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Karl Montgomery
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Karl Montgomery
Richard Candell
*Smart Connected Systems Division*
*Communications Technology Laboratory*

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**NIST Author ORCID iDs**
Karl Montgomery: 0000-0001-5405-6665
Richard Candell: 0000−0002−6679−8823

**Contact Information**
karl.montgomery@nist.gov

## Abstract

This report serves to determine how Orthogonal Frequency Division Multiple Access (OFDMA) is triggered in commercial IEEE 802.11ax (Wi-Fi 6) access points for industrial application scenarios. It presents an overview of OFDMA and how it works in IEEE 802.11ax (Wi-Fi 6). Then, it provides the measurement methodologies for determining OFDMA triggering conditions by performing experiments that vary the traffic, number of wireless stations, and transmitted packet lengths. A wireless sniffer is used to determine when OFDMA trigger frames are sent, indicating OFDMA activation. The resulting table shows what set of conditions activate OFDMA in the test environment. Of the two commercial access points tested in this report, both are observed to follow the same condition for OFDMA activation, namely when two or more stations send over 100 packets per second, regardless of packet size. Another contribution is a method to determine when OFDMA is activated using an industrial computer, configured as a wireless sniffer.

## Keywords

Industrial wireless; time-sensitive networking; manufacturing.

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# 1. Introduction

## 1.1. Orthogonal Frequency Division Multiple Access

Orthogonal Frequency Division Multiple Access (OFDMA) refers to a bandwidth-efficient payload delivery method for high-density user deployments serving multiple users simultaneously, but the users may have varying bandwidth needs. In previous versions of Wi-Fi, before IEEE 802.11ax (Wi-Fi 6), Orthogonal Frequency Division Multiplexing (OFDM) was implemented. However, the OFDMA features implemented in Wi-Fi 6 can divide the usable bandwidth into many subcarrier frequencies. Under the IEEE 802.11ax specification, OFDMA allows for simultaneous transmissions that are split into Resource Units (RUs), which have a minimum size of 26 tones. Each tone has a bandwidth of 78.125 kHz, which is equivalent to 20 MHz divided by 256. The Access Point (AP) determines how and when users are allocated RUs. Figure 1 illustrates the difference between OFDM and OFDMA in the frequency and time dimensions. There are more subcarriers present in the real implementation of OFDMA; however, only five are shown for simplicity.

