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RF & Wireless

802.11ac Wave 2 with MU-MIMO: The Next Mainstream Wi-Fi Standard

RF & Wireless Components (RFWC)

Report Snapshot

The 802.11ac Wave 2 standard provides significant benefits to users and a better Wi-Fi user experience compared to 802.11n and 802.11ac Wave 1. Despite low initial consumer awareness and OEM concerns over client device availability, OEMs, service providers and enterprises have embraced the standard, which is now gaining rapid traction and will become the highest shipping Wi-Fi standard yet.

Components

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1. Executive Summary

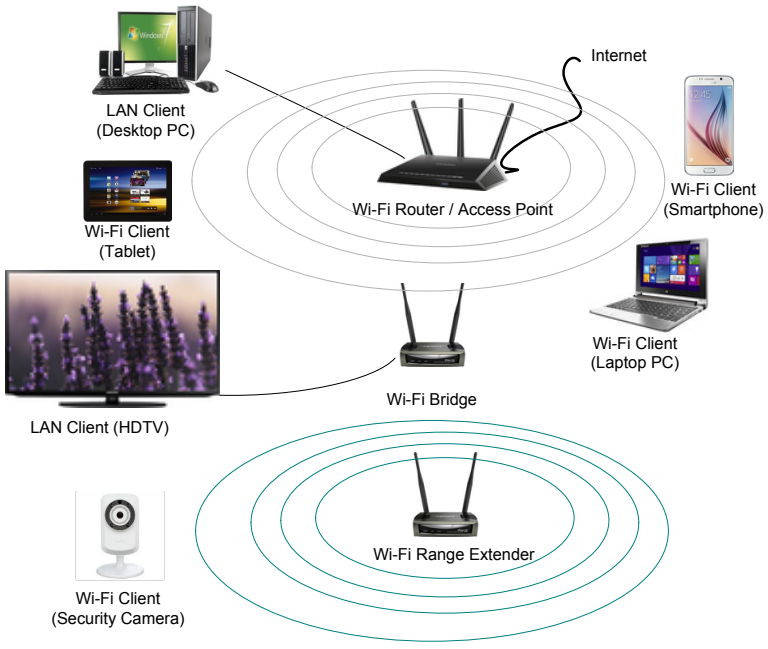
802.11ac Wave 2 Wi-Fi has exploded onto the market in the past few months, now shipping in more than 60 client devices and more than 25 routers, with more devices to follow in 2016. Users of Wave 2 experience noticeable benefits including reduced network congestion across residential and public networks, and lower Wi-Fi power consumption in mobile devices. It is now up to the industry to promote consumer awareness to further spur rapid adoption.

2. WLAN Terminology

In this report, we use the terminology shown below and in Exhibit 1 to describe various types of Wi-Fi devices and related networks:

- Wi-Fi infrastructure, consisting of routers, bridges, and range extenders, also known as access points (APs) collectively,
- Wi-Fi client devices, also referred to as stations (STAs),
- LAN (local area network), which describes devices connected via a wired network, Ethernet typically, as opposed to a wireless LAN or Wi-Fi network, and
- WAN, referring to the wired (usually) connection to the Internet.

Exhibit 1 Typical Residential or Small Office Wi-Fi Network



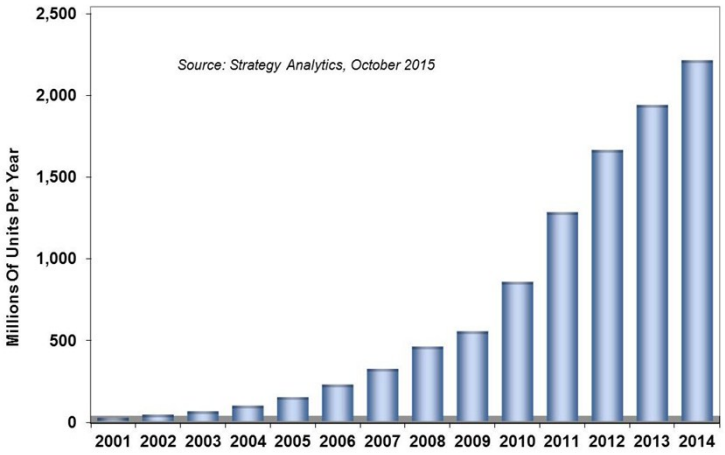
3. Market Growth & Standards

Wi-Fi has followed a path of continuous evolution since the first 802.11 devices in the late 1990s, with an astounding 62 percent per year compound annual growth rate in units shipped globally from 2001 to 2014:

- In 2001, about 4.1 million Wi-Fi systems shipped, most using 802.11b (11 Mbps).
- In 2007, shipments reached 300 million units with 802.11g (54 Mbps) and Wi-Fi in most notebook PCs. In 2011, shipments passed one billion units with 802.11n (450 Mbps).
- In 2014, adoption of 802.11ac (1.3 Gbps and above) in smartphones and wider adoption of Wi-Fi across consumer devices pushed Wi-Fi shipments past the 2 billion units per year mark. See Exhibit 2.

Future Wi-Fi standards will help Wi-Fi to keep up with the explosion in Internet-connected consumer devices and more video, music, social networking and firmware updates for mobile devices.

