WIFI ON STEROIDS: 802.11AC AND 802.11AD

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ABSTRACT

The advent of bandwidth-hungry wireless applications such as large file transfer, high definition video streaming, wireless display, and cellular data offload highlight the impending need for larger bandwidth and super speed WiFi links exceeding 1 Gb/s. This article introduces two emerging standards likely to shake the wireless world, namely IEEE 802.11ac and IEEE 802.11ad, and identifies the challenges in the path of multi-gigabit WiFi. We study the suitability of these standards for the new usage models enlisted in this article.

INTRODUCTION

Wireless networking is a fundamental technology as important as computing itself. WiFi has pushed the performance and user experience of wireless to guarantee that it is keeping pace with the ever increasing demand of higher speeds and new usage models

With the advent of bandwidth hungry applications, such as large file transfers (e.g., BluRay HD movies, raw uncompressed images, etc.), HD video streaming, wireless display, and cellular data offload, more bandwidth is sorely needed [1]. WiFi is proliferating in the consumer electronics (CE) domain providing a playground for faster media transfer communication applications [2–4]. Market statistics project number of WiFi enabled devices shipped in year 2012 to surpass 1.5 billion [5].

Extensive effort and work are in progress in IEEE on two emerging standards likely to shake up the wireless world: IEEE 802.11ac [6] and IEEE 802.11ad [7]. These standards target data rates faster than the gigabit Ethernet. The history of initiation and development of these standards up to the year 2011 is presented in [8].

This article addresses the following critical points:

- The need for multi-gigabit WiFi
- Key physical (PHY) layer features of 802.11ac and 802.11ad that enable multi-gigabit WiFi
- Challenges for achieving multi-gigabit WiFi
- Suitable use cases for 802.11ac and 802.11ad

The rest of the article is organized as follows. The next section justifies the need for multi-gigabit WiFi. Then, we present emerging multi-gigabit WiFi standards: 802.11ac and 802.11ad. We introduce multi-gigabit modulation and coding schemes, and go on to discuss challenges on the road to multi-gigabit WiFi. The artile then elaborates on the adaptability of 802.11ac and 802.11ad for multi-gigabit WiFi use cases; and we present our conclusions in the final section.

THE NEED FOR MULTI-GIGABIT WIFI

WiFi speed has proliferated, keeping pace with the usage model requirements. As of today, commercially available 802.11n-based WiFi products support PHY data rates up to 540 Mb/s. WiFi use cases have evolved to beyond wireless LAN for access to the Internet. The following use cases justify the need for multi-gigabit WiFi:

Sync data/file transfer: Multi-gigabit WiFi tremendously reduces the time for data synchronization between two devices. For example, a 1 Gbyte file transfer is at least 10 times faster (1 Gb/s vs. 100 Mb/s). In home, enterprise, and public kiosk environments, time for completion of the activity is critical for a good user experience.

Wireless LAN and backbone networks: Multi-gigabit WiFi enables faster access to the Internet by improving the PHY data rate between the device and the access point (AP) and between AP-to-AP in wireless backbone networks.

Small-cell backhaul network: Mobile broadband data is growing at exponential rates. Long Term Evolution (LTE) and fifth generation (5G) increase the capacity of the network leveraging small cells, but it has a major impact on the mobile backhaul network design. Backhaul is the transmission link between the small cell and the mobile network controller. Small cell controllers will be deployed in the streets (lamp posts, streetlights, etc.) and their deployment cost must be minimized. Fiber is not a scalable or cost-efficient way to reach all small cell sites, so a wireless solution will play a dominant role. The 60 GHz technology (802.11ad) is an excellent solution for small cell backhaul since it offers more than 1 Gb/s links at a low cost, particularly no license fee. Thus, mobile broadband technologies and multi-gigabit WiFi complement each other.

