Qualcomm Atheros, Inc.

802.11ac MU-MIMO: Bridging the MIMO Gap in Wi-Fi

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1 Executive Summary

The IEEE 802.11ac standard defines mechanisms and techniques for dramatically enhancing the speed and capacity that a Wi-Fi Access Point (AP) can deliver. Compared with the previous generation Wi-Fi, IEEE 802.11n, the 802.11ac standard contains several mechanisms to help ensure more efficient use of added capacity and support the growing number of fixed and mobile clients found in modern households and business environments.

One of the most significant enhancements in 802.11ac is Multi-User Multiple Input Multiple Output (MU-MIMO) technology. Most commercially available Wi-Fi routers and APs today are based on Single-User MIMO (SU-MIMO) or simply MIMO, which employs inefficient time-slotting protocols to share its single dedicated full-rate Wi-Fi link with multiple clients.

APs typically have 3-4 antennas, while most of the client devices they serve are limited to 1-2 antennas. As such, they cannot support the full range of MIMO channel operation, and the full AP capacity is rarely used. This difference is called the *MIMO gap*.

For example, a 3x3 Wi-Fi 11ac AP supports a peak physical layer (PHY) rate of 1.3 Gbps. But a smartphone or tablet with one antenna supports a peak rate of only 433 Mbps, leaving 867 Mbps capacity of the AP unused.

802.11ac addresses the MU-MIMO gap, allowing an AP to support up to four simultaneous full-rate Wi-Fi connections. Each of these connections is assigned to a different smartphone, tablet, laptop, multimedia player, or other client device. As a result, MU-MIMO gives the AP more options for serving its clients and enables it to make more effective use of its total available capacity, effectively bridging the MIMO gap.

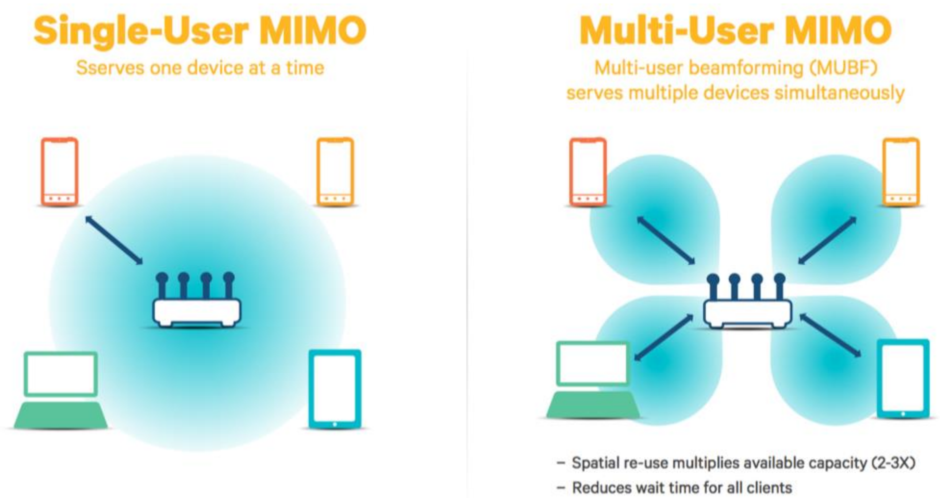

Figure 1. SU-MIMO vs. MU-MIMO

This paper examines the limitations of MIMO technology in current Wi-Fi networks. It also explains the MU-MIMO feature of the IEEE 802.11ac standard and the need for MU-MIMO to continue to achieve higher efficiency in Wi-Fi networks and devices. It discusses interactions between features and design challenges as well as the tradeoffs required to create a practical MU-MIMO solution to help 802.11ac Wi-Fi products deliver the best possible performance and to ensure future designs realize the full potential of the 802.11ac standard.