Exhibit 2 Wi-Fi Device Historical Shipments



3.1 Evolution of Wi-Fi

Devices using the 802.11ac Wave 2 standard have started to ship in earnest, and interoperability certification has begun, which will lead to accelerating adoption in 2016 and 2017. Some devices using 802.11ad, which adds 60 GHz to Wi-Fi, have also started to ship. After 802.11ac Wave 2 and 802.11ad, 802.11ax and 802.11ay will follow. See Exhibit 3 & Exhibit 4:

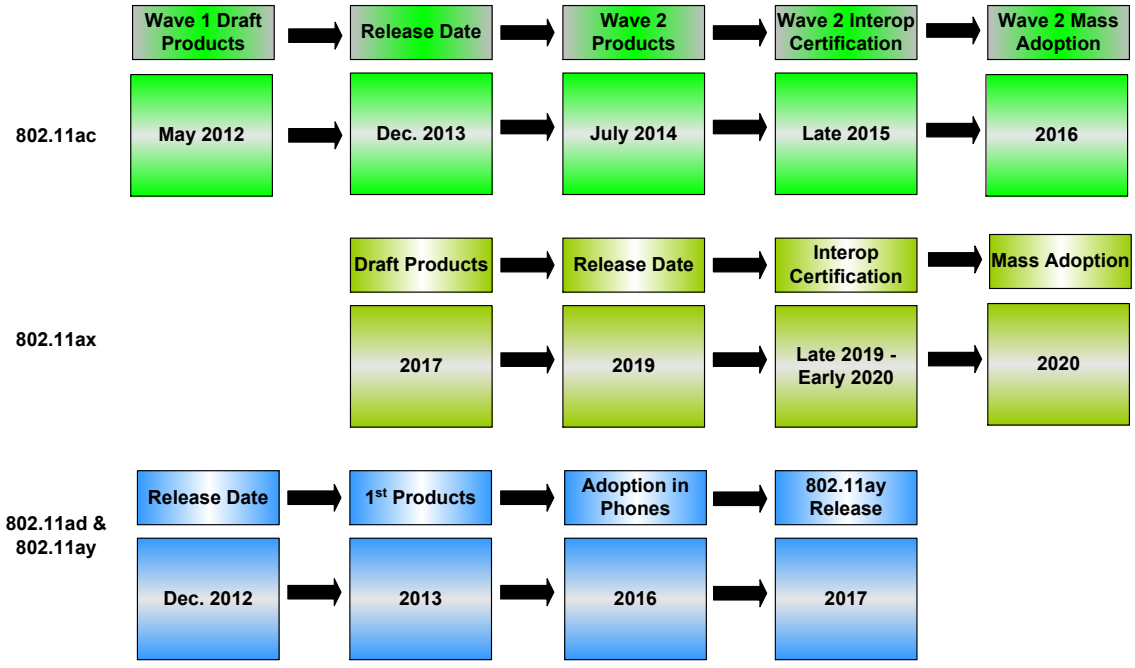
- 802.11ac Wave 2 uses downlink MU-MIMO (multi-user MIMO) to send data to up to four clients[1] simultaneously, reducing contention and improving overall network throughput substantially. In comparison, 802.11ac Wave 1 uses SU-MIMO (single user MIMO) to address multiple clients sequentially, using beamforming to direct the signal preferentially to each client.

[1] *Chip vendors say that serving three clients simultaneously provides better performance than four.*

  - Note that 802.11ac operates in the 5 GHz band using chipsets that generally support for 802.11n at 2.4 GHz as well. Devices that support both standards may be denoted as dual-band 802.11ac or 802.11n/ac.

- 802.11ax, the next evolution of the 802.11ac standard, will increase the maximum modulation rate to 256-QAM, and will use OFDMA (orthogonal frequency division multiple access) to direct different subcarriers to different intended users, increasing the number of clients that can receive data simultaneously in a 5 GHz network. The standard increases the power spectral density (PSD) per user, and therefore increases overall network throughput. The standard will also add uplink MU-MIMO:
  - Peak data rates for a single device could reach as high as **10 Gbps to 14 Gbps** under 802.11ax.
  - UL OFDMA and higher PSD increase the UL link budget by 9 dB, increasing range.
  - The standard could increase the maximum number of MU-MIMO streams and antennas from four to eight, requiring as many as 16 antennae for simultaneous dual-band operation in an AP.
  - The standard could add MU-MIMO to the 2.4 GHz band.
  - The IEEE is expected to approve the 802.11ax standard in 2019, but devices using Draft 802.11ax could ship in late 2017.
- 802.11ad, now shipping in low volumes, adds 60 GHz to 802.11ac for very high data rates (4.6 Gbps) within a walled-in area. Today 802.11ad is used mainly as a cable replacement in some wireless docking stations for laptop computers, but it has the potential to do much more thanks to its unchallenged data rate capabilities. Many premium-tier smartphones will include 802.11ad starting in 2016.
- 802.11ay will enhance 802.11ad, adding MU-MIMO to the 60 GHz band and potentially increasing the peak data rate to an astounding 100 Gbps.

