WHAT’S NEXT? OPPORTUNITIES IN WI-FI WITH 60 GHZ

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INTRODUCTION

As the 2.4 and 5 GHz spectrum used for Wi-Fi gets more crowded, another unlicensed band that can reliably support multiple gigabit transmission in the home has promise for home networking and other applications. The 60 GHz band offers a wide bandwidth with little interference from other sources. This paper gives an overview of 60 GHz and WiGig, also known as 802.11ad, and compares testing results with simulations. This paper also covers the upcoming revision still in progress with the IEEE called 11ay, highlighting some new features that will enable outdoor use cases for this versatile technology.

Where do we stand with Wi-Fi?

Devices using Wi-Fi for data communication encompass every area of technology and many different services. As an example, let's concentrate on using Wi-Fi for video for a moment. Wireless set-top boxes have been on the market for a few years now, yet more people are streaming video to anything with a screen: smart TVs, mobile devices like smartphones or tablets, even a refrigerator. A recent news announcement put the amount of Wi-Fi traffic that provides streaming video services at 65%. People also expect to be able to check the weather, stream music and see who just rang the doorbell, all using almost-ubiquitous Wi-Fi coverage. New uses for Wi-Fi will probably include virtual and augmented reality programming, whether they are games or scripted entertainment. As was mentioned in my paper last year, virtual reality (VR) headsets can consume far more bandwidth than any of today's video services.

Crowded spectrum, busy networks

All this growth has led to two complementary problems: 1.) bandwidth congestion driven by the sheer volume of traffic and 2.) protocol level congestion caused by the enormous number of devices competing for airtime. Video services in particular demand large amounts of data. Depending upon the device and its distance from its AP, an HD video stream may take up substantial amounts of airtime. For example an 802.11n device streaming a 5 Mb/s video program from an AP in the same room will take up about 5% of a 20 MHz channel. If the device is in another room, that percentage could rise to 40 or 50% of the channel.

Aside from the stress of the amount of data being consumed, the simple presence of large numbers of devices can place a substantial load on a Wi-Fi network. One paper showed that the presence of more than 25 devices on a single AP can reduce the overall throughput even if the amount of traffic is low. [1] The number of Wi-Fi devices is being driven by the increasing number of auxiliary devices incorporating wireless communications. It is useful to note that even if a group of IoT devices is not Wi-Fi, but

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Zigbee or BTLE, traffic on those networks can still contribute to the noise on the 2.4 GHz band, reducing the overall channel availability for Wi-Fi. Many IoT devices do not have high bandwidth usage and are battery powered. However, the highest bandwidth devices, such as webcams and other video originating or terminating devices, are commonly set up over Wi-Fi.

Expanded competition from commercial LTE-related devices

Most of the major telcos in the USA have announced MuLTEFire, LTE-U or LAA trials. These new systems attempt to recapture mobile traffic that is now commonly redirected to Wi-Fi networks in the home and elsewhere, and put it back onto the telco networks. A LTE-U cell typically uses bandwidth within the 5 GHz unlicensed band to augment the current licensed bands. Deployments of this technology are still limited, but if it becomes widespread, the congestion within the 5 GHz band is certain to increase.

60 GHz Wi-Fi offers interesting opportunities

With all of the other WLAN activities in the popular 2.4 and 5 GHz bands, why is the 60 GHz band getting attention? First and foremost, the 60 GHz industrial scientific medical (ISM) band supports unlicensed access across 14 GHz of spectrum in the US, from 57 GHz to 71 GHz. The band from 64 GHz to 71 GHz was recently added in 2016. [2] The FCC has also made a proposal to expand this band even further. The IEEE802.11ad specification supports three 2.16 GHz channels in North America and four channels in Europe. This comprises more raw bandwidth than the other unlicensed bands combined. The frequency is very high, so propagation models are more challenging, but modern technology is well equipped to provide good throughput for many applications. Some early demonstration units with this technology did not prove robust with respect to motion or temporary blockages of signal. Testing with the latest units has shown more robust results that we will discuss later in this paper.

Two related advantages can be attributed to the higher levels of attenuation in the 60 GHz band. Interference is much reduced, particularly from other active WLAN systems. This advantage is favorable over the current 2.4 and 5 GHz bands which are can be almost unusable in multiple dwelling units (MDUs), because of the number of closely spaced APs that compete for bandwidth. Security is also stronger compared to the other bands because stray power from the 60 GHz system is unlikely to make it outside the home. As most users have gotten the message that securing their Wi-Fi network is desirable, this issue is not as concerning as it once was. Even so, since many consumers still use weak passwords or weak encryption, overall security can be improved if signals from their WLAN are less likely to leave their premises.

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60 GHz propagation and antennas

To understand the deployment tradeoffs and advantages of 60 GHz, we need to understand 60 GHz propagation and device antenna characteristics. Propagation characteristics of 60 GHz signals are not the same as the 2.4 or 5 GHz signals with which we have all become familiar. Also, the higher frequencies necessitate a completely different antenna design approach to achieve optimal performance. The next paragraphs will discuss propagation and antenna design.

Millimeter wave propagation, as 60 GHz is also known, is very different than the 2.4 and 5.5 GHz frequency bands. The high frequency of the radio waves means that a transmission in free space is attenuated more quickly than at lower frequencies. A more challenging aspect is that one band of the 60 GHz spectrum is also absorbed strongly by oxygen molecules. A bit of good news is that the recent extensions enacted and proposed by the FCC are above the band that is most strongly absorbed by oxygen and should provide better performance. Most solid materials tend to reflect or absorb 60 GHz transmissions as opposed to the lower frequencies where transmission through solid materials was less highly attenuated. Because of the wide bandwidth and power limits, 60 GHz transmissions can still provide acceptable performance within one or two rooms in a residential environment. In a later section we will discuss our testing results characterizing the performance of 60 GHz transmissions in residential environments.