Multimedia streaming over IP: Uncompressed video at 1920 × 1080p, 24 b/pixel, and 60 frames/s generates 3 Gb/s of data and requires at least 3 Gb/s PHY data rate for wireless streaming. Conventional WiFi can only stream

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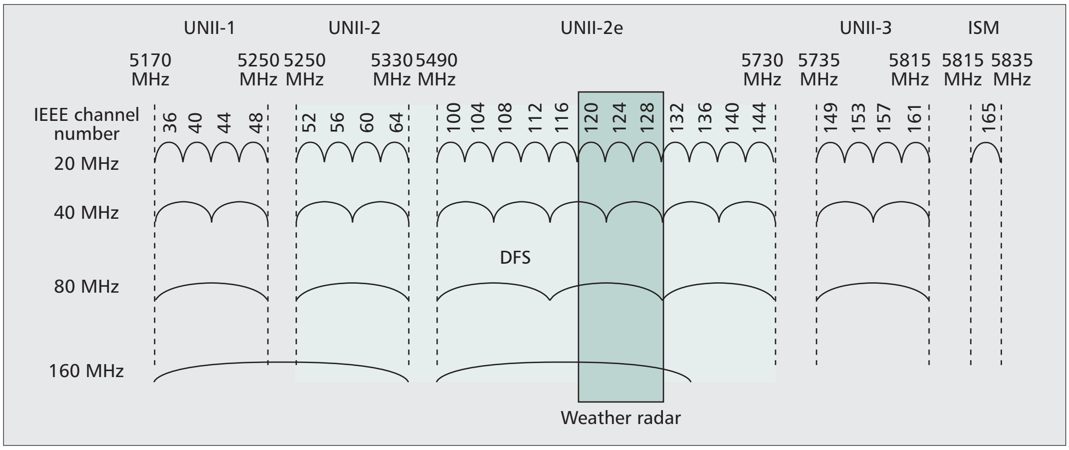

Figure 1. *The 5 GHz spectrum available for Wi-Fi usage with DFS and TDWR restrictions.*

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compressed multimedia contents. Multi-gigabit WiFi enables uncompressed multi-media content streaming, achieving the high quality and low end-to-end latency requirements critical for smooth user experience in wireless display use cases. WiFi is more suitable compared to wireless USB [9], wireless HD interface (WHDI) [10], and wireless HD (WiHD) [11] for wireless display, since the former has a larger deployment and user awareness, besides support for IP networking, ease of connection, and standardized security mechanism [3].

Cellular data offloading: The spectrum available for mobile data applications over cellular networks is limited and even the advent of LTE radio access is reaching the limits of Shannon's law. Cellular data offloading is one solution to increase the overall cellular network capacity by offloading mobile data to WiFi in high density places like shopping malls, universities, and enterprises. Multi-gigabit WiFi in this setting provides faster data transfer, improving the overall WiFi network performance.

MULTI-GIGABIT WIFI STANDARDS

This section discusses key features in 802.11ac and 802.11ad enabling multi-gigabit WiFi.

IEEE 802.11AC

Carrier Frequency — IEEE 802.11ac is an amendment to IEEE 802.11 [12] for very high throughput (VHT) operation in frequency bands below 6 GHz, excluding 2.4 GHz (i.e., unlicensed bands at 5 GHz band). Plurality of 802.11 a/b/g/n devices are currently operating at 2.4 GHz, crowding the channels and causing bandwidth crunch and higher signal interference. The 5 GHz band is comparatively cleaner with lower signal interference. The number of non-overlapping channels (of 20 MHz each) available at 5 GHz band is larger (24 in the United States, up to 24 worldwide) than a few non-overlapping channels at 2.4 GHz (3 in the United States), thus enabling channel bonding of 2 or more channels.

Channel Bandwidth — As shown in Fig. 1, 5 GHz spectrum is composed of a number of sub-bands including unlicensed national information infrastructure (U-NII)-1, 2, 2e, and 3 bands. The support of dynamic frequency selection (DFS), originally defined in IEEE 802.11h, is mandatory to use UNII-2 and 2e. DFS is the mechanism to ensure that channels containing radars are avoided by an AP and the energy is spread across the wireless channel to reduce interference to satellites.

IEEE 802.11ac supports 40 MHz, 80 MHz, and 160 MHz channel bandwidth compared to only 20 MHz and 40 MHz supported by 802.11n. The 160 MHz channel bandwidth is composed of two 80 MHz channels that may or may not be contiguous. The 80 MHz and 40 MHz channels are composed of two contiguous 40 MHz and 20 MHz channels, respectively. The support of 40 MHz and 80 MHz channel bandwidth is mandatory while support of 160 MHz and 80 + 80 MHz is optional.

These wide channel bandwidths and minimized co-channel interference are challenging to achieve in a dense wireless LAN (WLAN) environment (e.g., enterprise deployment) with plurality of APs deployed on non-overlapping channels. 802.11ac provides more spectrum and channel bandwidth by relying on DFS channels, which many WiFi devices do not support today.