2 Why MU-MIMO?

Many driving forces contribute to widespread anticipation and adoption of MU-MIMO. Among them:

- **More users and more devices per user:** The growth in the use of smartphones and tablets is leading to significant increases in the number Wi-Fi network users. The number of connected devices in the average U.S. home is expected to explode from nine devices today to more than 20 by 2020[1]. Many users regularly carry at least two devices: A mobile phone and a laptop or tablet computer. As a result, Wi-Fi networks are more crowded and serving devices in a limited amount of spectrum is a challenge.
- **Strong appetite for data:** Wi-Fi increasingly is used for content consumption such as streaming music and video on mobile devices such as smartphones and tablets. High-definition video content demand through set-top boxes, TVs, laptops, and even mobile apps for over-the-air data synchronization with cloud storage, Skype, video conferencing, and NAS all require high bandwidth. Wi-Fi network capacity must increase dramatically to meet this demand.
- **Need for simple clients:** With the proliferation of smartphones and tablets that have limited physical space to accommodate components, requiring a single antenna is an especially attractive benefit. Particularly if the smartphones experience higher throughput while reducing cost and space.
- **Cellular offload:** Global mobile data traffic grew 81% in 2013, and is expected to increase nearly 11-fold between 2013 and 2018[2]. This increased demand for data on the mobile networks is driving cellular carriers around the world to offload mobile WAN traffic to Wi-Fi wherever possible, as both subscribers and devices tend to connect to Wi-Fi whenever it is in reach. These trends indicate that Wi-Fi offloading will continue to grow exponentially over the next few years with the proliferation of Wi-Fi hotspots and as mobile users continue to increase consumption of data over mobile devices.
- **Demand in enterprise networks:** 89% of enterprise IT departments[3] allow employees to bring their own device (BYOD). Significantly more devices and new applications to facilitate employee mobility to increase flexibility and employee productivity mean enterprise networks are handling heavy Wi-Fi traffic and their connectivity demands will continue to increase. The dramatic increase in employees adding their personal smartphones, tablets, and laptops to enterprise networks is driving the need for enterprise IT to replace or augment their Ethernet networks with Wi-Fi in enterprise networks.

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[1] Machina Research, North American data, May 2014

[2] Cisco Visual Networking Index Global Mobile Data Traffic Forecast Updates 2013-2018 http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html

[3] Cisco Global Cloud Index 2012-2017 http://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/Cloud_Index_White_Paper.html

3 11ac Advanced Features: Transmit Beamforming (TxBF) and MU-MIMO

Many of the 802.11ac features are enhancements of existing features in the 802.11n standard, while others add important new capabilities to Wi-Fi technology. This section provides background on a key improvement – Single User Transmit Beamforming (SU-TxBF) – and the new feature in 802.11ac MU-MIMO or MU-TxBF.

3.1 Standardized Closed Loop TxBF

Beamforming is a technique that focuses the AP transmit energy of the MIMO spatial stream towards the targeted station (STA) or client device. Using channel estimation carefully to introduce a small difference in the phase and amplitude in the transmission (precoding) allows the AP to focus the transmitted signal in the direction of the receiving STA. The signal produced is strong enough to use more aggressive modulation techniques (which support higher data rates) at greater distance.

802.11n defined several methods of beamforming, however, none of them mandated for certification. As a result, chipset vendors implemented various non-interoperable techniques. The lack of a single, consistent method prevented this feature of 802.11n from providing the intended range enhancements across end-products and kept it from becoming mainstream.

The 802.11ac specification defines a single closed-loop method for transmit beamforming. In this method, the AP transmits a special sounding signal to all STAs, which then estimates the channel and reports their channel feedback back to the AP. This feedback from STAs is standardized so consumers can be sure any standards-based beamforming devices (APs and STAs) interoperates with all other 802.11ac compliant products.

3.2 MU-MIMO or MU-TxBF

The most significant advancement in 802.11ac is MU-MIMO technology, which provides a dramatic breakthrough in the performance and flexibility available to WLAN users. In SU-MIMO, a device transmits multiple spatial streams at once, but only to one device at a time. MU-MIMO allows multiple spatial streams to be assigned to different clients simultaneously, increasing the total throughput and capacity of the WLAN system.

MU-MIMO builds upon the transmit beamforming capabilities to establish up to four simultaneous directional Radio Frequency (RF) links. In MU-MIMO operation, an AP uses enhanced beamforming techniques to maximize transmission in the desired client direction while simultaneously minimizing transmission in the direction of undesired clients through null steering. Known as *spatial reuse*, this technique provides each of the four users with its own dedicated full-bandwidth channel in much the same way cellular phone networks use small cell nodes and spectrum reuse techniques to increase system capacity.

While MU-MIMO benefits nearly every scenario, it is most advantageous to mobile devices (smartphones, tablets, laptops, etc.) using one or two streams that typically are allocated only a relatively small portion of the network capacity.

