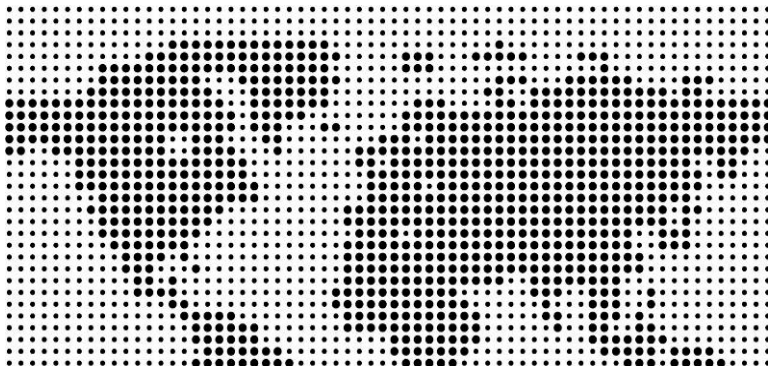




IEEE802.11ac: The Next Evolution of Wi-Fi™ Standards



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Executive Summary

Traditionally Wi-Fi® was a means for users to stay connected at home or in the enterprise to the internet and check emails, or surf the web. Today, that trend is rapidly changing whereby Wi-Fi is being used for content consumption such as streaming music and videos. Demand for video content is driven by easy-to-use video streaming services such as Netflix, YouTube, etc. Many users demand high-definition (HD) video content on set-top-boxes, TVs, laptops, and on their mobile devices such as smart phones and tablets. HD video content, as well as video content in general, presents a challenge for existing Wi-Fi 802.11n based networks, as they suffer from interference in the 2.4 GHz band.

802.11ac is the next evolution of the Wi-Fi standard that promises to deliver multiple HD video streams simultaneously. It can reach maximum throughputs well above a Gigabit per second. The 802.11ac specification mandates operation in the 5 GHz band, where there is relatively less interference and more channels are available compared to the 2.4 GHz band. 802.11ac achieves higher performance than 802.11n by using more spatial streams, wider bandwidth, higher order modulation, and improved bandwidth management techniques. Downlink Multi-user MIMO (MU-MIMO)¹ is an advanced feature defined in the 802.11ac standard that allows simultaneous multiple transmissions from the access point (AP) to up to four client stations (STAs). MU-MIMO mode increases client performance even with fewer antennas. With the proliferation of smart phones that have limited space, requiring only a single antenna is an especially attractive benefit as these smart phones experience higher throughputs while reducing cost and space.

This paper explains the new features of the IEEE 802.11ac standard. It also compares the performance results of 802.11n and 802.11ac for an in-home HD video content distribution scenario defined by IEEE. These simulation results indicate that 802.11ac can sustain significantly higher throughput and lower latency than 802.11n.

¹ MU-MIMO is an optional feature which is not part of Wi-Fi Alliance's initial 802.11ac product certification

[1] Introduction

To fulfill the promise of increasing Wi-Fi performance, effectively supporting more client devices on a network and delivering multiple HD video streams simultaneously, the IEEE group has been working on 802.11ac, a new standard that is in its advanced stages of standardization. The 802.11ac Draft 2.0 specification was released in February 2012 and leverages new technologies to provide improvements over 802.11n. It is also the first Wi-Fi standard to exceed the Gigabit-per-second throughput barrier.

Wi-Fi is playing an increasingly important role in home networking as it has consumer familiarity and a low cost of installation. There is a growing trend in homes to distribute multiple HD video streams and other high-bandwidth content to devices like HDTVs, laptops, tablets, and smart phones. Delivering multiple simultaneous HD video streams wirelessly requires a robust, low-latency, and high throughput Wi-Fi network.

