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ADVANCED WIRELESS LAN TECHNOLOGIES: IEEE 802.11AC AND BEYOND

In 2013, global mobile data traffic grew 81% and it is projected to increase 11-fold between 2013 and 2018. Further, it is predicted that by 2018, over two-thirds of the world's mobile traffic will be video and more than half of all traffic from wireless connected devices will be offloaded to Wi-Fi networks and femto-cells [1]. Consequently, wireless LANs need major upgrades to improve both throughput and efficiency. IEEE 802.11ac is an amendment to the 802.11 standard that was just ratified by IEEE 802.11. Promising up to gigabit data rates, many Wi-Fi products are being built based on this specification. In addition to technologies that improve throughput, IEEE 802.11ax is investigating and evaluating advanced wireless technologies that enable more efficient utilization of the existing spectrum.

In this article, we introduce advanced WLAN technologies that have been standardized by IEEE 802.11ac or are currently being evaluated by IEEE 802.11ax. Table 1 provides a summary of the basic technology parameters for 802.11ac and 802.11ax.

We will also review 802.11ac and discuss 5 GHz channelization, including the static/dynamic channel bandwidth operation with RTS/CTS, and downlink multi-user MIMO. In Section 3, we provide an overview of the likely direction of 802.11ax and describe Simultaneous Transmit/Receive (STR), downlink and uplink OFDMA, uplink MU MIMO, and dynamic CCA, which are being discussed in 802.11ax.

802.11AC

As an evolution to 802.11n, 802.11ac adds 80 MHz, 160 MHz and non-contiguous 160 MHz (80 + 80 MHz) channel bandwidths [3]. Static and dynamic channel bandwidth operation with RTS/CTS are defined to support the wider channel bandwidths.

Another major throughput enhancement feature is multi-user capability in the form of downlink multi-user MIMO (DL MU-MIMO).

Furthermore, 802.11ac increases the modulation constellation size from 64 QAM to 256 QAM. The number of spatial streams is increased to 8 to better support DL MU-MIMO. The packet aggregation size limits are also increased to better support the higher data rates.

Some 802.11n features are simplified for new 802.11ac devices [2]. Transmit beamforming in 802.11n had many options making interoperability between different manufacturers difficult. In 802.11ac transmit beamforming is limited to the explicit feedback mechanism (implicit feedback is not supported). Furthermore, the only type of feedback is compressed-V feedback, i.e. no uncompressed-V feedback nor Channel State Information (CSI) feedback. Channel sounding for transmit beamforming is limited to Null Data Packet (NDP), i.e., no staggered sounding. In addition, the modulation/coding schemes (MCS) are limited to the same MCS on each stream (no unequal modulation).

The following sections will go into detail on 5 GHz channelization, static and dynamic channel bandwidth operation with RTS/CTS and DL MU-MIMO.

5 GHz Channelization

Because partially overlapped channels introduce significant in-band interference, extremely complex coexistence schemes would have to be defined to mitigate such interference. To avoid such an in-band interference problem and to simplify protocol design, 802.11ac defines only non-overlapping channels. As illustrated in Figure 1, 80 MHz channels are comprised of adjacent 40 MHz channels, with no partially overlapped 80 MHz channels. As well, 160 MHz channels are comprised of adjacent 80 MHz channels, with no

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TABLE 1: Basic Technology Parameters for 802.11ac and 802.11ax

	802.11ac	802.11ax
Main Frequency Bands	5 GHz	2.4 GHz and 5 GHz
Channel Bandwidth (MHz)	20, 40, 80, 160, 80+80	Unlikely to change from 802.11ac
Number of spatial streams	1, 2, 3, 4, 5, 6, 7, 8	Unlikely to change from 802.11ac
Modulation	BPSK, QPSK, 16QAM, 64QAM, 256QAM	Unlikely to change from 802.11ac
Maximum PHY Data rate	6933 Mbps (8SS, 160MHz, 256QAM, short guard interval)	Unlikely to change from 802.11ac
Advanced technologies	Downlink MU MIMO, Dynamic/static channel bandwidth operation with RTS/CTS	STR, Downlink and Uplink OFDMA, Uplink MU MIMO, Dynamic CCA

partially overlapped 160 MHz channels.

