IEEE 802.11ad: Introduction and Performance Evaluation of the First Multi-Gbps WiFi Technology

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ABSTRACT

Multi-Gbps communication is the next frontier in high-speed local and personal wireless technologies, which will offer the necessary foundation for a new wave of applications such as wireless display, high-speed device synchronization, and the evolution of Wi-Fi. The wide harmonized spectrum in the unlicensed millimeter-wave (60 GHz) band is considered the most prominent candidate to support the evolution towards multi-Gbps data rates. As such, the industry is in the process of defining new 60 GHz PHY and MAC technologies that can serve a wide variety of applications and usages, as to avoid the proliferation of non-coexistent devices operating in this unoccupied spectrum. The most promising activity is taking place under the auspices of the IEEE 802.11ad task group, which is defining amendments to the 802.11 standard for operation in the 60GHz band. In this paper we describe the main components of the MAC and PHY amendments included in the current IEEE 802.11ad draft standard and that enable multi- Gbps data rates. We also provide a comprehensive set of simulation results for typical use cases, and argue that 802.11ad is poised to be the standard that will enable mass market adoption of multi-Gbps wireless communication in the 60 GHz spectrum band.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication

General Terms

Standardization, Design, Performance

Keywords

60 GHz, beamforming, WLAN, WPAN, 802.11, mmWave, MAC, PHY.

1. INTRODUCTION

In the last decade, wireless local and personal communications have experienced a tremendous growth. These wireless systems typically operate in the 2.4 and 5 GHz spectrum bands, and are based on protocols such as IEEE 802.11 (a.k.a., WiFi) and Bluetooth. Bluetooth is optimized for low data rate, low power applications with speeds up to 3 Mbps [6], while WiFi has been progressively increasing its data rate from 1 Mbps in its early version to 600 Mbps in the latest 802.11n amendment [4].

Recently, however, the widespread popularity of WiFi coupled with the availability of spectrum in the unlicensed millimeter-wave band (60 GHz) are driving WiFi to find new applications in the personal space, including uncompressed video transfer, fast synchronization of large files and wireless docking [13]. Collectively, these new application areas require data rates of at least 4 Gbps as measured in the physical layer (PHY). Hence, to meet these challenges, the IEEE 802.11 working group formed the 802.11ad task group to create an amendment to the 802.11 standard for operation in the 60GHz spectrum band, capable of achieving multi-Gbps data rates.

As described in [12], wireless communication in the 60GHz band experiences signal attenuation up to 20dB higher when compared to communication in the 2.4/5GHz bands. Such high path loss has led to the use of high gain directional antennas at 60 GHz in order to compensate for the large path loss [12]. While directional communication addresses the link budget issue, it also introduces numerous other challenges such as finding the direction of communication with a neighbor, new types of hidden node problem [9][10][12], challenges with 802.11 random access operation [12] and spatial reuse. In addition, depending on the extent directional communication is used, link reliability can be significantly affected by movement of devices and/or objects in the environment.

To address the challenges of operation in 60GHz and support the new wave of usages and applications of WiFi, the IEEE 802.11ad draft standard [4] provides a unified and interoperable MAC/PHY operation across all mmWave implementations, is scalable across different usages and platforms and can be adjusted to meet different power vs. performance tradeoffs. The 802.11ad draft standard supports data rates up to 7 Gbps and defines a highly efficient directional MAC layer with the random access operation optimized for directional communication as well as a new scheduled access mechanism. To deal with the link reliability problem in 60GHz, 802.11ad includes the first-of-its-kind multi-band operation mechanism that allows the fast transfer of a link among different channels across any frequency band. This multi-band mechanism allows applications to operate without any disruption, since it is transparent to upper layers and makes the MAC layer the responsibility to ensure session continuity.

Therefore, in this paper we introduce the MAC and PHY layers of the current IEEE 802.11ad draft standard, with special emphasis on those features that enable multi-Gbps data rates and robust operation in 60GHz. Additionally, we also provide a comprehensive set of performance evaluation results showing that 802.11ad meets the requirements of the new usages envisioned for WiFi, highlight that 802.11ad is the first multi-Gbps extension of 802.11, and argue that 802.11ad is poised to significantly increase the market penetration of WiFi. To the authors' best knowledge, this is the first paper ever that describes and analyzes the 802.11ad draft standard.