Wi-Fi based on 802.11n improved the performance compared to previous 802.11a/b/g standards. It increased the theoretical peak data rates to 600 Mbps compared to 54 Mbps. In order to get to these high rates and coverage however, it relied on single-user MIMO and beamforming. However, beamforming did not get widely adopted by the industry due to lack of a commonly specified mode. In addition, with multiple users, single-user MIMO relied on time-division multiplexing of the MIMO streams, which reduced overall throughput.

802.11ac overcomes the above limitations and achieves a maximum throughput of 6.93 Gbps in 160 MHz bandwidth mode in the 5 GHz band, using eight spatial streams and 256 QAM modulation. 802.11ac has also specified multi-user MIMO (MU-MIMO), which allows simultaneous transmission of MIMO streams to multiple client devices. In addition, 802.11ac has defined a single closed-loop method for transmit beamforming, which is expected to be an optional feature of the Wi-Fi Alliance certification plan. 802.11ac has also introduced dynamic bandwidth management to optimize the use of available bandwidth. These new features of 802.11ac deliver the next leap in performance, which also includes simultaneous streaming of multiple HD video streams.

[2] New Features in 802.11ac

2.1 Mandatory 5 GHz Operation

Previous Wi-Fi standards such as 802.11a/b/g/n operate in the 2.4 GHz band with 802.11n optionally supporting the 5 GHz band. The 802.11ac standard mandates operation only in the 5 GHz band. 2.4 GHz band is susceptible to greater interference from crowded legacy Wi-Fi devices as well as many household devices. The 5 GHz band has relatively reduced interference and there are a greater number of non-overlapping channels available (25 non-overlapping channels in US) compared to the 2.4 GHz band (3 non-overlapping channels in the US). 802.11ac is therefore expected to leverage the reduced interference and greater flexibility of multiple available channels in the 5 GHz band for increased performance.

2.2 Wider Bandwidth

802.11ac introduces 80 MHz and 160 MHz channel bandwidths in addition to the 20 MHz and 40 MHz specified in 802.11n. The 802.11ac standard requires all devices to support 20, 40, and 80 MHz channel bandwidths in the 5GHz band, with support of 160 MHz channel bandwidth being optional. 80 MHz channels can only be formed by combining two adjacent, non-overlapping 40 MHz channels. The optional 160 MHz channel can be formed by combining two adjacent or two non-adjacent 80 MHz channels. The wider channel bandwidths of 802.11ac are shown in Figure 1.

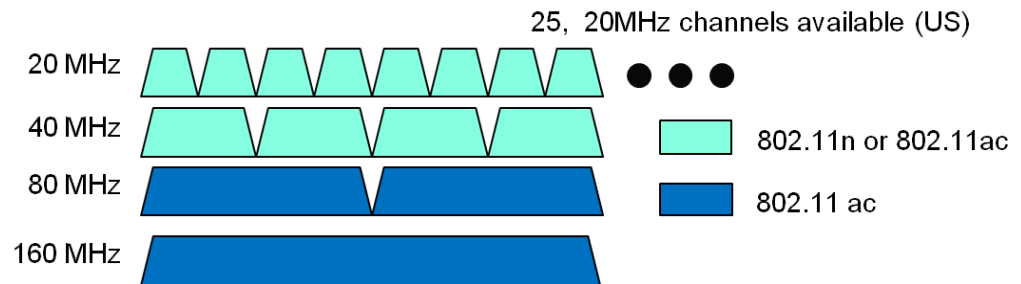


Figure 1: Wider Channel Bandwidths in 802.11ac (5 GHz Band)

Wider bandwidth allows higher data rates to be achieved. In 160 MHz mode, the maximum data rate that can be achieved using eight spatial streams, 256 QAM modulation, and code rate 5/6 is 6.933 Gbps. However, initial 802.11ac products will typically use 80 MHz bandwidth and be implemented in single-stream configuration for handsets and tablets, and up to three spatial streams in routers for a maximum achievable PHY data rate of 1.3 Gbps, slightly more than double the maximum data rate of 802.11n using four spatial streams. Table 1 shows the maximum possible data rates in 802.11ac depending on the highest possible modulation and coding scheme for a given bandwidth and given number of spatial streams. With gigabit throughputs