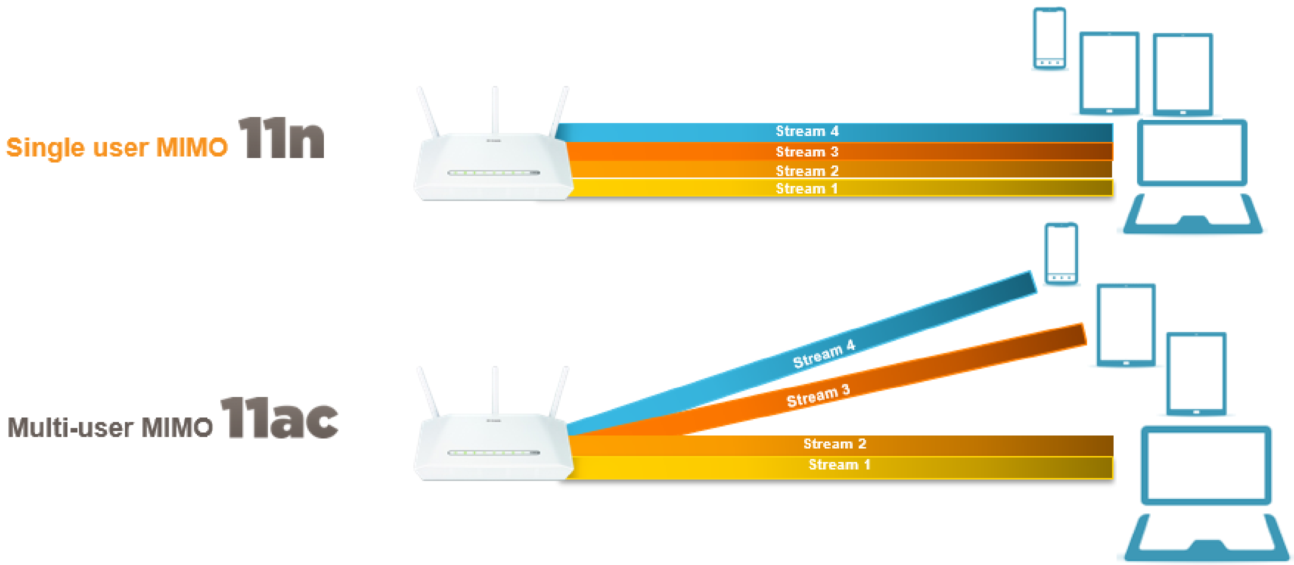

Figure 2. SU-MIMO and MU-MIMO operation

In the example shown in Figure 2, an 802.11ac MU-MIMO AP with four antennas can simultaneously transmit one spatial stream each to a laptop, a smartphone, and two tablets.

Since a MU-MIMO network does not require its client devices to time-share connections with other clients on the network, each device experiences less wait time, enabling a more responsive network and client devices.

4 MU-MIMO Benefits

MU-MIMO brings a number of benefits to the end user. Among them:

- **Increased network capacity:** MU-MIMO makes efficient use of available spectrum by effectively multiplying the total capacity of a network, typically by a factor of 2x-3x. This is a large advantage in urban areas, apartment buildings, enterprise networks, hot spots, or other crowded environments.