A bit of background on the design of millimeter wave antennas is helpful to understand some of 60 GHz strengths and weaknesses. An optimal single antenna supporting the 60 GHz band is very small, less than 2mm on a side for a patch antenna, and does not provide enough directivity or focus to be useful in most applications. To compensate for that fact, 60 GHz systems typically use antenna arrays. The size and configuration of the antenna array determine its performance.

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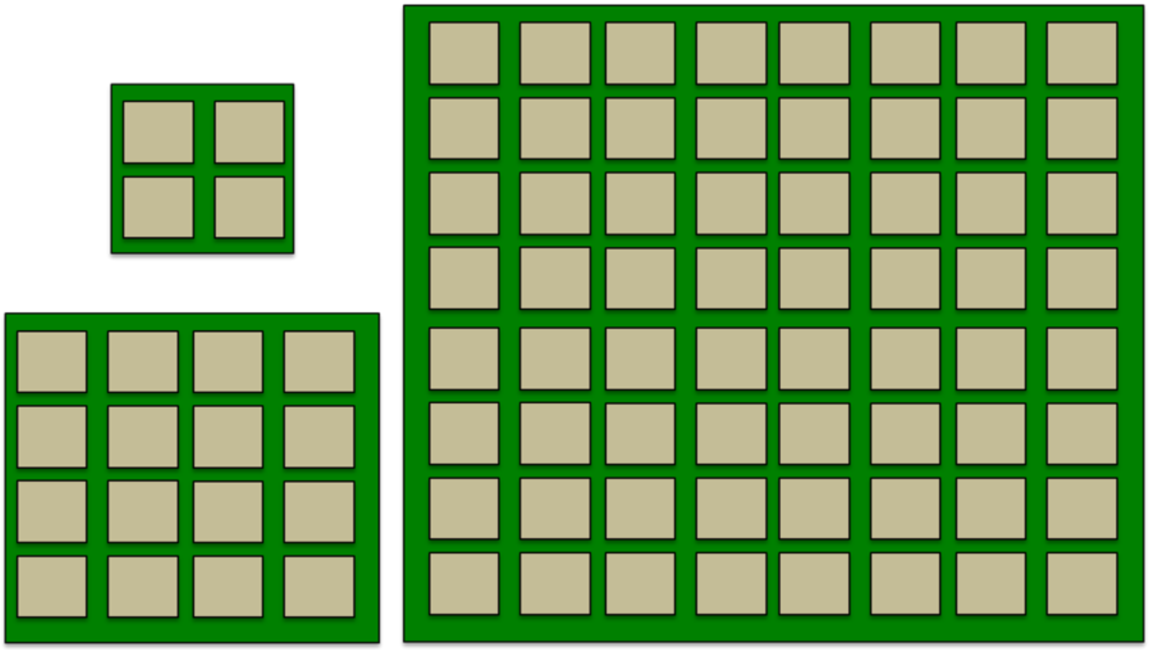

Figure 1 - Examples of Antenna Arrays, Not to Scale

The following simulations illustrate a set of results showing the increased focus that results from an increase in array elements. For a 4x4 array, the gain of the antenna is concentrated in a main lobe providing about 10dB of gain over a single antenna, as shown in Figure 2.

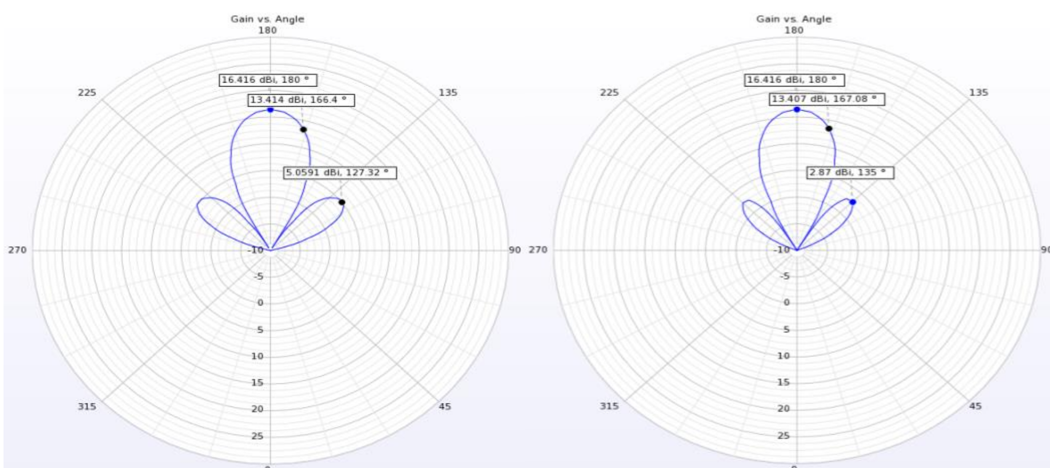

Figure 2 - 4x4 Element Array, X-Z and Y-Z Polar Plots

If the size of the array is increased to 8x8, the gain also increases to 16 dB over a single patch antenna. See Figure 3. Note that the tradeoff for these high gain arrays is that the 3dB beamwidth of the main lobe of the antenna pattern decreases as the gain increases. The 3dB beamwidth of an antenna pattern is defined as the angle of arc within which the antenna pattern's gain declined by 3dB, which is to the angle of arc over which the

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antenna's transmit power declines by half. The total power transmitted by a device is restricted by FCC regulations, so the increased relative gain thus effectively comes at a cost in the area covered by the beam from that antenna. The behavior is discussed in terms of using the antenna array as a transmitter, yet the same effects also apply when it is used as a receiver.