Bandwidth	20 MHz	40 MHz	80 MHz	160 MHz
# of Spatial Streams				
1	86.7 Mbps	200 Mbps	433.3 Mbps	866.7 Mbps
2	173.3 Mbps	400 Mbps	866.7 Mbps	1733 Mbps
3	288.9 Mbps	600 Mbps	1300 Mbps	2340 Mbps
4	346.7 Mbps	800 Mbps	1733 Mbps	3466 Mbps
5	433.3 Mbps	1000 Mbps	2166 Mbps	4333 Mbps
6	577.8 Mbps	1200 Mbps	2340 Mbps	5200 Mbps
7	606.7 Mbps	1400 Mbps	3033 Mbps	6066.7 Mbps
8	693.3 Mbps	1600 Mbps	3466 Mbps	6933 Mbps

Table 1: 802.11ac Maximum Achievable PHY Data Rates

easily achievable, 802.11ac promises to deliver high performance and address the capacity requirements of in-home HD content distribution.

2.3 Higher Order Modulation

In 802.11n the highest order modulation is 64-QAM (Quadrature Amplitude

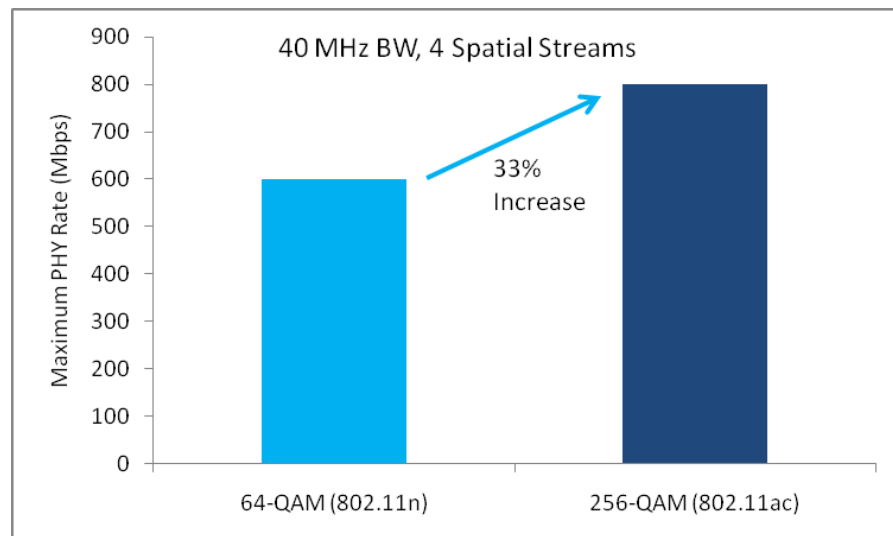


Figure 2: Higher Order Modulation (256-QAM) in 802.11ac

Modulation). Six bits of coded information can be represented in a 64-QAM constellation. 802.11ac increased the constellation configuration to 256-QAM that provides an incremental increase in data rates by 33% over 11n. This increase is achieved by representing eight coded bits per symbol instead of six. It should be noted however that higher signal-to-noise ratio (SNR) is required for 256-QAM compared to 64-QAM because the constellation symbols are closer to each other, as a result making them more susceptible to noise.

Figure 2 shows the impact of 256-QAM on performance. 600 Mbps is the maximum achievable PHY data rate in 802.11n using four spatial streams and 40 MHz bandwidth. However, for the same configuration, 802.11ac achieves 800 Mbps. These data rates assume the short guard interval option.

