Study of Wi-Fi for In-Home Video Streaming

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Abstract

With the introduction of 802.11ac and the promise of gigabit Wi-Fi, it seems to be, at least theoretically, possible to simultaneously stream multiple HD quality videos over the Wi-Fi network. This opens up opportunities for cable operators and their customers to distribute cable video to subscriber devices throughout the homes over Wi-Fi networks. This provides an attractive value-add to both MSOs and their customers.

In this paper, our goal is to evaluate the feasibility of using Wi-Fi for wireless distribution of HD quality cable video under different circumstances or configurations. Our results indicate that although Wi-Fi performance can not be guaranteed in all circumstances, it is generally possible to stream multiple HD videos if certain conditions, including conditions on radio configuration, interference, and signal attenuation are met. We present our test observations for 802.11n and 802.11ac Wi-Fi radios with different configurations and provide recommendations for video streaming over operator-managed Wi-Fi networks.

ACRONYMNS

ACS	Auto Channel Selection
AP	Access Point
COAM	Customer Owned and Managed
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DBDC	Dual Band Dual Concurrent
DBM	Dynamic Bandwidth Management
DTCP	Digital Transmission Content Protection
FCC	Federal Communications Commission
GoP	Group of Picture
HEW	High Efficiency Wi-Fi
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MoCA	Multimedia Over Coax Alliance
MPEG	Moving Pictures Expert Group
PER	Packet Error Rate
PLC	Power Line Communications
PLR	Packet Loss Ratio
QAM	Quadrature Amplitude Modulation
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
SDM	Spatial Division Multiplexing
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
SON	Self Organizing Networks
TCP	Transmission Control Protocol
TDLS	Tunnel Direct Link Setup
TxBF	Transmit Beamforming
UDP	User Datagram Protocol
UNII	Unlicensed National Information Infrastructure
WHDMI	Wireless High Definition Multimedia Interface
WLAN	Wireless Local Area Networks

INTRODUCTION

Consumers want to watch cable video services throughout their homes, but neither the subscriber nor service provider wants the expense and inconvenience of running new cables. Additionally, both subscribers and MSOs would like to avoid the cost of additional set-tops by leveraging Customer Owned and Managed (COAM) devices such as smartphones, tablets and smart TVs where Wi-Fi capabilities are ubiquitous. Wi-Fi offers the opportunity for the service provider to deliver video streaming throughout the home without the expense of new cabling.

Over the last decade Wi-Fi performance has improved exponentially. The latest Wi-Fi standard – 802.11ac – promises support for speeds greater than 1 Gbps. Many Wi-Fi products, including 802.11n, support Multiple Input Multiple Output (MIMO), Transmit Beamforming and operations in 5 GHz spectrum. These technologies promise greater reliability and even better performance. A number of Wi-Fi silicon vendors (e.g., Broadcom, Celeno, Qualcomm, Quantenna, etc.) are working on optimizing Wi-Fi silicon for in-home high definition video streaming.

To evaluate Wi-Fi technology for in-home distribution of Full HD cable video, CableLabs conducted Wi-Fi performance and video quality measurement tests on multiple Wi-Fi products including 802.11n and 802.11ac. The tests were conducted at CableLabs' Louisville facility and in homes of different sizes and construction materials in Colorado and on the East Coast.

This paper first provides a technical overview of wireless technologies enabling in-home video streaming. Following that the paper provides a discussion on challenges for using Wi-Fi for in-home cable video streaming. Subsequently, the paper provides observations from testing and recommendations for operators considering Wi-Fi for video streaming. Finally, the evolution of Wi-Fi networks and the closing thoughts are included in the conclusion section.

HOME MULTIMEDIA WIRELESS NETWORKS

This section provides a technical overview of wireless technologies enabling in-home video streaming.

WirelessHD: The WirelessHD defines a wireless protocol that enables consumer devices to create a wireless video area network. The WirelessHD uses 60 GHz Frequency band. Unlike the Wireless Gigabit Alliance (WiGig) technology, it does not include an option to fall back to 5 GHz band. The indoor coverage range is about 10 meters, which is adequate for video streaming between two devices in the same or the next room. The technology supports Transmit Beamforming and data transmission rates of up to 28 Gbps.

Additionally, it includes support for 3D content and 4K resolution including HDCP 2.0 and DTCP for content protection. WirelessHD products from a number of vendors such as Panasonic, Sony, and LG are available today. Silicon Image is the primary silicon vendor for WirelessHD. The competing technologies include WiGig and Wireless Home Digital Interface. The primary use for WirelessHD is the delivery of high quality, uncompressed A/V content. The picture below shows the logo for WiHD devices.

WHDMI: The Wireless High Definition Multimedia Interface (WHDMI) enables wireless delivery of uncompressed High Definition Television Vision. Unlike the WirelessHD, it uses 5 GHz frequency band and does not include support for 60 GHz band. The indoor coverage range is about 30 meters, which is about the same as 802.11ac. While the WirelessHD is only good for video streaming between two devices in the same or next room, the WHDMI claims support for video streaming throughout the home. The technology supports 20 MHz and 40 MHz channel bandwidth to support up to 1.5 Gbps for uncompressed 1080i and 720p, and up to 3 Gbps for uncompressed 1080p, respectively.

Additionally, it supports capabilities to prioritize the most visually significant bits of a video stream. WHDI products from a number of vendors such as Hitachi, Motorola, Samsung, Sharp, Sony, HP, and LG are available today. Amimon is the primary silicon vendor for WHDI. The competing technologies include WiGig and WiHD. The primary use for WHDI is the delivery of high quality, uncompressed A/V content. The picture below shows the logo for WHDI devices.

WiGig: The WiGig technology offers short-range multi-gigabit connections for a wide variety of applications including video, audio, and data, while the WHDI and WiHD focus is on delivering high quality uncompressed video. The following is a list of applications on which WFA is focusing:

- WiGig Display Extension
- WiGig Serial Extension
- WiGig Bus Extension
- WiGig SD Extension

The WiGig technology is the basis of the IEEE 802.11ad amendment and supports Beamforming and data rates up to 7 Gbps in a 60 GHz frequency band. Many WiGig products are also expected to support Wi-Fi, along with mechanisms for smooth handovers from 60 GHz to 2.4 GHz and 5 GHz band. Similar to the WiHD, the indoor coverage range is about 10 meters, which is adequate for communication between two devices in the same or next room.

A number of vendors, including Atheros, Marvell and Broadcom, Dell, Intel, Panasonic and Samsung, are working with the WFA in the development of technology and certification testing program. The WFA currently expects to launch the WiGig certification program in 2015. The competing technologies include WHDI and WiHD. The picture below shows the logo that WiGig certified products are expected to display.