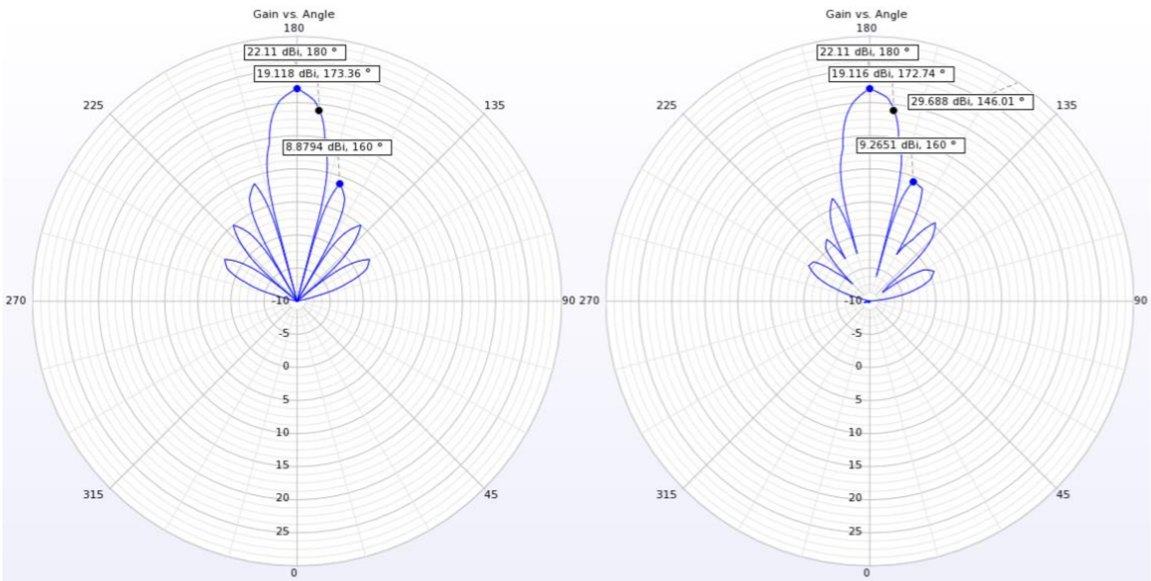

Figure 3 - 8x8 Element Array, X-Z and Y-Z Polar Plots

While beam steering can compensate by moving the focus of the array to focus on a particular direction, a planar array's beamforming shift is limited typically to 120°.

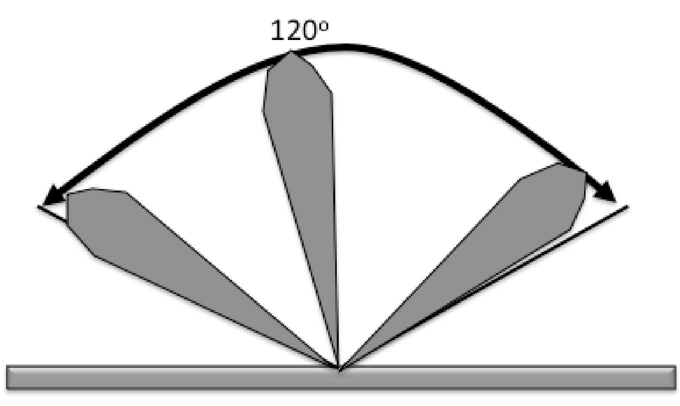

Figure 4 - Beamforming Example

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Figure 5 - Example 11n or 11ac Wi-Fi AP

The beamforming limits mentioned above are significant in the industrial design of a 60 GHz AP or client because the optimal placement of a 60 GHz AP may be quite different from the optimal placement of a traditional Wi-Fi AP in the 2.4 and/or 5 GHz bands. A typical 11n or 11ac Wi-Fi AP may have four or more antennas to support good coverage; together they generally cover 360º in at least one plane. Most current Wi-Fi APs provide their best coverage when placed in the center of a home so that the Wi-Fi signal can radiate evenly in a spherical fashion.

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The optimal placement of a 60 GHz device is heavily influenced by its antenna design. A device with a single antenna array may perform best placed in a corner of a room, or near the corner of a home so that the potential targets of the antenna are within 90º (at least in one plane) of the center of the antenna array.

For a device to be capable of reaching a client anywhere in the plane of the antenna requires three separate fixed antenna arrays to cover 360º. When similar technology has been used in other applications, such as radar, the antenna array is often constructed to spin, so that a single array can track targets spread across a full 360º horizon. This approach is probably not practical in a residential gateway. For a practical 60 GHz deployment, multiple antenna arrays can be cost-prohibitive and therefore less desirable.

Residential testing

We sponsored testing of 60 GHz equipment in a residential environment to determine how useful the technology can be outside of the lab or simple desktop applications. An 802.11ad AP was placed at various locations within a home and the actual throughput to a laptop equipped with 802.11ad was tested. The AP's location was tested in several locations shown on the diagram below.