Exhibit 3 Future Evolution of Mainstream Wi-Fi Standards



4. Benefits of MU-MIMO under 802.11ac Wave 2

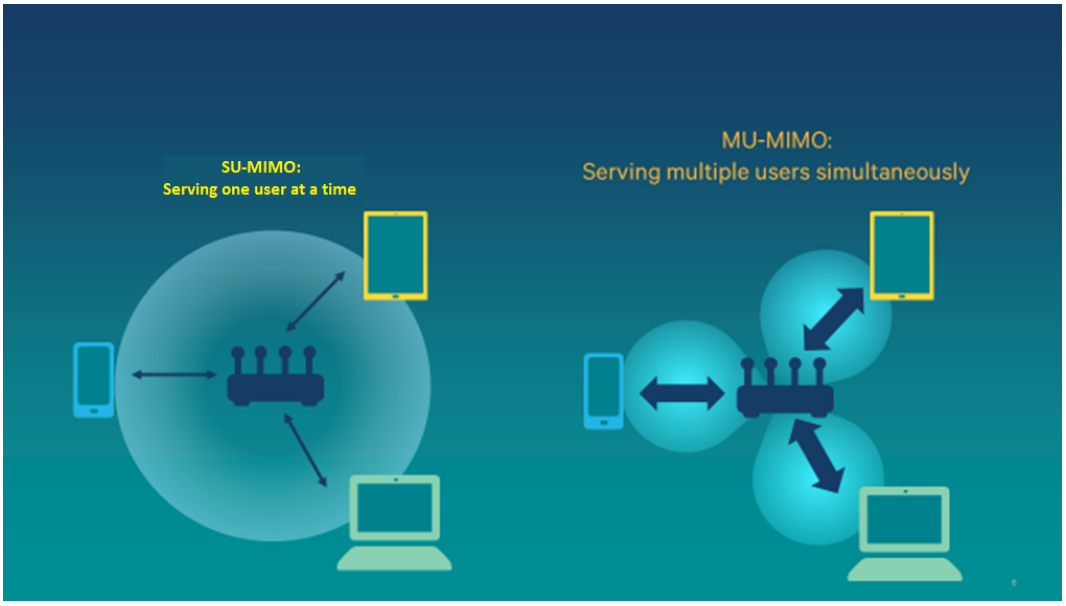
In public areas such as airports, hotspots and conferences, Wave 2 with MU-MIMO reduces the frustration that Wi-Fi users often experience in downloading web pages, e-mail file attachments and media content.

In homes, Wave 2 improves throughput where multiple Wi-Fi devices are in use at the same time, for example with parents watching Internet TV, one child watching YouTube videos on a tablet, and another child sharing pictures and user-generated video through social networking sites.

For cellular operators, Wave 2 provides a better Wi-Fi user experience, reducing the likelihood of users turning off Wi-Fi and putting more load on the cellular network.

For enterprises, Wave 2 can solve congestion issues in open work spaces and conference rooms, making a mission-critical difference in the performance of the Wi-Fi network.

Exhibit 4 802.11ac Wave 1 (SU-MIMO) Vs. Wave 2 (MU-MIMO)



Source: Qualcomm Atheros

MU-MIMO operating under 802.11ac Wave 2 has several specific benefits:

- Provides up to 3X higher aggregate throughput to a Wi-Fi network by making use of beamforming to differentiate among client devices, sending data simultaneously to groups of up to four clients simultaneously.
- Reduces wait time for MU-MIMO enabled clients, which can increase throughput for *all* clients in a mixed environment of SU and MU users:

- Improved video streaming with fewer stutters and pauses under high network loads, for example in crowded hotspots.
- Faster downloads for all using the network, but especially for MU-MIMO-enabled clients.

- Allows use of lower-cost client devices with fewer antennas and less powerful Wi-Fi computational engines, potentially reducing power consumption in battery-operated handsets and tablets.

4.1 How Wave 2 Works

To realize these benefits, MU-MIMO uses closed-loop beamforming to turn multipath from a disadvantage into an advantage. An MU-MIMO-enabled AP transmits a sounding signal to the client devices in the network. The clients then each send an easily computed frame back that specifies CSI (channel state information) based on the received sounding signal.

The AP receives the CSI for each client and computes the phase and signal strength for each transmit antenna in an array of up to eight antennas. The AP then combines the data streams to be transmitted to up to four devices for simultaneous transmission, relying on spatial differences in reception among the client devices to keep the data separate at the clients:

- This is known as spatial division multiple access (SDMA). With typical multipath in an indoor environment, each client's receiving antenna sees a different signal from each AP transmit antenna.
- MU-MIMO under Wave 2 only works in the downlink (DL, AP to client) direction. Clients usually consume more data than they generate, so MU-MIMO is most useful in the DL direction.
- CSI information has to be recalculated every 25 milliseconds or so to make up for changes in channel states. This may seem onerous, but the overhead associated with sounding and exchanging CSI information amounts to only about 1 percent of airtime.

MU-MIMO provides gains with more than four MU-MIMO-enabled clients, a typical expected situation. For example, by sending data to five groups of three MU-MIMO devices, a network with 15 Wave 2 clients could operate with 3X the throughput compared to a network with 15 SU-MIMO (Wave 1) clients.