802.11n and 802.11ac: Both 802.11n and 802.11ac technologies support enough throughput to support in-home HD video streaming. 802.11ac is the current generation Wi-Fi technology, and it supports some features that were not part of the 802.11n standard. The table below provides a highlight of some of the differences between 802.11n and 802.11ac.

FEATURES	802.11N	802.11AC
Frequency Band	2.4 or 5 GHz	5 GHz only
Channel Bandwidth	20, 40 MHz	20, 40, 80, 160, 80+80 MHz
Modulation & Coding Scheme	64 QAM	256 QAM
Spatial Streams	Up to 4	Up to 8
Transmit Beamforming	Optional	Standardized
Max Throughput	600 Mbps	3.2 Gbps
MU-MIMO	No	Yes
Availability	Available for some time now	First generation available now

In addition to the features in the previous table, 802.11ac also includes support for features such as Dynamic Bandwidth Management, which can be very handy in mitigating interference and improving spectral efficiency. This feature allows an AP to dynamically select channel bandwidth to each client on a frame-to-frame basis.

The first generation 802.11ac products support only 20, 40 and 80 MHz channel bandwidth. The current FCC spectrum rules do not allow for a continuous and homogenous 160 MHz channel. Channel bandwidth of 80 MHz+80 MHz and 160 MHz are expected in the second-generation 802.11ac products. Support for MU-MIMO and Dynamic Bandwidth Management are also expected in the second-generation 802.11ac products.

Tunnel Direct Link Setup (TDLS): TDLS allows network-connected client devices to create a secure, direct link to transfer data more efficiently. The client devices first establish a control channel between them through the AP. The control channel is then used to negotiate parameters (e.g., channel) for the direct link. APs are not required to support any new functionality for two TDLS compliant devices to negotiate a direct link.

TDLS offers multiple benefits, including efficient data transmission between client devices by removing the AP from the communication link. Use of a direct communication channel also allows the client to negotiate capabilities independent of the AP. For example, clients can choose a wider channel, efficient modulation scheme, and a security and channel that are more suitable for direct link between the client devices.

TDLS devices, communicating with each other over a direct link, are also allowed to maintain full access to the Wi-Fi network simultaneously, which, for example, allows the client device to stream video to another device in the home over the direct link; and at the same time allows the user to surf internet via connectivity to the AP. If the TDLS direct link is switched to another channel, the stations periodically switch back to the home channel to maintain connectivity with the Wi-Fi network.

The WFA has certified multiple products for TDLS, including Broadcom and Marvel. TDLS is based on IEEE 802.11z, and is one of the optional features of Miracast (Wi-Fi Display).

Wi-Fi Direct: Wi-Fi Direct allows Wi-Fi client devices to connect directly without use of an AP. Unlike TDLS, Wi-Fi client devices are not required to be connected to an AP to establish a Wi-Fi Direct link. Wi-Fi Direct also includes support for device and service discovery. Wi-Fi Direct devices can establish a one-to-one connection, or a group of several Wi-Fi Direct devices can connect simultaneously.

Wi-Fi Direct offers multiple benefits, such as ease of use and immediate utility; enables applications such as printing by establishing a peer to peer connection between the Wi-Fi Direct enabled printer and client device; content sharing between two Wi-Fi Direct enabled devices; and displaying content from one Wi-Fi Direct device to another without requiring any Wi-Fi network infrastructure. Wi-Fi Direct certifies products, which implement technology defined in the WFA Peer-to-Peer Technical Specification. The WFA has certified multiple products for Wi-Fi Direct. As of 2012, there are over 1100 Wi-Fi Direct certified products. Wi-Fi Direct is the core transport mechanism for Miracast (Wi-Fi Display).

Miracast: Miracast provides a seamless display of content between devices using Wi-Fi Direct as the transport mechanism. Miracast also includes optional support TDLS as a transport mechanism.

The key features supported in Miracast include device and service discovery, connection establishment and management, security and content protection, and content transmission optimization. Similar to Wi-Fi Direct and TDLS, Miracast is client functionality and does not require updates to AP devices.

Primary use cases for Miracast are screen mirroring and video streaming. Miracast certifies products which implement technology defined in the Wi-Fi Display Technical Specification. As of this writing many devices (e.g., Smart phones) have been certified for Miracast.

Airplay: AirPlay is an Apple proprietary technology. It enables iTunes and other media systems to use local area networks to stream audio and video to Apple TV or other AirPlay-enabled sound systems or remote speakers. AirPlay is built on bonjour technology, which uses Multicast DNS (mDNS) and DNS-based Service Discovery (DNS-SD).

AirPlay includes support for media protocols such as RTSP, RTP, RTCP and HTTP Live Streaming. The supported audio format includes AAC and MP3. The supported video format is H.264. AirPlay also includes support for FairPlay – another Apple proprietary technology - for DRM and link Protection.

AirPlay is incompatible with DLNA in many ways. For example, the service discovery and link protocols used by the two technologies are different. DLNA also supports many more options for video and audio format.

AirPlay has a limited objective: media networking within Apple's closed ecosystem. Apple builds nearly all of the hardware and software, with the exception of audio-streaming components for music players. With these limited goals, AirPlay requires a simple set of protocols and media formats. Testing interoperability and usability of all the combinations and permutations takes very little time.

Digital Living Network Alliance (DLNA): DLNA is a generalized approach to media networking, designed to work with all media devices – methodologies which interconnect everything from everyone. In contrast to Airplay, DLNA incorporates every possible media format. Universal Plug and Play (UPnP) provides the principal underlying structure for DLNA. The UPnP Forum was formed "to enable device-to-device interoperability and facilitate easier and better home networking." Nearly a thousand companies are now members of UPnP Forum. The UPnP Forum develops and publishes UPnP Device Architectures that "define how to use IP to communicate between devices" and Device Control Protocols, which define specific services between devices.

DLNA divides devices into two broad categories: "home network devices" (essentially anything that is plugged into an electrical outlet and provides at least Ethernet networking) and "mobile handheld devices" (anything that runs on batteries and uses Wi-Fi). The mandatory and optional requirements for these two categories are quite different. Home network devices are required to support only JPEG images, LPCM audio, and MPEG2 video. Everything else is optional. Mobile handheld devices are required to support more formats: JPEG images, MP3 and AAC LC audio, and MPEG4 AVC video.