2.4 Higher Order MIMO

802.11n was the first standard that introduced single-user multiple-input, multiple-output (MIMO) transmissions. 802.11n allowed a maximum of four MIMO streams that could be sent to a single device at a time. This increased throughput over the previous standards such as 802.11a/b/g. 802.11ac further increased the maximum number of MIMO streams from four to eight. An 802.11ac STA can now receive up to eight spatial streams, to effectively double the total network throughput of 802.11ac compared to 802.11n.

2.5 Multi-User MIMO (MU-MIMO)

802.11ac is the first Wi-Fi standard that introduces multi-user MIMO (MU-MIMO). In MU-MIMO, the AP can serve multiple STAs simultaneously. This technique allows the AP transmitter to send multiple packets simultaneously to multiple STAs. This is achieved using up to eight spatial streams that can be divided among up to four STAs. These STAs can employ different numbers of spatial streams. Each individual STA can have a maximum of four spatial streams in an MU-MIMO transmission. For example, a configuration can include four STAs each with two antennas, and an eight antenna AP forms a four-way MU-MIMO to serve all four STAs with data on two spatial streams each. Without MU-MIMO, the AP would have to multiplex the four STAs and serve them one at a time, thus effectively reducing their throughputs by a factor of four.

Single user MIMO (SU-MIMO) has to time-division multiplex the data to support multiple STAs and requires more antennas for reception, increasing the device cost. As shown in Figure 3 for example, if an AP has three antennas and there are three

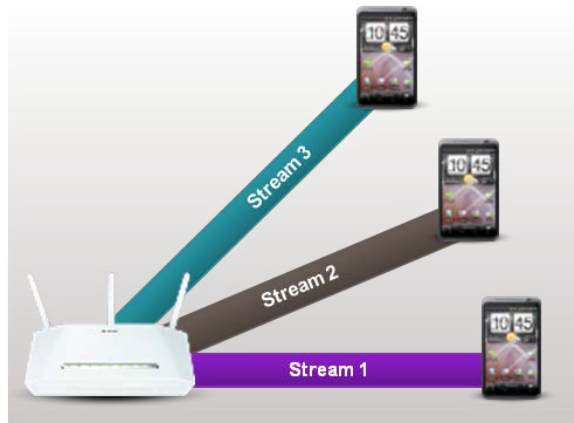


Figure 3: Multi-User MIMO (MU-MIMO)

STAs in an SU-MIMO system, each STA requires three antennas to receive data from the AP one-third of the time to achieve the same throughput as that of an MU-MIMO STA with a single antenna. In an MU-MIMO scenario with the same three-antenna AP, the three STAs require only a single antenna to receive the same throughput as that of the SU-MIMO case. All three STAs in MU-MIMO case simultaneously receive a single spatial stream from the AP 100% of the time.

MU-MIMO is especially beneficial with the proliferation of smart phones. With faster throughput, power consumption can be reduced and with only a single antenna required instead of three, cost and space requirements are reduced.

2.6 Dynamic Bandwidth Management

Bandwidth management is an important aspect of any Wi-Fi standard. 802.11ac has several bandwidth combinations allowed from 20 MHz to 160 MHz wide channels. With this increase in available channel bandwidth comes greater flexibility. However, with this greater flexibility, comes the challenge of optimizing the use of wider bandwidth in an efficient manner. Each 802.11ac network includes a 20 MHz primary channel. This primary channel is accessed using carrier sensing to make sure the channel is free from interference from other networks. Another use for the primary channel is co-existence and backwards compatibility with older Wi-Fi standards. Once the access to the primary channel is obtained, additional secondary channels for wider bandwidth may be added.