4.2 More Technical Considerations

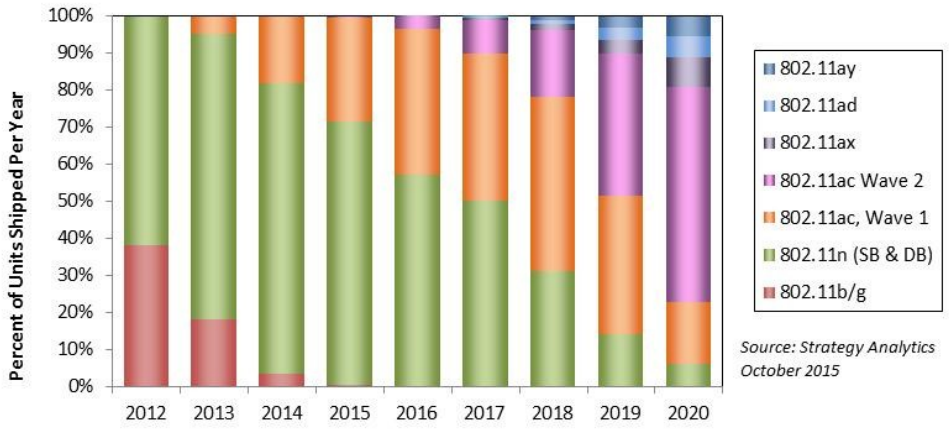
- **More than one MU-MIMO client is necessary.** At least two clients must support MU-MIMO and have the ability to report CSI to allow grouping them together for spatial diversity. A network with only one MU-MIMO client does not benefit from using an MU-MIMO AP:
  - In a mixed network of legacy and **at least two MU-MIMO clients,** the efficiency of the network will improve with an MU-MIMO AP, and both Wave 2 and legacy client performance will improve.
  - To realize full benefits in a mixed client network, the AP must intelligently prioritize data streams between MU and SU clients:
    - One AP vendor reported some interference issues in network tests with mixed clients.

  - The prioritization algorithms **are not part of the Wave 2 standard** and represent an opportunity for **chipset vendors to differentiate**, so it is a safe bet that vendors will quickly address any circumstances associated with inter-client interference with firmware updates.

- **MU-MIMO works especially well indoors.** If spatial diversity is insufficient, the AP has to make the decision to not attempt to group clients together for simultaneous transmission, otherwise the network will suffer from inter-client interference. However, in typical indoor environments, multipath conditions provide **more than adequate spatial diversity** for MU-MIMO even if only a few centimeters separate client devices.
- **MU-MIMO works well at intermediate ranges.** At short ranges, the MU-MIMO client is already receiving at the maximum possible data rate. At long ranges near the edge of the network, MU-MIMO may not provide significant performance gains as all spatial streams may have to traverse approximately the same path to the client.

5. Wave 2 and the Wi-Fi Infrastructure Market

Exhibit 5 Wi-Fi Infrastructure Forecast by Mainstream Standard



The 802.11ac Wave 2 standard, now shipping with the many of the latest routers, will soon reach high volume as interoperability certification progresses and a wider variety of mobile devices and other clients supporting MU-MIMO reaches the market:

- Shipments of 802.11ac Wave 2 AP devices will accelerate to more than 10 percent of the market in 2017 in the view of the ten equipment and chipset suppliers that we interviewed.
- In 2020, shipments of 802.11ac Wave 2 will dominate the AP market. Around this time, 802.11ax will begin to ship, displacing 802.11ac. See Exhibit 5.
- Note that in 2015, approximately 250 million to 300 million Wi-Fi infrastructure products will ship according to most estimates.

Historically, the Wi-Fi AP market closely mirrors the client device market, and shipments of both clients and AP should follow an adoption pattern similar to the forecast above.

5.1 Wave 2 for Residential

In putting this study together, Strategy Analytics identified 24 announced infrastructure products supporting 802.11ac Wave 2 with MU-MIMO, all routers. Of these, 14 had reached retailers and distributors as of the end of October 2015 (see Exhibit 6 and Exhibit 7). Most of the others should ship before the end of 2015.

- All support 802.11n in addition to 802.11ac, and most feature at least four antennas, typically transmitting four streams in the 5 GHz band.
- Most residential products include USB 2.0 and/or USB 3.0 for connecting printers and external storage drives, four Gigabit Ethernet LAN ports, the ability to set up and control the router from a phone or tablet, and NAS, Cloud and/or FTP file sharing capabilities.
- Although all residential MU-MIMO routers have similar features, they do not all use the same Wi-Fi chipsets or applications processors, and some have easier- to-use features depending on the software and UI. A few stood out:
    - Buffalo shipped the first MU-MIMO capable router in mid-2013.
    - Suppliers that we spoke with considered the Linksys EA8500, which started to ship in April 2015, as the most capable Wave 2 router shipping as of the end of August 2015, and the benchmark to beat.
    - D-Link's new Wave 2 routers have a distinctly aggressive appearance, resembling stealth fighters sporting menacing antennas. D-Link has the highest market share in residential routers, and hopes to capture the high-price, high-performance tier of the residential market with its two new Wave 2 units.
    - Netgear's Nighthawk X4S AC2600 (D7800) includes a built-in VDSL/ADSL modem, allowing consumers to upgrade their ISP-supplied unit.