DLNA uses DTCP-IP for link protection. DTCP (Digital Transmission Content Protection) is a widely- accepted mechanism to protect high-value digital media such as movies and network videos when they are transferred between devices – such as between a digital set-top box and a TV. DTCP-IP (DTCP for Internet Protocol) is an extension of DTCP for protected transmission over IP networks – such as between a PC and a digital

TV, or over a network link between a cable gateway and a remote digital TV.

POTENTIAL CHALLENGES OF VIDEO OVER WI-FI

This section provides a discussion on factors that can have an impact on video service delivery using Wi-Fi.

Video is known to be a demanding application with strict requirements on throughput, delay, packet loss and jitter. One reason for stringent requirements is the way video is compressed. The common objective of all the video compression methods is to reduce redundancy in the spatial and temporal domains. Corresponding to spatial and temporal redundancy, intra-frame and inter-frame compression have been applied in video coding algorithms. Video packets can be classified as inter-frame (I frame) and intra-frame (P and B frames) packets. Intra-frame packets serve as reference for other inter-frame packets and their loss leads to error propagation to adjacent packets. Video transmission over the error-prone wireless channels is, therefore, inherently a challenging task.

One other unique characteristic of video is that it exposes the deficiencies in the network in an abrupt manner. In other words, unlike other applications, there may not be a smooth transition from good quality video to the poor quality video, and if the network cannot guarantee some minimum thresholds on any or a combination of throughput, delay, jitter or packet loss, the video may not be intelligible and its quality may drop immediately.

In the following sections, the main challenges of video transmission over Wi-Fi will be discussed in more detail.

Throughput: Video applications require some minimum throughput depending on the type of coding method used for compression of video. The more advanced video coding algorithms compress the video with a fewer number of bits and, as such, require lower data-rate transmission media. However, mobility and temporal variation of wireless channels lead to orders of magnitude fluctuation of throughput for wireless clients. As a client moves away from the AP with which it is associated, the Wi-Fi signal experiences higher path loss and therefore the client will receive smaller average throughput. In addition, wireless signals experience significant multipath in indoor environments. Even for a fixed position of the Wi-Fi client, the received signal strength may vary significantly over time due to movement of objects and variation in multipath. As a result, during the lifetime of a video session, it is possible that the client’s throughput is below or above the minimum requirement. This presents a challenge to the conventional QoS approaches like admission control. While the client can receive sufficient throughput for reliable video transmission at the time of admission to network, there is no guarantee that its throughput will remain above the threshold all the time.

Delay and Jitter: Delay and jitter can be particularly important for interactive real-time video applications. These applications typically use UDP transport protocol to avoid packet retransmissions and meet the delay requirements. That said, UDP is a connectionless transport protocol that can lead to increased packet loss, which can also lead to poor video quality. There can be, therefore, a tradeoff between delay and packet loss for these applications. Due to delay and delay variation (jitter), playback buffers may be needed at the client and AP to smooth out the video when packets arrive after their playout times. Delay and jitter may also have an impact on the buffer size at the client and AP.

Packet loss: As described earlier, a sequence of compressed video frames, called group of picture (GoP), consists of both intra-frame

packets and inter-frame packets. The inter-frame packets act as reference for decoding other packets in the GoP. Loss of inter-frame packets can lead to error propagation which can significantly degrade the video quality. Consequently, for the same packet loss ratio (PLR), video quality can degrade more noticeably compared to other applications.
802.11 networks, on the other hand, are inherently prone to packet loss. One reason is the use of the CSMA/CA random access method in these networks. Although CSMA/CA is based on carrier sensing and collision avoidance, collisions and packet loss cannot be completely avoided due to the distributed nature of this protocol. CSMA/CA uses a retransmission mechanism to resend the lost packets. In addition, the retransmission mechanism can introduce additional delay and jitter.

The other contributor to packet loss is the short-term fast fading which results in rapid fluctuation in received signal strength. The Modulation and Coding Scheme (MCS) chosen by the AP must be adapted corresponding to the variation in the received signal-to-interference-plus-noise ratio (SINR) to keep the bit error and packet error rate below an acceptable level. However, it is possible that the rate adaptation algorithm, chosen by the AP, is not able to keep up with fast channel variation, and some packets may be lost in this transition. In addition, the rate adaptation algorithms are proprietary algorithms chosen by the AP vendors. The more aggressive rate adaptation algorithms can also lead to higher packet loss.

Unlicensed spectrum: Wi-Fi operates in the unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band and 5 GHz in the Unlicensed National Information Infrastructure (UNII) band. The ISM unlicensed band is shared by other communications devices and appliances including Bluetooth, Zigbee and microwave ovens, which generate interference to Wi-Fi devices. Wi-Fi devices also share UNII bands with 5 GHZ cordless phones; however the UNII bands are much less crowded compared to the ISM bands. These non-Wi-Fi devices generate interference and can degrade the Wi-Fi throughput and packet loss performance.

Interference: Unlike cellular networks, where frequency planning and interference management is an integral part of the network design, in-home Wi-Fi networks are generally not methodically planned and coordinated. It is not uncommon to have multiple co-channel APs operate in close proximity. Both co-channel and adjacent channel interference can substantially degrade the Wi-Fi performance.

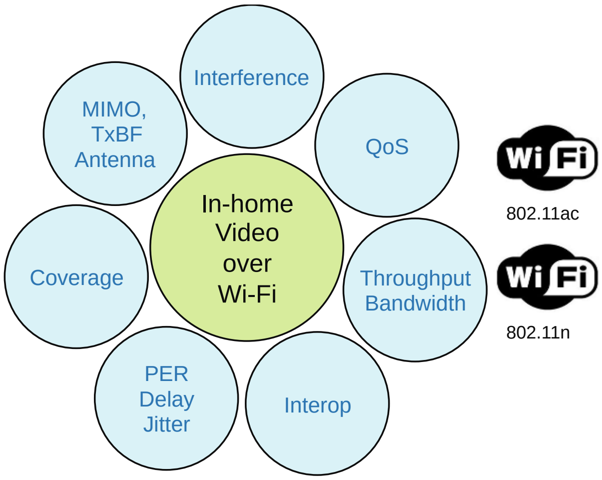
Coverage: The video requirements on throughput, delay and jitter introduce constraints on the coverage of Wi-Fi inside a residential area with acceptable video quality. The farther a client is from the AP, the lower its achievable throughput and potentially the higher the packet delay and jitter will be experienced by the client. The situation is more severe in 5 GHz compared to 2.4 GHz, as path loss for 5 GHz signals is larger for a given distance. In addition, for most of the construction material, 5 GHz signals experience more attenuation compared to 2.4 GHz signals.

The following section provides an overview of observations from the Wi-Fi testing done a CableLabs.

