or both. For a downlink OFDMA transmission opportunity from an AP to STAs, AP allocates a number of data frames for multiple STAs and assigns each of those data frames for each of the scheduled RUs in different sections of the frequency channel for a transmission to multiple STAs over air interface. The radio interface of each of the STAs allocated for the downlink OFDMA operation will tune to its own sub-channel to independently receive and decode its own data from the assigned RU. The preamble field of each MU frame specifies the frame duration and subcarriers assignment for each RU for OFDMA. When the STAs successfully receive the OFDMA data, AP sends a multi-user (MU) Block Acknowledgment Request (BAR) frame called MU-BAR to STAs, so that they can use uplink OFDMA to simultaneously send back Block Acknowledgment (BA) to the AP.

DL MU-BAR is usually a trigger frame type as an independent transmission, but it can also be a part of the MU PPDU to each STA for DL OFDMA as shown in Figure 6. More popular, the new MU-BAR frame introduced in 802.11ax is a multicast frame for all STAs as shown in Figure 7. The STAs may also use sequential OFDM transmission sending BA back to the AP, in case uplink OFDMA is not available. However, this may not be an efficient ACK mechanism as multiple series BAs from the STAs consumes more airtime and bandwidth as shown in Figure 8 below.

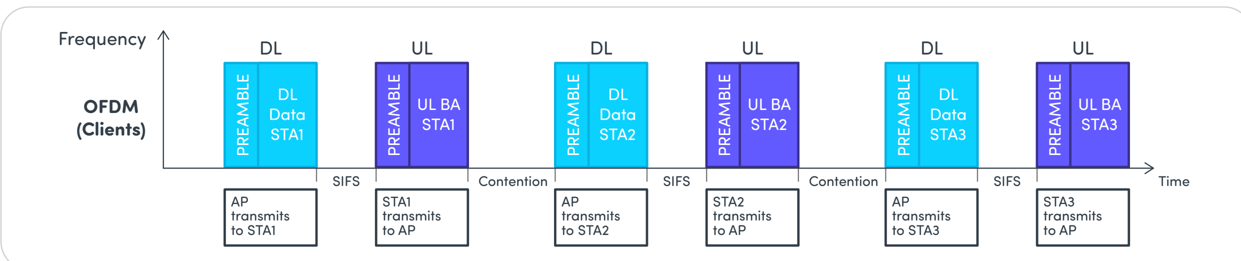


Figure 5. DL OFDM – Multi-STA Receives Sequentially

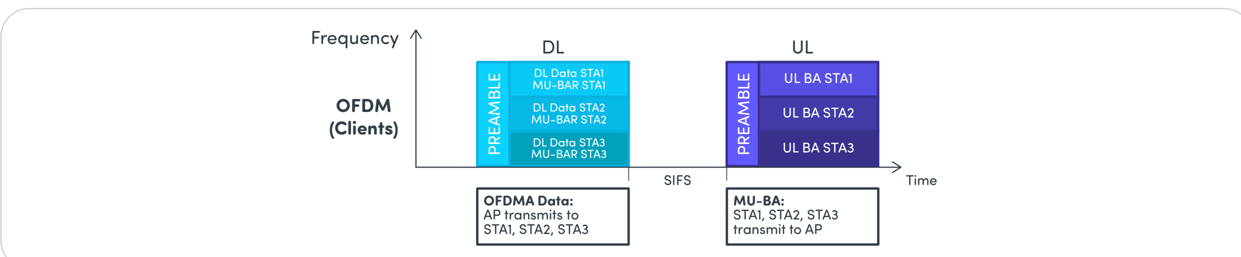


Figure 6. DL OFDMA Multi-STA Receives Simultaneously with a Single Frame Where MU-BAR Included

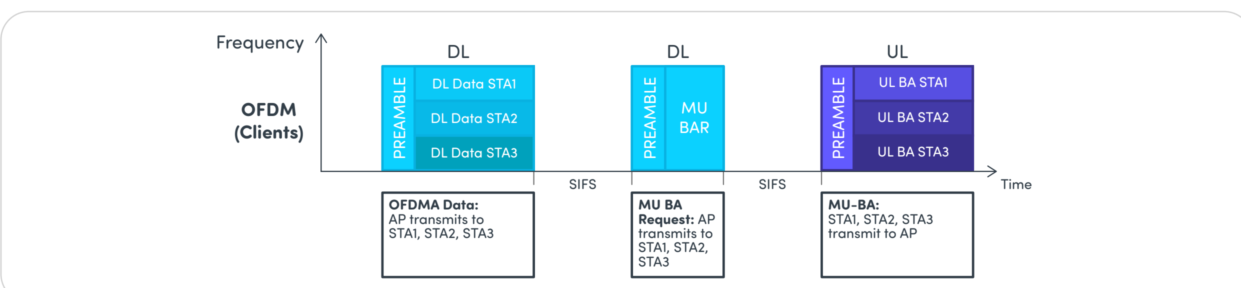


Figure 7. DL OFDMA Multi-STA Receives Simultaneously with a Single Frame

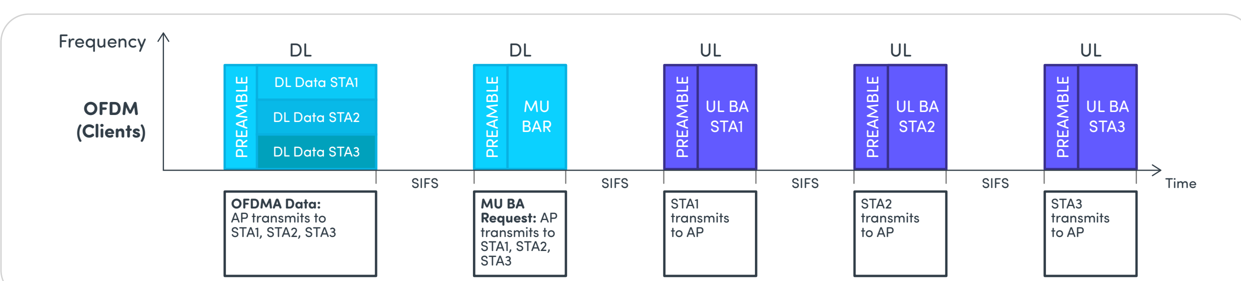


Figure 8. DL OFDMA Multi-STA Receives Simultaneously with a Single Frame but Individually BA from each STA Sequentially

Uplink OFDMA Transmission

UL MU operation allows an AP to solicit simultaneous immediate response frames from one or more HE STAs. UL OFDMA transmission is more challenging. For an uplink OFDMA operation, AP gets STA's information including data buffer status through a query or STA's report. AP is also the center of the scheduling hub that sets a synchronized transmission timing for all STAs being allocated for an uplink OFDMA transmission along with assigned RUs, and allocated OFDMA STAs must have data to transmit. 802.11ax introduces a new type control frame called trigger frame that specifies the common parameters of the upcoming UL MU transmission (duration, GI that should be the same for all the STAs selected for the UL MU transmission), allocated RUs for the STAs, and defines transmission parameters such as MCS type, coding, etc.