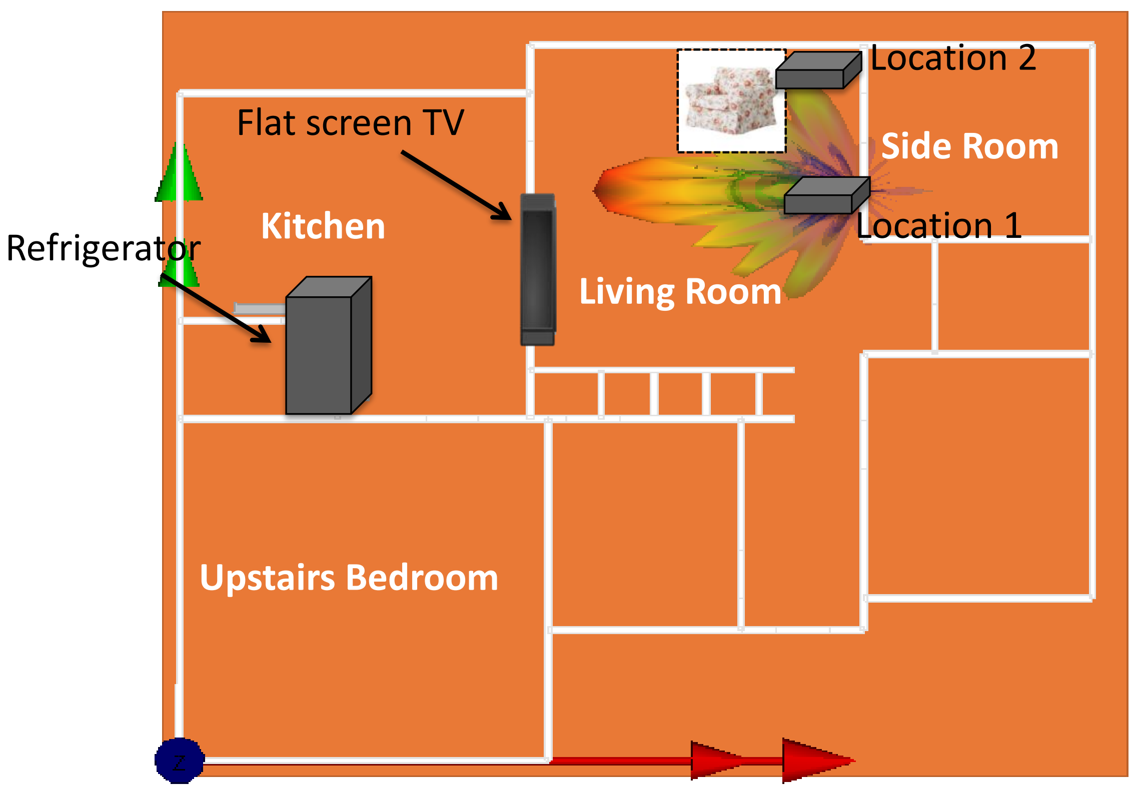

Figure 6 - Schematic of Test House Showing AP Locations

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Location 1 was along an unobstructed wall facing across the living room. The AP was placed on a small table. The table was moved to a corner of the living room for Location 2 as shown in the diagram. The AP was tested once without any obstructions and once with a large chair placed in front of the table. Also shown in the diagram are the location of a refrigerator and a wall-mounted flat screen TV, both of which were found to affect the radiation pattern.

The rooms were divided into grids for testing. Throughput was repeatedly measured from the AP to a laptop as the laptop was placed in grid locations across the rooms. A few locations were also used on the second floor. The following diagrams (Figures 8, 9, 10 and 11) show the throughout results from the AP covering the family room, the adjoining kitchen and side room using a color-coded representation of the throughput results for that location. The color coding corresponds to the throughput measurement and the signal level as shown in Figure 7.

No	Signal Level(%)	RSSI(dBm)	Throughput(Mbits/s)
1	80	-60	946
2	70	-65	940
3	60	-70	934
4	50	-75	851
5	40	-80	738
6	30	-85	585
7	20	-90	233

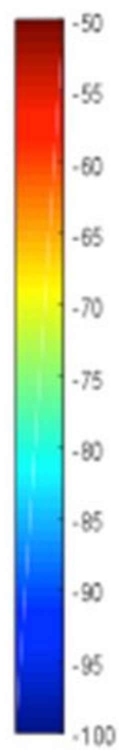

Figure 7 - Legend for Color-coded Diagrams

As an example, a yellow block in the throughput diagrams indicates that the signal level was about -70dB and the throughput was about 900 Mb/s. The test system used for these measurements was two years old. A newer system would likely achieve higher

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throughput than the one used for this testing. The table comparing throughput to signal level and RSSI indicates that at the highest signal levels, the system was limited by its Gigabit Ethernet port, not by its radio interface.