OBSERVATIONS FROM VIDEO OVER WI-FI TESTING

The observations in this section are based on the Wi-Fi and video quality measurement tests on three Wi-Fi products, including 802.11n and 802.11ac. Wi-Fi silicon vendors provided both the Wi-Fi Access Point (AP) and client (STA) for testing.

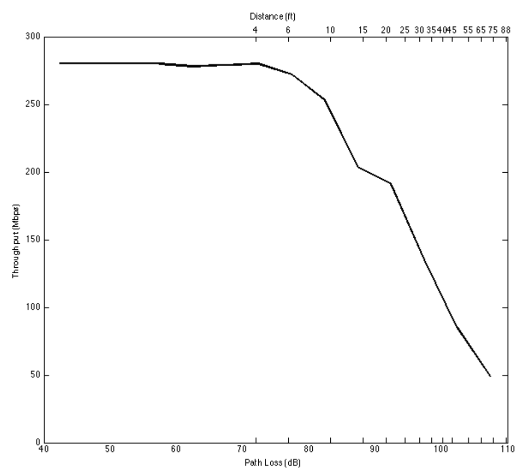
The tests were conducted in CableLabs' Louisville facility and multiple houses of different sizes and construction material (five in Colorado and six on the US East Coast). Wi-Fi coverage data was collected from an additional 25 Colorado houses to supplement the Wi-Fi performance data. As shown in the figure below, the Wi-Fi performance was measured using a number of metrics.



The test results indicate that Wi-Fi can reliably transport HD video in the home; but Wi-Fi network performance is highly dependent on a number of variables, including construction materials, distance between AP and Client, level and type of interference, Multiple Input Multiple Output (MIMO) configuration, Transmit Beamforming, antenna orientation, RF spectrum, background traffic, and device capabilities.

Based on the testing, some of the important considerations and observations for using Wi-Fi for in-home video distribution include:

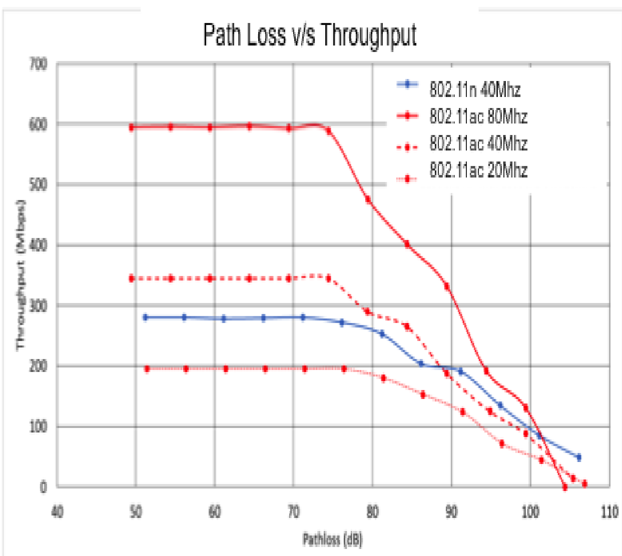
- Interference can be a significant issue and AP location and channelization should be set to avoid it. Not only co-channel, but also adjacent channel and alternate channel interference are significant issues when the two Wi-Fi APs are less than 20 and 10 feet apart respectively. Interference from 5.8 GHz cordless phones also impacts Wi-Fi performance significantly.
- Wi-Fi signals in the 5 GHz band provide excellent coverage in homes with drywall panel walls. Analysis shows that three MPEG-2 streams can be successfully transmitted to three Wi-Fi clients up to 80 feet from the AP in a home with drywall construction. Wi-Fi signals in the 5 GHz band offer more limited coverage in houses with brick walls (or concrete floors). In these houses, HD Video streaming is possible if there is only one wall between the AP and clients. Wi-Fi signal attenuation is too high for two or more brick walls to reliably support HD video streaming. As the graph below shows, in a drywall house Wi-Fi is capable of serving 60 Mbps up to ~80 feet away from the AP. There are two X-axes in the graph - one at the bottom and the other at the top of the chart. The X-axis at the bottom of the chart is for pathloss and the X-axis at the top shows the distance between AP and the client. The Y-axis shows the TCP throughput in Mbps.



- Wi-Fi networks with the same vendor's AP and clients offer better performance than a Wi-Fi network with multi-vendor Wi-Fi products.
- Support for WMM and airtime fairness is useful on an AP and clients, if the same band and channel are used for both video as well as other services (e.g., data). Some of the APs were successfully able to prioritize video traffic in the presence of congestion from data traffic once the

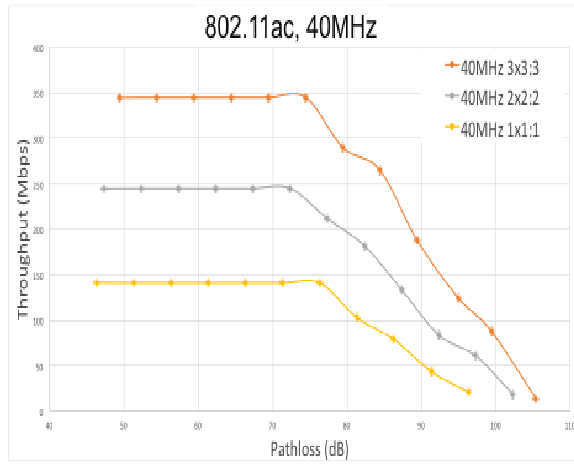
WMM tags were added to the video traffic.

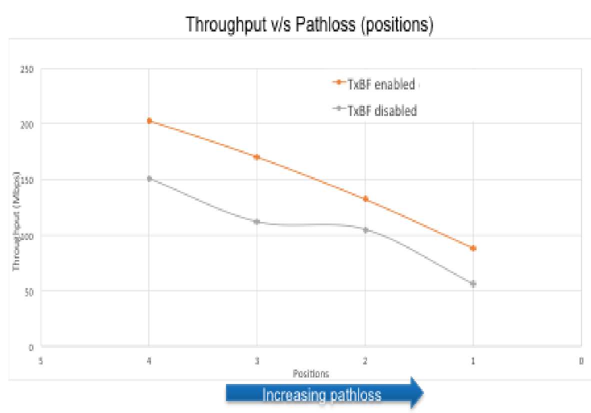
- Both 802.11ac and 802.11n technologies are capable of supporting in-home video streaming. 802.11ac can deliver higher throughput than 802.11n as a result of the support for 80 MHz channel and 256-QAM. This advantage is more obvious when Wi-Fi clients are at close range to the Wi-Fi AP. The performance of 802.11ac and 802.11n technologies is comparable at longer ranges. (e.g., around < -70 dBm RSSI). The following graph, *Path Loss v/s Throughput*, shows average TCP throughput measured in a conducted environment for 802.11n and 802.11ac AP and Client using 20, 40 and 80 MHz channels.