As seen in Fig. 1, 80 MHz channel bandwidth allows 5 non-overlapping channels in the United States (channels 120–128 are prohibited due to terminal Doppler weather radar [TDWR]) and 5 in the United Kingdom/European Union (channels 149 and higher require light licensing for outdoor use only) when DFS is used, but only 2 channels in the United States and 1 in the United Kingdom/European Union without DFS. DFS is mandatory for 160 MHz channel bandwidth with 1 non-overlapping contiguous 160 MHz channel in the United States and 2 in the United Kingdom/European Union.

MIMO — Higher data rates can be achieved with the multiple-antenna system known as multiple-input multiple-output (MIMO). Data for transmission is divided into independent data streams to be transmitted through multiple antennas. This is known as spatial multiplexing. Typically, a MIMO system has m transmit and n receive antennas. The number of streams M is always less than or equal to the minimum number of

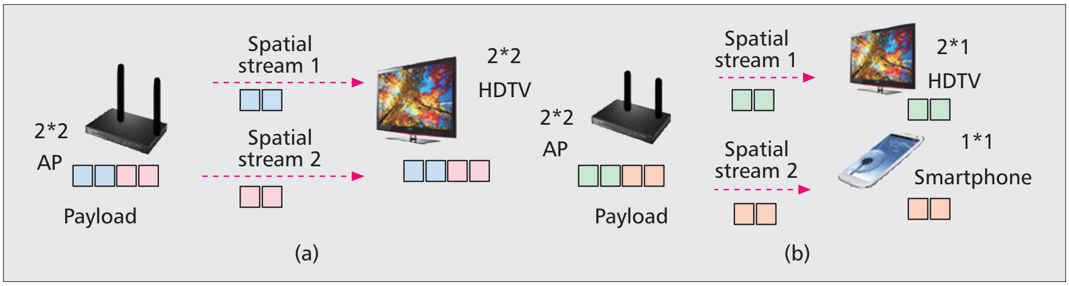

Figure 2. *a) SU-MIMO concept; b) downlink MU-MIMO concept.*

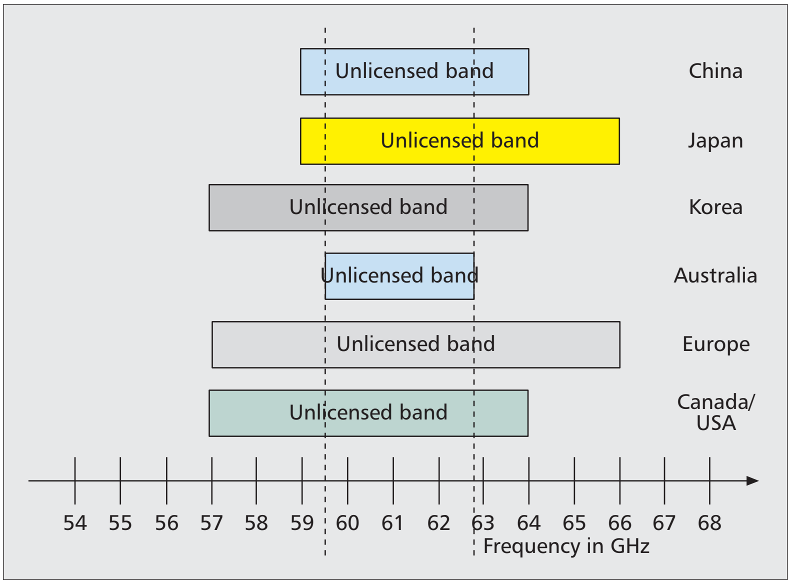

Figure 3. *Worldwide frequency allocation for unlicensed operation at 60 GHz band.*

antennas available in an $m \times n$ MIMO system. The channel capacity C increases linearly with M,

$$C = M \times B \times \log_2(1 + SNR),$$

where B is the channel bandwidth and SNR is the signal-to-noise ratio. The 802.11ac supports up to 8 spatial streams compared to the maximum 4 in 802.11n.

IEEE 802.11ac supports multi-user MIMO (MU-MIMO) as well as single-user MIMO (SU-MIMO). SU-MIMO as shown in Fig. 2a is a method by which an AP can transmit multiple independent streams at the same time to a *single* device. MU-MIMO as depicted in Fig. 2b is a technique by which the AP can transmit multiple independent streams at the same time to *multiple* devices. In 802.11ac, MU-MIMO system supports four users with up to four spatial streams per user with the total number of spatial streams not exceeding eight.