Also, channel 144 has been added, which was not included in 802.11n. With this addition, there is a maximum of six 80 MHz channels possible, where regulatory bodies permit. There are only two 160 MHz channels, which is the primary reason for the inclusion of non-contiguous 160 MHz operation. Non-contiguous 160 MHz (80 + 80 MHz) channels are comprised of any two valid, non-adjacent 80 MHz channels. With non-contiguous operation many 80 + 80 MHz combinations are possible.

Dynamic and Static Channel Bandwidth Operation with RTS/CTS

With the numerous 20 and 40 MHz channels in the 5 GHz band in 802.11n, overlapping channels between BSS's are largely avoided if each AP surveys the available channels and selects an unused or little-used channel. In the worst case if an overlap between neighbors using 40 MHz is unavoidable, the primary 20 MHz sub-channels are chosen to match to maximize coexistence capability. With much wider channels in 802.11ac, it becomes much harder to avoid overlap between neighboring BSS's. In addition it becomes harder to choose a primary channel common to all overlapping networks. To address this problem, 802.11ac improves co-channel operation with extended dynamic channel bandwidth operation, and an enhanced RTS/CTS mechanism.

In 802.11, the CCA mechanism is employed to detect other signals and defer transmission appropriately. The basic requirement for an OFDM-based device is to receive a valid 20 MHz 802.11 signal at a level of at least -82 dBm. It must also detect any other signal at a level of -62 dBm or higher, termed Energy Detect (ED). When 802.11n added the 40 MHz channel, comprised of a primary 20 MHz channel and a secondary 20 MHz channel, only ED was required on the secondary channel due to the added complexity of detecting a valid 802.11 signal on the secondary channel. This meant that other systems occupying the secondary channel of another 40 MHz BSS would be disadvantaged by 20 dB. In 802.11ac, valid signal detect on the secondary channels was added at a level of -72 dBm or -69 dBm according to bandwidth, to improve CCA performance on the secondary channels. In addition, it is required that a device detect a valid packet on the secondary channels not just based on the preamble of a packet, but also in the middle of the packet.

The basic Request-to-Send (RTS) and Clear-to-Send (CTS) mechanism of 802.11 is modified to improve dynamic channel bandwidth operation, where bandwidth signaling is added to the RTS and CTS frames [5]. As illustrated in Figure 2, the Access Point (AP) sends an RTS with the bandwidth of the intended transmission, which is 80 MHz comprised of channels 36, 40 44, and 48 in this example. The RTS frame is duplicated over all four channels. Before the STA replies with a CTS frame, it senses the medium on all secondary channels for PIFS. In this example, since the secondary 40MHz channel is not free, the STA sends a CTS response with the bandwidth of the clear channels, i.e. 40 MHz comprised of channels 36 and 40 in this example. Then AP sends data to the STA only on the clear channels and the STA replies with Block Ack (BA) frames that are duplicated over the clear channels.

However, if the interference in this example is frequent, another new mechanism may be employed. In such a case, the STA can send an Operating Mode Notification frame to the AP to tell the AP that the STA is changing the bandwidth on which it operates. For example, the STA can change its operating bandwidth from 80 MHz to 40 MHz with the constraint that the client still needs to use the same primary channel as the AP. Subsequently the AP will only send data frames to the STA at this reduced bandwidth.

Downlink Multi-User MIMO

In 802.11n, one device transmits multiple data streams to another device using spatial division multiplexing (SDM). In 802.11ac, utilizing DL MU-MIMO, an AP simultaneously transmits data streams to multiple client devices. For example, consider an AP with 6 antennas, a handheld client device with one antenna (STA1), a laptop client device with two antennas (STA2), and a TV set top box client device with two antennas (STA3). An AP can simultaneously transmit one data stream to STA1, two data streams to

STA2, and two data streams to STA3. This is illustrated in Figure 3.

The primary advantage of DL MU-MIMO is that client devices with limited capability (few or one antenna) do not degrade the network capacity by occupying too much time on air due to their lower data rates. With DL MU-MIMO, network capacity is based on the aggregate of the clients of the simultaneous transmission. However, this benefit comes with increased cost and complexity.

