IEEE 802.11ad: Defining the Next Generation Multi-Gbps Wi-Fi

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***Abstract* — IEEE 802.11ad will take advantage of the large swath of available spectrum in the 60 GHz band to develop a protocol to enable throughput intensive applications such as wireless display and high speed sync-and-go file transfer. Functional requirements, evaluation methodology, and channel models are currently being developed by the task group in preparation for a call for proposals. Likely enhancements to 802.11 beyond a new 60 GHz PHY include Personal Basic Service Set, MAC modifications for directional antennas, fast session transfer between PHYs, beamforming, and spatial reuse. Therefore in this paper we give an overview of IEEE 802.11ad, which is poised to define the next generation multi-Gbps Wi-Fi.**

Keywords: 60 GHz, IEEE 802.11, IEEE 802.11ad, beamforming, VHT, Wi-Fi, MAC, spatial reuse, BSS

I. INTRODUCTION

The large swath of available spectrum in the unlicensed 57-66 GHz band (60 GHz band in short) represents one of the largest unlicensed bands being allocated and harmonized around the world. This directly translates into the potential to achieve multi-Gbps wireless communication performance. Recent advances of using SiGe and CMOS to build inexpensive 60 GHz transceiver components has created intense commercial interest to productize and standardize 60 GHz radio technology for bandwidth demanding mass market wireless applications.

High end consumer electronic industry is among the first embracing this technology for HDMI cable replacement. A very thin HDTV that can be hung on the wall without a trailing cable has huge aesthetic appeal to the consumers. Only 60 GHz can provide the bandwidth needed for uncompressed HDTV content streaming from the set top box to the TV (3Gbps for 1080p). PC and Handheld industries are also interested in the potential of using 60 GHz for usages such as sync-and-go, wireless docking, etc.

Such intense commercial interest led to multiple industrial efforts including WiHD [1], WiGig [2], and standard development efforts including ECMA TC48 [3], IEEE 802.15.3c [4] and IEEE 802.11ad [5]. WiHD is the first industrial consortium developing a specification to transmit uncompressed HDMI signal over 60 GHz radio link. The specification has been designed and optimized for HDMI cable replacement. WiGig is an industrial SIG (Special Interest Groups) with the objective of developing a unified 60 GHz specification that has the flexibility to support a broader range of applications including but not limited to uncompressed HDMI cable replacement.

ECMA TC48, IEEE 802.15.3c and IEEE 802.11ad are 3 separate standard efforts; each being influenced heavily by its technical heritage in the respective standard body. ECMA TC48 is developing a 60 GHz PHY and MAC standard to provide high rate WPAN transport. The MAC in ECMA is rooted in WiMedia UWB MAC with necessary changes to accommodate the characteristics of 60 GHz. The IEEE 802.15.3c Task Group is developing a millimeter-wave-based alternative PHY to work with the existing 802.15.3 WPAN MAC Standard 802.15.3-2003. IEEE 802.11ad is another installment of the successful 802.11 (a.k.a. Wi-Fi) family and so it will maintain its affinity with 802.11 in many aspects. One key advantage of IEEE 802.11ad over the other standardization activities in the 60 GHz arena is that it builds on the already existing strong market presence of Wi-Fi in the 2.4/5 GHz bands.

Therefore, this paper is devoted to provide a detailed overview of the charter, activities and status of IEEE 802.11ad, and how this group promises to enable the next generation multi-Gbps Wi-Fi.

II. STANDARDS PROCESS REVIEW

As described in [6], in the 802.11 working group there are five steps in developing an amendment to the standard. These are 1) discussion of new ideas in the Wireless Next Generation Standing Committee, 2) development of the purpose and scope for the amendment in a study group, 3) drafting of an amendment in a task group, 4) approval of the draft by the working group, and 5) review by a sponsor ballot pool and approval and ratification of the draft by the IEEE Standards Association board.

In step 3, a task group typically starts by identifying functional requirements and a selection procedure for choosing proposals. The task group develops the first draft, which is sent to the entire working group for a letter ballot vote for approval. As part of the vote, the working group members may submit comments identifying deficiencies with the draft. Typically there are many rounds of letter ballot votes until the work group believes the draft is ready to proceed to step 4. According to the Project Authorization Request (PAR) [8], the group expects this to occur in December 2011.

The sponsor ballot pool consists of members from beyond 802.11. This process provides a broad review of the draft. Similar to letter ballot, sponsor ballot members may submit comments as part of their vote. The expected completion date of sponsor ballot is December 2012 [8].