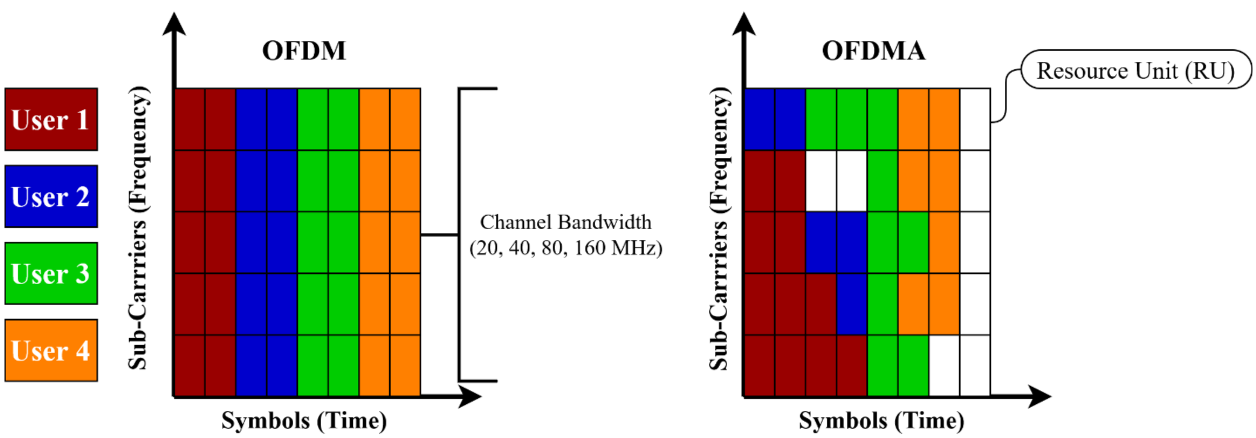


**Figure 1: OFDM vs OFDMA for multiple users**

## 1.2. How OFDMA is Used in Wi-Fi 6 to Improve Performance

In IEEE 802.11ax, the AP determines when and which packets to allocate to the possible RUs using OFDMA, given the traffic patterns from the stations. In OFMDA, the AP allocates a certain number of RUs to the transmissions to efficiently split up the bandwidth, with the number of RUs specified by the IEEE 802.11ax standard [1]. The effect of this on performance is greatly increasing the number of transmissions with multiple users without sacrificing as much latency as without OFDMA [2]. Table 1, from [3], shows the maximum number of RUs possible for each channel bandwidth. Note that “N/A” is used in the table where there is insufficient channel capacity for the number of tones.

**Table 1: Maximum number of RUs for each channel bandwidth**

| Tones per RU | RUs per 20 MHz Channel | RUs per 40 MHz Channel | RUs per 80 MHz Channel | RUs per 160 MHz Channel |
|---|---|---|---|---|
| 26 | 9 | 18 | 37 | 74 |
| 52 | 4 | 8 | 16 | 32 |
| 106 | 2 | 4 | 8 | 16 |
| 242 | 1 | 2 | 4 | 8 |
| 484 | N/A | 1 | 2 | 4 |
| 996 | N/A | N/A | 1 | 2 |
| 2 x 996 | N/A | N/A | N/A | 1 |

As more clients are queuing to transmit, it is important that a large enough bandwidth is used. For example, with the 20 MHz channel, only up to 9 RUs can be allocated. Whereas, for the 160 MHz channel, up to 74 RUs can be allocated. This greatly increases the number of stations that can send packets simultaneously. Figure 2 shows possible RU allocations for the 20 MHz bandwidth. Note that there are guard tones and null subcarriers that do not contain information and are used to reduce adjacent subcarrier interference from other transmissions. The null subcarriers are used to fill out the entire channel bandwidth.