The remainder of this paper organized as follows. In Section II we discuss the usages and applications of 60GHz and the existing efforts in 60GHz specification development. In Section III we provide description of the key features of the 802.11ad MAC and PHY layers that enable multi-Gbps rates. The performance evaluation results for selected uses cases are shown in Section IV. Finally, Section V concludes the paper.

2. PRELIMINARIS

The last few years have seen intense activity in the development of 60GHz technologies. In this section we provide an overview of the key usages and applications of 60GHz, and then describe the various standards and special interest groups (SIGs) formed to develop technologies to tackle those usages.

2.1 Usages and applications of 60GHz

Typical environments where 60GHz will be used are varied [13], and include hotspots, living room, airport lounges, conference room, and office cubicle. Usages such as wireless PC display, TV, or projector that demand uncompressed video will require data rates exceeding 1 Gbps. For example, the data rate for uncompressed 1080p with 24 bits/pixel and 60 frames per second is 3 Gbps. Video streams may be distributed simultaneously around the home to different displays requiring the wireless network to be capable of much higher total throughput than any one individual stream. Applications like sync-and-go between handheld devices or downloading movies or pictures from a camera require increasingly higher throughput as the quality increases. With a 1 Gbps wireless link, copying a 30 GB video file will take 4 minutes and a few hundred picture files each 20 Mbytes in size will take one minute. For data networking applications such as file transfer or data backup, wireless technology must keep up with the continued increases in wired capability and most new computers today already come with Gigabit Ethernet.

2.2 Standards and SIGs

The intense commercial interest led to multiple efforts around 60GHz, including WiHD [15], WiGig Alliance [14], and standard development efforts such as ECMA TC48 [16], IEEE 802.15.3c [7] and IEEE 802.11ad [4]. Amongst all efforts, one key advantage of IEEE 802.11ad and WiGig over the other standardization activities in the 60 GHz arena is that it builds on the already existing strong market presence of WiFi in the 2.4/5 GHz bands. Also, since the WiGig Alliance, WiFi Alliance and 802.11ad are actively seeking harmonization [17], this paves the way for a successful and widespread development of 60GHz in the marketplace.

3. The 802.11ad Air Interface

The current 802.11ad draft standard provides a suite of features that can meet the demands of the new usages and applications envisioned for multi-Gbps WiFi, including:

- Support to data transmission rates up to 7 Gbps
- Supplements and extends the 802.11 MAC, supporting both scheduled access and contention-based access
- Enables both the low power and the high performance devices, guaranteeing interoperability and communication at gigabit rates
- Supports beamforming, enabling robust communication at distances beyond 10 meters
- Supports GCMP security and advanced power management
- Supports fast session transfer among 2.4GHz, 5GHz and 60GHz, which is known as multi-band operation

The next subsections provide more in-depth detail of the PHY and MAC layers of the current 802.11ad draft standard.

3.1 The Physical Layer

In this subsection, the PHY parameters and features are summarized. Further details can be found in [4].

3.1.1 Channelization

For better coexistence, the 802.11ad draft [4] has identical channelization with IEEE 802.15.3c [7]. The channel bandwidth is 2160 MHz. Four center frequencies are defined at 58.32, 60.48, 62.64, and 64.8 GHz.

3.1.2 Modulation and Coding Schemes (MCSs)

In the 802.11ad draft standard, three different MCSs are defined: 1) Single Carrier (SC) MCS, 2) OFDM MCS, and 3) Control MCS. A common FEC (forward error correction) is used for all MCSs. Four Low-Density Parity-Check (LDPC) codes are defined, each with a different rate but with a common code rate of 672 bits. The modulation schemes, code rates, and PHY rates of the three MCSs are summarized in Table 1.