The mechanism for uplink OFDMA is more complicated than downlink OFDMA due to the fact that multiple individual STA transmitters, in different physical locations, must be synchronized to complete the operation. It is difficult to synchronize STAs due to clock drafting. To achieve a synchronization, STAs are required to start MU transmission immediately after one SIFS after the Trigger frame. When AP receives the data from all scheduled STAs, it will send back BA by using a downlink OFDMA transmission as shown in Figure 9.

The STAs assigned for a UL OFDMA must meet the requirements with the required transmission timing window, transmission power, and allowed frequency offset error. For a UL OFDMA transmission, the AP receives signals from multi-STA at almost the same TX power level. 802.11ax defines a power pre-correction mechanism for this purpose. AP indicates, in the Trigger frame, its current transmit power and the target signal strength that the AP is expected to receive from an STA in the following UL transmission. Therefore, having known the AP's transmit power and the signal strength of the received Trigger frame, an STA can estimate the path loss to the AP, and it can calculate an appropriate transmit power. This implies that the STAs that are very close in the range to an AP and STAs that are very far from the AP may not be able to perform a UL OFDMA together due to the large difference in RSSI that the AP senses.

An AP may require an STA to perform carrier sensing before an OFDMA transmission, as the AP does not know whether the channel is idle from the STA point of view. An STA can cancel its UL OFDMA transmission if it detects high energy, even if it is only on part of the allocated frequency.

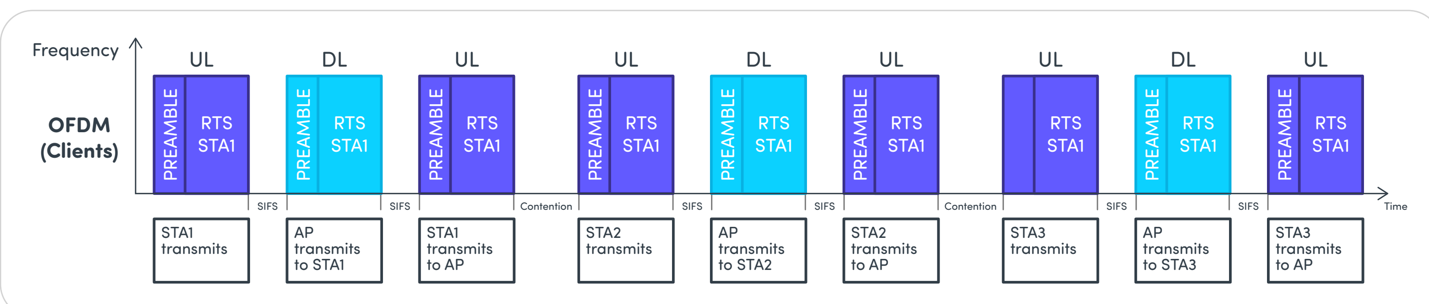


Figure 9. UL OFDM – Multi-Client Transmits Sequentially

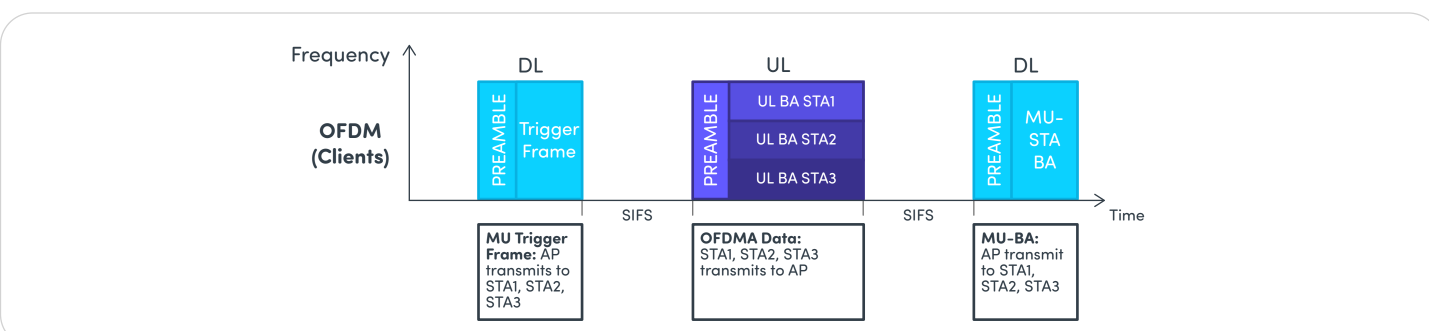


Figure 10. UL OFDMA - Multi-Client Transmits Simultaneously

Maximum RUs per PPDU

IEEE 802.11ax standard specifies a few possible RUs per PPDU for different channel bandwidth as shown in Table 1; each of the RU types can have any one of 26, 52, 106, 242, 484, 996, or 2x 996 subcarriers. These RU types are represented as RU26, RU52, RU106, RU242, RU484, and RU996 in this white paper. IEEE 802.11ax standard does not allow multiple RU allocations for an STA.

Table 1 shows the maximum RU allocation scenarios in terms of the possible RU numbers that can be scheduled for each specific channel bandwidth of 20MHz, 40MHz, 80MHz, and 160MHz. It only shows a single type of RU used in each allocation, so it does not cover other possible mixed RU allocations cases that are also allowed in 802.11ax. It is also clear from Table 1 that RU sizes can be larger when the channel bandwidth in use is larger. The possible RU allocation scenarios with mixtures of different RU types under the maximum allowed RUs per PPDU conditions are numerous and complicated. Refer to the RU allocation examples shown in Table 2, where some RU allocations consist of a mix of different types of RUs. A few examples in Table 2 show an RU type mixed with one or more 26-subcarrier type RUs to use the frequency spectrum more efficiently.

Table 1. Maximum Number of RUs for Each Channel Bandwidth

RU type	Channel Bandwidth (CBW20) 20MHz	Channel Bandwidth (CBW40) 40MHz	Channel Bandwidth (CBW80) 80MHz	Channel Bandwidth CBW80+80 and CBW160 80+80MHz and 160MHz
RU26: 26-subcarrier RU	9	18	37	74
RU52: 52-subcarrier RU	4^{+1}	8^{+1}	16^{+5}	32^{+10}
RU106: 106-subcarrier RU	2^{+1}	4^{+2}	8^{+5}	16^{+10}
RU242: 242-subcarrier RU	1	2	4^{+1}	8^{+2}
RU484: 484-subcarrier RU	N/A	1	2^{+1}	4^{+2}
RU996: 996-subcarrier RU	N/A	N/A	1	2
2x996 subcarrier RU	N/A	N/A	N/A	1

Notes:
1: x+n means + n 26-subcarrier RUs
2: The darker colored rows show the subcarrier RUs that can be used with MU-MIMO simultaneously

Aggregated Frame Rate

An OFDMA allocation for multiple clients to share a whole channel does not increase the total aggregated rate. While the basic concept of employing OFDMA vs OFDM is to share the channel bandwidth in frequency with multiple clients at a given time, there is some overhead due to a specific type of RU allocation shown in Table 2. This overhead can slightly reduce the maximum possible aggregated rate per frame in OFDMA compared with an OFDM aggregated rate with a theoretical calculation. This is evident that a scheduled OFDMA operation with multiple RUs sharing the channel bandwidth can potentially cause a lower aggregated rate on a per-PPDU basis than a simple single client or a single maximum allowed RU using the entire bandwidth.