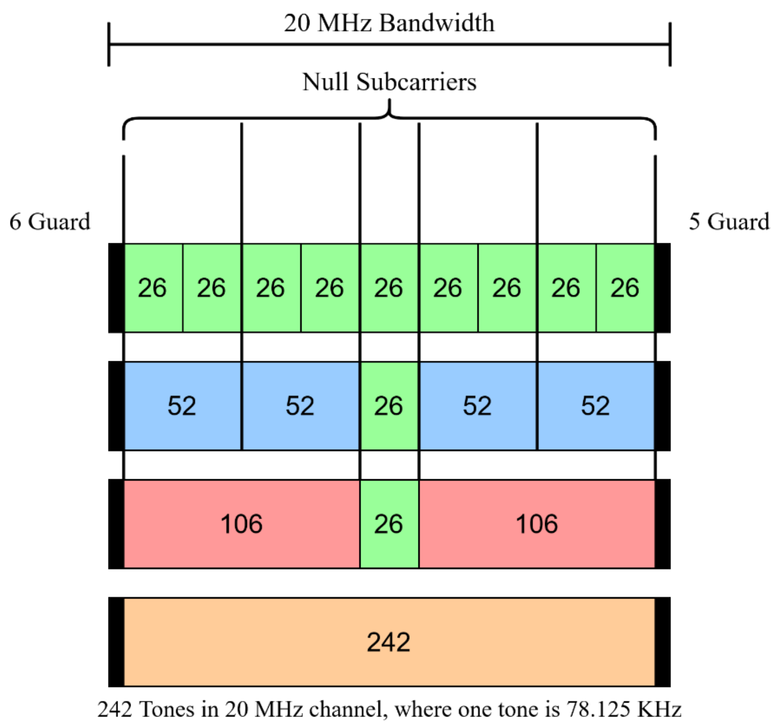


**Figure 2: RU allocation for a 20 MHz channel**

## 1.3. Motivation for Experiments

The manufacturer of the AP sets the triggering condition for OFDMA activation; therefore, it is important to determine the conditions for when OFDMA activates. Specifically, the OFDMA trigger conditions should be known for the experiments executed within the NIST Industrial Wireless Testbed [4]. To characterize triggering condition boundaries, a series of experiments were performed with varying traffic loads, packet sizes, and number of stations transmitting data simultaneously to determine the conditions when OFDMA is activated. With this knowledge, we plan to design traffic flows utilizing the Industrial Wireless Testbed with high data rate applications.

## 2. Experimental and Measurement Methodology for Characterizing OFDMA

As seen in Figure 3, there is a wireless AP that connects to three stations. For the experiment, the stations run iPerf Clients, which connect to the iPerf Traffic Sink [5], running the server instance. They transmit user datagram protocol (UDP) packets with different packet lengths and transmission rates. The iPerf traffic streams are considered uplink transmissions, due to the traffic flows, which are transmitted from the wireless stations to the iPerf Traffic Sink. The AP and Traffic Sink are connected via Ethernet to a common local area network (LAN) switch, which enables the connectivity and configuration of the devices. All the traffic sent to the sink was received without loss through the experimental runs. Lastly, a wireless sniffer is configured to capture the over-the-air packets to determine when OFDMA is active.

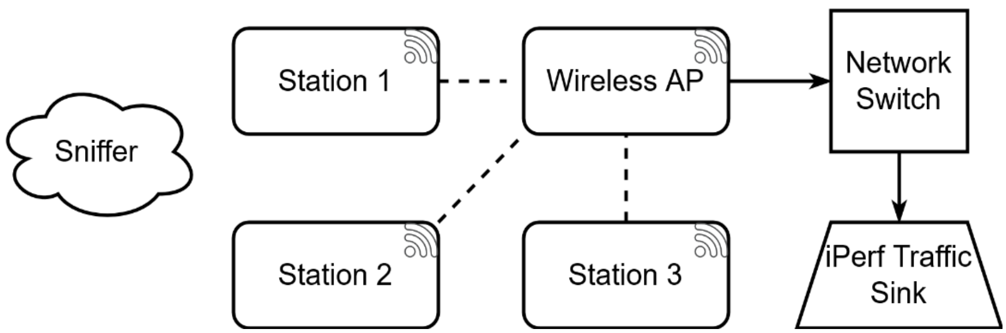


**Figure 3: Network diagram of OFMDA experiment**

### 2.1. Experimental Methodology

To explain how the experiment was developed, it was observed that sending the traffic at different packet lengths made a difference for OFDMA activation at a given data rate, thus, the resulting packets per second change was influential. Also, the number of stations transmitting packets was observed to impact results. Therefore, we used two different packet lengths for the experiment, which were 100 B and the Ethernet maximum transmission unit of 1500 B. We also varied the data rate from as low as 80 kilobits per second (kbps) to 100 megabits per second (Mbps). The AP was set to use channel 36, corresponding to a center frequency of 5.18 GHz, with up to a 160 MHz channel bandwidth, using 802.11ax with OFDMA mode enabled. Data for each run was captured for 1 minute.

### 2.2. Equipment Used for Experimentation

Two different APs were used for comparison. A TP-Link Archer AXE16000 was used for the results shown in Section 3, and then an ASUS RT-AX82U was used as the AP, which showed that the same conditions that triggered the TP-link AP also triggered the ASUS AP. Therefore, not all data points were repeated for the ASUS AP. The stations and sniffer were Onlogic ML 100G-52 industrial Next Unit of Computing (NUC) devices, which have updated Intel AX210 IEEE 802.11ax Wi-Fi chips installed with two antennas per station. All stations, sniffer, and iPerf traffic sink had the Ubuntu 20.04 operating system.