- The Packet Error Rate (PER) performance for some Wi-Fi solutions is consistently low, while for others PER performance varied from one test run to another.

- Transmit Beamforming (TxBF) and spatial division multiplexing improved wireless system performance. Increasing the number of spatial streams increases the Wi-Fi system throughput; however, the relative gain in throughput is less as the number of spatial streams increases. For example, the gain in throughput as a result of going from 2 spatial streams to 3 spatial streams is less than the gain in throughput as a result of going from 1 spatial stream to 2 spatial streams. TxBF is not standardized in 802.11n, resulting in a lack of interoperability. TxBF is standardized in 802.11ac, but wide scale interoperability across multiple vendor products needs to be verified.





- Wi-Fi utilizes unlicensed spectrum that is not solely under the control of operators. Numerous devices with a variety of technologies may utilize the spectrum. Compared to shielded environments such as the HFC network, video over Wi-Fi may be subject to more frequent radio disturbances that are not possible to be completely mitigated by the operator.

<u>OPERATOR GUIDELINES AND RECOMMENDATIONS</u>

This section provides guidelines and recommendations for the operators considering deployment of Wi-Fi for video streaming.

802.11ac vs. 802.11n: 802.11ac delivers higher throughput than 802.11n, as a result of the support for 80 MHz channels and 256-QAM. This advantage is more obvious when Wi-Fi clients are at close range to the Wi-Fi AP. The throughput performance of the two technologies is comparable at long range (e.g., < -70 dBm RSSI). While either 802.11n or 802.11ac can be used for video streaming, 802.11ac is the current generation Wi-Fi technology, and supports some features that were not part of the 802.11n standard. 802.11ac also includes support for features such as Dynamic Bandwidth Management, which can be very handy in mitigating interference and improving spectral efficiency. This feature allows an AP to dynamically choose channel bandwidth to each client on a frame-to-frame basis.

The first generation 802.11ac products support only 20, 40 and 80 MHz channel bandwidth. The current FCC spectrum rules do not allow for a 160 MHz channel. Channel bandwidth of 80 MHz+80 MHz and 160 MHz are expected in the second-generation 802.11ac products. Support for MU-MIMO and Dynamic Bandwidth Management are also expected in the second-generation 802.11ac products.

Installation Consideration: Wi-Fi performance can be affected by a number of factors, including construction material of the house, location of the AP, and interference from other Wi-Fi networks using the same/adjacent/alternate channel as well as non-Wi-Fi sources such as 5 GHz cordless phones. An optimum placement of the AP in the customer house makes a big difference in Wi-Fi signal coverage and performance. MSOs deploying Wi-Fi for video streaming should consider development of best practices for in-home Wi-Fi installation and for educating technicians. The following paragraphs provide recommendations and guidelines for in-home Wi-Fi installation.

APs used in residential deployments normally come equipped with omnidirectional antennas with minimal to no directional antenna gain. For equal coverage in each direction, AP should be placed in a central location in the house. In a multi-storied house, the technician should place the AP on the middle floor. While placement of the AP in the middle of the house is normally a good strategy, there is value in developing a test tool that can identify optimum location for the AP in a house since some factors such as high density of furniture in one location of the house can make the central location non-optimum.

Frequent movement of the AP by customers is also undesirable and should be avoided since antenna orientation and placement can impact performance. At a minimum, the technician should place the client and AP devices in correct orientation (i.e., a wireless bridge that was intended for vertical (“standing”) position, should not be installed horizontally). The location for Wi-Fi devices should be chosen such that they are out of high foot traffic and the children’s play area.

For AP and client devices with external antennas, manufacturer-provided instructions should be followed to properly configure the antennas before leaving the house. It may also be helpful to explain the proper antenna orientation to the customer.

With the AP in place, the MSOs should conduct a Wi-Fi signal coverage survey around the house. If the signal strength at the TV locations is insufficient to support HD video streaming, the AP location should then be adjusted until “appropriate” signal strength (e.g., RSSI) is available at all TV locations. In addition to taking signal strength measurements, the technician should also conduct a throughput test to verify that enough capacity is available to support simultaneous video streaming to all TVs connected to the Wi-Fi network.

One method for throughput measurement is to first identify the number of TVs connected wirelessly, second, take signal strength measurement at each TV location, and then measure network throughput to a client supporting the least Wi-Fi signal strength. If the measured throughput to this client is greater than the throughput required for each video stream times the number of TVs plus a margin of 20%, then the Wi-Fi network can be considered good for delivering video in that house. Changes in the environment (e.g., interference, door closing) can still interrupt the video streaming but a built-in 20% margin should provide some protection. If the Wi-Fi performance is not sufficient (in some parts of the house) for video streaming, operators should consider deploying multiple APs or use other Wi-Fi extension technologies such as Multimedia over Coax (MOCA) or Power Line Communications (PLC) or a combination thereof.

Currently, CableLabs is working on a new project called Future Home Networks; as a part of that, we are taking a look at various home network technologies, including G.hn , PLC etc.

It is also recommended that the technician take following measurements during installation for later review and use by the engineering and customer support team to determine what has changed in the environment over time.

- Collect Wi-Fi coverage data in each room of the house
- Number of other Wi-Fi networks seen from the house, including their signal strength, channel size, channel number, frequency band, MAC address of the APs, number and type of active clients.
- SNR and RSSI at each video client
- Identify legacy Wi-Fi APs and client devices in the home and neighborhood

MSOs should choose a Wi-Fi channel to avoid co-channel, adjacent channel and alternate channel interference. If such choice is not available, to minimize the impact of Adjacent and Alternate channel interference, the technician should first find the location of other APs in the house and neighborhood and place the AP and IP STB in such a manner that it is at least 20 feet away (assuming open air) from the other nearby APs. If it is not feasible to measure the distance then the technician should verify that the signal strength of adjacent channel is no more than 6dB higher than that of the wanted signal. Similarly, the technician should verify that the signal strength of the alternate channel is no more than 36dB higher than that of the wanted signal.

Wi-Fi signals attenuate differently through different materials. Furniture and accessories built with metal can cause significant attenuation. The technician should avoid placing Wi-Fi devices directly behind computers, monitors, TVs or other metal obstructions.