Table 2: RU Allocations, Subcarriers, and Maximum PHY Rates

Channel Bandwidth (MHz)	RUs Allocation	Bandwidth of the largest RU	Data subcarriers with pilots	Data subcarriers excluding pilots	Lower-end guard subcarriers	Higher-end guard subcarriers	DC sub-carriers	Pilot sub-carriers	Null sub-carriers	Maximum Phy Rate per Spatial Stream (Mbps) (Short GI=800ns, SS=1, MCS11)	Total sub-carriers
20	9 x 26	1.88 MHz	234	216	6	5	7	18	4	132.3	256
	4 x 52, 1x 26	3.91 MHz	234	216	6	5	7	18	4	132.3	256
	2 x 106, 1 x 26	7.97 MHz	238	228	6	5	7	10	0	139.7	256
	1 x 242	18.3 MHz	242	234	6	5	3	8	0	143.4	256
40	18 x 26	1.88 MHz	468	432	12	11	5	36	16	264.6	512
	8 x 52, 2x 26	3.91 MHz	468	432	12	11	5	36	16	264.6	512
	4 x 106, 2 x 26	7.97 MHz	476	456	12	11	5	20	8	279.4	512
	2 x 242	18.3 MHz	484	468	12	11	5	16	0	286.8	512
	1 x 484	36.6 MHz	484	468	12	11	5	16	0	286.8	512
80	37 x 26	1.88 MHz	962	888	12	11	7	74	32	543.9	1024
	16 x 52, 5x 26	3.91 MHz	962	888	12	11	7	74	32	543.9	1024
	8 x 106, 5 x 26	7.97 MHz	978	936	12	11	7	42	16	573.5	1024
	4 x 242, 1x 26	18.3 MHz	994	960	12	11	7	34	0	588.3	1024
	2 x 484, 1x 26	36.6 MHz	994	960	12	11	7	34	0	588.3	1024
	1 x 996	76.6 MHz	996	980	12	11	5	16	0	600.4	1024
160	74 x 26	1.88 MHz	1,924	1,776	24	22	14	148	64	1,087.80	2.048
	32 x 52, 10x 26	3.91 MHz	1,924	1,776	24	22	14	148	64	1,087.80	2,048
	16 x 106, 10 x 26	7.97 MHz	1,956	1,872	24	22	14	84	32	1,147	2,048
	8 x 242, 2x 26	18.3 MHz	1,988	1,920	24	22	14	68	0	1,176.60	2,048
	4 x 484, 2x 26	36.6 MHz	1,988	1,920	24	22	14	68	0	1,176.60	2,048
	2 x 996	76.6 MHz	1,992	1,920	24	22	10	32	0	1,200.80	2,048

HE-SIG-B Format

RU allocation information is in the HE-SIG-B field of the preamble of an HE MU PPDU frame. The HE-SIG-B field is used to communicate RU assignments to STAs. As shown in Figure 10, the HE-SIG-B field consists of two sub-fields: the common field and user-specific field. A sub-field of the common field is used to indicate how a channel is partitioned into various RUs. For example, a 20 MHz channel might be subdivided into two 106-tone RU and one 26-tone RUs. The user-specific field comprises multiple user fields that specify which users are assigned to each individual RU.

The HE-SIG-B field of a 20MHz HE MU PPDU contains one HE-SIG-B content channel. The HE-SIG-B field of an HE MU PPDU that is 40 MHz or wider contains two HE-SIG-B content channels. In summary, the HE-SIG-B field can perform the following:

- Provide OFDMA and MU-MIMO resource allocation
- Present only in HE MU PPDUs for an OFDMA or MU-MIMO transmission
- Include different number of bits depending on RU allocation

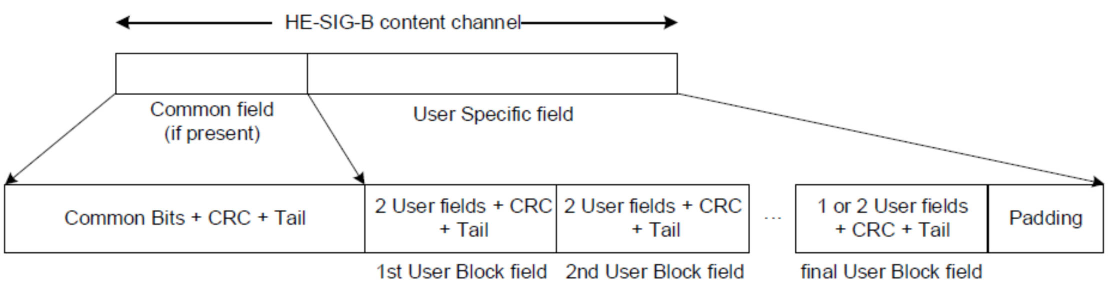


Figure 11. HE-SIG-B Content Channel Format (from IEEE 802.11AX Draft Standard)

HE-SIG-B User Common Field			
RU Allocation (N x 8 bits)	Center 26-tone RU (1 bit)	CRC (4 bits)	Tail (6 bits)
For RU allocation and number of users in each RU for MU-MIMO. N=1 for 20MHz and 40MHz, N=2 for 80MHz, and N=3 for 160MHz and 80+80MHz	0 for 20MHz and 40MHz, and 1 for bandwidth >= 80MHz	Calculated over bits 0 to N x 8 if bandwidth >= 80MHz, otherwise bits 0 to N x 8-1	Used to terminate the trellis of the convolutional decoder. Set to 0

Figure 12. HE-SIG-B Common Field

HE-SIG-B User Specific Field		
User Field (N x 21 bits)	CRC (4 bits)	Tail (6 bits)
User field for either MU-MIMO or non MU-MIMO: N:1 for non MU-MIMO. N=2 otherwise	Calculated over bits 0-20 for one user field and bits 0-41 for two user field	Used to terminate the trellis of the convolutional decoder. Set to 0

Figure 13. HE-SIG-B User-Specific Field

MU-MIMO and MU-MIMO-OFDMA

MU-MIMO as a spatial domain multiple access technology makes full use of the advantages of multiple antennas, and further improves both the transmission rate and the spectrum utilization. It allocates different spatial streams for different users, and the receiver must separate the spatial streams of different users by using signal processing technology. AP collects the channel state information (CSI) from STAs through an HE sounding protocol. STAs are further divided into several groups, and those in the same group can simultaneously transmit data, and the signals of different STAs can be distinguished via spatial streams. IEEE 802.11ac has already adopted DL MU-MIMO, IEEE 802.11ax further improves DL MU-MIMO, and introduces UL MU-MIMO, thus enabling symmetrical high throughput of both DL and UL. IEEE 802.11ax allows up to eight STAs to simultaneously transmit or receive through DL/UL MU-MIMO assuming a Wi-Fi 6 AP can support up to 8x8 MIMO.