## 2.3. Measurement Methodology

To measure when OFDMA was active, wireless captures were taken by a NUC, with its wireless interface set to a monitor mode on channel 36 by using the airmon-ng package [6]. Then, the tcpdump package [7] was used to capture the packets. To analyze the captures, the files were copied to a machine that has a development version of Wireshark, version 4.1, which was able to display the trigger frames sent by the AP. These trigger frames were observed to allocate RUs for a multi-user OFDMA transmission. If there were no trigger frames during the run, then the conditions were not met to activate OFDMA.

## 3. Results

The results of the experiment are presented in Table 2, for which the “n” represents when OFDMA was not active, and “y” represents when OFDMA was active. The results shown describe the experiments utilizing the TP-Link AP. OFDMA requires two or more users, thus, a single station would not activate OFDMA, regardless of the data rate.

**Table 2: OFDMA activation for 2 and 3 stations sending iPerf uplink traffic**

| iPerf Uplink Data Rates | 2 STA (1500 B[1]) | 2 STA (100 B) | 3 STA (1500 B) | 3 STA (100 B) |
|---|---|---|---|---|
| 80 Kbps | n | n | n | n |
| 90 Kbps | n | y | n | y |
| 100 Kbps | n | y | n | y |
| 1 Mbps | n | y | n | y |
| 2 Mbps | y | y | y | y |
| 5 Mbps | y | y | y | y |
| 10 Mbps | y | y | y | y |
| 20 Mbps | y | y | y | y |
| 50 Mbps | y | y | y | y |
| 100 Mbps | y | y | y | y |

Note that the results show the same pattern of OFDMA activation for both 2 and 3 stations sending uplink traffic. Also, OFDMA uplink trigger frames could be activated with a lower data rate when sending 100 B-length packets. Further traffic testing was performed to find the exact point when OFDMA activates, which was determined to be based on the packet transmission rate in packets per second (pps). The observation based on the results presented for OFDMA uplink trigger activation, is that OFDMA is triggered when at least two stations send over 100 pps. An example that confirmed this observation was that when one station sent over 300 pps and two other stations sent 95 pps each, OFDMA activated. Other conditions may exist that would activate OFDMA uplink frames with more than two users transmitting simultaneously; however, those conditions may be further explored in future work. Lastly, when the second AP, the ASUS RT-AX82U, was used, it was observed that the trigger conditions for OFDMA activation were the same as for the TP-Link AP.

[1] 1500 B represents the payload size of the iPerf UDP packets. Note that the 100 B packets transmit 15 times more packets per second compared to 1500 B at a constant iPerf Data rate.

## 4. Conclusion

This report first presents a primer of OFDMA operation based on the IEEE 802.11ax specification, then follows with the experiment and measurement methodologies for determining OFDMA triggering conditions. The results in Table 2 showed the conditions required for OFDMA trigger frames to be activated in the commercial APs by observing the presence of trigger frames in the packet captures detected by a Wi-Fi sniffer capable of trigger frame detection. The two commercial APs used for conducting the test for this report exhibit the same condition behavior for OFDMA uplink trigger frame activation. In our system, OFDMA activated when two or more stations transmit over 100 pps, regardless of packet size. Given this information, OFDMA could be used to shorten transmission intervals for time-sensitive data. Fake transmissions over 100 pps could be transmitted wirelessly to activate OFDMA uplink frames. This could benefit operational systems utilizing OFDMA-capable WLANs in scenarios requiring deterministic latency. Furthermore, OFDMA could be used to prevent the need for a time-sensitive networking implementation within Wi-Fi under certain conditions. To investigate this further, a comparison of OFDMA with our previous work, in [8], utilizing TSN with Wi-Fi to determine trade-offs between the two approaches is needed. This concept will be explored in our future work.

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