Table 1. SC, OFDM, Control MCSs

MCS	Modulation	Code rate	PHY rate
SC MCS	π/2-BPSK π/2-QPSK π/2-16 QAM	1/2, 5/8, 3/4, 13/16	385 Mbps ~ 4620 Mbps
OFDM MCS	Spread QPSK QPSK 16-QAM 64-QAM	1/2, 5/8, 3/4, 13/16	693 Mbps ~ 6756.75 Mbps
Control MCS	π/2-DBPSK	1/2 (spreading factor of 32)	27.5 Mbps

Control MCS is used before setting up a beamformed link between a transmitter and a receiver. The main usages of Control MCS are beacon transmissions and beamforming training. Control MCS is designed to support 15 dB lower SNR sensitivity than the sensitivity point of 1 Gbps data rate. SC MCS symbol (chip) rate is 1760 Msym/sec. OFDM MCS has a FFT size of 512, total 355 subcarriers per an OFDM symbol: 336 data subcarriers, 16 pilot subcarriers, and 3 DC subcarriers. The OFDM sample rate is 2640 MHz and the subcarrier frequency spacing is 5.15625 MHz (=2640 MHz/512). IDFT/DFT period is 0.194 usec and the guard interval duration is 48.4 nsec. The total occupied bandwidth is 1830.5 MHz. All the MCSs are evaluated in [8].

3.1.3 *Common Preamble*

Each PPDU starts with a preamble. Preamble is used for packet detection, AGC, timing/frequency synchronization, channel estimation, and signaling MCSs used for the PSDUs following the preamble. In order to simplify implementation and to have better coexistence, SC and OFDM MCSs share a common preamble. The preamble is composed of two parts: 1) the Short Training field (STF) and 2) Channel Estimation field (CEF). Control MCS uses a longer preamble but a similar design to SC and OFDM MCSs to operate at lower SNR.

3.1.4 *Frame Formats*

SC MCS frame format is shown in Figure 1(a). The SC MCS frame starts with a preamble (STF and CEF) and a PLCP (physical layer control packet) header and the data blocks (BLKs) follow the preamble. For the data blocks, the payload bits are broken into 336, 420, 504, or 545 data bits and encoded into blocks of 672 bits. There are optional AGC and TRN-R/T subfields used for beamforming. Figures 1(b) and 1(c) illustrate the frame formats of OFDM MCSs and Control MCS.

STF	CEF	Header	BLK	BLK	…	BLK	AGC	TRN-R/T

(a) SC MCS frame format

STF	CEF	Header	Sym	Sym	…	Sym	AGC	TRN-R/T

(b) OFDM MCS frame format (Sym=OFDM symbol)

STF	CEF	Header	Data	TRN-R/T

(c) Control MCS frame format

Figure 1. SC, OFDM, and Control MCSs frame formats

3.2 The MAC Layer

At this subsection the MAC parameters and features are summarized. Further details can be found in [4].

3.2.1 *Network Architectures*

The 802.11 defines two types of network architecture known as Infrastructure Basic Service Set (BSS) and Independent BSS (IBSS). The infrastructure BSS is characterized by having a dedicated station, the Access Point (AP) which provides access to the backhaul network to wireless stations (STAs) associated with the AP. The IBSS is designed to support peer-to-peer communication without the need for an AP.

Given the characteristics of important usage scenarios (e.g., absence of AP, all stations in the network can be battery powered, etc.) and the challenges of directional communication in 60GHz [12], the infrastructure BSS and the IBSS are not suited for many usage scenarios in 60GHz.

Therefore, a new network architecture named as the Personal BSS (PBSS) is defined in 802.1ad draft standard. Similar to the IBSS, the PBSS is a type of IEEE 802.11 ad hoc network in which STAs are able to communicate directly with each other not relying on a special device like an AP. As opposed to the IBSS, in the PBSS one STA is required to assume the role of the PBSS central point (PCP). The PCP provides the basic timing for the PBSS as well as allocation of service periods and contention-based periods.

It is important to note that even though 802.11ad introduces the concept of the PBSS, the infrastructure BSS and the IBSS are still supported. This allows, for example, that a multi-Gbps WLAN be deployed in the 60GHz band using the well-known infrastructure BSS architecture with a 60GHz capable AP.

3.2.2 *Medium Access*

Medium is divided in beacon intervals (BI), which have the structure depicted in Figure 2. To support the wide variety of applications and usages envisioned, the MAC supports both random access and scheduled TDMA access. To improve the robustness of TDMA in overlapping network scenarios, TDMA is improved to include a protection mechanism similar to the RTS/CTS frame exchange found in 802.11 CSMA/CA.