Both MU-OFDMA and MU-MIMO are for concurrent multi-user service, and an AP can schedule SU-MIMO, MU-MIMO, and OFDMA interactively based on the channel conditions, QoS, device types, service types, and more. These are two key differences between the transmission types:

- OFDMA allows multi-user access by subdividing a channel with many RUs.
- MU-MIMO allows for multi-user access by using different spatial streams.

In other words, OFDMA splits a channel and MU-MIMO uses separate channels. From an RF condition aspect, MU-MIMO is primarily for short and medium range with STAs, while OFDMA can work all those conditions that STAs can be near and further to an AP. From the data traffic side, MU-MIMO is more suitable for high-bandwidth data traffic, while OFDMA is effective for low-bandwidth multi-client service scenarios.

PPDU frame structures to support MU-MIMO are comparable to those used for OFDMA. For DL MU-MIMO, AP uses the HE MU PPDU format to support both OFDMA and MU-MIMO. Spatial stream and RUs allocation information is embedded in the HE-SIG-B of the HE preamble portion, and then AP simultaneously transmits frames to multiple STAs through allocated spatial streams. For UL MU MIMO, AP uses trigger frame (TF) to trigger multiple STAs and allocate RUs and spatial streams. After that, the STAs triggered by AP use HE TB PPDU format to simultaneously transmit frames to AP through allocated spatial streams.

MU-MIMO and OFDMA can work simultaneously, i.e., multiple STAs can send frames through MU-MIMO in the same RU, to further increase transmission efficiency. IEEE 802.11ax standard limits that both UL and DL MU-MIMO can be performed only for RUs with at least 106 subcarriers, and MU-MIMO-OFDMA can support up to 128 RUs to service 128 clients STAs in a group/schedule for a 160MHz channel. With an 80MHz channel, the supported RUs is reduced to a maximum of 64.

802.11AX OFDMA: What to Test?

Testing OFDMA from either AP or STA side, can be a challenging task, as OFDMA operation is a complex process, and OFDMA scheduling is mainly handled by an AP based on many real-time parameters such as a number of STAs in the network, RF condition, current serviced traffic loading, traffic characteristics (packet size, type, etc.). Also, each AP product could have chipset vendor-specific implementations in terms of OFDMA scheduling. An AP is more like a black box in the way it handles OFDMA scheduling and employing all of the OFDMA rules imposed by 802.11ax standard, so there is much more to learn about the OFDMA operation on the AP side, compared with an STA end. The focus in this paper on OFDMA testing is on how to test an AP's OFDMA functionalities with many Wi-Fi 6 STAs. A list of testing challenges is included below, with more detailed testing items are listed in Table 3:

- Multi-user testing requires many individual client devices with different configurations
- Single radio interface to emulate multiple client devices for sequentially RX/TX is not feasible
- Many test cases require a lot of time
- Difficult to validate the OFDMA performance gain
- AP as the center hub usually a black box for OFDMA scheduling
- Traffic model complexity: Mix of packet types, L2 to L7, etc.
- Sniffer mode limited on per-client basis
- Uplink OFDMA challenges:
  - AP derived OFDMA STA synchronization: All STAs listen and talk at the same time (< 400ns difference)
  - At the same carrier frequency (< 350Hz)
  - STA power control: Adjustment needed for near and farther devices to the AP
- A lot of data to process: Real time statistics and counters vs post PCAP file processing

Table 3. OFDMA Testing Checklist

Item	Note
OFDMA capability	Both AP and STAs must support OFDMA in HE mode. The capability is communicated between AP and STAs during association process.
Maximum number of RUs per PPDU	Determine the maximum number of RUs per PPDU for different channel bandwidths
Traffic models to trigger	OFDMA is triggered by data traffic
Instantaneous RU allocations	AP's RU allocation is dynamic on a per-frame basis
Individual STA activity	STA's physical location, traffic loading, channel condition matters
AID sniffing for packet capture	Sniffer capture for MU packets is usually on a per-STA basis, so it requires multiple sniffers for multiple STAs
Single trip latency or Round-Trip Time (RTT) measurement	Latency improvement with OFDMA must measure per-packet travel time per STA
Throughput with L2-7 traffic	Throughput improvement with OFDMA is related to traffic types, packet size, loading, and priorities.

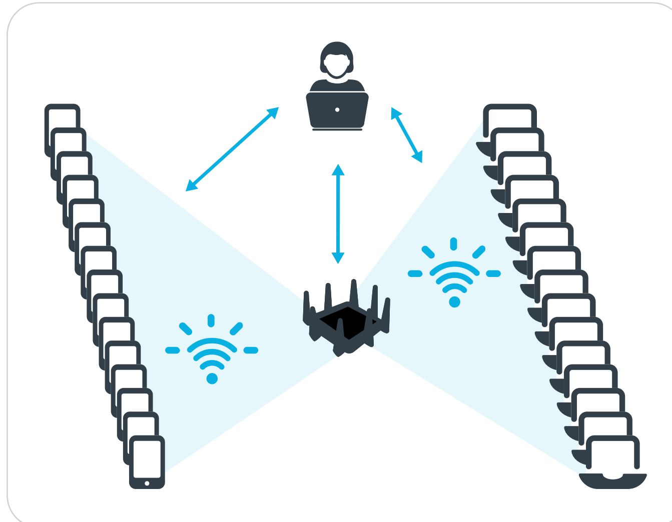


Figure 14. OFDMA Test Setup with Many Real STAs

It is easy to put many real STAs, such as the latest Wi-Fi 6 enabled mobile phones or laptop PCs together in a lab, like the example shown in Figure 14, as an OFDMA testing environment in a completely OTA and uncontrolled fashion. A synchronized operation among all of the individual client devices can be a challenge for testing purposes. This kind of testbed can be cost moderate but comes with major limitations in terms of achieving the testing objectives listed in Table 3. These are some example limitations:

- Testing accuracy and repeatability is not assured
- Impossible for conductive testing
- Multi-User (Many RUs) coordination
- Difficult to retrieve RU statistics from one or more devices
- Complex setup
- Traffic generation/analysis using the same CPU that is running the Wi-Fi driver
- Handling uncertainty

Spirent Wi-Fi 6 Appliances

Testing instruments with some level of integration among various interfaces including many 802.11ax STAs are needed to overcome testing challenges and limitations. Spirent Wi-Fi 6 platforms are designed to support the necessary test cases for OFDMA operations. The C50 HRC appliance shown in Figure 15 is a small 3U appliance form factor that combines Spirent's industry-leading IEEE 802.11ax WLAN interface cards (NICs) with multiple real Wi-Fi 6 client radios with Spirent 4-port IEEE 802.3bz BASE-T 100Mbps/1Gbps/2.5Gbps/5Gbps/10Gbps Ethernet card on a copper interface.

This test instrument has the industry's highest integration in terms of radio counts within a single small appliance box, in a unique platform hardware design, to adequately emulate multiple clients with required RUs for testing. Each radio interface is operated independently with a dedicated process engine for control and data plane operation.