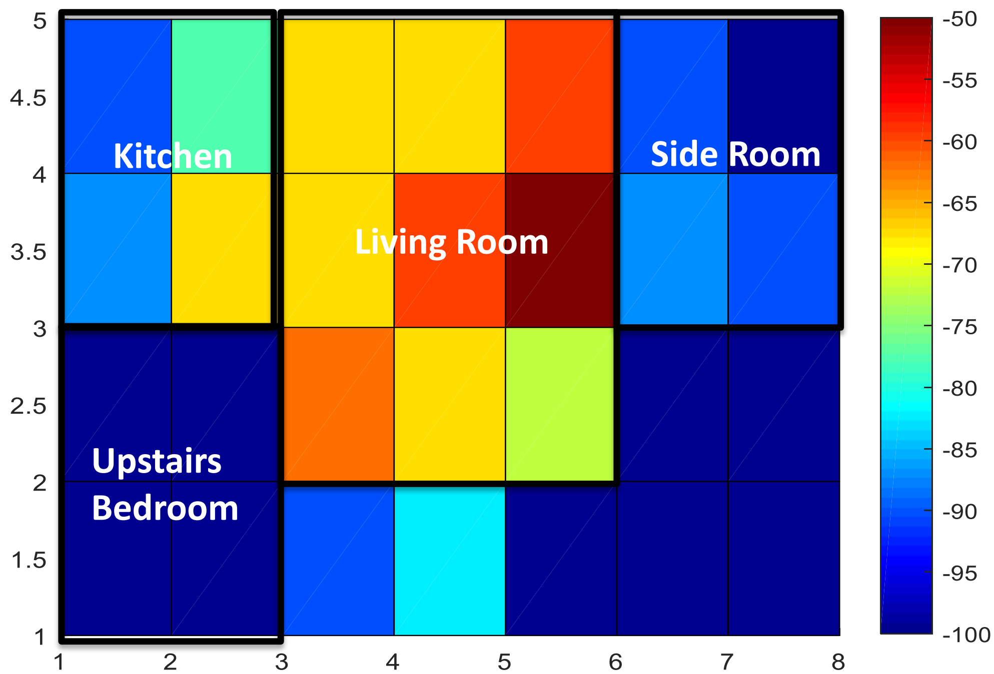

Figure 8 - Throughput Measurements for Location 1

The throughput results for Location 1 show that good coverage was achieved in the living room, with data rates still above 100 Mb/s even in NLOS locations in adjoining rooms. A location that probably fell outside of a direct propagation path can be seen just below the dark red square. As was mentioned earlier, beamforming with a planar array has blind spots. Due to the large amount of reflections, the throughput in that area was still over 700 Mb/s. Subsequent simulations showed that 60 GHz signals are reflected strongly by many common in-home building materials leading to good NLOS coverage.

The picture below shows a ray tracing example simulating the coverage due to an AP in Location 1. Testing has shown that sheet rock has a relatively high permeability to 60 GHz transmissions, while brick or cinder block walls tend to reflect most of the energy. That difference can be seen in Figure 9 where energy can cross the sheet rock wall between the living room and the kitchen, yet transmissions hitting the outside walls, which have a brick facing, are strongly reflected.

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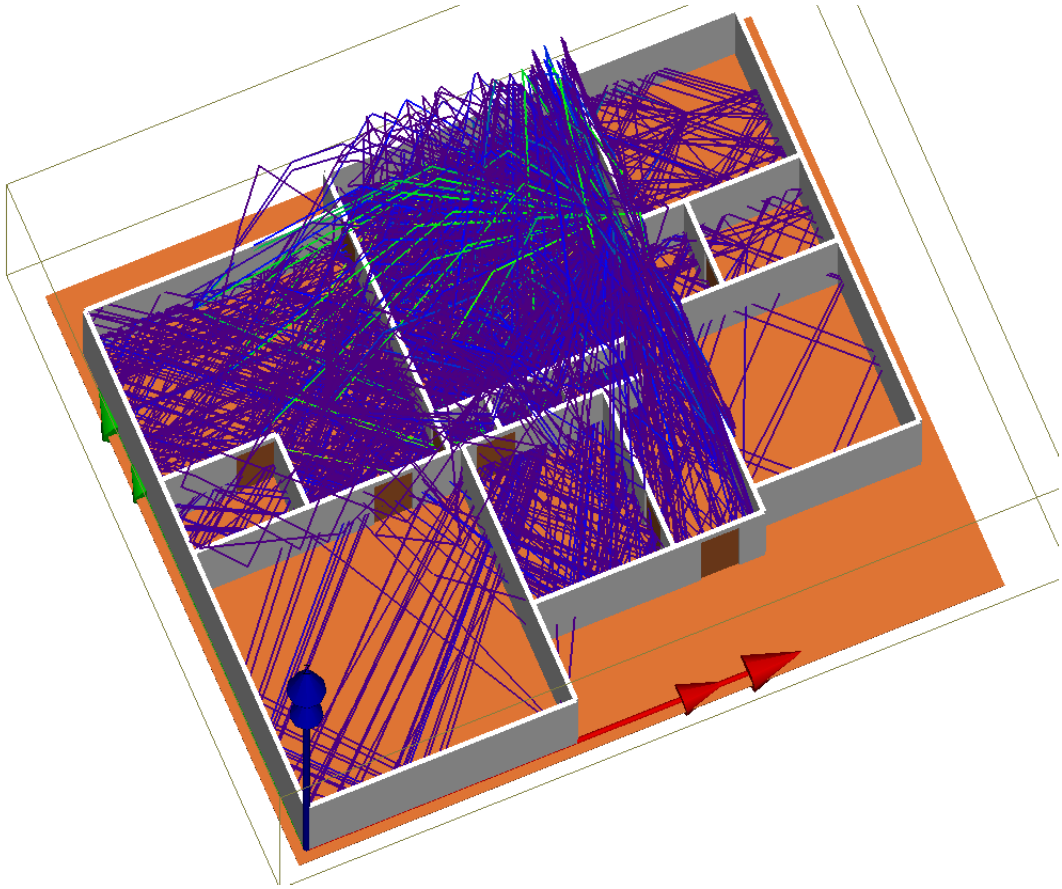

Figure 9 – Ray Tracing Example for Location 1

In this image, the 2nd floor has been kept invisible to observe the ray propagation in the 1st floor.

The next diagram shows the measurements taken in Location 2, near the corner of the room. Figure 10 shows better coverage in the kitchen, as well as coverage in the upstairs bedroom, which was marginal when the AP was in Location 1. There is a definite slow spot behind the TV most likely due to the change in the angle of the AP. In the test with location 1, the two open doorways on either side of the TV allowed reflected rays to provide good coverage. After the AP shifted to the corner of the room, the farther doorway was not at a good angle for reflections, and the TV prevented most through wall transmissions, resulting in the lull in coverage behind the TV.