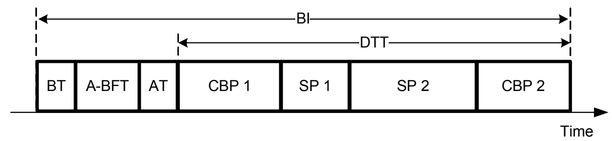

Figure 2. Beacon interval structure

The beacon time (BT) is a time period during which the PCP/AP transmits one or more beacon frames in different directions. In addition to network management information carried in the beacon, the beacon frame is also used to bootstrap the beamforming procedure between the AP/PCP and a receiving station. A station willing to join the network scans for a beacon, continues the beamforming process with the AP/PCP in the A-BFT, and finally associates with the PCP/AP during the AT or CBP.

The association beamforming training time (A-BFT) is a time period to perform initial beamforming training between the station and the AP/PCP. The A-BFT follows the BT to provide continuity to the beamforming process that was bootstrapped through the beacon transmission in the preceding BT. The structure of the A-BFT is slotted, which allows for multiple stations to do beamforming with the PCP/AP concurrently in the same A-BFT.

The announcement time (AT) is a time period to perform management request-response frame exchanges between the PCP/AP and a station. The PCP/AP uses this time to exchange frames with stations, distribute information about contention-based period (CBP) and service period (SP) allocations in the data transfer time (DTT), to name a few.

The DTT is divided into SPs and CBPs that provide transmission opportunities for stations that are part of the network. Any frame exchange can take place during a CBP and a SP, including application data frame transmission. Access during the CBP is based on a modified 802.11 EDCA operation fine-tuned for directional communication, while access during SPs is scheduled and assigned to specific stations. As described in [12], one of the major problems with SP type of TDMA scheduling is robustness when overlapping networks are considered. Therefore, to improve the robustness of transmissions during SPs, the 802.11ad draft standard defines what is called as protected period used during SPs. Basically, a station that owns a SP can protect the SP by transmitting an RTS frame at the start of the SP, which serves to reserve the medium. If a CTS frame is received from the destination of the SP in the response to a transmitted RTS, the SP is considered protected. This has been shown to significantly improve the robustness of TDMA in overlapping network scenarios [11].

3.2.3 *Multi-Band Operation*

One of the major innovations in the 802.11ad draft standard is the introduction of a MAC layer multi-band mechanism that supports fast transfer of a link from one band to another band. This is also known as fast session transfer (FST).

FST enables transition of communication of stations from any band/channel to any other band/channel in which 802.11 is allowed to operate. However, in order to provide a seamless transfer between bands, 802.11ad introduces what is known as transparent FST. In transparent FST, a station uses the same MAC address in both bands/channels involved in the FST. By doing that, there is no impact to the binding that exists between the upper layer (e.g., IP) and the MAC, making the FST completely transparent. In addition, FST supports both simultaneous (radios operating at the same time) and non-simultaneous operation. To further speed-up the FST switching time, several other improvements such as security key establishment prior to FST, multi-band resource allocation, and Block Ack operation over multiple bands are defined in 802.11ad. All in all, FST enables a much more powerful user experience and improved application performance than can be achieved today.

3.3 Beamforming

Beamforming (BF) is the process that is used by a pair of stations to achieve the necessary link budget for subsequent communication. BF training is a bidirectional sequence of BF training frame transmissions that provide the necessary signaling to allow each STA to determine appropriate antenna system settings for both transmission and reception.

Beamforming consists of two phases: sector level sweep (SLS) and an optional beam refinement process (BRP). During sector level sweep devices establish initial (coarse-grain) direction of communication sufficient to communicate at a low PHY rate. The following BRP may be used to fine tune antenna settings to improve quality of directional communication, and hence obtain a multi-Gbps link.