The C50 HRC appliance can be set up with either RF cabled conductive or OTA mode. A testbed setup example is shown in Figure 15 where several external RF combiners along with a multi-channel programmable RF attenuator to connect a C50 to an RF chamber/enclosure. The required transmission power level can be properly adjusted with the programmable attenuator. This testbed can support multiple test cases such as OFDMA, MU-MIMO, rate vs range, etc.

With this C50 HRC appliance, users can emulate up to 20 full-featured 802.11ax STAs to connect with an AP via a cabled conductive or over-the-air (OTA) link. Each radio stream path is characterized with the minimum internal RF signal path loss. This provides assurance for the typical use cases of 802.11ax with a need to support the maximum achievable performance in radio interface level. The appliance has an internal hardware clock based timing crossing all radio interfaces and Ethernet interfaces with a high precision timing synchronization intended to emulate true realistic clients operating individually and for an accurate latency measurement. This proprietary timing interface allows inter-connection of multiple Spirent appliances and chassis to share a commonly shared timing clock. Consequently, two or more C50 appliances can be easily inter-connected with an RJ45 cable to achieve even higher OFDMA or MU client counts for higher scale test cases. Basic WLAN control plane and data plane features, along with the Spirent's signature L2-7 and rich set of protocols for timing, traffic, and throughput performance test cases are supported over the WLAN network involving those Wi-Fi 6 clients and the APs under test. All those features enable testing of complex new 802.11ax features like OFDMA.

Figure 15. Spirent Wi-Fi 6 C50 Appliance

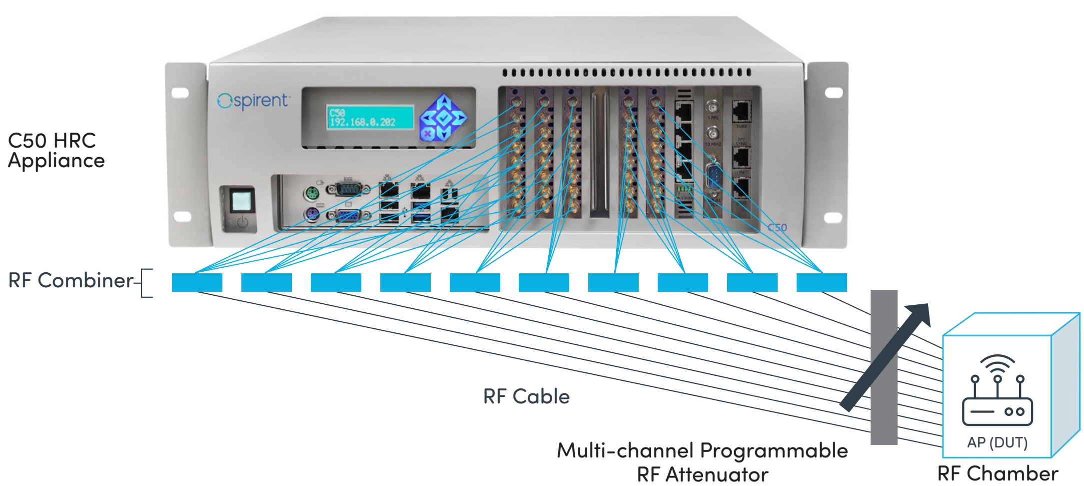


Figure 16. C50 Setup in Either Conductive or OTA Mode

OFDMA Statistics and Counters

The following OFDMA statistics and counters are reported with the testing tool in real-time during testing:

- PPDU type, RU type
- RU counters
- MU and SU packet counter
- RU allocation/placement table on per AID basis

Statistics and counters are shown in Table 5. Here, PPDU type mainly shows whether a packet in HE PHY layer is transmitted in either SU or MU PPDU format. This statistic parameter only has a valid meaning when there are data packet traffic. It is interesting to note that an HE PPDU type as an instantaneous status can be one of those listed in Table 4. With this testing tool, OFDMA related statistics and counters are captured and decoded based on MU-BAR, MU-BA, preamble of a PPDU frame, and are subsequently analyzed and reported in real-time while testing.

Table 4. HE PPDU Type

HE PPDU Type
SU
MU-OFDMA
MU-MIMO
MU-MIMO-OFDMA

Table 5. OFDMA Statistics and Counters

Item (RX/TX per STA)	Value
PPDU Type (Instantaneous)	One of: • SU • MU-OFDMA • MU-MIMO • MU-MIMO-OFDMA
RU Type (Instantaneous)	One of: 26, 52, 106, 242, 484, 996
MU Counter	Ethernet packet transmitted with MU
SU Counter	Ethernet packet transmitted with SU
RU26 Counter	Total transmitted packets with 26 subcarrier RU
RU52 Counter	Total transmitted packets with 52 subcarrier RU
RU106 Counter	Total transmitted packets with 106 subcarrier RU
RU242 Counter	Total transmitted packets with 242 subcarrier RU
RU484 Counter	Total transmitted packets with 484 subcarrier RU
RU996 Counter	Total transmitted packets with 996 subcarrier RU

For example, the downlink OFDMA results table reported by the tool is shown for testing with an AP that supports 16 RUs per PPDU. The AP was set with 80MHz channel support. The most common RU type for the RUs is a 52-subcarrier RU with 80MHz channel. It also showed that when the AP is set to support 160MHz channel bandwidth, 16 RUs loaded on per PPDU is most commonly with 106-subcarrier RUs. This makes sense because the AP can support up to 16 RUs per PPDU, and with 160MHz, each RU can take more subcarriers from 52-subcarrier case in 80MHz channel to 106-subcarrier in 160MHz. However, if the AP is set to support 40MHz, it then shows that the most RUs are loaded with 26-subcarrier RU for up to 16 RUs per PPDU in the 40MHz channel case. If the AP is further set to support only 20MHz channel bandwidth, then the maximum RUs per PPDU with 26-subcarrier RU will drop to 9 RUs.

In 802.11ax, AP can use SU-MIMO, MU-MIMO, and OFDMA interactively according to the channel conditions, QoS, device types, service types and more. Each AP optimizes scheduling and selects the best method for the next action based on their own or customized algorithms. OFDMA RUs allocation is dynamic and complex on per PPDU basis. Understanding how the AP is doing the RUs allocation and placement becomes one of the major tasks from testing point of view. An AP assigns an RU per AID with an RU type and in an exact frequency portion with sub-carriers assigned on the channel within the bandwidth in use. As shown in Tables 6 and 7, the testing tool reports the instantaneous RU type along with the RU location number. This information can be easily used to interpret the exact RUs allocation for each AID within 80MHz channel spectrum as shown in Table 8. Since the RUs allocation is not always same for each OFDMA transmission, it is important to include RUs placement results over time (samples) to view a history of the data on the RUs allocations. Refer to Figure 17 for an example including a few samples for illustration purposes.