- The **Amped Wireless Athena RTA2600** features four high-gain antennas with eight PAs (4 x 2 bands) for high power and long range. The Athena includes advanced security with stateful packet inspection firewall, and can adjust network coverage and block websites. The Athena also uses StreamBoost to optimize bandwidth for HD & 4K content and prioritize specific applications and devices. The Athena includes USB 2.0 & USB 3.0 for external storage.
- The **ASRock G10 Gaming Router** includes the H2R USB dongle (2.4 GHz) for HDMI streaming or use as a portable travel router.
- The **ASUS RT-AC87U** supports smooth 4K UHD video streaming, fast file sharing of large files and low-latency online gaming. The router offers easy setup, Cloud support for remote access to files, high-strength security, and USB 2.0 and USB 3.0 ports for printer sharing, external storage and 3G/4G cellular dongles. The **ASUS RT-AC5300U** will support 1,000 Mbps in the 2.4 GHz band and 2,167 Mbps in each of two portions of the 5 GHz band, using eight antennas total. The router offers USB 2.0 and USB 3.0 ports in addition to four GbE LAN ports.

Exhibit 6 Residential 802.11ac Wave 2 Infrastructure

Brand	Model	Antennas	Radio Chipset	Ship Date	Typ. Street Price	Comments
Amped Wireless	Athena RTA2600	4 external	Qualcomm QCA9984	July '15	$275	2,553 Mbps, 800 mW out, GbE (4), USB 3.0 & 2.0
ASRock	G10 Gaming Router w/ USB dongle	4 internal	Qualcomm QCA9980	Q4 '15	TBD	2,533 Mbps, GbE (4), USB 3.0 (2), HDMI
Asus	RT-AC87U	4 external	Quantenna QSR1000 (QT3840BC, QT2518B), Broadcom BCM4360	July '14	$234	2,334 Mbps, GbE (4), USB 2.0, USB 3.0, media server & Cloud software. Broadcom BCM4709A platform SoC.
Asus	RT-AC5300U	8 external	Broadcom BCM4336 (Qty. 3)	Q4 '15	TBD	5,330 Mbps, GbE (4), USB 3.0, USB 2.0. Three radios.
AVM	Fritz!box 4080	4 internal	Qualcomm	Q3 '15	$285	2,533 Mbps, GbE (4), USB 3.0 (2). Versions available with ISDN and DECT for Europe, MyFritz cloud access.
Buffalo	WZR-1750DHP-EU	3 internal	Broadcom + Quantenna?	May '14	$135	1,750 Mbps, GbE (4), USB 3.0, USB 2.0
Buffalo	WXR-2533DHP	4 external	Qualcomm	June '15	$172	2,533 Mbps, GbE (4), USB 3.0. Japan model.
D-Link	DIR-885L/R AC3200	4 external	Broadcom BCM4336 (Qty 2)	Q4. '15	TBD	3,200 Mbps, GbE (4), USB 3.0.

Brand	Model	Antennas	Radio Chipset	Ship Date	Typ. Street Price	Comments
D-Link	DIR-895L/R AC5300	8 external	Broadcom BCM4366 (Qty 3)	Q4 '15	~$400	5,330 Mbps, tri-band, GbE (4), USB 3.0. Three radios.
Hitron Tech.	CGNVM-3589	4 internal, 3 internal	Qualcomm	Q3 '15	Lease*	1,750 Mbps. DOCSIS 3.0 & MoCA cable gateway with GbE (4), USB 3.0.
Linksys	EA8500 Max-Stream	4 external	Qualcomm QCA9980	Apr. '15	$259	2,533 Mbps, GbE (4), USB 3.0, eSATA / USB 2.0. "Smart Wi-Fi," Cloud & mobile app.
NEC	Rotary (Aterm) PA-WG2600HP	4 internal	Qualcomm	May '15	$126	2,533 Mbps, GbE (4), USB 3.0. Japan model
Netgear	Nighthawk X4 AC2350 (R7500)	4 external	Quantenna & Qualcomm	Sept. '14	$249	2,333 Mbps, GbE (4), USB 3.0 (2), eSATA, dynamic QoS. Qualcomm IPQ8064.
Netgear	Nighthawk X4S AC2600 (D7800)	4 external	Qualcomm	Sept. '15	$530	2,533 Mbps, GbE (4), USB 3.0 (2), eSATA, with VDSL/ADSL.
Netgear	Nighthawk X8 R8500	4 external + 4 internal	Broadcom BCM4366 (Qty 3)	Q4 '15	TBD	5,330 Mbps, tri-band, GbE (4?), USB 3.0 (?), three radios.
TP-Link	Archer C2600	4 external	Qualcomm QCA9984	Sept. '15	TBD	2,533 Mbps, GbE (4), USB 3.0 (2), Android & iOS management apps.
Trendnet	TEW-827DRU AC2600	4 external	Qualcomm QCA9880	Oct. '15	~$280	2,553 Mbps, GbE (4), USB 3.0 (2).

**All the routers above support 4 x 4 spatial streams, but some dedicate additional antennas to 2.4 GHz or high / low 5 GHz bands. All routers include one WAN (wired) port for internet access. Lease: offered by Internet service providers as part of service packages.*

- **AVM** markets the **Fritz!Box 4080** as a high-end home router for NAS, media server applications, smart home, and "MyFRITZ" cloud storage access from mobile devices anywhere in the world.
- The **Belkin / Linksys Max-Stream EA8500** can operate on both 802.11n and 802.11ac simultaneously. With the "Smart Wi-Fi" cloud and mobile app, a user can prioritize client devices and websites for video streaming and online gaming, control access to content inappropriate for children, monitor network activity and speed, set up a guest network, or turn off access for any client device. The EA8500 includes USB 3.0 port and eSATA / USB 2.0 port for adding external storage for NAS. According to Linksys, this was the first router to ship with Wave 2 enabled right out of the box.
- The **Buffalo WZR-1750DHP-EU** (EU version), the company's first dual-band 802.11n/ac router, was apparently the first on the market to support MU-MIMO. The newer **WZR-2533DHP** raises the bar with much higher performance.
- **D-Link's DIR-885 and DIR-895** have four and eight antennas, respectively, in a unique enclosure that looks like a stealth fighter. Both target "pragmatic high performance," according to D-Link, using Broadcom's new BCM4366 chipset. The DIR-885 has two radios, while the DIR-895 has three radios, which allows splitting the 5