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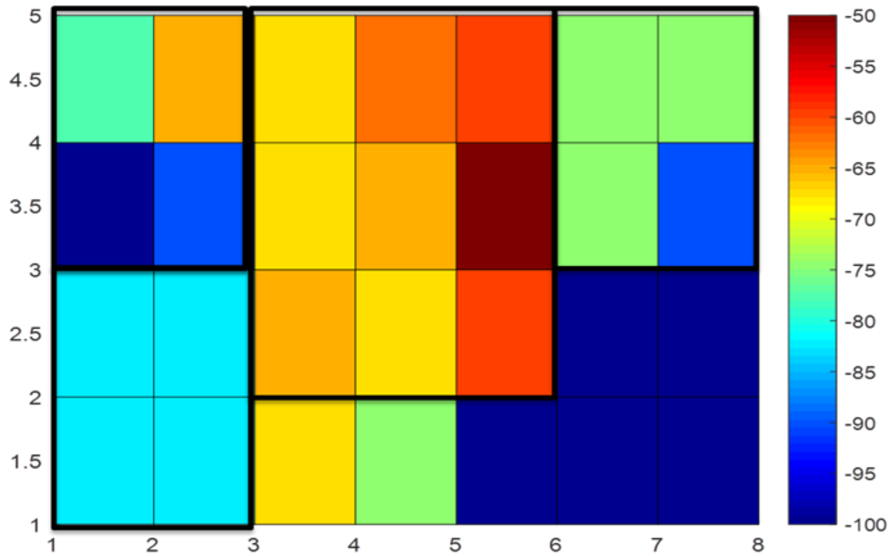

Figure 10 - Throughput Results for Location 2 without Chair

The results matched antenna theory expectations that a corner location for an AP is optimal to minimize blind spots. With the AP still in Location 2, the tests were repeated with an overstuffed chair placed in front of the table holding the AP. As shown in Figure 11, the chair absorbed enough energy to lower throughput levels throughout the room, but also directed some reflected energy into the side room.

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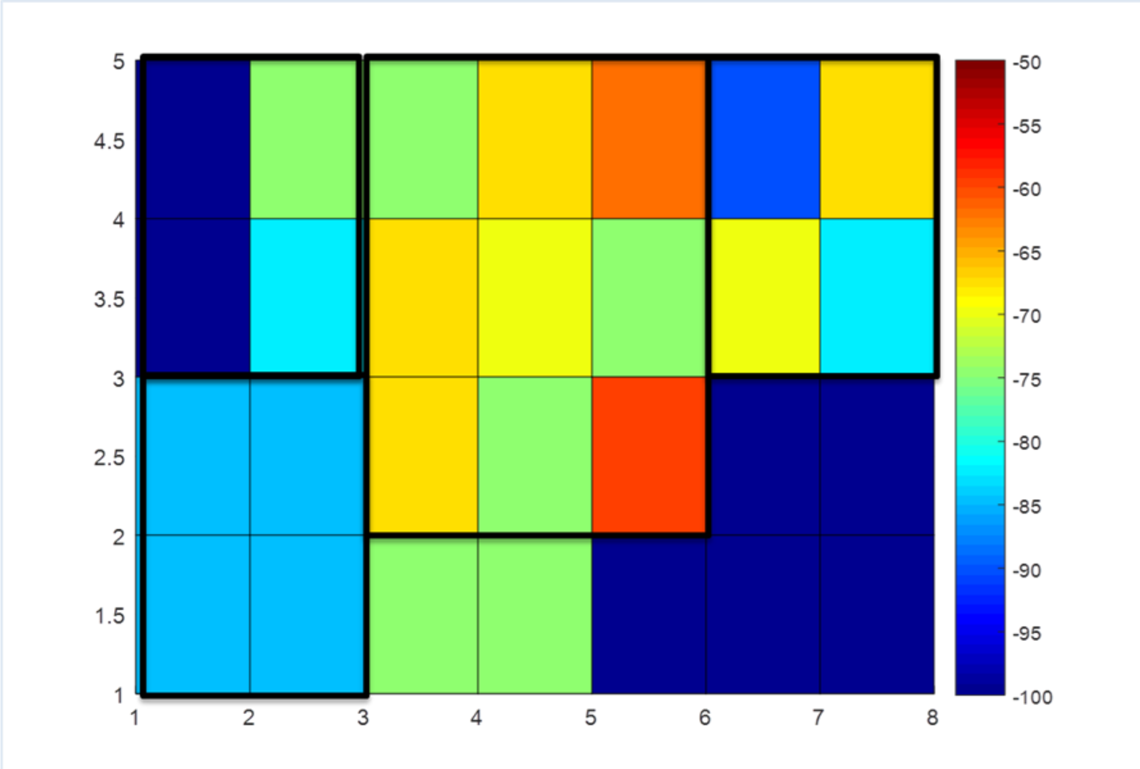

Figure 11 - Measurement Results for Location 2 with Chair

Summing up the residential test results:

1. Achieving consistently high throughput is very feasible as long as one takes the propagation characteristics of millimeter wave antennas into consideration.
2. The principal obstacles to good transmission are metal or metal backed objects and stone or cement, though they can provide good reflections for NLOS paths.
3. We noted with some surprise that wood and cloth furniture seemed to affect 60 GHz signals more readily than expected.

With these factors in mind, the optimal placement for 60 GHz APs may be as a wall mounts so that they may be located above furniture which might degrade the signals. A creative mind might integrate a 60 GHz AP into a wall mount lighting fixture or a shelf mounted in a corner.

Potential residential use cases

The early 11ad demonstrations and products have focused on the elimination of wires, usually in an office or enterprise context. Up until recently, the marketplace for 60 GHz products has been limited as the vendor community struggled to find a niche that fit the strengths of 60 GHz systems. That state of affairs has begun to change with the first

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generally available AP with 11ad support being released in 2016. WiGig holds promise in a residential environment for several features and services, with inter-AP and local access backbones, as well as virtual reality as potentially the most significant. These use cases rely on the high-bandwidth offered by 60 GHz systems as well as the low added latency of the 11ad MAC.