Only 20, 40, 80, and 160 MHz bandwidths are allowed in 802.11ac. 60 and 120 MHz bandwidths are not allowed. To manage a set of primary and secondary channels in a

wide bandwidth configuration, 802.11ac introduced a new concept of dynamic bandwidth management. 802.11n did not properly define a handshake (ready to send/clear to send, or CTS/RTS) mechanism for bandwidth management. This sometimes caused the bandwidth of the receiver to not strictly relate to the actual bandwidth available at the receiver. This is shown in Figure 4. In this case the sender has no interference in both the primary and secondary channels; however, the receiver has interference in the secondary channel. The sender sends the handshake signal called ready to send (RTS) on both channels. The receiver cannot acknowledge its respective handshake signal called clear to send (CTS) on either primary or secondary channel as that is the protocol in static mode. As a result, no transmission occurs in this case.

On the other hand, in dynamic mode defined in 802.11ac, channel interference is

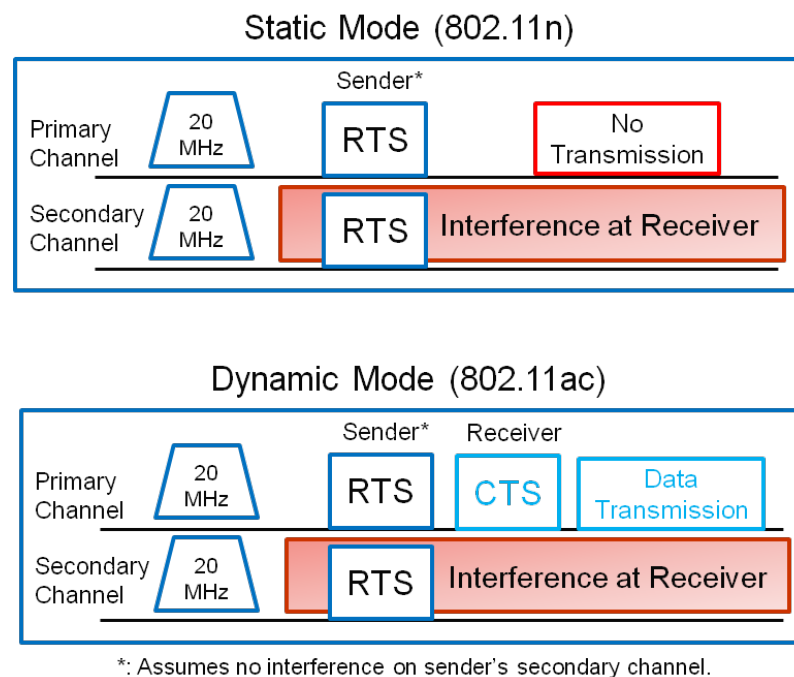


Figure 4: Static and Dynamic Bandwidth Management

measured per channel, and the receiver can send CTS signals per channel to indicate which channels are interference-free. In this case transmission is allowed to take place on the primary channel, which improves overall bandwidth utilization and network performance.

In 802.11ac the interference detection threshold has also improved. Wi-Fi APs use interference detection to reduce overlap and collisions with other APs operating on secondary channels. The standard defines a sensitivity threshold for the signal strength on the secondary channel that an AP must measure in order to determine if