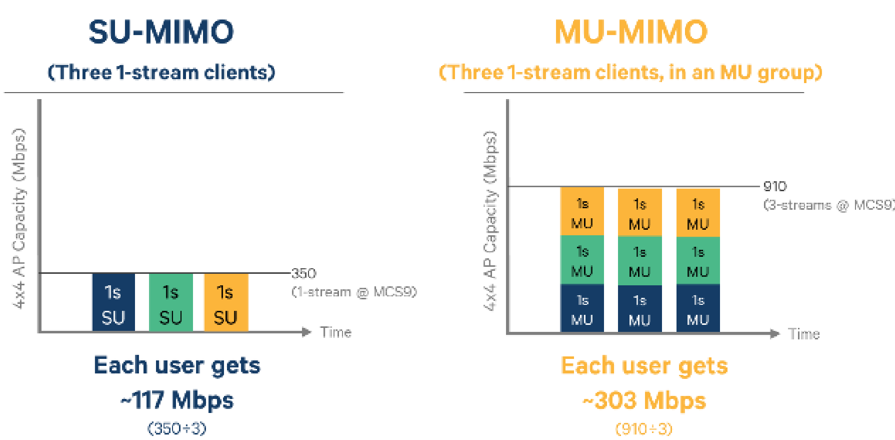

Figure 3. MU-MIMO delivers ~2.5x more throughput per device

- **More traffic over the network:** Increased capacity with MU-MIMO results in the system supporting much higher traffic compared to SU-MIMO and bridging the MIMO gap. This allows the Wi-Fi network to meet the increase in data demand resulting from streaming HD video, audio, and other data-hungry applications.
- **Increased throughput and reduced latency:** Since a MU-MIMO network does not require its client devices to time-share connections with other clients on the network, each device experiences less wait time, enabling a more responsive network and client devices.
- **Increased spectral efficiency:** MU-MIMO makes efficient use of available spectrum by effectively multiplying total capacity of a network, typically by a factor of 2-3x. This is a significant advantage in urban areas, apartment buildings, large offices, or other crowded environments.
- **Simpler, cheaper clients:** MU-MIMO is especially beneficial with the proliferation of smartphones. In a MU-MIMO system with three clients, all three STAs can simultaneously receive a single spatial stream from the AP 100% of the time. To achieve the same throughput in SU-MIMO, each STA requires three antennas receiving data from the AP one-third of the time. In contrast, in the MU-MIMO scenario, the faster throughput means that the device only needs one or two antennas instead of three, reducing cost and space requirements.
- **Benefit to legacy clients:** With 2-3x greater efficiency for MU clients, the network has more free time or capacity to serve other clients, which means even legacy clients benefit with MU-MIMO.

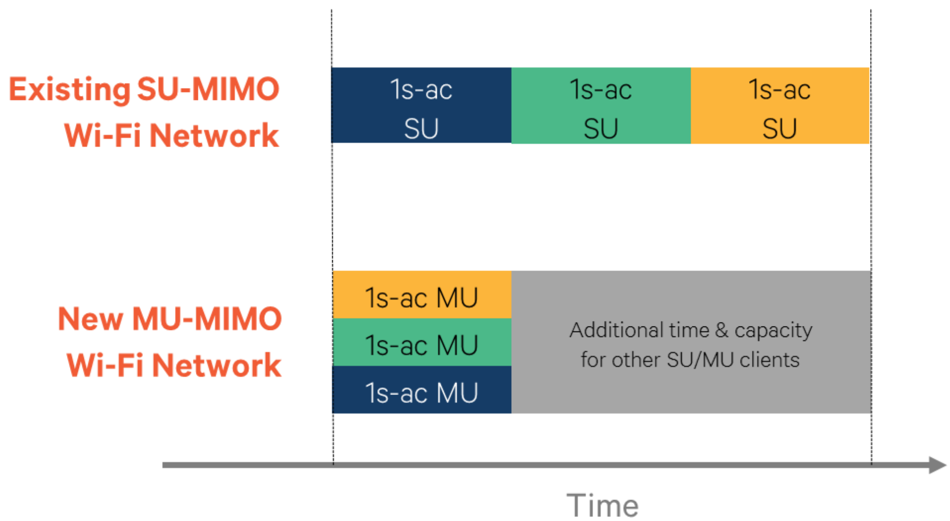

Figure 4. Benefits of MU-MIMO to legacy clients

5 MU-MIMO Design Considerations

As with any complex design task, the first step in designing our MU-MIMO technologies was to identify the variables that have the greatest impact on the critical features, cost, and performance objectives of the design, and any possible interactions with other variables. There are many, but all of the design choices and trade-offs flow from just two top-level issues:

- Number of spatial streams
- Number of simultaneous users

Let's look more closely at both.

5. 1 Number of Spatial Streams

The 802.11n standard first introduced MIMO, allowing a maximum of four MIMO streams to be sent to a single device at a time. 802.11ac increases the maximum number of MIMO streams received by a STA to eight, effectively doubling the network throughput with 802.11ac compared to 802.11n.

The number of spatial streams and the transmission bandwidth together indicate potential throughput performance and number of devices supported. Since each spatial stream needs its own dedicated transmit/receive chain, an 802.11ac 8x8 AP capable of supporting all eight spatial streams needs eight independent radio chains and antennas. Getting full MIMO benefit with 8x8 AP requires 8x8 client configuration, which is not practical.

Many of the devices that connect to Wi-Fi networks increasingly are mobile devices such as smartphones and tablets, which typically support 1x1 or 2x2 configuration. MU-MIMO allows multiple clients to share the high number of streams on the AP. This makes use of the available spatial streams and bandwidth and increases the overall capacity of the system to the maximum capacity possible with the AP configuration.