60 GHz home network backbones

As today's consumers bulk up on wireless devices, the traditional single home router is having trouble addressing the expectation that Wi-Fi can be everywhere from the garage to the backyard to every room in the home. Many Operators and consumer electronics manufacturers are considering how to provide added coverage that may be needed in other parts of the home. Extender APs and repeaters are popular, but they must still be connected back to the main home router. If a wired connection path is available, that can provide the highest reliability, but often there is not a wired connection that can sustain a high bit rate connection, if it's available at all.

Wireless extender APs are showing up on the market, but if they use a standard 5 GHz backbone connection, they are only adding to the congestion already present in the air. A 60 GHz backbone has the advantage of providing a high bit rate connection without impacting the existing services in the home. The testing done to this point has shown that 60 GHz multi-element arrays can provide enough signal to get through at least sheet rock walls.

It is also important to remember that in-home testing and simulation has shown that NLOS connections can be significant for 60 GHz transmissions. Impediments to using a 60 GHz backbone are related to home construction materials. In parts of the world where interior walls are commonly made of cinderblocks, the performance of 60 GHz backbones will struggle, just like 5 GHz systems.

Since 60 GHz connections are more dependent on LOS and NLOS reflections than lower frequency Wi-Fi connections, a backup method may be needed for 60 GHz connections that are affected when the home's configuration changes. For example, a bedroom might get enough reflected energy to achieve a useful bit rate when the bedroom door is open, but performance might drop when the door is closed. If the AP(s) can recognize that issue and reconfigure the bedroom's connections to use lower bit rate 5 GHz channels, the end user might experience a lower bit rate connection. However, a change in performance is better than a complete disconnection. Similarly, if there are several 60 GHz APs within the home, they may be able to shift their beamforming to work around changes in the home's physical configuration in real time to continue to provide uninterrupted services.

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Last 100ft broadband access over 60 GHz

Another potential use case related to inter-AP backbones is the need for a fixed wireless extension to the home from a local broadband termination facility. That facility might be a fiber node or a strand-mounted DOCSIS® 3.1 cable modem. A 60 GHz distribution system could feed high speed connections to outdoor antennas mounted on nearby homes. In particular, the new 11ay specification amendment underway with IEEE 802.11 has new features designed to improve outdoor performance.

Outdoor 60 GHz systems have several challenges with which to contend. An outdoor distribution system has to overcome water as fog, rain, snow or ice potentially collecting on outdoor antennas. A broadband to wireless distribution node may have enough internal heat generated to avoid some problems with snow or ice, while leaves and tree branches may also block or absorb transmissions. In areas with buried utilities, the other barrier to using 60 GHz services may be the need to get high enough for a substantially LOS view of the distribution node or nodes for the best performance. While within a room or in rooms connected by hallways, reflections may provide a NLOS path to hidden nodes. Reflections out of doors are as likely to result in energy being reflected into the sky as back in a useful path, making outdoor use cases more challenging than indoor use cases.

To overcome these challenges, complex element arrays that can provide high levels of gain and directivity will be important. Depending upon the network architecture, a distribution node may require multiple antenna arrays to cover different angles. Comprehensive network designs will be needed, similar to the designs of cell sites now, to ensure that nodes with potential overlapping coverage can operate on different channels. An integrated operational management system may be needed to ensure that the network adapts to changing conditions, and that the stations, which may themselves have multiple radios, are kept up to date with their recommended node and channel usage.

Virtual reality needs 60 GHz

Virtual reality systems require significant amounts of data to generate and maintain the VR illusion. The data must also be provided with low latency. As an example, if a person turns his head, the viewing area must be redrawn within at most 20 milliseconds to prevent the inner ear from disagreeing with the eyes, which can lead to nausea. This requirement is also known as motion to photon (MTP). Certain types of entertainment with lots of fast motion, such as live sports or gaming, may require even lower latency than 20 milliseconds to avoid the appearance of stuttering video during the active portions of the program, particularly if combined with the user’s motion. The amount of data required to reach that level of performance is still up for debate, but it may be reliably estimated at above 1 Gb/s. VR can require these rates across several steps. If a

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VR program is streaming from the wide area network, it will drive high data rates over the broadband access facility to the VR controller. The number of cost-effective options supporting multi-gigabit throughput is small for home networking solutions. Wireless connectivity using 11ad is an option that gets the high bitrate streaming feeds to the VR controller. Additionally, a wireless VR headset would also need a high bit rate solution. The headset/controller link is needed even if the VR content is from a local source, versus content streaming from the WAN.

If there is more than one user of VR in the same room or if the VR data is passing over two hops (from the WAN to the controller and from the controller to the headset), the rates of course double. Current Wi-Fi systems, while they can reach rates above a gigabit in good conditions, struggle to maintain high throughput levels if other devices are also on the same network. If the systems are in use in an environment with many other overlapping APs serving their own demanding clients, it is very unlikely that they can keep up with even one high quality VR experience.

802.11ad systems can provide very low latency and high bandwidth without interference, making them ideal for VR applications. While 11ac systems might be able to keep up with a VR transmission data rate, in many homes they may have trouble achieving the low latency required by VR. This is due to interference from surrounding Wi-Fi systems, as well as range and power difficulties serving a very high bit rate to a VR headset that may not be located in the same room as the serving AP. Even if 60 GHz becomes wildly popular, it is unlikely to ever experience the same interference problems currently afflicting conventional Wi-Fi. The level of attenuation when a 60 GHz signal tries to traverse an outside wall of brick or stone helps overcome interference issues. Signals from a neighboring building will certainly not get through outside walls with enough energy to disrupt a system in an adjacent building. Even signals from a neighboring apartment are unlikely to line up at just the right angle to interfere with a system in an adjacent apartment since the antenna arrays are highly directional.