The 60 GHz activity in 802.11 is currently in step 3. As will be described in the following sections, the Very High Throughput Study Group (VHT SG) completed its primary activity of drafting a PAR, which contains the purpose and scope statements, in November 2008. In January 2009, Task

Group AD (TGad) began the process of developing a 60 GHz amendment to 802.11.

III. Very High Throughput Study Group

The VHT SG began in May 2007. Initial presentations highlighted the benefits of advanced technology in microwave bands. However, to address single link data rates in the giga-bit per second range, the group began investigating opportunities in the 60 GHz ISM band [7]. This led to the development of a 60 GHz PAR [8].

The 60 GHz PAR outlined the scope of PHY and MAC modifications to the 802.11 standard. The primary requirement is that the amendment must enable a *throughput* of at least 1 Gbps at the top of the MAC. The use of the term throughput dictates that MAC efficiency must be addressed, not just an improvement to the PHY data rate.

As described in Section I, several other organizations are also defining specifications for 60 GHz operation, particularly IEEE 802.15.3c. Two requirements in the PAR address distinct identity from other groups. The first is maintaining the 802.11 user experience. This means maintaining the network architecture of the 802.11 system, e.g. infrastructure basic service set, extended service set, access point, station. This also implies reusing and maintaining backward compatibility to the 802.11 management plane, e.g. association, authentication, security, measurement, capability exchange, management information base (MIB). The other requirement addressing distinct identity is fast session transfer between PHY's. A fast session transfer mechanism could provide seamless rate fall back between VHT and 802.11n for multi-band devices. Consumers will be provided their expected WLAN coverage from combo 60 GHz and 2.4 / 5 GHz devices.

A great deal of discussion took place in VHT SG regarding coexistence with various other systems in the 60 GHz band. As such, the 60 GHz PAR has a requirement that the system will provide mechanisms that enable coexistence with other systems.

In a parallel effort in VHT SG, usage models were discussed in order to set the framework for the type of applications that may be targeted by this next generation technology. The Wi-Fi Alliance presented a collection of usage models requiring higher throughput than available by current technology [10]. These included wireless display, in home distribution of HDTV and other content, rapid upload and download of large files to/from a server, backhaul traffic, campus / auditorium deployments, and manufacturing floor automation. The WFA report did not specify which band of operation would be better suited to which usage model. There was some discussion in the study group to identify which of the WFA usage models would be more suited to <6 GHz versus 60 GHz [11]. Short distance, single link applications requiring high data rates like uncompressed video and desktop storage and display were associated solely with 60 GHz. However, other applications like lightly compressed video streaming around a home were mapped to <6 GHz.

IV. Current Task Group Activity

TGad began in January 2009. The initial plans were highlighted to be the development of the following task group documents: selection procedure, functional requirements, evaluation methodology, and channel models. An initial proposal for a selection procedure in [12] describes a "call for complete proposals" procedure. A proposal is considered complete if it addresses all the functional requirements and evaluation methodology requirements. In [12], the expectation is that the task group documents will be complete by January 2010 and presentation of complete proposals will occur in May 2010.

A. Functional Requirements

The approved initial draft of the TGad Function Requirement document is [13]. Most of the requirements mirror those in the PAR; however there are three additional requirements. First, all devices are required to support a maximum PHY rate of at least 1 Gbps. Second, the amendment must provide a means of achieving 1 Gbps throughput at a range of at least 10m in some NLOS conditions. This mostly means that transmit beamforming scheme will be included as part of TGad. The third additional requirement is actually a set of requirements to support uncompressed video. The ability to support uncompressed video is a major differentiating feature from 2.4 / 5 GHz 802.11 systems. A rate of 3 Gbps throughput with a packet loss rate of 1e-8 and a maximum delay of 10 msec must be supported. The basis of these requirements is uncompressed 1080p video.

B. Evaluation Methodology

The TGad Evaluation Methodology document defines conditions for functional requirements compliance (with a simple synthetic point-to-point test case), PHY performance (PER vs. SNR curves using a 60 GHz channel and hardware impairments), and a limited set of simulation scenarios and comparison criteria for evaluating proposals [14]. While much work has gone into developing [14], the task group has yet to approve an initial draft.

For 802.11n, the task group defined a large set of simulation scenarios, of which only a very small number were ever used to compare proposals. Learning from this, the current version of the TGad Evaluation Methodology document only defines three simulation scenarios addressing the most likely markets. These scenarios are home living room, office conference room, and enterprise cubicle. In the home living room, the usage scenario is a set top box transmitting uncompressed video to the TV.