5.2 Number of Simultaneous Users

The 802.11ac MU-MIMO specification defines radio configurations that support up to four simultaneous MIMO channels. Much like the spatial streams discussed earlier, adding the capability to support each additional user increases a product's power budget and total solution cost. But as previously discussed, MU-MIMO beamforming introduces several other tradeoffs that have even more significant impact, and therefore, also have to be considered before deciding on the number of users supported.

To enable MU-MIMO, 802.11ac includes channel sounding mechanisms. Each client provides channel feedback, which the AP uses to give its spatial streams the necessary mobility for practical use. Once channel probing provides the AP with a clear picture of its environment, it uses MU-MIMO beam-shaping capabilities to maximize signal in the desired direction and null the signal in the undesired direction.

In practice, the beamforming process is imperfect, and some of the energy of a spatial stream emerges in *side lobes*. These smaller beams emerge from either side of the primary beam and are pointed several degrees off-axis. While not a problem in SU-MIMO, two adjacent MU-MIMO streams begin to interfere with each other as soon as their side lobes begin to overlap. The presence of this interference adds to the overall noise floor of the channel at the AP.

Since the number of simultaneous users the AP solution can support drives so many facets of the design, our interdisciplinary team thoroughly reviewed the MU-MIMO mechanism. Careful analysis revealed that adding a fourth MU spatial stream (with 4TX) adds intrastream interference but increases the number of usable spatial streams. So there is a tradeoff. What gives the best network capacity? It depends on the channel multipath environment. The multipath characteristics of the indoor channel determine how much intrastream interference is created when adding another MU stream. A highly diverse indoor environment supports up to three spatial streams with a tolerable amount of interstream interference to get the highest MCS to work. When adding a fourth stream, the interstream interference raises to the level that the highest MCS modes cannot support, and thus throughput goes down.

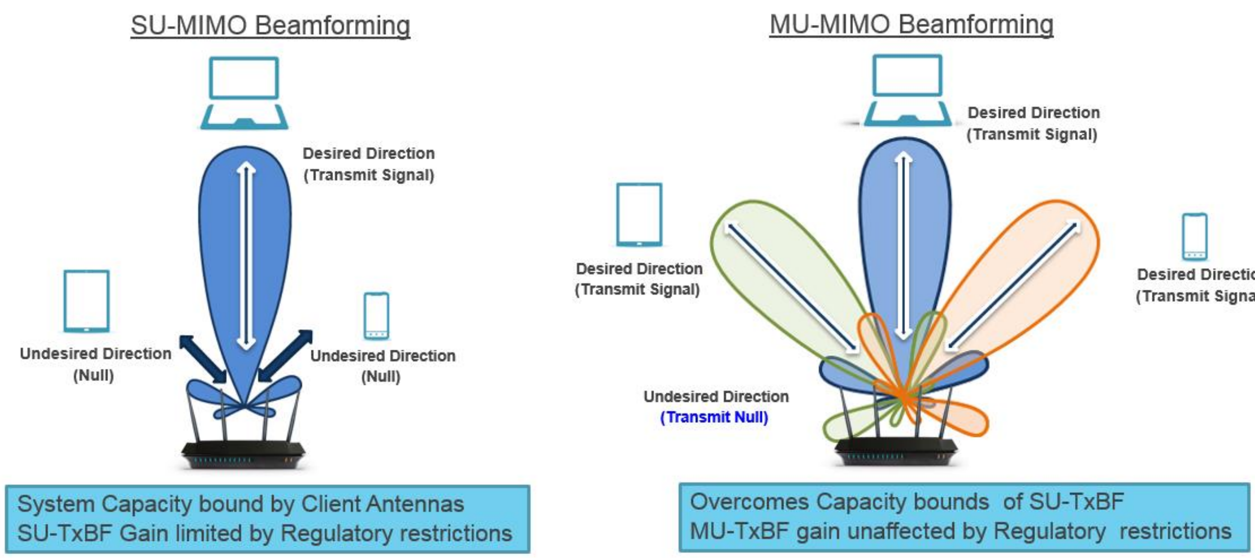

Figure 5. SU-MIMO TxBF vs. MU-MIMO TxBF

Qualcomm Atheros researchers thoroughly explored these issues as they searched for the optimal architecture for its first 802.11ac MU-MIMO-capable access point solution. After seven years of pioneering MU-MIMO research and four years of hardware prototype development, the team came to several important conclusions, including:

- A 4x4 system with three simultaneous users achieves the best MU-MIMO performance and stability. The enhanced beamforming and nulling techniques used by our 4-antenna 3-user N+1 AP radio gives MU-MIMO beamforming capabilities a much wider range of motion by mitigating interference and improving overall channel capacity and rate over range.