Table 6. OFDMA Statistics and Counters

IEEE 802.11 Client Rx OFDMA Results (Not Saved) LIVE

Device Name	RX RU Type	Rx PPDU Type	Rx RU26	Rx RU52	Rx RU106	Rx RU242	Rx RU484	Rx RU996	Rx MU Packets (frames)	Rx SU Packets (frames)
STA1	52-tone	MU-OFDMA	0	77,638	302	3,183	2,965	511	2,353,741	31,596
STA2	52-tone	MU-OFDMA	0	83,686	551	1,811	2,296	696	2,369,097	19,888
STA3	52-tone	MU-OFDMA	0	83,254	547	2,006	2,289	703	2,362,791	23,943
STA4	52-tone	MU-OFDMA	0	83,317	567	2,085	2,410	680	2,369,617	22,264
STA5	52-tone	MU-OFDMA	0	75,040	189	3,763	2,826	336	2,359,878	24,358
STA6	52-tone	MU-OFDMA	0	81,597	476	2,392	2,580	661	2,363,499	25,422
STA7	52-tone	MU-OFDMA	0	81,906	514	2,343	2,506	638	2,361,726	24,467
STA8	52-tone	MU-OFDMA	0	82,375	521	2,229	2,613	662	2,361,873	25,939
STA9	52-tone	MU-OFDMA	0	83,646	615	2,179	2,520	711	2,373,098	13,980
STA10	52-tone	MU-OFDMA	0	81,416	477	2,441	2,652	590	2,371,530	15,560
STA11	52-tone	MU-OFDMA	0	81,792	506	2,371	2,518	652	2,373,638	15,212
STA12	52-tone	MU-OFDMA	0	81,837	470	2,363	2,607	605	2,368,945	19,682
STA13	52-tone	MU-OFDMA	0	82,395	545	2,293	2,624	663	2,355,922	29,939
STA14	52-tone	MU-OFDMA	0	82,451	496	2,236	2,588	739	2,374,493	14,736
STA15	52-tone	MU-OFDMA	0	83,007	554	2,091	2,576	679	2,373,659	15,925
STA16	52-tone	MU-OFDMA	0	83,313	559	2,097	2,433	717	2,372,677	17,457
STA17	52-tone	MU-OFDMA	0	83,039	565	2,132	2,526	680	2,350,862	38,920
STA18	52-tone	MU-OFDMA	0	85,781	723	1,418	1,941	771	2,367,948	23,530
STA19	52-tone	MU-OFDMA	0	85,141	658	1,526	2,068	780	2,375,175	15,108

19 results shown

Table 7. Instantaneous OFDMA RU Allocations

Downlink OFDMA Instantaneous RU Placement Results LIVE

AID	RU26	RU52	RU106	RU242	RU484	RU996
1		9				
4		14				
5		7				
6		10				
7		0				
8		12				
9		2				
10		1				
11		5				
13		8				
14		11				
15		15				
16		13				
17		3				
18		6				
19		4				
2						
3						
12						

19 results shown

Table 8. AID RU Allocation Details on 80MHz Channel

AID7	AID10	AID9	AID17	AID19	AID11	AID18	AID5	AID13	AID1	AID6	AID14	AID8	AID16	AID4	AID15
RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52	RU52
80MHZ CHANNEL															

	AID1	AID2	AID3	AID4	AID5	AID6	AID7	AID8	AID9	AID10	AID11	AID12	AID13	AID14	AID15	AID16
9	RU52	RU52	RU52	RU52	RU242	RU52	NS	RU52	RU52	RU52	NS	NS	NS	RU52	RU52	RU52
8	RU52	RU52	RU52	RU52	RU52	RU52	NS	RU52	NS	NS	NS	NS	NS	RU52	RU52	NS
7	RU52	RU52	RU52	RU52	NS	RU52	NS	RU52	RU52	RU52	RU52	RU106	RU52	RU52	RU52	RU52
6	RU52	RU52	RU52	RU52	RU52	RU52	NS	RU242	NS	NS	NS	RU52	NS	NS	RU52	RU52
5	RU52	RU52	RU52	RU52	NS	RU52	RU52	RU52	RU52	NS	RU52	RU106	RU52	RU52	RU52	RU52
4	RU484	RU52	RU52	RU52	RU52	RU52	NS	RU52	NS	NS	NS	NS	NS	RU52	RU52	NS
3	RU52	RU52	RU242	RU52	RU52	RU52	NS	RU52	RU52	NS	NS	RU52	NS	RU52	RU52	RU52
2	RU52	RU52	RU52	RU52	NS	NS	NS	RU52	NS	RU52	NS	NS	NS	RU52	RU52	NS
1	RU52	RU52	RU242	RU52	RU52	NS	NS	RU52	RU52	NS	RU52	NS	NS	NS	RU52	NS

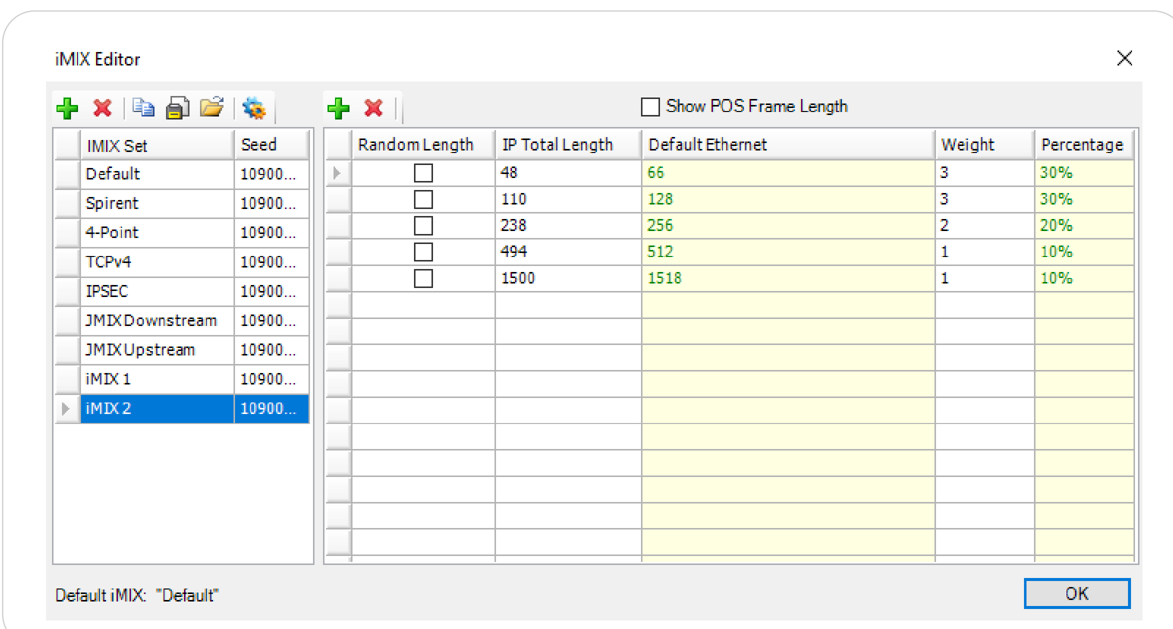
Figure 17. AID RU Allocation over Samples

Traffic Models for OFDMA

Multi-user OFDMA for 802.11ax is mainly for data traffic frames, although some control frames can also be transmitted with MU PPDUs. To examine how OFDMA is being triggered, in terms of frequency, type of RUs, performance change, etc., it is important to carefully consider the traffic models and characteristics for designing test cases. Real life data traffic flow data can play a critical role in defining meaningful traffic test cases.