Typically, many of today's CE devices have one transmit and one receive antenna, while the APs have m transmit and n receive antennas. The MU-MIMO system is well suited for downlink from AP in this situation as the network performance is improved, keeping the complexity of the device side minimal by using only one receive antenna.

Modulation and Coding Scheme — According to 802.11ac, the PHY data subcarriers are modulated using binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (QAM), 64-QAM, and 256-QAM. Note that 256-QAM is not supported by 802.11n. FEC (Forward Error Correction) coding is used with coding rates of 1/2, 2/3, 3/4, and 5/6. Use of BCC (Binary Convolutional Coding) is mandatory, but LDPC (Low-Density Parity-Check Coding) is optional.

Backward Compatibility — IEEE 802.11ac is backward compatible with 802.11n at 5 GHz ensuring the interoperability of 802.11ac and the already deployed 802.11n devices.

IEEE 802.11AD

Carrier Frequency — 802.11ad is an amendment to 802.11 for enhancements for multi-gigabit throughput in 60 GHz band. Figure 3 depicts the spectrum allocation for unlicensed operation at 60 GHz. In this band, typically 7 GHz of spectrum is available for unlicensed usage compared to 83.5 MHz in 2.4 GHz band. This standard defines 4 channels, each with 2.16 GHz bandwidth, for operation at 60 GHz band. These channels are 54 times wider than the 40 MHz bonded channels available in 802.11n.

Modulation and Coding Scheme — 802.11ad defines both SC (Single Carrier) modulation and OFDM (Orthogonal Frequency Division Multiplexing) modulation. OFDM enables longer distance communication and greater delay spreads. This provides flexibility in handling obstacles and reflected signals. OFDM allows SQPSK, QPSK, 16-QAM, and 64-QAM modulation with the maximum achievable PHY data rate of 6.756 Gb/s. SC PHY is low on power consumption and focuses on small form factor devices like handsets. SC uses π/2-B/SK, π/2-QPSK, and π/2-16-QAM modulation with the maximum achievable PHY data rate of 4.620 Gb/s. In this standard, the data is encoded by an LDPC encoder with 1/2, 5/8, 3/4, and 13/16 code rates.

Beamforming — Signal attenuation is high at 60 GHz band and hence link budgeting is challenging. To improve the signal strength at the receiver, high gain antennas are deployed. These high gain antennas, mostly phased-array antennas, utilize beamforming to create beams in a particular direction allowing the transmitted power to be focused.

Modulation	Code rate	PHY data rate (Mb/s)					Spatial streams	Standard
		20 MHz channel	40 MHz channel	80 MHz channel	160 MHz channel	2.16 GHz channel		
BPSK	1/2	6.5	13.5	—	—	—	1	802.11n[2]
QPSK	3/4	19.5	40.5	—	—	—	1	802.11n
16-QAM	3/4	26	81	—	—	—	1	802.11n
64-QAM	5/6	65	135	—	—	—	1	802.11n
64-QAM	5/6	260	540	—	—	—	4	802.11n
BPSK	1/2	6.5	13.5	29.3	58.5	—	1	802.11ac[2]
QPSK	3/4	19.5	40.5	87.8	175.5	—	1	802.11ac
16-QAM	3/4	39	81	175.5	351	—	1	802.11ac
64-QAM	5/6	65	135	292.5	585	—	1	802.11ac
256-QAM	5/6[1]	78	180	390	780	—	1	802.11ac
256-QAM	5/6[1]	312	720	1560	3120	—	4	802.11ac
256-QAM	5/6[1]	624	1440	3120	6240	—	8	802.11ac
p/2-BPSK	1/2	—	—	—	—	385	1	802.11ad
p/2-BPSK	3/4	—	—	—	—	1155	1	802.11ad
p/2-QPSK	3/4	—	—	—	—	2310	1	802.11ad
p/2 16-QAM	3/4	—	—	—	—	4620	1	802.11ad
64-QAM	13/16	—	—	—	—	6756.75	1	802.11ad

[1] Code rate of 3/4 for 20 MHz channel width.
[2] Guard interval = 800 ns.

Table 1. *Modulation and coding schemes for 802.11n, 802.11ac, and 802.11ad.*

Backward Compatibility — The backward compatibility factor is irrelevant as IEEE 802.11ad is the first standard for WiFi operation at 60 GHz.