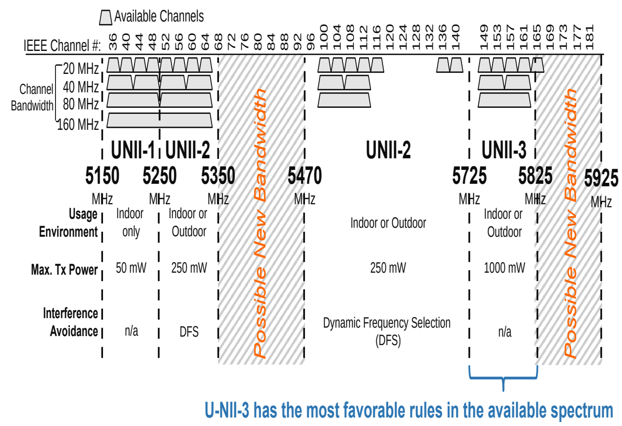
Several vendors also advocated that Wi-Fi clients used for video streaming should also include LED lights to indicate the health of the wireless link. For example, a green light could indicate excellent signal strength for video streaming, yellow could indicate border line signal strength for video streaming and red could indicate poor signal strength to support any video streaming. Further work is needed to define exact mapping between signal strength (e.g., RSSI) and color of the light. The LED could be a simple method for consumers to understand the signal strength and help with customer care.

Wi-Fi Band and Channel: Although the 2.4 GHz band promises better coverage, for video over Wi-Fi, use of the 5 GHz band and a 40 MHz channel is recommended. The 2.4 GHz band is typically too crowded to utilize 40 MHz channels. There are more 40 MHz channels available in the 5 GHz band than in the 2.4 GHz band. The wider channel bandwidth of 40 MHz provides greater capacity to deliver video services. Additionally, there is potential availability of more channels in 5 GHz band. NCTA, CableLabs, and other operators and suppliers are advocating for more unlicensed spectrum and improved rules for Wi-Fi in the 5 GHz band.

CableLabs recently submitted a paper, "Toward Expanded Wi-Fi Access in the 5 GHz Band" to FCC. This paper analyzes the interference risk to certain incumbent services posed by expanding Wi-Fi access, with a particular focus on two sub-bands known as UNII-1 and UNII-4 [4].

As shown in the figure below, 5 GHz band supports multiple sub-bands – UNII-1, UNII 2, UNII 2E and UNII-3 - for Wi-Fi use. Each of these sub-bands enforces unique requirements on devices.

- UNII-3: Devices using UNII-3 band are allowed to transmit using maximum EIRP of 36 dBm (IR=30 dBm, antenna gain=6 dBi)
- UNII-2 and UNII-2E: Devices using UNII-2 and UNII 2E band are allowed to transmit using maximum EIRP of 30 dBm (IR=24 dBm, antenna gain=6 dBi). Additionally, devices working in UNII-2 and UNII-2E band are expected to vacate this band upon detecting any radar activity. After vacating these bands as a result of radar detection, devices are allowed to come back to UNII-2 and UNII-2E bands only after scanning these bands for no radar activity for at least a minute.
- UNII-1: Devices using UNII-1 band are allowed to transmit using maximum EIRP of 23 dBm (IR=17 dBm, antenna gain=6dBi).



For video over Wi-Fi, UNII-2 and UNII-2E are excellent options for medium size homes (up to 4000 sq. ft.) built using drywall panel walls in locations with no radar activity. Use of UNII-2 and UNII-2E is suggested since it offers interference protection from retail Wi-Fi APs working in the 5 GHz band. The retail Wi-Fi APs are not expected to support UNII-2 and UNII-2E bands due to the expense involved in obtaining DFS and FCC certification . UNII-1 should be a good option for use in buildings with small apartments and studios. Use of UNII-3 band is suggested for large (4000 sq. ft. or larger) homes with decent gap (10 to 20 feet to avoid interference from adjacent and alternate channels respectively) between houses and also in places with regular radar activity.

As 802.11ac products start to penetrate the residential market in 2014, the use of the 5 GHz band for Wi-Fi is going to increase, resulting in worsening interference. Consequently, the increased use of 5 GHz band may result in improved interference in 2.4 GHz band. Because of the changing dynamics and need for reliable service, MSOs should consider deployment of Dual Band Dual Concurrent (DBDC) radio APs for residential deployments. The video over Wi-Fi clients (e.g., IP STB) should also support both bands.

Wireless Link Margin: Indoor wireless communication is a very dynamic and multipath rich environment. Environmental changes in such as opening and closing of doors, people and pets moving around, change in AP or client location, and interference are some of the factors that can impact wireless network performance. When designing an in-home Wi-Fi network for video streaming, MSOs should consider a wireless link margin to protect against the uncontrollable changes in the environment.

It is recommended to use a minimum of 5dB margin to factor for these environmental changes. This margin should be included regardless of type and size of home. For example, if a Wi-Fi solution in a lab environment is capable of streaming three MPEG-2 streams to clients with an RSSI of -90dBm, then for real deployments all video clients should be placed in locations supporting -85dBm or better RSSI. Additional margin for various factors discussed in the following below will help improve the robustness of the in-home Wi-Fi network for video streaming.

- Wireless link margin to accommodate for changes in antenna orientation on AP and client. In the worst case tester observed a throughput variation of as much as 30% with changes in AP antenna orientation. This variation is different for different products.
- Video over Wi-Fi networks using 5 GHz spectrum should be designed to avoid legacy devices (802.11a) on the same channel as used by video over Wi-Fi devices. If legacy device must use the same band as video over Wi-Fi devices, a healthy wireless link margin should be included in the design. Further study is required to find the exact number as the margin will vary on factors such as number of active legacy devices, and whether the network supports airtime fairness and WMM.
- Wireless link margin to accommodate for background traffic if the same band and channel are used for both video and data services.
- Implementation loss (e.g., different product casing and design may cause different amount of attenuation). Several vendors indicated that, in their experience, implementation loss can be as much as 5dB.
- Interference (e.g., different source, amount and type of interference will require different amount of wireless link margin).

Airtime Fairness and WMM QoS: Wireless Multimedia (WMM) offers four priority levels by using different minimum and maximum back-off slots, allowing some applications better transmit opportunity than the others. Airtime fairness prevents slow clients from slowing down the fast clients by “fairly” allocating the airtime to clients.

Support for WMM and airtime fairness is recommended on AP and IP STBs, if the same band and channel are used for both video as well as other services (e.g., data,). Additionally, the management of Wi-Fi resources allocated to non-video clients, including slower (as a result of poor link quality or low MCS) and legacy clients is critical.