Spirent Wi-Fi 6 C50 test system provides best in class L2/3 traffic generation, testing, and analysis capability, to enable benchmark testing OFDMA in either downlink or uplink.

It is noted with L2/3 traffic testing that smaller packet sizes such as 64 byte or 128 byte can more easily trigger OFDMA operations than larger packet size traffic.However, even with the maximum 1518 byte packet size, multi-user OFDMA can be observed less frequently. It is practically useful that, for OFDMA testing, a more advanced traffic mixture of different packet sizes can be employed; this feature is called iMix traffic generation as shown in Table 9. Both the number of different packet sizes, and the weight on each packet size, can be easily configured with the iMix in a user friendly interface.



IMIX Set	Seed
Default	10900...
Spirent	10900...
4-Point	10900...
TCPv4	10900...
IPSEC	10900...
JMIX Downstream	10900...
JMIX Upstream	10900...
iMIX 1	10900...
iMIX 2	10900...

Random Length	IP Total Length	Default Ethernet	Weight	Percentage
☐	48	66	3	30%
☐	110	128	3	30%
☐	238	256	2	20%
☐	494	512	1	10%
☐	1500	1518	1	10%

Table 9. iMix UDP Traffic Configuration

Spirent Enhanced L4-7 test solution enables easy testing for stateful TCP traffic such as FTP, HTTP, POP3, and more, along with many realistic application-layer traffic testing. This new tool is extremely useful for examining OFDMA operations in terms of many meaningful traffic scenarios. The supported testing topologies are over emulated interfaces such as Wi-Fi and different speed Ethernet interfaces as shown in Figures 18 and 19. Other application traffic testing also covers some typical Wi-Fi features such as captive portal testing, video and audio quality, and performance measurement over a Wi-Fi interface.