From a PHY perspective, the AP should have more antennas than the total number of spatial streams for diversity gain. In addition, the AP requires channel state information from each of the clients participating in the DL MU-MIMO transmission in order to form the antenna weights [7]. With DL MU-MIMO, the antenna weights are much more sensitive to changes in the channel. In the case of transmit beamforming, if the antenna weights are stale, the system performance degrades to the case without transmit beamforming. However with DL MU-MIMO, if the antenna weights do not accurately match the channel, the streams to one client introduce interference to the other clients, potentially leading to negative (in dB) signal-to-interference-plus-noise ratios. Therefore channel state information must be higher resolution and more frequently updated. To constrain the dimensions of the system to a manageable size, 802.11ac defines that the maximum number of users in a transmission be four, the maximum number of spatial streams per user be four and the maximum total number of spatial streams (summed over the users) be eight.

As designed, a MU packet has the same preamble structure as a single user packet. However, beginning with the VHT-STF, the remaining fields in the preamble are directionally transmitted to recipient clients, simultaneously in time and frequency. The parameter information conveyed in VHT-SIG-B and the SERVICE field is specific for each client. In addition, MAC padding is required to fill the MAC frames to the last byte to make them equal in time for each client. The PHY fills in the last few bits for each client to ensure that each has the same number of OFDM symbols. For detailed discussion of DL MU MIMO protocol design and performance improvement, please refer to [6].

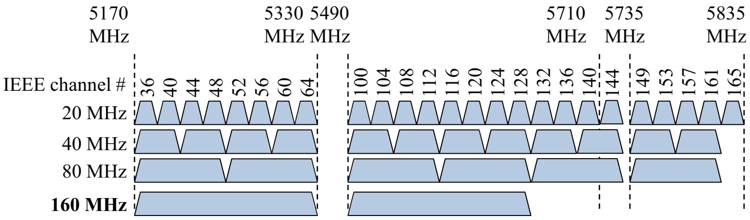

FIGURE 1. 802.11ac Channelization.

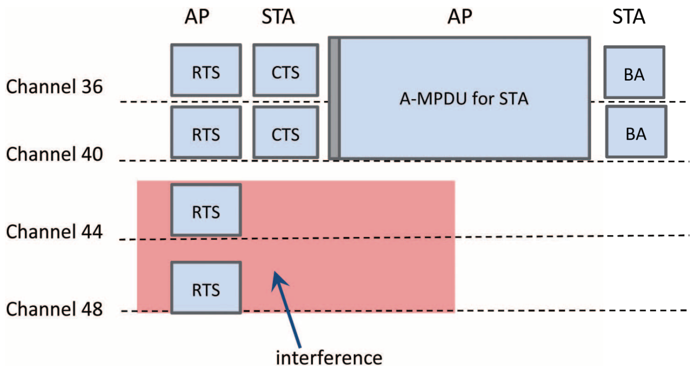

FIGURE 2. MAC protection for dynamic bandwidth operation.

802.11AX

The emphasis in 802.11ax, named High Efficiency WLAN, is to improve real world performance as experienced by end users. Although 802.11ax is in its early days (its formation was approved in March 2014) and its ultimate feature set will be the subject of much technical investigation and debate, at present it is expected that 802.11ax will achieve its goals by considering a mix of the following:

- Improving the status quo
  - Porting valuable 802.11ac features from 5 GHz to 2.4 GHz (such as DL MU MIMO, explicit feedback for transmit beamforming, and 256QAM)
  - Improved troubleshooting tools

- Standardizing advanced technologies
  - Simultaneous transmit/receive (also known as Full Duplex)
  - Downlink and/or Uplink OFDMA
  - Uplink MU-MIMO
  - Dynamic CCA

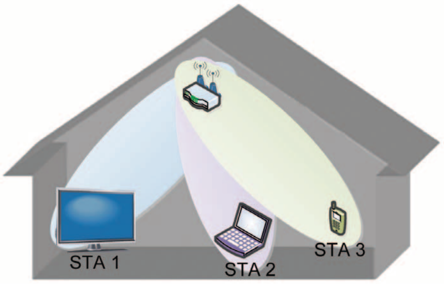

FIGURE 3. Example of Downlink Multi-User MIMO.