GHz band into two bands, one for high-priority clients, for example for video streaming, the other for lower-priority clients. D-Link offers easy-to-set up software, remote reboot, ports for an external hard drive, and a built-in network recording capability that works with D-Link's popular Wi-Fi enabled video cameras.

- **Hitron's CGNVM-3589** is equipped with a DOCSIS 3.0 cable modem and MoCA for use in residential installations offered by Internet service providers.
- **NEC's Aterm PA-WG2600HP**, sold mainly in Japan, appears to lead in terms of performance per dollar.
- **Netgear** announced three MU-MIMO-capable routers in 2015. The latest on store shelves (as of Sept. 2015) was **the Nighthawk X4S AC2600 (D7800)**, which uses a Qualcomm chipset and features QoS management. The router includes eSATA and two "ReadySHARE-enabled" USB 3.0 ports for external drives and printers. The router also includes a built-in VDSL/ADSL modem, allowing consumers to upgrade their Internet Service Provider modem to one with Wi-Fi with greater range, faster data rates and improved video streaming and gaming. The router includes VPN support and the ability to set up a personal FTP file server, and the router allows the user to control a guest network, block unsafe web sites, and view bandwidth use.

  The upcoming **Netgear Nighthawk X8 R8500** will use three radios to split the 5 GHz band in two using eight antennas. This router could potentially out-perform the X4S in Wave 1 client environments by prioritizing traffic to some clients in one of the two 5 GHz bands.

- **Trendnet's TEW-827DRU** router uses Qualcomm Atheros' StreamBoost technology to provide data rates up to 1,733 Mbps in the 5 GHz band and 800 Mbps on the 2.4 GHz band. StreamBoost automatically manages network bandwidth, giving each client the bandwidth it needs for adequate QoS depending on the application. The router includes two SuperSpeed USB 3.0 ports, and when connected to an external hard drive, it supports file and print services using Samba, can work as an iTunes music server, and also can serve as a BitTorrent download client.
- **TP-Link's Archer C2600** uses a Qualcomm Wi-Fi chipset with "MU | EFX" MU-MIMO to support 4K UHD video streaming to PCs, smart TVs, and gaming consoles. The router comes with two USB 3.0 ports for connecting printers, cameras and external drives for sharing files, photos, music, and video. The unit uses WPA-WPA2 encryption for security, and uses TP-Link's "Tether" app for management from iOS and Android devices, allowing the user to set up a guest network and to set when and how clients can access the Internet.

Most residential 802.11ac routers claim non-I3E compliant peak data rates greater than 600 Mbps over 802.11n. For example, the ASUS RT-AC5300U uses Broadcom's NitroQAM (1024-QAM) and TurboQAM technologies, which require similarly equipped clients for claimed data rates of 1,000 Mbps at 2.4 GHz. In all cases actual useable throughput is considerably lower than the peak data rate claims quoted by manufacturers and used in this report.

Residential AP makers reported to us that:

- Infrastructure suppliers have embraced MU-MIMO, and plan to roll out more products using the technology late this year and next including range extenders, bridges, and new client-side devices such as USB Wi-Fi dongles and PCIe adapters.

- As prices drop below the $300 price limit for most consumers, volumes for MU-MIMO AP devices will increase. Most MU-MIMO routers are entering the market just below $300 retail today except for units with eight antennas.
- Most consumers buy new routers based on aggregate max data rates printed on the boxes ("AC2600" beats "AC1900") and apparently do not understand the 2x to 3x potential benefit of MU-MIMO.
- The trend in routers is bigger boxes with more antennas, an apparent antenna war. Internal antennas can function just as well, and research by at least one AP vendor suggests that most consumers hate external antennas:
    - One downside of external antennas is that consumers tend to misadjust them.
    - Eventually more MU-MIMO routers that favour internal over external antennas will reach the market, especially at lower price points as volumes ramp next year and in 2017.
- Faster Gigabit Ethernet ports are needed to make full use of 802.11ac under some high-rate conditions, especially on the WAN side. Many router suppliers mentioned that they plan to offer routers with 2.5GbE, 5GbE, and even 10GbE ports to make full use of 802.11ac Wave 2.
- Consumers tend to hide APs behind furniture or in a closet. Web-enabled smartphone apps seem more convenient and popular for consumers to manage their APs than units with displays in most cases, although AP displays can help with initial set-up.

AP suppliers will add more features in 2017 with the approval of 802.11mc, which will roll up 802.11aa, ae, af and other amendments with 802.11ac.

5.2 Wave 2 for Enterprise

Enterprise APs, as summarized in Exhibit 7, typically use ruggedized construction, incorporate PoE, internal antennas, high-end security and management software. Ruckus Wireless was the first to market an enterprise router supporting 802.11ac Wave 2, the ZoneFlex R710, but other vendors are now following.