MULTI-GIGABIT MODULATION AND CODING SCHEMES

Multi-gigabit PHY data rates in 802.11ad are achieved by using a large chunk of spectrum (≈2 GHz) with simple modulation schemes (BPSK, QPSK), while in 802.11ac it is based on sending more bits per symbol (256-QAM) and use of simultaneous data streams (up to 8), because bandwidth is limited to a maximum of 160 MHz (with channel bonding).

Table 1 illustrates modulation and coding schemes (MCSs) used in 802.11n, 802.11ac, and 802.11ad to achieve multi-megabit and multi-gigabit PHY data rates. Note that both 802.11n and 802.11ac support a long guard interval of 800 ns and optionally a short guard interval of 400 ns between transmission of two symbols. The guard interval is 48.4 ns in 802.11ad. Table 1 assumes the long guard interval for 802.11n and 802.11ac. With short guard interval, the data rates increase accordingly; for example, 802.11n's maximum data rate increases from 540 Mb/s to 600 Mb/s, and 802.11ac's maximum data rate increases from 6.240 Gb/s to 6.933 Gb/s.

The 802.11n PHY data rates range from 6.5–600 Mb/s, achieved through various combinations of modulation scheme, code rate, channel bandwidth, guard interval, and number of spatial streams. 802.11ac PHY data rates range from 6.5 Mb/s to 6.933 Gb/s. PHY data rates achieved by 802.11ac with 256-QAM modulation scheme and by 802.11n with 64-QAM modulation scheme, 800 ns guard interval, 40 MHz channel bandwidth, and 4 spatial streams is 720 Mb/s and 540 Mb/s, respectively (i.e., a 33 percent increase in the PHY data rate), thanks to the 256-QAM modulation scheme.

802.11ad PHY data rates range from 385

802.11ad systems require simpler hardware compared to 802.11ac, due to simpler modulation schemes and use of only one stream of data (SISO vs. MIMO). To have multiple independent data streams in 802.11ac, multiple RF and baseband chains are required.

Modulation	Code Rate	Receive sensitivity (dBm)					EVM (dB)
		20 MHz channel	40 MHz channel	80 MHz channel	160 MHz channel	2.16 GHz channel	
BPSK	1/2	–82	–79	–76	–73	—	–5
QPSK	3/4	–77	–74	–71	–68	—	–13
16-QAM	3/4	–70	–67	–64	–61	—	–19
64-QAM	5/6	–64	–61	–60	–57	—	–27
256-QAM	5/6	–57	–54	–51	–48	—	–32
p/2-BPSK	1/2	—	—	—	—	–78	–6
p/2-BPSK	3/4	—	—	—	—	–64	–10
p/2-QPSK	3/4	—	—	—	—	–59	–13
p/2 16-QAM	3/4	—	—	—	—	–53	–21
64-QAM	13/16	—	—	—	—	–47	–26

Table 2. *Transmitter EVM and receiver sensitivity for a few modulation and code rates used in 802.11n, 802.11ac, and 802.11ad.*

Mb/s to 6.7 Gb/s, achieved through combinations of modulation scheme and code rate. For the BPSK modulation scheme, PHY data rate achieved by 802.11ad using 2.16 GHz channel bandwidth and 802.11n employing 20 MHz channel bandwidth is 385 Mb/s and 6.5 Mb/s, respectively, i.e., a 58 times increase in the PHY data rate, leveraging larger channel bandwidth.

CHALLENGES FOR MULTI-GIGABIT WIFI STANDARDS

Table 2 shows the receiver sensitivity and required transmitter EVM (Error Vector Magnitude) values for some key MCSs of 802.11n, 802.11ac, and 802.11ad. A higher receive sensitivity means that a higher signal strength (or SNR) is required for detection. A lower EVM means that system errors such as local oscillator phase noise, transmitter nonlinearities, and IQ imbalance must be controlled more precisely.

HARDWARE COMPLEXITY AND POWER CONSUMPTION

802.11ad systems require simpler hardware compared to 802.11ac, due to simpler modulation schemes and use of only one stream of data (SISO vs. MIMO). To have multiple independent data streams in 802.11ac, multiple RF and baseband chains are required. In practice, for better radio link performance, the number of RX and TX chains may be larger than the number of desired streams, N_S (i.e., number of independent and separately encoded transmit signals or streams). This implies more than N_S times increase in power and RF chip/device area.