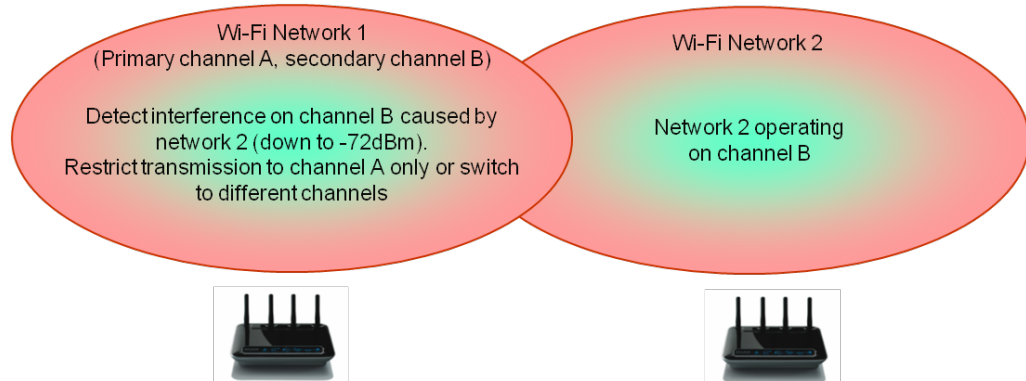


Figure 5: Improved Sensitivity of CCA Threshold in 802.11ac

that secondary channel is busy. Shown in Figure 5 is an example to illustrate this concept. 802.11n uses -62 dBm as the sensitivity threshold for inferring 802.11n signals, whereas 802.11ac improved this to -72 dBm, which means that 802.11ac networks have improved sensitivity towards collision avoidance and overlap detection.

Dynamic bandwidth management and increased sensitivity of the clear channel assessment (CCA) threshold are additional features that improve the performance of 802.11ac and help meet the requirements of in-home HD content distribution.

2.7 Single-Method Closed Loop Transmit Beamforming

In MIMO channels, beamforming is a technique that focuses the APs transmit energy of the MIMO spatial streams towards the target STAs. This is achieved by using channel estimation to precode the transmission in such a manner that when the transmitted streams reach the STA they optimally combine their energies thus producing a stronger signal as seen by the STA. In 802.11n, several methods of beamforming were defined, however none of them was mandated for certification and as a result, chipset vendors implemented a variety of non-interoperable techniques. Lack of a single method prevented this feature of 802.11n from providing the intended range enhancements across end-products, and becoming mainstream.

The 802.11ac standard defines a single closed-loop method for transmit beamforming. In this method, the AP transmits a special sounding signal to all STAs who estimate the channel and report their beamforming matrices back to the AP. This feedback from

STAs is standardized so that APs and STAs from different vendors would still interoperate correctly as long as they are certified to be standard compliant.

Transmit beamforming (TxBF) is an optional feature in the 802.11ac specification and it will be an optional-tested item in the Wi-Fi certification testing. TxBF is a technique that can enable a higher modulation and coding scheme (MCS) at a given range. TxBF does not extend the maximum range or increase the maximum rate. In the 5 GHz band, regulatory requirements limit the transmit power that reduces the TxBF gain. The reduction in power depends on the array gain which is a quantity proportional to the number of antennas used at the transmitter.

2.8 Backwards Compatibility

802.11ac is an IEEE standard amendment to 802.11n specification. It is required to be fully compatible with 802.11n and 802.11a. 802.11ac only applies to 5 GHz band because there are no 80 MHz and 160 MHz channels available in the 2.4 GHz band. 802.11ac standard enables coexistence with 802.11n/a devices by requiring a backwards compatible preamble that has a section which is understandable by 802.11n/a devices. This would allow legacy devices to operate as intended.

[3] 802.11ac Usage Model Example: In-home HD content distribution

IEEE has defined various usage models for 802.11ac. For the purpose of this paper, we focus on the models developed for distributing compressed video streaming throughout the whole home. This usage model addresses the increasing requirement