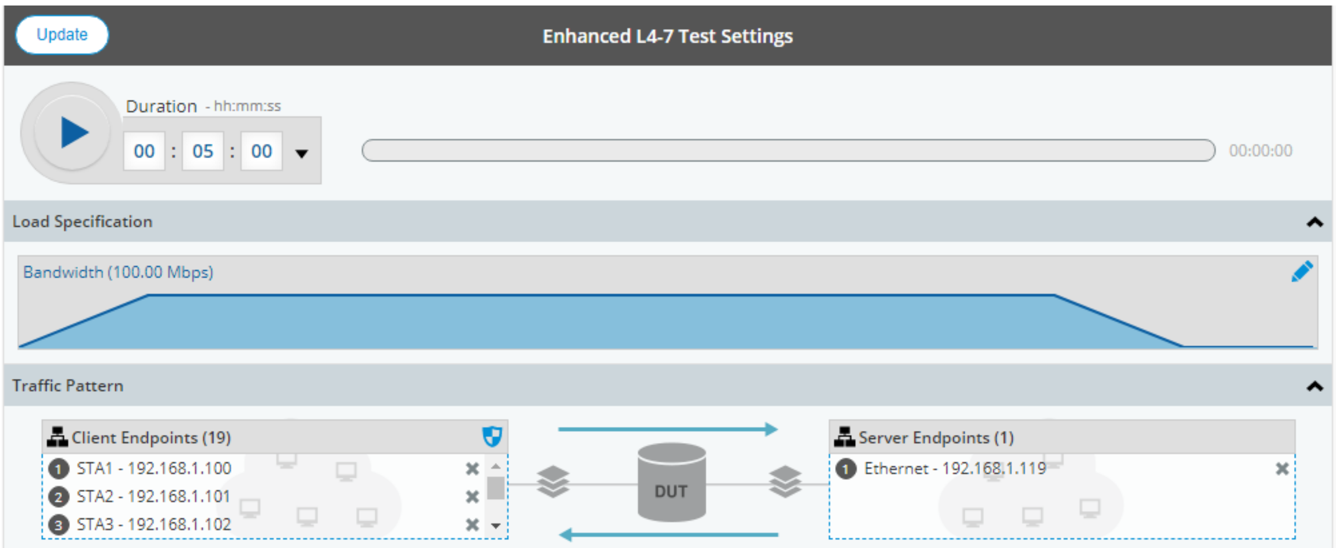


Figure 18. Spirent TestCenter Enhanced L4-7 Testing Topology

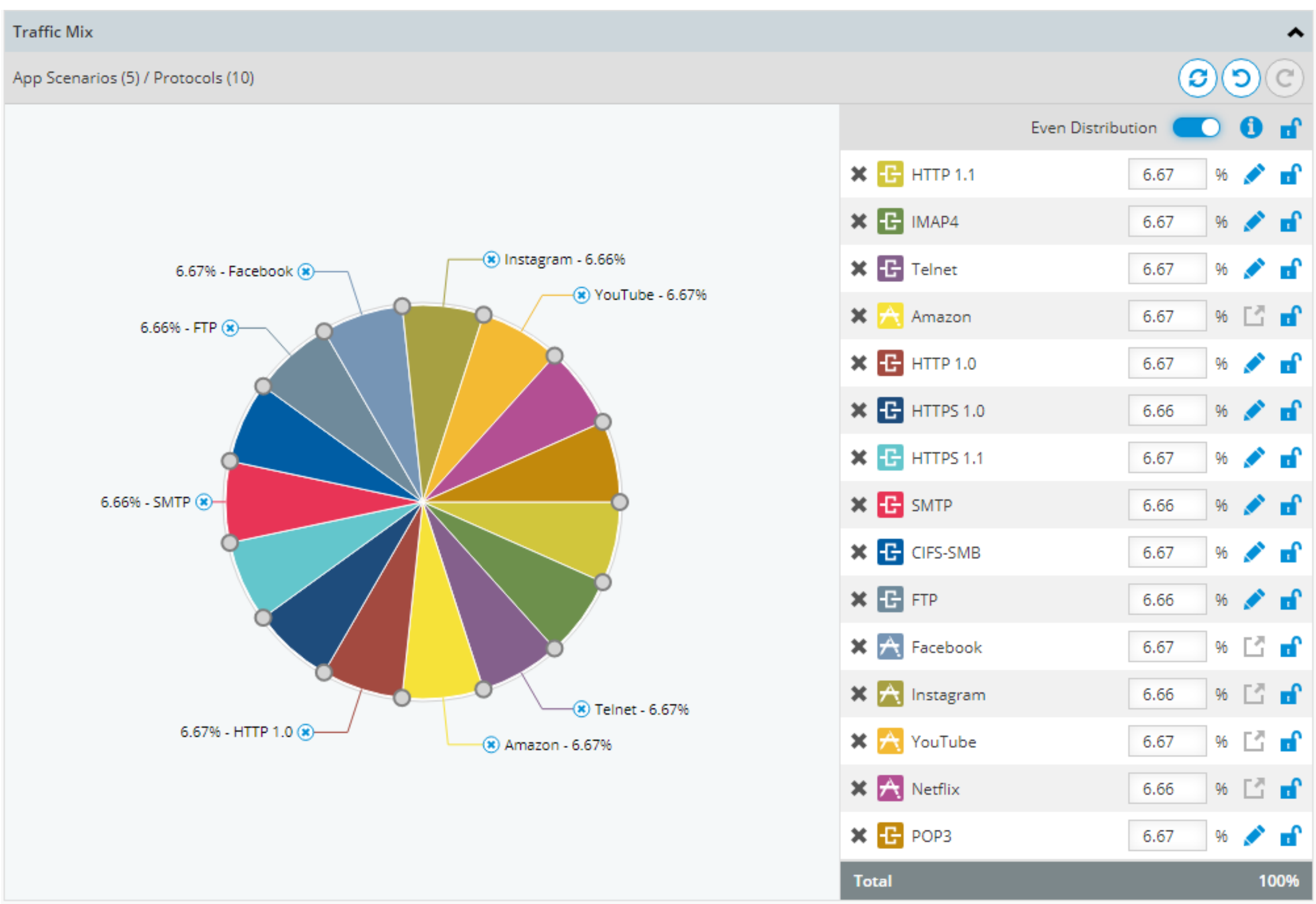


Figure 19. Enhanced L4-7 traffic mix

Testing Observations

Expectations for Wi-Fi 6 OFDMA can be very different from one use case to another. Usually, an in-lab testing coverage for an AP product tends to be wide and meaningful with a set of selected test cases. Based on the testing experience there are some observations and understandings that could be relevant to OFDMA testing in general. When a tester designs test cases to validate OFDMA features of their Wi-Fi 6 AP products, these points should be considered:

- **Downlink OFDMA tests are more easily triggered and performed successfully than uplink**
  DL OFDMA is based on a single PPDU for all STAs, while UL OFDMA involves multiple STAs performing synchronized transmission. Therefore, DL and UL OFDMA are largely asymmetrical in operation.
- **AP does not usually load maximum numbers of RUs per PPDU**
  OFDMA RU scheduling is on a best effort basis, AP may or may not be able load the maximum RUs per PPDU. This can be more visible for uplink OFDMA.
- **Mixture of different RU types is very common**
  In addition to 26-subcarrier RU combining with other RUs, larger RUs can also be scheduled with smaller RU types.
- **Not always expect to see a clear throughput performance gain**
  OFDMA can provide a clear improvement in performance with certain types of traffic, but we cannot see the throughput gain with all traffic mixes.
- **Uplink OFDMA improves RF contention, so expect to see more throughput gain**
  UL OFDMA with multiple STAs transmits simultaneously with its own portion of sub-channel within the whole channel. This largely eliminates RF contention among the OFDMA scheduled STAs and so improves the RF channel utilization.
- **Smaller packet sizes trigger OFDMA more frequently**
  Transmission of larger packet size could require more channel bandwidth. This seems to be true, as 802.11 frame aggregation can include more packets into a single frame with smaller packet sized traffic. This helps the OFDMA scheduler with multiple STAs to share the channel with RUs.
- **Lower traffic loading per user triggers OFDMA more frequently**
  When there are low data demand STAs, there is a higher possibility that multiple STAs share the channel with other STAs in OFDMA transmission.
- **Downlink OFDMA can clearly show latency improvement over OFDM**
  If multiple STAs can share a single DL OFDMA transmission, the packet waiting time in the buffer queue to be transmitted from an AP to STAs can be generally improved in the downlink.
- **For larger packet size, OFDMA scheduling can cause a lower throughput in general**
  As shown in Table 2, there could be some overhead in sharing the spectrum among multiple STAs with OFDMA than with a single STA (single RU) occupying the entire channel.
- **For larger packet sizes, MU-MIMO can be more effective in gaining throughput than OFDMA**
  MU-MIMO and OFDMA provide complementary techniques to concurrently serve multiple users. MU-MIMO best serves multiple users with full buffer traffic, while OFDMA is utilized when multiple connections transmit relatively limited amounts of data. Simply speaking, OFDMA is more suitable with low-bandwidth data traffic, while MU-MIMO better serves high-bandwidth cases.
- **Combined MU-MIMO with OFDMA (partial bandwidth MU-MIMO) is not easy to see**
  AP must support this feature and 802.11ax standard restricts that only RU type 106 or larger can be scheduled for this type of MU operations involving both MU-MIMO in spatial stream dimension and OFDMA in frequency axis. MU-MIMO-OFDMA is an optional feature from either IEEE 802.11ax or WFA perspective. It is complicated to implement, and many Wi-Fi 6 chipsets are not yet available to support the feature.

Conclusions

Testing Wi-Fi 6 OFDMA can be a challenging task with the complex nature of the feature defined in 802.11ax with many operating scenarios. It is essential to understand how Wi-Fi 6 OFDMA works, based on the 802.11ax standard including the specifics of the OFDMA triggering mechanism, information exchange protocol, and PPDU transmission.

Spirent Wi-Fi 6 C50 test system provides a highly integrated solution for testing OFDMA features. It enables both RF cabled conductive testing and more realistic OTA setup, while collecting OFDMA statistics and counters in real time to help quickly analyze OFDMA operation behavior and performance.

The solution also supports full multiple and synchronized MU sniffer captures for MU packets for post data processing. The embedded L2-7 traffic generation and analysis helps perform thorough validation with various realistic and meaningful traffic models for OFDMA use cases.

Acronyms

ACK	Acknowledgment
AID	Association ID
AP	Access Point
BA	Block ACK
BAR	Block ACK Request
BSR	Buffer Status Report
BSS	Basic Service Set
CSMA/CA	Carrier Sense Multiple Access with Collison Avoidance
CTS	Clear To Send
DL	Downlink
GI	Guard Interval
HE	High Efficiency
HE-LTF	HE Long Training Field
HE-STF	HE Short Training Field
IEEE	The Institute of Electrical and Electronics Engineers
LAN	Local Area Network
L-SIG	Legacy Signal Field
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple Input and Multiple Output
MRG	Margin
MU	Multi-user
MU-CTS	MU Clear To Send
MU-RTS	MU Request To Send
NAV	Network Allocation Vector
NSS	Number of Spatial Streams
OBO	OFDMA Back-off
OBSS	Overlapping BSS
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PER	Packet Error Rate
PHY	Physical Layer
PPDU	PHY Protocol Data Unit
QoS	Quality of Service
RSSI	Received Signal Strength Indicator
RTS	Request To Send
RU	Resource Unit
SIFS	Short Interframe Space
STA	Station
STC	Spirent TestCenter
SU	Single User
TB	Trigger Based
TWT	Target Wake Time
UL	Uplink
WFA	Wi-Fi Alliance
WLAN	Wireless LAN

About Spirent

Spirent Communications (LSE: SPT) is a global leader with deep expertise and decades of experience in testing, assurance, analytics and security, serving developers, service providers, and enterprise networks. We help bring clarity to increasingly complex technological and business challenges. Spirent's customers have made a promise to their customers to deliver superior performance. Spirent assures that those promises are fulfilled.

For more information visit: www.spirent.com

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Americas 1-800-SPIRENT
+1-800-774-7368 | sales@spirent.com

Europe and the Middle East
+44 (0) 1293 767979 | emeainfo@spirent.com

Asia and the Pacific
+86-10-8518-2539 | salesasia@spirent.com