- This sophisticated AP enables an enhanced MU-MIMO to maintain high total downlink throughput and longer useful range to simple (inexpensive) clients.
- Under many conditions, adding a fourth user actually reduces available capacity of the system and rate-over-range performance.

6 The Qualcomm Atheros Implementation Advantage

The IEEE 802.11ac standard defines set of specifications to enable MU-MIMO operation. These include sounding procedures for channel calibration, MU signaling, packet aggregation, and data transmission to multiple clients. However, the signal processing and other algorithms required for creating a solution is left to implementation.

As previously discussed, creating a practical silicon solution for MU-MIMO applications requires a series of careful trade-offs and implementation choices. For example, when to perform sounding, how to choose a set of clients from the candidate clients, and data rates to use in MU transmission. Through our pioneering work in MU-MIMO research and extensive modeling and hardware prototyping, Qualcomm Atheros researchers developed unique algorithms for scheduling, sounding, grouping, and rate control for the most effective MU-MIMO implementation.

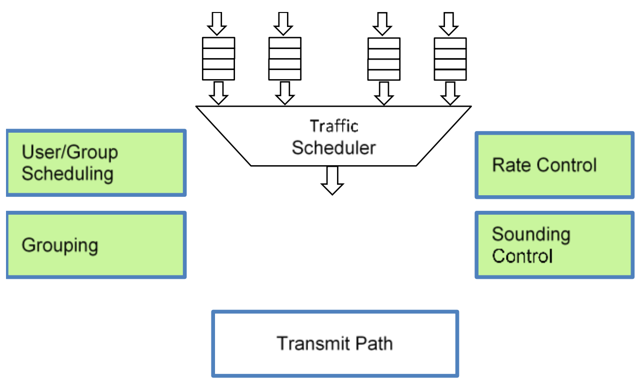

Figure 6. Key decision variables for MU-MIMO transmission

- **Scheduling of SU/MU transmissions:** In a network with clients of mixed capabilities (MU/SU, different number of antennas), the AP schedules MU and SU transmissions according to the location of clients within the network to maximize overall network capacity. A simple algorithm is based on round-robin scheduling, while sophisticated algorithms take into account client traffic profiles, quality of service (QoS) requirements, and airtime fairness among clients.

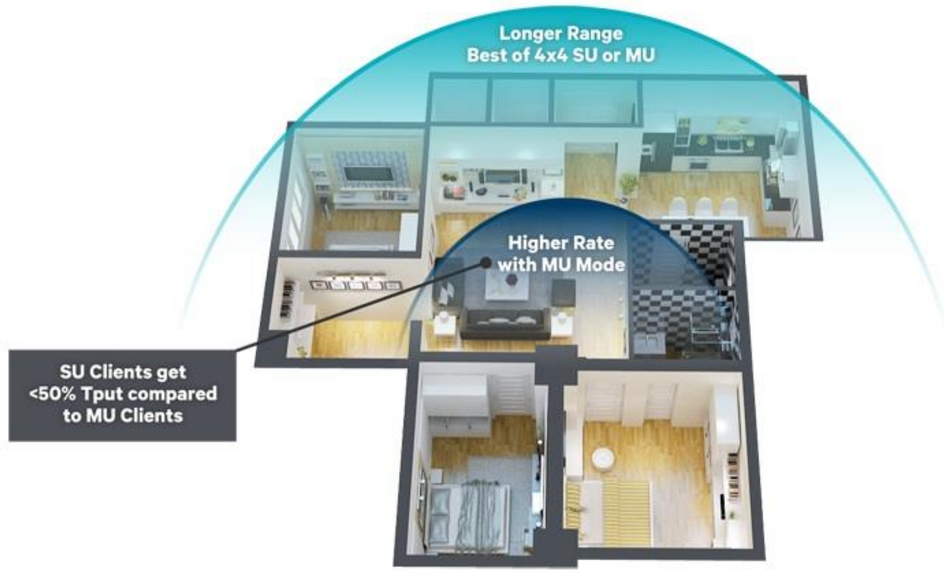

Figure 7. MU-MIMO – Dynamic, optimized throughput, coverage, and range

- **Grouping:** As previously mentioned, Qualcomm Atheros research concluded that a 4x4 AP supporting three single-stream clients results in the best MU-MIMO configuration. The grouping refers to the selection of the three clients from the pool of candidate MU clients, taking into account traffic type at each MU-client and ensuring high overall network throughput.