Bandwidths wider than 160 MHz, more than 8 spatial streams and modulations higher than 256QAM are not expected to be part of 802.11ax (or at least not a leading part) due to the following reasons:

- It is challenging to find more than one non-overlapping 160 MHz channel (let alone a contiguous 320 or noncontiguous 160+160 MHz channel),

- Two years into the 802.11ac roll-out, few 802.11ac devices implement more than 4 spatial streams, and

- The 25% speed increase of 1024QAM does not justify the increased analog complexity or power consumption, especially noting that only a very short range is achievable.

In the following subsections we describe the advanced technologies under consideration for 802.11ax in greater detail. During the on-going evaluation process, lower performing or more complicated techniques will be identified and may not be included in the final 802.11ax amendment.

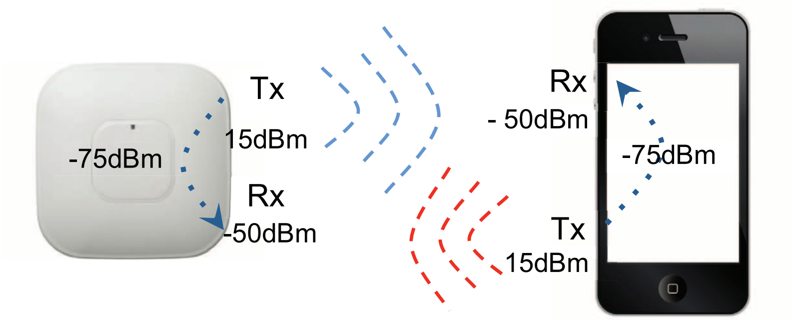

FIGURE 4. Examples of STR Paired Operation.

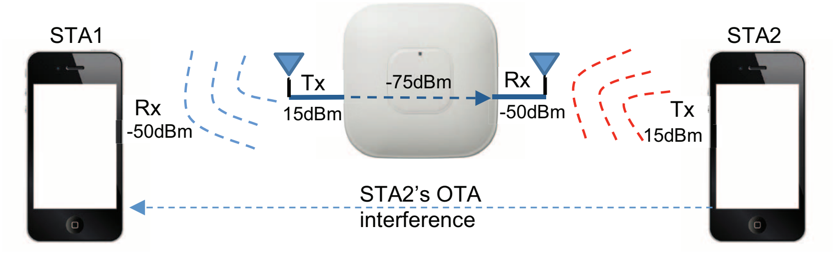

FIGURE 5. Examples of STR Unpaired Operation.

Simultaneous Transmit/Receive

Simultaneous transmit/receive (STR) is an innovation whereby a device can transmit and receive on the same channel at the same time, potentially doubling throughput. The device achieves this by cancelling leakage of its transmit signal through its receive path, so as to ensure an adequate signal/self-interference ratio (SIR). The ideal requirements for self-cancellation are challenging, since a device typical transmits at 10 to 25 dBm, but the thermal noise floor over 20 MHz is -101 dBm. In the noise-limited case, this indicates that at least 126 dBm of cancellation is preferred, but many cases of practical interest are interference not noise limited: such as two devices in moderate proximity transmitting at 15 dBm and receiving each other at an RSSI of -50 dBm (see Figure 4). Then, if self-interference can be reduced to -75 dBm, the SIR is 25 dB and only 90 dB of cancellation is required.

STR can operate either paired or unpaired (various names are in use). With paired operation, two STAs are each transmitting to and receiving from one another. To achieve a doubling of throughput, the offered traffic should be symmetric (although there is a useful throughput improvement even if only acknowledgements are sent on one link within the pair). A greater concern is that both devices must support a high degree of self-cancellation: i.e. the complexity cannot be concentrated at APs.

With unpaired operation, as illustrated in Figure 5, an AP transmits to STA1, while at the same time STA2 transmits to the AP. Here only the AP needs a high degree of self-cancellation, since STA1 is receive-only and STA2 is transmit only. However, while STA1 is receiving from the AP, STA1 may also receive interference from STA2's transmissions, oftentimes degrading the SIR to 5 or 10 dB, so there are many topologies in unpaired operation where the throughput of the link to STA1 is poor.