Other features of enterprise AP often include:

- Bluetooth LE to support location-based services, beacons, location-aware analytics and IoT devices.
- Two Cat. 6 or Cat. 7 (RJ45) cables are sometimes connected to each 802.11ac AP to accommodate full gigabit data rates on the wired side using link aggregation.
- Some enterprise-class 802.11ac APs can run at full functionality using 802.3af PoE, but most require the newer 802.3at, which often means customers have to upgrade their LAN switches.

The cost of upgrading Ethernet cables, PoE and network switches to handle 802.11ac initially put many enterprises off, as did a dearth of clients supporting 802.11ac. However, AP suppliers told us that the future proofing value of Wave 2 for relieving congestion has overcome most concerns, and will lead to **strong adoption in the enterprise and related hotspot segments** starting by the end of 2016.

Exhibit 7 802.11ac Wave 2 Infrastructure for Enterprise

Brand	Model	Config.	Antennas	Radio Chipset	Ship Date	Typ. Street Price	Comments
Aruba	AP-324 and IAP-324	4 x 4	4 internal	Qualcomm QCA9994	Q3 '15	$1,370	2,533 Mbps, PoE, USB 2.0 Bluetooth LE, GbE (2).
Aruba	AP-325 and IAP-325 (Octomore)	4 x 4	8 external	Qualcomm QCA9994	Q3 '15	$1,395	2,533 Mbps, PoE, USB 2.0 Bluetooth LE, GbE (2).
Cisco	Aironet 3700i with Wave 2 Module	4 x 4	4 external	Marvell (?)	Q4 '15	$865	**1,500 Mbps, PoE, Cisco security. Wave 1 version shipping now. 2 x RJ45.
Cisco	Aironet 1850 Series	4 x 4	4 external	Qualcomm	Q3 '15	$712	1,740 Mbps, PoE, USB 2.0, GbE (2) combinable.
Ruckus Wireless	ZoneFlex R710	4 x 4	4 internal	Qualcomm QCA9994	Q2 '15	$1,390	2,533 Mbps, GbE (2), USB, PoE, Bluetooth LE. BeamFlex.
Xirrus Wireless	XD2-240	4 x 4	4 internal	Quantenna (?)	Q4 '15	$1,295	7,000 Gbps, GbE (2), PoE. Two radios.
Xirrus Wireless	XR-320 with Wave 2 Module	4 x 4	4 internal	Quantenna (?)	Q4 '15	TBD	1.1 Gbps. Wave 2 Upgrade Module required for MU-MIMO. GBE (3), PoE (1).

**All the routers above support 4 x 4 spatial streams, but some dedicate additional antennas to 2.4 GHz or high / low 5 GHz bands. All routers include at least one WAN (wired) port for internet access.*

Internet service providers (ISPs) such as T-Mobile, Comcast and Verizon have relatively long product life cycles for CPE leased to subscribers, and ISPs have been slow to adopt new Wi-Fi technology. However, most operators now view Wi-Fi as essential for adding wireless capacity, and many now provide modems with integrated Wi-Fi and a quasi-public channel for roaming subscribers. As a consequence, many ISPs have issued new requirements for cable modem AP with Wave 2 to equipment OEMs.

In addition to the chips described in the exhibits above, future MU-MIMO APs could use those shown in Exhibit 8, many of them just announced. Other new chipsets for APs supporting MU-MIMO will probably follow from Broadcom, Intel, Marvell, MediaTek, Qualcomm, Quantenna, and Realtek.

Exhibit 8 Other 802.11ac Wave 2 Radio ICs for Infrastructure (& Additional Details)

Supplier	Part Number	Comments
Broadcom	BCM43465	4 x 4
Broadcom	BCM43525	3 x 3
Marvell	88W8964	4 x 4
MediaTek	MTK7615	4 x 4, expected to ship Q3 or Q4 '15.
Qualcomm	QCA9980/2	3 x 3. Announced Apr. '14.
Qualcomm	QCA9990/2	4 x 4. Announced Apr. '14.
Qualcomm	QCA9984 / 9994	4 x 4. 160 MHz contiguous and 80 + 80MHz non-contiguous channels. The QCA9994 supports 5 MHz /10 MHz narrow channels for public safety. Announced July '15.
Qualcomm	IPQ40x8/9	2 x 2, dual-band dual-concurrent, two 2-stream 5 GHz radios in single band simultaneous operation, ability to add a third radio,11ac or 11ad. Announced October 2015.
Quantenna	QSR10GU	8 x 8 + 4 x 4 (hi /lo band) in one SoC

6. Client Devices

Led by adoption in smartphones, the installed base of client 802.11ac MU-MIMO will likely reach hundreds of millions of units by late 2016. Strategy Analytics found more than 60 client devices and variants already shipping globally with 802.11ac Wave 2, most of them smartphones and most shipping in Asia (see Exhibit 9):

- A common complaint we heard from the AP vendors' marketing units in Western countries was that as of August 2015, relatively few MU-MIMO enabled client devices had reached the market. Wi-Fi chip share leader Broadcom was absent from the client side in MU-MIMO; Qualcomm was the only supplier shipping MU-MIMO-enabled chipsets into clients in production volumes as of November 2015:
    - MU-MIMO clients have consisted mainly of smartphones equipped with Snapdragon 808, 810, 610, and 615 cellular baseband-apps processors. These processors incorporate MU-MIMO-capable Wi-Fi basebands. To one of these an OEM must add the QCA6174A or QCA6164A (for the 808/810) or the WCN3680B (610/615) or equivalent external Wi-Fi transceivers and a few RF front-end components.
    - For PCs and adapters, Qualcomm offers the QCA9978 (2 x 2) and QCA9377 (1 x 1) with Bluetooth 4.1, PCIe and USB interfaces. Many laptops use Qualcomm's QCA6164A and QCA6174A transceivers.
- It appears that a lack of drivers for the iOS and Android operating systems initially limited the MU-MIMO client universe in terms of units with MU-MIMO activated.
- Client and AP support for MU-MIMO has started to improve dramatically with interoperability testing of Wave 2 devices now underway in earnest.