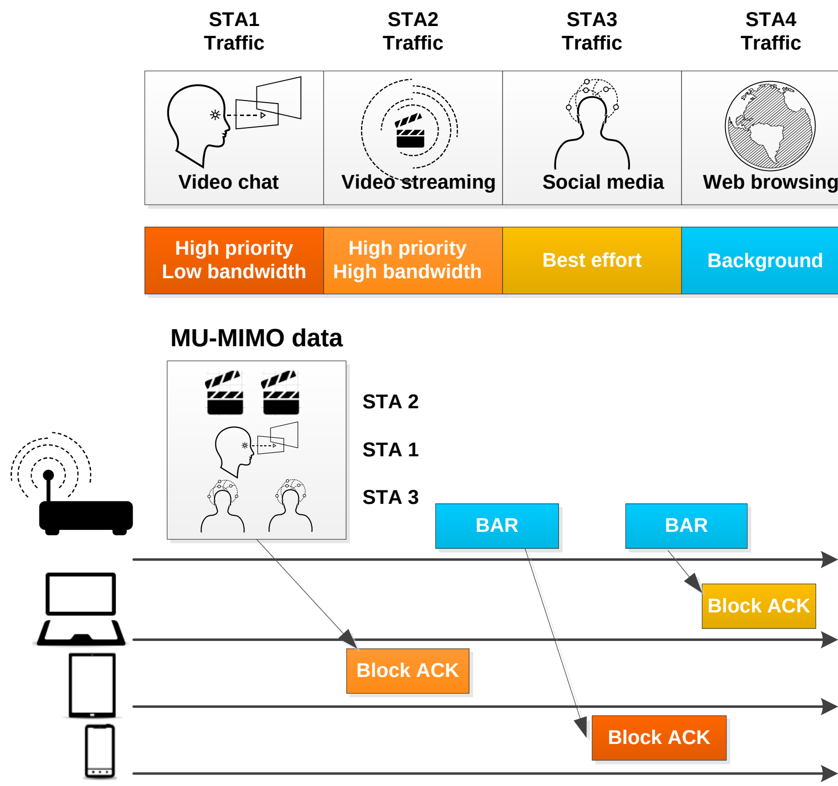

Figure 8. MU-MIMO data transmission

- **Sounding and rate control:** As previously discussed, channel sounding enables proper calibration of the channel between the AP and client to ensure the most accurate channel information is available at the AP effectively to steer transmissions, select the best rate for MU-MIMO operation, and maximize the network throughput. Since clients in a Wi-Fi network are mobile, frequent sounding ensures that the AP has the most up-to-date information from the client at the expense of increased overhead. Reduced sounding means less overhead, but the AP uses other open loop techniques to estimate the right data rate to use with MU transmissions. Qualcomm Atheros algorithms ensure a balance between sounding frequency and rate selection to ensure high overall network throughput.

6.1 Wi-Fi Migration to MU-MIMO

Delivering the dramatic improvements in range and capacity promised by 802.11ac MU-MIMO technology requires that an end-to-end ecosystem supporting MU-MIMO technology is available. At the same time, the silicon solutions and associated reference designs must make it easy for the OEM to deliver competitively priced market-ready routers, APs, smartphones, tablets, PCs, notebooks, or other end products.

Qualcomm Atheros enables OEMs with the only end-to-end ecosystem of 802.11ac solutions with MU-MIMO. With more devices connecting via Wi-Fi, Qualcomm® MU | EFX MU-MIMO, a product of Qualcomm Atheros, Inc. technology-enabled devices multi-task like never before, supporting more simultaneous devices to make better use of wireless capacity that is wasted in Wi-Fi networks that serve one device at a time. As a result, Qualcomm MU | EFX helps consumers experience Wi-Fi to its maximum effect, with connections up to three times faster than other 802.11ac solutions currently available.