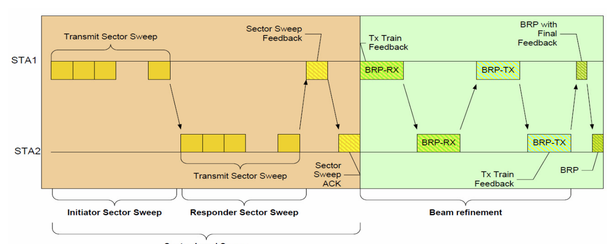

Figure 3. Beamforming protocol example

Figure 3 illustrates an example of the beamforming procedure. In this example, STA1 initiates the beamforming with STA2 by performing a SLS. In the 802.11ad draft, the station that initiates beamforming is known as the Initiator, while the receiving station is known as the responder. At the end of the SLS, both STA1 and STA2 know the best transmit sector for communication with each other. This is used in the following BRP phase, where STA1 and STA2 train their receiving antennas and fine-tune their beams to achieve the desired link budget for the forthcoming data communication.

4. PERFORMANCE EVALUATION

To evaluate performance of the 802.11ad draft standard, a comprehensive 802.11ad simulator was developed using the OPNET simulation environment. Several simulations were performed to investigate if the new MAC and PHY techniques within 802.11ad can support the new usage cases and applications envisioned for 60GHz, and hence enable the next generation multi-Gbps Wi-Fi. Two typical uses cases and one artificial range test were simulated as required in the 802.11ad evaluation methodology document [3], and the following metrics have been studied: 1) Goodput: the average aggregated and per flow goodput measured at the top of the MAC, 2) Delay: the average and per flow delay measured as the difference between the packet arrival at the top of the sending MAC and its reception at the receiving MAC, 3) Number of packets that exceeded the delay requirement for each traffic type, and 4) Packet loss rate. Additional simulation results can be found in [11].

4.1 Simulation Environment

4.1.1 *Range Test*

A range test scenario used to validate link budget parameters [3]. In this text, 802.11ad stations should be able to achieve a throughput of at least 1Gbps at the distance of 10 meters. To achieve that, we have used an uncompressed video application. Application data is sent over 4 scheduled SPs per BI with a length of 3.174ms each. A PHY rate of 2.079Gbps was used for directional data transmission and a PHY rate of 1.386 was used for control and management transmissions.

4.1.2 *Living Room*

This scenario represents a typical living room. A 60GHz capable set to box (STB) is transmitting uncompressed video with a load of 3Gbps to a TV on a wall. No other traffic is present. In the simulation, the video was delivered using 7 scheduled SPs per BI, each SP with duration of 1.923ms. A PHY rate of 4.158Gbps was used for directional data transmission. PHY rates of 2.772 and 1.386 were used for directed ACK and control/management transmission, respectively. More details can be found in [11]

4.1.3 *Conference Room*

This scenario represents conference room with a projector on the table, an AP on the ceiling and users with various devices including laptops and handhelds. Three types of traffic flows are defined: lightly compressed video between two stations with offered load of 600 Mbps, file transfer between five pairs of stations each with offered load of 30 Mbps, and web browsing between the AP and four stations each with offered load of 0.5 Mbps. Video traffic is transmitted using 7 scheduled SPs per BI, each with 0.734us duration. The remaining time is left is allocated for CBP, which resulted in a total of 7 CBP intervals each of 1.394ms duration. A PHY rate of 4.158Gbps was used for directional data transmission. A PHY rate of 2.772 and 1.386 was used for directed ACK and control/management frames, respectively.

4.2 Simulation Results

4.2.1 Living Room

The simulation results for the living room are shown in Figure 4, and show an average goodput of 3Gbps, an average delay of 74us, and a maximum delay is 6.4ms. There were no packet losses during the simulation.

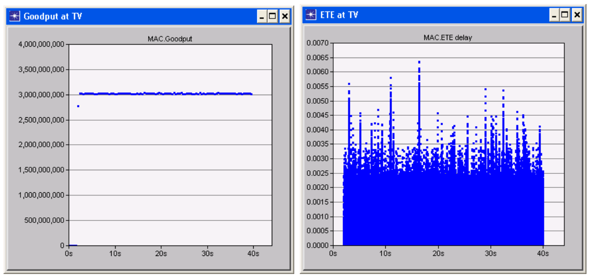

Figure 4. Living room simulation results

4.2.2 Conference Room

Table 2 presents the results obtained for the conference room environment. The achieved aggregated goodput is 0.754Gbps. The packet loss rate was zero for all data links and all frames met the QoS requirement of the video application.