While WMM is standardized in IEEE 802.11e, airtime fairness is vendor proprietary. For consistent customer experience, the cable industry should consider defining requirements for airtime fairness algorithm and contributing to wireless standards bodies.

For near term video over Wi-Fi deployments, operators should use the default WMM parameter set as defined in IEEE 802.11e. Additionally, the video, data and voice traffic should be tagged as suggested below to assign video higher priority than data.

- Voice- 0xE0 (Decimal TOS precedence value= 6,7)
- Video- 0xB8 (Decimal TOS precedence value= 5,4)
- HTTP- 0x20 (Decimal TOS precedence value=1)

In the long run, the cable industry should consider research to identify an optimum WMM parameter set for in-home video over Wi-Fi use case.

Some vendors offer the capability to provide higher priority to video traffic without having operators to tag the traffic. Vendors claim to prioritize traffic by identifying the video using proprietary traffic signature methods. One example of this technology is "streamboost" from Qualcomm. This technology appears useful and very promising. As part of the Future Home Networks project, CableLabs plans to analyze and test some of these technologies and provide recommendations to the operators.

Interoperability: The basic interoperability exists – different vendor clients seamlessly attach to and send traffic through other vendor APs. However, the Wi-Fi network with same vendor AP and clients offers better performance than the Wi-Fi network with multi-vendor Wi-Fi products.
Interoperability between multi-vendor 802.11ac products is not as seamless as it is with 802.11n products. In at least one case, clients from one vendor were unsuccessful when associating with a different vendor AP. We expect this to improve with WFA certification maturity.

For initial video over Wi-Fi deployments, operators who consider a multi vendor network should consider testing products for interoperability. The cable industry should work with vendors to improve performance in a multi-vendor environment. The cable industry should also consider sharing interoperability test results with industry organizations such as the Wireless Broadband Alliance and the Wi-Fi Alliance. For example, a joint test plan could be proposed based on MSO requirements and vendor recommendations to improve interoperability.

Interference Management: Wi-Fi in 5 GHz has comparatively fewer sources of interference than Wi-Fi in 2.4 GHz in today's deployments. Interference is a significant factor; we expect it to increase in the 5 GHz bands, and it should be avoided and managed. Major issues are not only co-channel, but also adjacent channel and alternate channel interference. Video over Wi-Fi devices should be placed at least 20 ft. away (assuming open air environment) from the other nearby APs. Nearby APs should be configured to use the other available channels.

Some of the cordless phones available today use the same spectrum as Wi-Fi in 5 GHz. Interference from these phones on the Wi-Fi network can be significant. Operators should identify channels used by 5.8 GHz cordless phones in each house and avoid them for Wi-Fi use. To achieve this, MSO technicians should have access to survey tools that not only identify interference but also the source and type of interference. If a subscriber installs cordless phones after the initial Wi-Fi installation, Wi-Fi features such as ACS should be able to detect interference and move Wi-Fi operations to a better channel.

Sources for interference are many and dynamic in nature. To manage interference, operators should consider the following additional tools:

- Support for Automatic Channel Selection (ACS) at boot up and during operation
- Support for Dual Band Dual Concurrent (DBDC) with support for multiband steering
- Support for Radio Resource Management (RRM) and Self Organizing Networks (SON)
- Site survey and record the interference environment at installation time to help with troubleshooting the post install environmental changes that degrade performance.

Automatic Channel Selection: APs, supporting ACS constantly sense the presence and amount of interference around them. APs then use this information to select and use a channel with "better" operating conditions.
Since the channel conditions can change with time, it is recommended that the AP should be capable of performing Automatic Channel Selection at boot-up and during run-time. The channel selection must be done carefully with consideration to a number of factors, including:

- The transmit power of each band. Different sub-bands within 5 GHz band have different transmit power requirements. Simply moving from high power band, as a result of increased interference, to a low power band can introduce coverage challenges.
- APs are required to scan the UNII-2 and UNII-2E band for at least 60 seconds for radar activity before the APs can use these channels again. APs should be thoroughly tested to make sure they don't move out of UNII-2 and UNII-2E bands a result of false positive radar detection.
- APs should also support background scanning of these bands for the presence of radar without leaving the current channel of operation and potentially affecting services.

CableLabs performed basic ACS tests on three vendors and found that all the vendors support ACS at both boot-up and run-time. CableLabs recommends further testing of this feature to verify proper operation in more complex scenarios. For example, ACS operation in the presence of different amounts and types of interference in multiple channels (e.g., 5.8 GHz cordless phones) should be considered for future testing.

Dual Band Dual Concurrent (DBDC): Wi-Fi APs could be classified into four categories based on the frequency band in which they operate.

- 2.4 GHz only: Supports 2.4 GHz band only
- 5 GHz only: Supports 5 GHz band only
- Dual Band switchable (DB switchable): Supports both 2.4 and 5 GHz bands, but not concurrently
- Dual Band Dual Concurrent (DBDC): Supports both 2.4 and 5 GHz bands concurrently

DBDC would allow operators to use separate bands for video and data services. For example, use of 5 GHz for video and 2.4 GHz for data and voice. With DBDC, CableLabs also suggests support for multiband steering, which, for example, allows operators to load balance between bands, keep slower devices on non-video band and move video services and devices to a band that's less occupied. Several Wi-Fi AP vendors claim support for multiband steering capabilities using proprietary methods.

Multiband steering is an active work item in Wi-Fi Alliance (WFA), and CableLabs actively follows and contributes to the WFA multiband steering working group.

Radio Resource Management (RRM): In addition to ACS, DBDC and site survey, operators should also consider the use of RRM/SON for interference mitigation and performance improvement, especially in dense Wi-Fi deployments.

Wi-Fi networks may be large in scale, comprising of hundreds of thousands or millions of operator managed APs. Self-organizing methods are required for the efficient management of the Wi-Fi resources with large numbers of APs. Wi-Fi SON approaches can include techniques supported by each AP for immediate response to air interface conditions. Wi-Fi SON approaches can also include placing a centralized SON servers in the cloud or network that provides a high level management of specific parameters based upon a wider view of the Wi-Fi network that may be available to individual APs. The goal of the RRM/SON is to provide operators with a centralized Wi-Fi SON control based on a wide view of the Wi-Fi access network, which consists of Wireless Controllers as well as standalone APs from different vendors.

Spatial Division Multiplexing and Transmit Beamforming: Spatial Division Multiplexing (SDM) allows an AP to send multiple streams of data simultaneously to a client using multiple antennas. This results in better throughput at the client.