Even if intelligent power management is applied to TX, MIMO RX system may consume at least N_S times more power compared to a single chain RX. Furthermore, the processing power required to form MIMO streams must be added to the total power budget.

DEVICE FORM FACTOR

In a multi-antenna system the adjacent antennas must be separated by a minimum distance, around half a wavelength (27 mm for 802.11ac), to reduce the coupling between antennas as well as correlation between streams. For applications where size matters, this requirement limits the number of antennas and consequently the number of streams and maximum bit rate.

At 60 GHz the carrier wavelength is only 5 mm, so relatively high gain antennas can be implemented in a small package. For example, a 13 dB patch array antenna printed on Duroid substrate ($\varepsilon_r = 2.2$) occupies an area of 5 mm × 6 mm [13]. Thus, instead of using a dipole antenna with 2 dBi gain on each side as in 802.11ac, a compact higher gain antenna can be used at each end to compensate for the extra path loss.

SEMICONDUCTOR COST

Complementary metal oxide semiconductor (CMOS) technology is used for fabrication of WiFi transceivers. 2.4/5 GHz band WiFi transceivers can be synthesized with more conventional CMOS technologies, which are cheaper, whereas 60 GHz WiFi transceivers can only be synthesized with state-of-the-art CMOS technology (65 nm, 40 nm, etc.) As of today, 40 nm CMOS technology is expensive, thus making 802.11ad transceivers more costly than 802.11ac transceivers.

802.11AC AND 802.11AD SUITABILITY FOR MULTI-GIGABIT USE CASES

Considering the challenges discussed above, an important question is raised: are 802.11ac and 802.11ad suitable for the same type of applications, or there are preferred classes of applications for each one?

To answer this question, first we need to get a better idea of wave propagation at 5 GHz and 60 GHz bands. At 60 GHz spectrum, radio signals suffer from higher propagation and atmospheric loss compared to 5 GHz. For the same range, free space loss at 60 GHz is 21 dB more than free space loss at 5 GHz (e.g., for 1 m range free space loss is 68 dB at 60 GHz, and 47 dB at 5.5 GHz). Note that a general rule of thumb is every 6 dB increase in propagation loss halves the coverage distance. Furthermore, obstruction loss is significant at 60 GHz. For example, human body loss is between 20 and 40 dB [14].

Therefore, 802.11ad is more appropriate for line-of-sight, room-scale, low-cost, short-range, very-high-throughput applications, such as in-room uncompressed and lightly compressed multimedia wireless display, sync data/file transfer, and so on.

IEEE 802.11ac is proper for longer-range high-throughput applications, such as in-home WLAN, (lightly) compressed multimedia wireless display, and so on. In summary, IEEE 802.11ad leveraging small device form factor and low power consumption characteristics is apt for portable power-constraint multi-gigabit wireless devices.

While 802.11ac seems to be more appropriate for longer-range applications, the transmitter power regulatory and power consumption requirements limit the applicability to the differnet use cases. As seen in Tables 1 and 2, 802.11ac requires –48 dBm receive sensitivity with 256-QAM modulation and up to 8 spatial streams to achieve multi-gigabit WiFi. To deploy the highest data rates of 802.11ac, AC-powered units are more suitable. Since the obstruction loss at 5 GHz is lower than at 60 GHz, multi-gigabit 802.11ac is more appropriate for home-scale (both line-of-sight and non-line-of-sight) wireless applications where portability is not a bottleneck.

On a different note, at 60 GHz high gain antennas with low cost and small size can be realized for point-to-point applications such as small-cell backhaul networks. Despite lower propagation loss at 5 GHz band, strict regulatory requirements limit the transmit power proportional to the transmitter antenna gain [15]. Thus, range extension required for backhaul networks cannot be achieved at 5 GHz.

CONCLUSIONS

In this article the need for multi-gigabit WiFi links is articulated. We introduce two emerging standards likely to shake the wireless world (802.11ac and 802.11ad), highlight the challenges in the path of multi-gigabit WiFi, and discuss suitability of 802.11ac and 802.11ad for supporting multi-gigabit use cases. WiFi is booming rapidly and is used for wireless connectivity between devices in a plethora of scenarios. It remains to be seen how the consumer market responds to multi-gigabit WiFi link capabilities.

Wi-Fi is booming rapidly and is used for wireless connectivity between devices in a plethora of scenarios. It remains to be seen how the consumer market responds to multi-gigabit Wi-Fi link capabilities.

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