Table 2. Simulation results for conference room

Flow information	Goodput (Mbps)	Average delay (ms)	Max delay (ms)
STA2->STA1	600.8	0.7835	2.916
AP ->STA2	29.9	0.3325	2.821
STA3->STA5	30.3	0.4469	4.286
STA7->STA8	30.1	0.4448	3.360
AP ->STA7	29.1	0.3410	3.050
STA4->AP	30.1	0.4415	2.625
AP ->STA3	0.30	0.2465	2.017
AP ->STA4	0.83	0.2890	4.935
AP ->STA5	0.46	0.2379	1.381
AP ->STA6	0.37	0.3296	1.401

4.2.3 Range Test

Figure 5 shows the results obtained from the range test. As can be seen, an average goodput of 1.612Gbps at 10 meters can be achieved primarily due to the use of beamforming.

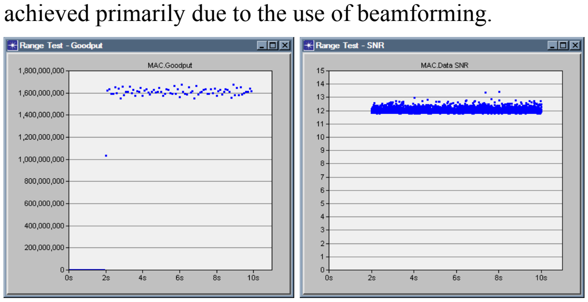

Figure 5. Range test results

5. CONCLUSION

The next few years will experience a significant growth in the availability of commercial wireless technologies capable of multi-Gbps data rates. Amongst all of the current efforts, the 802.11ad standard stands out as the leading technology in the 60GHz space since it leverages WiFi's existing presence in the marketplace. In this paper we provided an overview of the MAC and PHY layers of the current IEEE 802.11ad draft standard, and presented a comprehensive set of performance results showing that 802.11ad can meet the requirements of the various usage cases that demand multi-Gbps wireless.

6. REFERENCES

[1] S. Yong, C. Chong, "An Overview of Multigigabit Wireless Through Millimeter Wave Technology: Potentials and Technical Challenges", EURASIP Journal on Wireless Comm. and Networking, vol. 2007.

[2] S. K. Moore, "Cheap chips for next wireless frontier," *IEEE Spectrum*, vol. 43, 2006.

[3] Eldad Perahia, "TGad Evaluation Methodology", IEEE 802.1108/0296r16.

[4] IEEE 802.11 working group for wireless LANs, http://www.ieee802.org/11/.

[5] M. Park, C. Cordeiro, E. Perahia, and L. Yang , Millimeter-Wave Multi-Gigabit WLAN: Challenges and Feasibility, PIMRC 2008.

[6] Bluetooth specifications, http://www.bluetooth.org.

[7] IEEE 802.15.3c, MAC and PHY Specifications for High Rate Wireless PANs, IEEE Std 802.15.3c-2009, Oct. 2009.

[8] C. Hansen et. al. "PHY simulation results and methodology," IEEE 802.11-10/431r3.

[9] R. Choudhury et al, "Using Directional Antennas for Medium Access Control in Ad Hoc Networks," in *ACM Mobicom*, Sep. 2002.

[10] T. Korakis et al, "A MAC protocol for full exploitation of Directional Antennas in Ad-hoc Wireless Networks," in *ACM Mobihoc*, June 2003.

[11] C. Cordeiro et al. "MAC simulation results and methodology," IEEE 802.11-10/435r0.

[12] C. Cordeiro, "Evaluation of Medium Access Technologies for Next Generation Millimeter-Wave WLAN and WPAN," in ICC 2009.

[13] Myles, Andrew and de Vegt, Rolf, "Wi-Fi (WFA) VHT Study Group Usage Models", IEEE 802.11-07/2988r4.

[14] Wireless Gigabit Alliance (WiGig), http://wirelessgigabitalliance.org/.

[15] WirelessHD, http://www.wirelesshd.org/.

[16] http://www.ecma-international.org/memento/TC48-M.htm.

[17] http://www.engadget.com/2010/05/10/wi-fi-alliance-and-wigig-sync-up-for-60ghz-wifi/.