Exhibit 9 802.11ac Wave 2 Client Devices

Brand	Model	Comments
Acer	Aspire E 14, E15, R13, V13, V Nitro, Predator	Notebook PCs
Asus	Zenfone 2 (2 variants)	Smartphones
Asus	Transformer TP200SA Flip book	2-in-1 PC
Compex	WLE 1200V2-22 and WLE 1200V5-22	Mini PCIe adapters.
Dell	DW1820, Alienware 13, 15, 17	Notebook PC
Fujitsu	Arrows NX F-04G	Smartphone
Gigabyte	GA-Z170X-Gaming G1	Motherboard
HTC	One M8	Smartphone
LeTV	LeMAX, LePro1	Smartphones
LGE / Google	Nexus 5X	Smartphone
Microsoft / Nokia	Lumia 950XL, Lumia 950	Smartphones
MSI	GT72, GT80	Gaming laptop PCs
MSI	X99A Godlike	Gaming motherboard
Oppo / OnePlus	OnePlus 2	Smartphone
Rivet Networks	Killer Wireless AC-1535	Wi-Fi adapter for notebook PCs
Samsung	Galaxy S5, Galaxy S6	Smartphone (MU-MIMO not enabled?)
Samsung	NT500R5H-K28L	Notebook PC
Sharp	Aquos Zeta, Aquos Pad, Aquos Serie, Aquos XX	Smartphones
TCL	Evoque (Aurora)	Smartphone
Xiaomi	Mi Note Pro (7 variants)	Notebook PCs
Xiaomi	Mi 4i (9 variants), Mi 4C	Smartphones
ZTE	Nubia Z9 (7 variants), Axon (2 variants)	Smartphones

Chip suppliers have announced several new chips to support MU-MIMO on the client side:

- Qualcomm will continue to aggressively seed the device market with the new Snapdragon 820 processor targeting premium smartphones in 2016. The SD820 supports 2 x 2 802.11n/ac Wave 2 and 802.11ad using optional additional Wi-Fi chips available as part of the platform.
- The Marvell 88W8997, due in 2016, supports 2 x 2 802.11n/ac Wave 2 and Bluetooth 4.2 in clients.
- The Celeno CL2440 supports 4 x 4 802.11n/ac Wave 2 in mini PCIe adapters. The SoC includes on-chip RF transceivers.
- Broadcom is likely to announce Wave 2 radio SoCs for phones, tablets and notebook PCs in 2016.

Rather than waiting for Wi-Fi Alliance testing to ramp up, the Wi-Fi chip vendors have recently brought third party testing houses into the game for interoperability testing of clients and AP. For example, Qualcomm provides

detailed test plans developed with a third-party test organization for conformance, interoperability, and performance testing of Wi-Fi AP and stations. The tests include MAC tests, security, and range versus throughput tests under real traffic conditions. This testing in combination with more chips for clients should go a long way toward easing any remaining concerns among AP vendors, and should help accelerate adoption of Wave 2.

7. Conclusions & Implications

The benefits of Wave 2 are real, and with some modest marketing efforts by OEMs and chip suppliers, Wave 2 will soon grow into the most popular Wi-Fi standard yet.

802.11ac Wave 2 provides substantial benefits to network efficiency, throughput, capacity and reduced power consumption for battery-operated client devices, providing tangible benefits to consumers. However, for Wave 2 to reach its full potential in terms of shipment volumes:

- OEMs have to figure out how to increase consumer awareness of MU-MIMO and help consumers to make intelligent choices. The "Wave 2" certification stamp on the retail box logo helps, but consumers have to be made aware that Wave 2 is the newest and best dual-band Wi-Fi standard:
    - Wave 2 should be marketed with descriptions such as "Highest available dual-band data rates with multiple Wi-Fi devices in the house" in addition to a "Wave 2" logo.
    - 802.11ad should be marketed with a distinct message, perhaps with the qualifier "fastest in-room Wi-Fi," otherwise 802.11ad could further confuse consumers.
- Since Apple has not adopted Wave 2 in the new iPhone 6S, the Android community and chipset suppliers have an opportunity to exploit Wave 2 as a means of differentiation against Apple in terms of Wi-Fi performance in mobile devices.

The AP community has enthusiastically embraced Wave 2, and more MU-MIMO clients will soon reach consumers:

- Interoperability testing and certification among AP and client devices is crucial, and this has now begun in earnest.
- More Wi-Fi chip vendors have started to support Wave 2 on the client side. More choices will help convince more OEMs to offer MU-MIMO-enabled clients, and this will broaden the appeal of MU-MIMO to lower price-tier client devices.