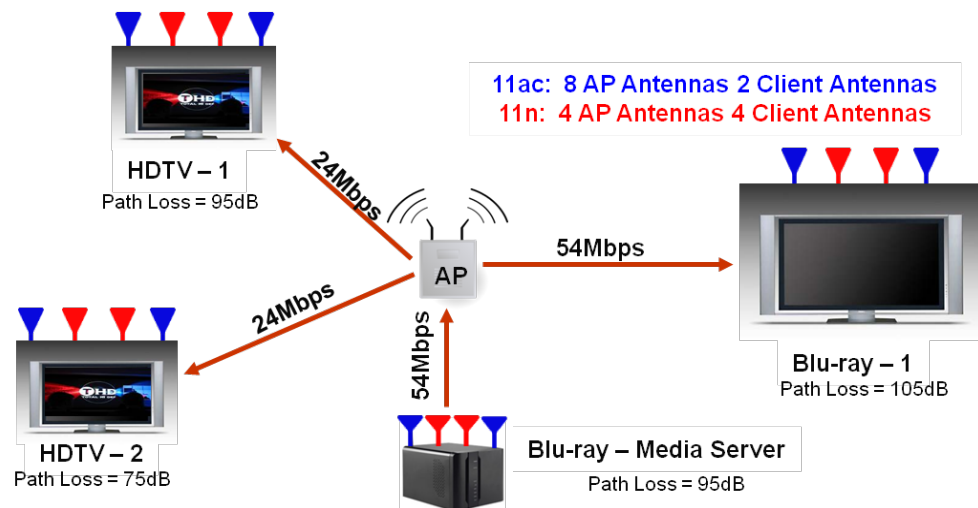


Figure 6: In-home HD Content Distribution

from service providers who want the home network to support multiple HD streams. Content comes into the home over a wired link such as DSL, Fios, or Cable. A set-top-box (STB) combined with a Wi-Fi access point (AP) can receive this content. Alternatively, there can be locally stored content in a media server. The STB/AP distributes multiple HD video streams wirelessly to HDTVs or other set-top-boxes throughout the home. This eliminates the restrictions on placing STBs very close to wall outlets as done today. With Wi-Fi, the flexibility to place the STB increases, and makes it more convenient to install an HDTV anywhere in the home.

An in-home HD content distribution usage model shown in Figure 6 defines four wireless video streams. Two HD video streams at 24 Mbps each go to two HDTVs in two separate rooms. One Blu-ray video stream at 54 Mbps comes from the media server to the AP, and one Blu-ray video stream goes from the AP to a Blu-ray TV. Real path losses are modeled to reflect the distance between different rooms within the home and wall penetration losses.

802.11ac is a suitable technology to address this scenario. It achieves high throughputs, low latencies, and reduced cost using many of the advanced features introduced in the standard.

[4] 802.11ac HD Content Distribution Performance

Figure 7 shows the simulation results for the in-home HD content distribution scenario shown in Figure 6. Both 802.11n and 802.11ac operate at 40 MHz bandwidth. 802.11n uses four antenna AP and each client uses four antennas. Additional antennas increase the cost of the solution. 802.11ac uses eight antenna AP and only two

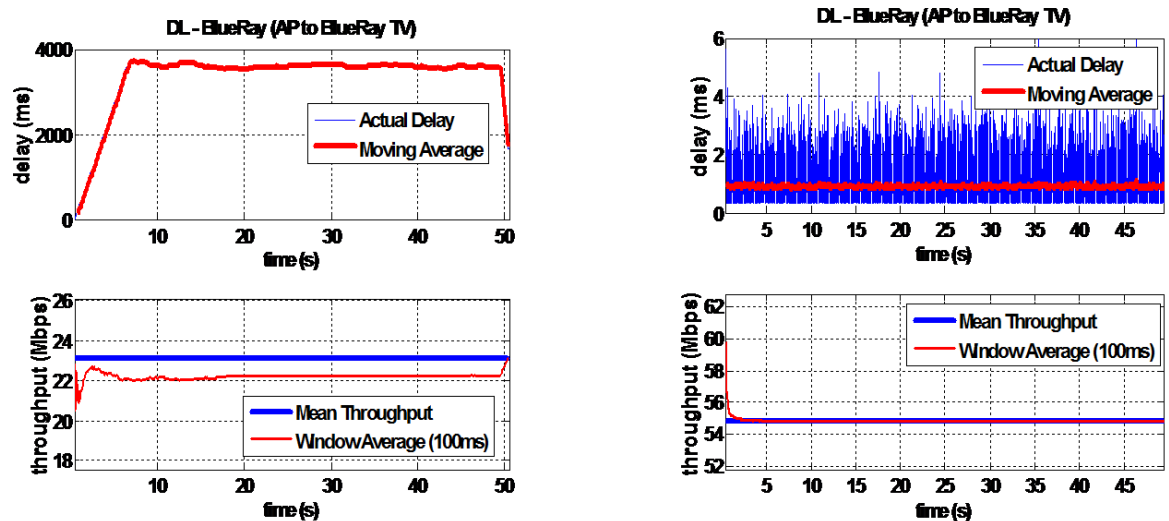


Figure 7: In-Home HD Content Distribution Simulation Result: 802.11n (Left) 802.11ac (Right)