The office conference room consists of six laptops, a projector, a hand held device, and an access point. This scenario includes a range of applications. First, a laptop is transmitting lightly compressed video to the projector. Second, multiple laptops are performing local file transfer from the AP or between the laptops. Third, multiple laptops are performing web browsing via the AP. The last application includes a laptop engaged in sync-and-go with the handheld device.

The enterprise cubicle scenario defines a cubicle layout with each cubicle containing a laptop simultaneously transmitting lightly compressed video to a monitor, connected to an AP, and wirelessly connected to a hard drive. Multiple cubicles will be simulated to model interference between cubicles, especially when there are not enough free channels to avoid overlap.

In order to simulate these scenarios, traffic models are required. Uncompressed video is assumed to be 3 Gbps constant bit rate traffic. A traffic model for lightly compressed video was proposed in [15] based on modeling of a much smaller slice as opposed to an entire video frame. Local file transfer is modeled by TCP. Web browsing and hard disk file transfer have yet to be defined.

C. Channel Model

A large effort has gone into developing 60 GHz channel models for TGad. The current version is fairly developed with respect to the conference room model and is contained in [16], but models for the home living room and enterprise cubicle are still under development. When complete, the channel models will comprise of both channel impulse response and path loss models for all three simulation scenarios.

Four key requirements were followed in the development of the channel model. The first requirement is to provide accurate space-time characteristics of the propagation channel. Experiments were used to measure the properties of the clusters of rays in addition to the properties within each cluster, following the Saleh and Valenzuela model [17], and compared to ray tracing techniques. Good alignment was found between the two allowing the channel models to be based on a combination of measurements and ray-tracing. The channel model enables generating a channel realization that includes space, time, amplitude, phase, and polarization characteristics of all rays comprising the particular channel realization [16].

Since beamforming will be necessary to achieve the range specified in the functional requirements, the second requirement is that the channel model must support beamforming with steerable directional antennas at both the transmitter and receiver. The third requirement is to account for the polarization characteristics of the antennas. It was demonstrated in [18] that the impact of polarization in 60 GHz is substantial, even on reflected signals. The last requirement for the channel model is to support non-stationary characteristics of the environment arising from motion of people. In 60 GHz, the attenuation of a signal due to a human body is significant, generally more than 20 dB [19].

An implementation of the 60 GHz WLAN channel model has been made publically available. The current version of Matlab® code for the TGad channel model is contained in [20].

V. EXPECTED TECHNOLOGY ENHANCEMENT TO 802.11

In order to support the challenging new usages and operate in the 60 GHz spectrum, TGad and the existing 802.11 standard (including amendments) is faced with a number of significant technical hurdles such as channel propagation, beamforming, channel access, fast session transfer between the 60 GHz band PHY and the 2.4/5 GHz band PHY, to name a few. In this section we describe some of the challenges presented in TGad through several submissions, and discuss what is considered to be some of the major and likely enhancements to 802.11 that TGad will have to make.

A. Beamforming

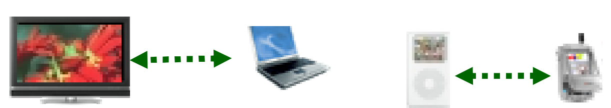
Beamforming is a strong candidate to compensate for the additional 20 dB free space propagation loss in the 60 GHz band. Beamforming utilizes multiple antenna elements to form a beam toward a certain direction with increased signal strength. This beamforming gain is achieved by transmitting phase shifted signals from multiple antenna elements. The signals are phase shifted so that the signals are added up coherently at the target location [25]. The peak beamforming gain (G_b) increases as the number of antenna (N_a) increases (i.e. G_b [dB] = $10\log_{10}N_a$). For example, 16 elements antenna array can provide approximately 12 dB of peak beamforming gain. If used at both the transmitter and the receiver, the additional 20 dB loss can be easily compensated.

Compared to 2.4 GHz and 5 GHz bands, beamforming is well suited for millimeter-wave communications in 60 GHz band since many antenna elements can be packed in a very small area. For example, a square antenna array with 16 antenna elements (4x4 configuration) can be packed in 1 cm^2 when adjacent antenna elements are separated by half wavelength. This is a very critical aspect when considering small form factor devices.