Overall, 60 GHz wireless connections have real promise for VR entertainment systems because of their high-bandwidth, low latency and resistance to interference.

Next-generation of 60 GHz Wi-Fi – 11ay

In 2015, the IEEE 802 standards group started a new effort to expand the capabilities of the 60 GHz Wi-Fi interface introduced with 11ad. The goal of the group is to increase throughput to at least 20 Gb/s, while maintaining backward compatibility to the current 11ad amendment. The specification is still in progress with work expected to complete in 2019. A new proposed feature will provide the ability to transmit to multiple devices on multiple channels simultaneously with channel bonding to a single device also supported. To support the higher speeds, wider channel definitions have been proposed along with downlink MU-MIMO.

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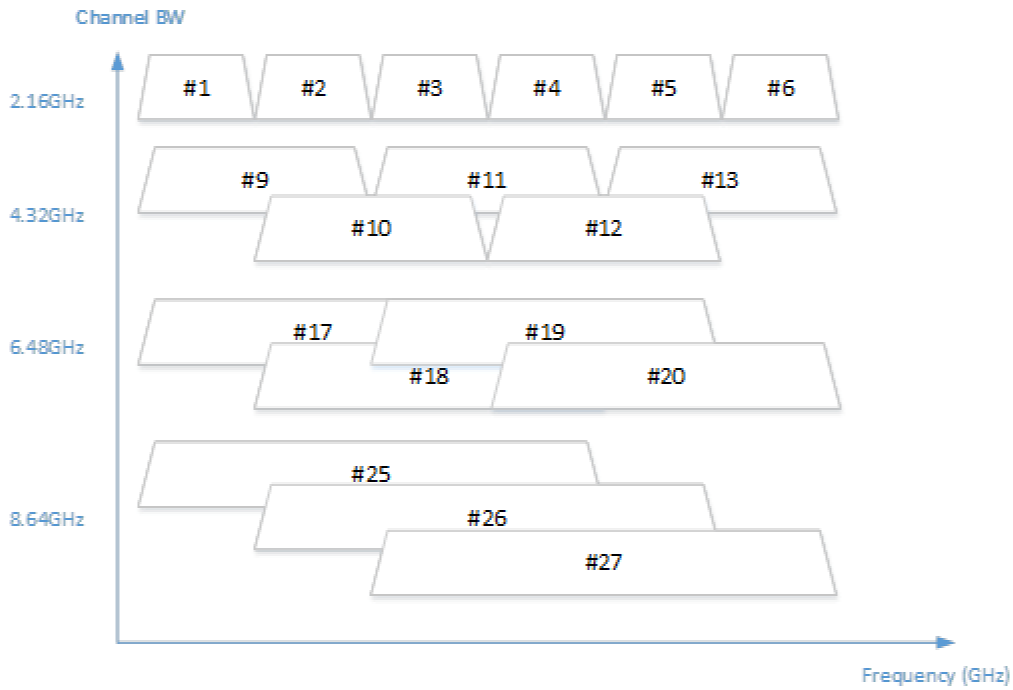

Figure 12 - Proposed Channels for 802.11ay [3]

The high throughput expectations of the 11ay effort have led some to question whether there is a need for such a service. In the timeframes of 11ay, Fiber Deep and/or DOCSIS 3.1 access technologies may bring data speeds approaching this level to the home. In-home services such as gaming consoles or other entertainment, may be supporting VR with its very high throughput demands. Current home wireless networks are already strained with the current service demands, primarily streaming video. The homes of the future are unlikely to require less bandwidth or demand fewer services. The ability of 60 GHz services to provide targeted bandwidth to several users could be the linchpin of an in-home VR deployment. No other potential home networking technologies have the mix of high throughput and resistance to interference as 11ay.

CONCLUSION

60 GHz wireless has many names: WiGig, 11ad, 11ay and millimeter wave. No matter what label is used for this wireless technology, it can provide real advantages to residential home networking. The current generation of 11ad systems demonstrates high throughput and good robustness to common home characteristics. The lack of interference means that it can immediately improve the wireless experiences of many consumers in MDUs or other densely populated areas who are frustrated with the congestion caused by local interference.

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As broadband services provide higher multi-gigabit service rates, higher bandwidth wireless will be needed to provide those faster speeds to wireless devices. The 5 GHz band has difficulty providing high speeds because of the bandwidth limitations in many regions and the high number of other 5 GHz devices. Multi-gigabit speeds can be met by 60 GHz solutions, both last 100ft outdoor links and in home solutions.

As a potential driver of multi-gigabit services, VR is also a good fit for 60 GHz networking due to its high speeds and low latency. The possibilities for 60 GHz Wi-Fi, or WiGig, in the residential and home networking space are numerous and compelling.

ABBREVIATIONS

AP	Access Point
AR	Augmented Reality
BTLE	Bluetooth Low Energy
GHz	Gigahertz
HD	High Definition
IoT	Internet of Things
ISM	Industrial Scientific Medical
LOS	Line of Sight
MDU	Multiple Dwelling Unit
MU-MIMO	Multi-User Multiple Input Multiple Output
NLOS	Non-Line of Sight
SCTE	Society of Cable Telecommunications Engineers
VR	Virtual Reality
WLAN	Wireless Local Area Network

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(3) Figure 24, Specification Framework for 802.11ay, 11-15-1358-09-00ay, Oct. 8, 2016

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