Transmit Beamforming (TxBF) allows an AP to concentrate its signal energy at the client location. The AP does this by sending the same signal from multiple antennas and carefully controlling the phase of the transmitted signal from each antenna. This results in better signal to noice ratio (SNR) and throughput at the client, and can reduce interference across the network.

Video over Wi-Fi application benefits from the support and use of both TxBF and SDM. Vendors' use proprietary algorithms to select between SDM and TxBF based on the channel conditions to each client. APs tested were capable of intelligent antenna resource allocation using some antennas (e.g., 2 out of 4) for TxBF while simultaneously using the remaining for SDM. Two transmitters cannot be used to perform both SDM and TxBF simultaneously.

TxBF and SDM improved wireless system performance when enabled. Increasing the number of spatial streams increases the Wi-Fi system throughput; however, the relative gain in throughput is less as the number of spatial streams goes up. For example, the gain in throughput as a result of going from 2 spatial streams to 3 spatial streams is less than the gain in throughput as a result of going from 1 spatial stream to 2 spatial streams (T2ss-T1ss > T3ss-T2ss > T4ss-T3ss).

TxBF is not standardized in 802.11n, resulting in a lack of TxBF interoperability. TxBF is standardized in 802.11ac, but wide-scale interoperability across multiple vendor products needs to be verified.

Key Performance Indicators and Network Management: Wireless is a very dynamic environment. In order to proactively manage the network, operators should be able to keep track of the following key performance indicators and take appropriate proactive actions to prevent impact on services.

- Number of currently associated clients and type (Current and historical)
- Current channel of operation
- Quality of wireless link to each client, including Downstream throughput (avg., peak), Upstream throughput (avg., peak), Packet Error Rate (PER), Type of client (e.g., iPhone, IP Set top), MAC address, RSSI,) the highest supported Wi-Fi version by the device, SNR, Number of spatial streams currently being used for transmission, Modulation and Coding

Scheme (MCS), Channel size for each client, Connection state

- Level and type of interference in different channels of a Wi-Fi bands (including current channel)
- Number of channel change events, for example as a result of Automatic Channel Selection
- Channel switch time
- Reason for client device disassociation (e.g., legacy device not supported, SNR below threshold)
- Error events of wireless link state for a client (e.g., IP set-top box) goes below operator defined values
- Maximum Transmit Power
- Channel Utilization (airtime percentage)
- Wi-Fi Carrier Sense threshold used
- Noise floor
- Number of radar detection instances
- Amount of time Wi-Fi service is affected when AP was trying to switch to DFS channels (UNII-2 and -2E)
- Number of packet re-transmissions
- Number of Forward Error Correction (FEC) events: Number of Un-errored FEC Code-words, Number of Correctable FEC Code-words, Number of Uncorrectable FEC Code-words.

Wi-Fi EVOLUTION AND FUTURE WORK

The convergence of voice, video and data, along with the evolution of HD and 3D video, is driving the need for increased throughput connectivity throughout the home, while assuring a high level of reliability and sustained performance. With the proliferation of a number of handheld devices per home, it becomes stringent for any access technology to deliver high speed throughput rates delivery in a reliable and contiguous manner. Wi-Fi has a strong deployment base with a diverse and healthy vendor ecosystem. A lot of newer technologies have been stemming up in the past couple of years to help support the ever-increasing thirst for bandwidth. For example, High Efficiency Wi-Fi (HEW), Phase 2 features of 802.11ac, Cloud-based AP co-ordination functionality, utilization of 802.11ad for faster throughput rates (at a distance less than 20m), multiband steering, etc. A number of standard bodies (like IEEE, WBA and WFA) are actively working on standardizing these features. CableLabs is actively participating and contributing in the WFA, WBA and IEEE to move the Wi-Fi technology and interoperability forward.

Phase 2 features of 802.11ac

The following table shows the features of 802.11ac phase 2 and the corresponding benefits.

Features	Projected Benefit
Dynamic Bandwidth Management	• Interference Mitigation • Improved Spectrum Efficiency
Mu-MIMO	• Reduced Jitter • Improved System throughput • 1 4x4 STA= 4 1x1 STAs • Highly useful for video streaming
160Mhz/80+80Mhz	• Improved throughput
8x8 MIMO	• Improved throughput • Improved coverage (3db more)

Vendors are actively working on supporting these features. Wi-Fi devices with support for phase 2 features are expected to start certification later this year.

High Efficiency Wi-Fi (HEW)

With dense AP deployments becoming a norm nowadays, IEEE 802.11 HEW group aims to improve efficiency in the use of spectrum resources and achieve a very substantial increase in the real-world throughput. IEEE is working on enhancing the PHY and MAC to support real time applications by improving the power efficiency for battery powered devices.

Carrier Grade Wi-Fi

IEEE, WFA and WBA have active work items that address Carrier Wi-Fi, which is a recent industry movement to promote operator requirements for managed Wi-Fi networks. Carrier Wi-Fi scenarios target dense AP deployments with many device associations, Community Wi-Fi where public and private SSID's coexist on the same AP, Transparent Mobile data off load as well as Customer Experience, Device Requirements and Network Management on par with Licensed Cellular Technologies. CableLabs is working on defining proper device behavior which consists of Minimum Performance Requirements, Minimum Standards Compliance and Interoperability for the Wi-Fi APs and clients as a part of Carrier Grade Wi-Fi.

CONCLUSIONS

Our test results indicate that Wi-Fi can reliably transport HD video in the home; but Wi-Fi network performance is highly dependent on a number of variables, including construction materials, distance between the AP and client, level and type of interference (co-channel, adjacent and alternate), Multiple Input Multiple Output (MIMO) configuration, Transmit Beamforming, Spatial multiplexing, antenna orientation, RF spectrum, background traffic, QoS settings on the APs, and device capabilities.

Wi-Fi provides the convenience for consumers to have access to their subscribed video content without being restricted to predefined locations. On the other hand, Wi-Fi utilizes unlicensed spectrum that is not solely under the control of operators. Numerous devices with a variety of technologies like Bluetooth, cordless phones, microwave ovens, etc., may utilize the spectrum. Compared to shielded environments such as the HFC network, Wi-Fi may be subject to more frequent radio disturbances that may not always be completely mitigable by the operator. On the other hand, with video becoming an increasingly important application over WLANs, the Wi-Fi technology trend seems to be cognizant of this fact. Phase 2 features of 802.11ac, High Efficiency WLAN standardization in IEEE, Cloud-based AP co-ordination functionality, utilization of 802.11ad for faster throughput rates (at a distance less than 20m) and Multiband steering are example evolution areas in Wi-Fi which enhance the video streaming performance.

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