The required cancellation is achieved via a mix of antenna separation (one antenna for transmit, a different antenna for receive), analog cancellation and digital cancellation. Self-cancellations up to 110 dB are reported [4]. There remain several challenges and research topics:

- Self-cancellation for MIMO devices
- Self-cancellation in the presence of nearby reflectors, with device or reflector mobility
- PHY preamble design to support STR and backwards compatibility
- MAC design for paired and unpaired operation. For example, in unpaired operation, how does is a single device optimally selected to be the third device?
- Performance comparison with DL and UL MU-MIMO

Downlink and Uplink OFDMA

802.11 is optimized for bursty data, where it makes sense to give the whole channel to one device, up to some maximum TXOP duration, to transmit its buffered data. However, a 3 ms TXOP, using 160 MHz, 256QAM, and 4 spatial streams, carries 10 Mb of data. Very few networking stacks can supply this load and the net effect is shorter TX-OPs and so reduced real-world efficiency. In these cases, it makes more sense for an AP to aggregate traffic for multiple clients and send it to them in parallel. Parallelization can be in time (but different clients prefer different MCSs, which complicates the PHY design) or in space (as per DL MU-MIMO, as long as there is recent channel state information) or in frequency (i.e. OFDMA). DL OFDMA is one of the simplest solutions to this problem, since different MCSs can be used for different clients, and there is no prerequisite for recent channel state information. Here, the AP indicates to different clients which channel to expect their data on - on a per-packet basis or in a more long-lived scheme - then transmits downlink packets with different headers (SIG fields) on each different 20 MHz sub-channel. Each user's sub-channel is naturally constructed from bonded 20 MHz sub-channels to minimize backwards compatibility issues [8].

Uplink OFDMA solves the same problem, and also improves client range at the same time, since each client's energy

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is concentrated over a narrower noise bandwidth. Uplink OFDMA moderately complicates the baseband design, particularly of the AP, since different clients are received at slightly different times, with different oscillator-induced carrier frequency and baseband clock offsets, and at different power levels. These are all solvable:

- OFDM/OFDMA are robust to different start times, up to a large fraction of the cyclic prefix duration,
- Oscillator offsets can be mitigated by requiring clients to track their offset with respect to their AP and transmit at that offset,
- OFDMA is relatively robust to received power imbalance, and power control and/or client grouping can be applied to lessen any impact

The MAC design challenge is how to efficiently schedule clients so that they can transmit at the same time for much the same duration, thus maximizing spectrum utilization. Challenges for deploying OFDMA in cellular networks may be found in [9].

Uplink Multi-User MIMO

Uplink MU MIMO is the uplink counterpart of DL MU MIMO standardized in 802.11ac, but its implementation characteristics are closer to UL OFDMA. Recent channel state information is not required. However, the AP must contend with different start times, oscillator offsets and RSSI imbalances, and a similar MAC design challenge arises: how to efficiently schedule clients to maximize spectrum utilization.

Since UL MU-MIMO signals overlap completely in time and frequency, and can only be distinguished via spatial processing, UL MU-MIMO is more sensitive to oscillator offsets and RSSI imbalances. Protocol support and tight PHY requirements will be required [11].

Dynamic CCA

CCA is a major component of 802.11's distributed politeness protocol. As we described in Section 2.2, different but fixed CCA thresholds are applied, so as to minimize collisions and to minimize the need for RTS/CTS even for longer range links. However, there are circumstances where these CCA thresholds are overly conservative, such as an apartment building where the transmitters and intended receivers are in close proximity, but non-intended receivers are well separated via extra distance and walls/floors. Here, there is no need to defer a transmission if it would not have impeded existing communications (i.e. the exposed node problem).

One optimization under consideration at 802.11ax is dynamic CCA, where the CCA thresholds may be raised to increase the number of active links, albeit at a lower S/I, with overall benefits to the throughput in aggregate and potentially of worst-off devices too [10]. Higher CCA thresholds can achieve these goals under specific circumstances, but even in the apartment building problem the design of a safe/robust dynamic CCA algorithm is confounded by the likelihood of longer links (e.g. from apartment to garage/pool, or a sparse deployment of APs across an apartment complex for administration/maintenance purposes).

In this article, we gave a brief overview of 802.11ac and advanced technologies that helped 802.11ac to achieve its Gigabit throughput. Wi-Fi products based on 802.11ac are already in the market to address use cases that demand higher throughput. We also talked about 802.11ax, an upcoming standard amendment, and the advanced technologies being considered to address coverage, coexistence, and efficiency issues in real deployments. ■

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