antenna clients which reduces cost of the solution. 802.11n cannot sustain the downlink Blu-ray reception by the TV because of the required 54 Mbps in presence of the other stream. 802.11ac on the other hand successfully streams the Blu-ray to the TV by achieving 54 Mbps throughput and by keeping the delay well below one millisecond.

[5] Conclusion

The IEEE 802.11ac standard leverages new technologies to achieve Gigabit per second throughputs. Smoother in-home HD video content distribution can be achieved using 802.11ac over a robust high throughput, low latency Wi-Fi network.

Improvements in performance come from wider bandwidth, more spatial streams, higher order modulation, dynamic bandwidth management, and multi-user MIMO. In addition, 5 GHz operation allows for reduced interference. Small form factor devices such as smart phones sensitive to space and cost can enjoy higher throughputs with single antennas.

Simulation results show 802.11ac in 40 MHz bandwidth using eight antenna AP can easily support two HD video streams at 24 Mbps each and two Blu-Ray video streams at 54 Mbps each. The additional benefit is the cost reduction at the client that only requires two antennas. Thus 802.11ac is a promising technology that can robustly deliver simultaneous HD video streams throughout the home.

Initial pre-certification 802.11ac devices are starting to become available this year. Wi-Fi certification is expected to start in the first quarter of 2013. Multi-user MIMO certification is expected to start some time in the first half of 2014.

[6] APPENDIX

6.1 Mandatory and Optional features in 802.11ac

<i>Mandatory</i>	<i>Optional</i>
5GHz operation	160MHz channels
20, 40, and 80MHz channels	80+80MHz channels
1 Spatial Stream in clients	2 or 3 Spatial Streams (Tx and Rx) in clients and APs
2 Spatial streams in APs	4 Spatial Streams in clients and APs
MCS 0-7 (BPSK, $r=1/2$ through 64-QAM, $r=5/6$)	MCS 8 (256-QAM, $r=3/4$)
VHT A-MPDU delimiter for Rx and Tx for single MPDU	MCS 8-9 (256-QAM, $r=3/4$ and $r=5/6$)
Rx A-MPDU and Tx A-MPDU	Rx A-MPDU of A-MSDU
Clear Channel Assessment (CCA) on Secondary	Short Guard Interval (GI)
CTS with BW signaling in response to RTS with BW signaling	RTS with BW signaling
	MU-MIMO
	Transmit beamforming (TxBF)
	AP STBC Tx 2x1 and STA STBC Rx 2x1
	TXOP sharing
	VHT TXOP power save
	Low Density Parity Check (LDPC) coding

[7] Glossary

A-MPDU	Aggregate MAC Protocol Data Unit
A-MSDU	Aggregate MAC Service Data Unit
AP	Access Point
CCA	Clear Channel Assessment
CTS	Clear To Send
DSL	Digital Subscriber Line
HD	High Definition
HDTV	High-Definition Television
IEEE	Institute of Electrical and Electronics Engineers
LDPC	Low Density Parity Check
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi User Multiple Input Multiple Output
PHY	Physical Layer

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QAM	Quadrature Amplitude Modulation
RTS	Ready to Send
STA	Station
STB	Set Top Box
STBC	Space Time Block Coding
SU-MIMO	Single User Multiple Input Multiple Output
TxBF	Transmit Beamforming
TXOP	Transmit Opportunity
VHT	Very High Throughput