B. The Personal Basic Service Set (PBSS)

The most popular commercial use of 802.11 has unquestionably been for access to a backhaul network (e.g., Internet and/or Intranet) in the enterprise, hotspots, home and office. This usage is characterized by having a special station, the Access Point (AP), which provides access to the backhaul to wireless stations (STAs) that are associated with the AP. In 802.11 terms, this type of network architecture in which STAs always communicate with one AP is called a Basic Service Set (BSS).

Many of the usages TGad is addressing [10], however, have characteristics different than those exhibited in a BSS. As an example, Figure 1 illustrates two of the top usages, ranked based on anticipated market volume [10], which TGad is required to support. The first aspect to note in these usages is that they are peer-to-peer (i.e., ad-hoc) in nature and no single device is dedicated for a particular function, as it is the case with an AP. Secondly, all devices in the network operate as either creating content or consuming content. In an AP-based BSS, however, the AP does not create or consume any content but simply relays traffic across the network. Thirdly while power consumption is not a concern for an AP, in several TGad usages, such as the one shown in Figure 1(b), all devices in the network are battery powered which makes power conservation critical.



(a) – Projection to TV (also known as wireless display)   (b) – Sync-and-go file transfer

Figure 1 – Top usages as per the WFA [10]

Since the BSS does not fit many target usages of TGad, the next option is the Independent BSS (IBSS) architecture defined in 802.11. The IBSS allows peer-to-peer communication without the need for an AP, and hence could be suited to support TGad's key usages. However as described in V.A, the fact that channel access in 60 GHz is based on directional transmissions and "true" (i.e., as in 2.4/5 GHz) omni-directional transmission cannot be practically accomplished [21], it makes the IBSS inappropriate for use in 60 GHz. In the IBSS any STA is allowed to send Beacons and a STA defers its Beacon transmission upon reception of another STA's Beacon frame. However, since true omni-directional transmission is not practically feasible in 60 GHz, preemption of a STA's Beacon transmission on the basis of the detection of another's STA Beacon can no longer be guaranteed.

Based on this, a new network architecture named as the Personal BSS (PBSS) has been proposed to TGad [22]. The PBSS is similar to an IBSS in the sense that it does not rely on special device like an AP and the network functions as an ad-hoc, peer-to-peer architecture. However, in order to deal with challenges in channel access in 60 GHz (see V.C), improved power saving, QoS support, spectrum management, to name a few, a PBSS defines one STA in the network as being the PBSS Central Point (PCP). As shown in the example of Figure 2, differently from the IBSS where any STA can transmit a Beacon, in the PBSS only the PCP can transmit Beacons. Centralizing this function at the PCP allows the directional channel access problem to be considerably more manageable, since STAs know when and from whom to expect the Beacons and hence can direct their antennas to the appropriate direction at the right time. Furthermore having a PCP can also facilitate QoS support and power management, since these functions can be handled at the PCP level. In the IBSS, on the other hand, accomplishing these would be a challenge due to its fully distributed nature.

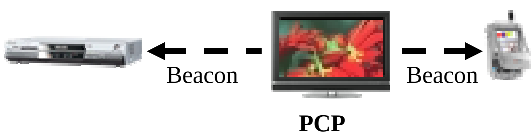


Figure 2 – PBSS with a PCP: only the PCP transmits Beacon frames

C. *MAC channel access*

There are significant technical issues for operation in 60 GHz. For example, the signal propagation characteristics impose more challenges in terms of link budget than those at lower frequencies (e.g., 2.4 GHz and 5 GHz bands). Due primarily to its high frequency and hence short wavelength, the signal attenuation in 60 GHz can be as much as 20 dB higher than in the 5 GHz band. 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 [24]. To enable STAs to talk to each other in such directional communication environment, a beamforming protocol needs to be defined which introduces another level of design challenge to the channel access mechanism.

On top of the technical challenges, the requirements of the usages TGad is set out to support are extremely varied in nature [10]. Applications such as wireless display have very stringent requirements in terms of QoS guarantees and are very sensitive to delay and jitter. On the other hand, applications such as web browsing are very sensitive to access latency (i.e., response time), but are less impacted by jitter and may not require bandwidth guarantees.

The unique propagation challenges in 60 GHz combined with the diverse set of requirements originating from the envisioned usages and applications, creates a considerable challenge for the MAC design. Current 802.11 MAC in 2.4/5 GHz is based on CSMA/CA access and is built upon three main thrusts: i) omni-directional reception capability; ii) omni-directional transmission capability; iii) and random backoff due to collisions. As discussed in [24], omni communication in 60 GHz is not only extremely inefficient, but also it is not practically possible to realize a true omni-directional antenna pattern in 60 GHz. Moreover, the fact that STAs are capable of dynamically changing the antenna pattern towards different directions, introduces synchronization problems which violates some of the most basic CSMA/CA assumptions.