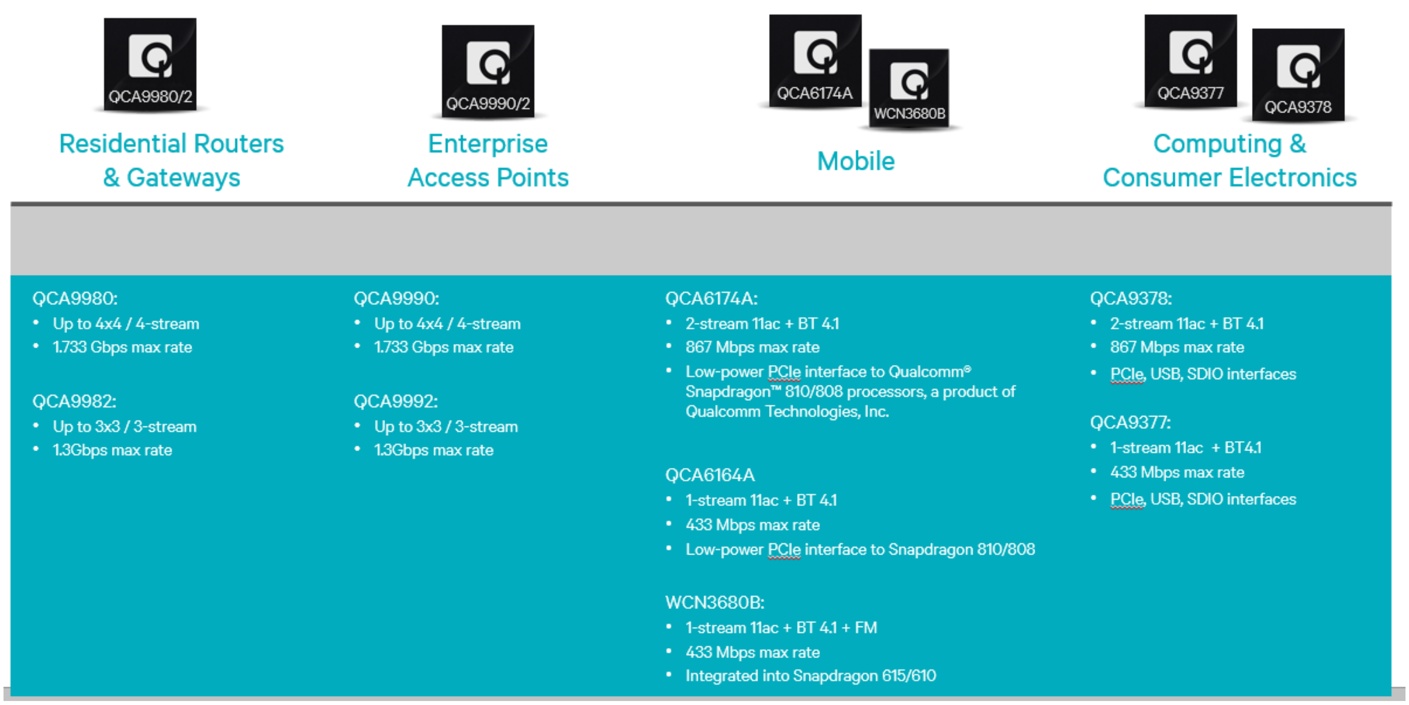

Figure 9. Qualcomm 802.11ac MU-MIMO portfolio shipping 2015+ from OEMs

7 Conclusion and Summary

802.11ac with MU-MIMO is designed to provide the capacity and performance necessary to keep up with applications in the pervasive multimedia environment of today and opens up new possibilities for future applications. But its widespread acceptance and deployment hinges on the availability of 802.11ac solutions with MU-MIMO that deliver demonstrable benefits over the previous generation of 802.11n equipment.

Qualcomm VIVE™ 802.11ac technology, a product of Qualcomm Atheros, Inc., with Qualcomm MU | EFX is the only complete line of 802.11ac solutions for networking equipment, smartphones, tablets, computing devices, and consumer electronics applications. VIVE solutions deliver the benefits of MU-MIMO, such as greatly improved systems capacity and rate over range performance and other advanced features directly to the newer 802.11ac clients, and indirectly to a large installed base of Wi-Fi enabled consumer gear manufactured before the arrival of the 802.11ac standard.

VIVE solutions with Qualcomm MU | EFX represents the best possible combination of performance, compatibility, and affordability available for the 802.11ac solution. The technology and know-how embodied in these solutions will form the foundation of future products that further expand the capabilities of Wi-Fi data systems and networks.