As a result, a MAC design has been proposed to TGad that is not solely based on CSMA/CA [23]. It is proposed that the 802.11 MAC be extended to allow scheduled access, which would allow a STA to know beforehand the periods of time when it is expected to be awake and towards which other STA it should point its antenna pattern. With this, it is argued that improved power management, QoS provisioning and better support to directional communication can be achieved. As for CSMA/CA support, in [23] it is proposed that CSMA/CA periods be scheduled as part of the scheduled access period. Figure 3 illustrates how the 802.11 beacon interval would look like based on the proposal in [23].

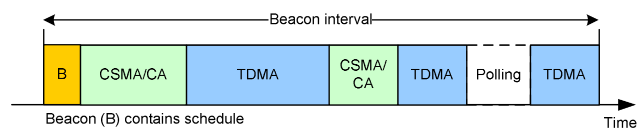


Figure 3 – Possible enhancement to 802.11 MAC [23]

As we can see, the 802.11 beacon interval would comprise of TDMA and CSMA/CA that are allocated by the PCP on an as-needed basis. For example, if the application to be supported is video then TDMA may be the appropriate choice due to its better QoS support and efficiency. On the other hand if a bursty-type of application such as web browsing is the target, CSMA/CA is probably a more desirable solution since it can provide lower average latency than TDMA. Polling is suggested in [23] to be used on top of the CSMA/CA and TDMA access periods. It has been shown that polling can be an efficient and effective way to deal with dynamic (re-)allocation of channel time that is scheduled but unused. This happens, for example, with wireless display applications that use compression. In addition, polling may also provide higher priority medium access during CSMA/CA periods.

D. *Spatial reuse*

Although communicating over 60 GHz channels is challenging and requires a directional antenna with very high gain, this brings a new opportunity for spatial reuse amongst adjacent links in a dense office environment. This is because as the gain of antenna increases, the beamwidth of the antenna decreases and thus more interference to and from neighboring links can be mitigated. In [26], spatial reuse gain has been modeled for an office environment with 9 cubes (3x3 configuration). In each cube, two stations are placed randomly and each station is equipped with a 16 element square antenna array. The simulation results show that directional communication with beamforming provides approximately five times higher spatial reuse gain over omni-directional communication, when measured in terms of the number of simultaneous active links. This example clearly shows that spatial reuse gain in a dense networking environment is significant and needs to be exploited for important TGad usages [10].

Many simultaneous links, however, may also lead to increased interference if not designed carefully. This is clearly shown in [26] with an example where two PBSSs are operating simultaneously but interfering with each other due to their overlapping schedules. The example shows that if the stations can detect interference from neighboring PBSS and the measured interference is utilized for rescheduling transmissions, the packet drop rate decreases significantly and thus can improve the network performance substantially.

VI. Conclusions

The Wi-Fi community has begun addressing new peer-to-peer usages requiring very high data rate links. Modifications to the 802.11 MAC in the form of a Personal BSS are necessary to optimize for peer-to-peer communications to allow one station to act as a center point for management and control of the BSS. To meet the throughput needs of usages like high speed sync-and-go requires large swaths of bandwidth available at 60 GHz. The antenna patterns in 60 GHz are directional by nature. Further MAC modifications are required to address the directional nature of the medium in which the 802.11 beacon interval is compromised of both TDMA and CSMA/CA periods, also allowing the interval to be better tailored to the QoS requirements of the traffic.

To overcome the large free space propagation loss in 60 GHz, beamforming will be used to increase the signal strength in a certain direction. Beamforming with large number of antenna elements is possible due to the small wavelength. The use of a directional antenna enables neighboring links that would have been interferers with omni-directional transmission to operate simultaneously. Simulations have shown that spatial reuse enables five times as many simultaneous links.

The IEEE 802.11ad task group is in the early stage of development of a very high throughput amendment to 802.11. Currently the task group is laying the ground work by developing the Functional Requirements, Evaluation Methodology, and Channel Model documents. When these are complete, the next step in the process will be to issue a call for proposals that will include new technological advancements for 60 GHz as described here in. Following this in the next few years will be the typical 802.11 process of letter ballot and sponsor ballot phases.

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