Millimeter-Wave Multi-Gigabit WLAN: Challenges and Feasibility

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Abstract — **The wide harmonized spectrum in the unlicensed 60 GHz band has been considered for WPAN standardizations. Recently there is also growing interest in the industry to use the same band for multi-Gigabit WLAN usages and standardization. In this paper, we describe the unique challenges and analyze the feasibility of realizing a multi-Gigabit WLAN in this band. We present analysis and simulation findings on the transmission range and spatial reuse opportunity with beamforming. We also explore options for range extension and multi-band integration.**

Keywords: mmWave, 60GHz, WLAN

I. INTRODUCTION

In the last decade, 802.11 based Wireless Local Area Networks (WLAN) technologies (also known as Wi-Fi) has enjoyed tremendous market adoption around the world, bringing the convenience of broadband wireless access to millions of users in the home, office and hot spots. Within a short decade, the data rate of 802.11 family products have evolved at an amazing pace, from 1 Mb/s with the first generation of 802.11 products, to 11 Mb/s with 11b, to 54 Mb/s with 11a/g, to up to 600 Mb/s with 11n MIMO products. The next challenge going forward is to achieve multi-Gigabit data rate. The IEEE 802.11 working group recently began a new "Very High Throughput" study group (VHT SG) to investigate technologies beyond 802.11n capabilities. It becomes clear that the physical layer link throughput achievable in the 2.4 and 5 GHz bands would be limited by the available bandwidth in these bands; and coexistence concerns with the legacy Wi-Fi products that are already deployed in those bands make it difficult to apply very wide channel in order to achieve data rate beyond Gbps. On the other hand, the abundance of bandwidth in the unlicensed 60 GHz band (also known as millimeter-wave or mmWave band, specifically 57-64 GHz in the US, 59-66 GHz in Europe and Japan) makes it feasible to achieve multi-Gigabit link throughput. Therefore, the VHT SG has been exploring possible solutions for both microwave band (under 6 GHz) and mmWave band (60 GHz) as the next generation WLAN technologies.

There has been much standardization work done recently using 60 GHz bands to achieve multi-Gigabit rate for Wireless Personal Area Network (WPAN) applications (e.g., ECMA TC48, IEEE 802.15.3c) which typically require only short range (e.g., a few meters) within one room [1][2]. To our knowledge, there has been much less work done in 60 GHz specifically targeted for WLAN applications. One related prior work is the European Information Society Technologies (IST) Broadway project [3] which developed key components of a hybrid dual frequency system based on HIPERLAN/2 at 5 GHz and a fully ad-hoc extension at 60 GHz. While IST-Broadway project targeted specifically for WLAN applications, it was developed based on HIPERLAN/2 instead of 802.11 and it limited its channel in 60 GHz band to no more than 240 MHz and hence the max data rate was only 720 Mb/s. It was assumed that in 60 GHz band only AP (Access Point) uses directional antenna and all stations use omni-directional antenna. We believe it is feasible for stations to employ directional antenna which can provide significant antenna gain to improve the range and/or data rate, and also allows significant spatial reuse benefit between overlapping networks. This is an important distinction as it affects the design substantively in both the physical and MAC layer. On the other hand, we believe IST-Broadway project did explore a couple of important concepts that can be incorporated to realize 802.11 based multi-Gigabit WLAN solution. For example, its dual band RF integration supported seamless switching between 5 GHz and 60 GHz bands, and enabled fallback to 5 GHz band when the 60 GHz link is broken. The ad hoc extension of all the 60 GHz devices formed a separate network to alleviate congestion in 5 GHz band and hence increased overall network capacity. Our paper will explore these concepts further within the general framework of 802.11 and with the assumption of all devices may be capable of directional communication.

While many of the challenges in realizing multi-Gigabit WLAN are similar to those found in WPAN applications, there are also unique challenges for WLAN which will be the focus of this paper. In Section II, we will discuss the usage models and requirements for WLAN, and the associated challenges in PHY and MAC design by employing 60 GHz radio. In Section III, we will analyze the feasibility of using 60 GHz technology for WLAN, presenting analysis and simulation results on the transmission range, the spatial reuse opportunity in dense environment such as offices, various range extension techniques, and multi-band integration options. Section IV will highlight the future work as we see it and conclude the paper.

II. 60GHZ USAGE MODELS AND CHALLENGES

In this section, we will first describe the usage models and requirements for a 60 GHz WLAN and the challenges associated in the physical layer and MAC layer design.

A. *Usage Models and Requirements for WLAN*

IEEE 802.11 VHT SG solicited usage models from the Wi-Fi Alliance (WFA). The WFA produced six categories of usage

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models: 1) wireless display, 2) in home distribution of video, 3) rapid upload and download to and from a remote server, 4) mesh or point-to-point backhaul traffic, 5) campus or auditorium deployments, and 6) manufacturing floor automation [4]. Within each of the six categories many detailed usage models were developed. These usage models cover a range of environments, including the home, office or enterprise, outdoor or hotspot, campus, and a factory floor. Home usages include short range and line-of-sight (LOS) (e.g. on a desk), medium range and mostly LOS (e.g. in a room), and long range and most likely non-line-of-sight (NLOS) (e.g. entire home). Similarly in the enterprise the coverage on a desk or in a cube would be short range and a conference room would be medium range. Dense enterprise deployments designed for higher capacity may be shorter range than the typical home environment.

Desktop display, TV, or projector requiring uncompressed video will require data rates exceeding 1 Gbps. For example, the data rate for uncompressed 1080p with 24 bits/pixel and 60 fps is 3 Gbps. Video distribution throughout the home will typically consist of lightly compressed video which is expected to be around 150 Mbps. 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.

Usages like rapid sync-and-go or downloading movies or pictures from a camera require increasingly higher throughput as the quality and resolution increases. In the future 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 Giga-bit Ethernet.

B. Challenges

B.1 Physical layer

The biggest challenge for 60 GHz is to cover the range for WLAN to which consumers have become accustomed. In some environments, such as construction with cement, it may not be possible to achieve typical WLAN coverage. However, in many WLAN environments, such as construction with drywall or fabric cubicle walls, the higher propagation loss of millimeter wave may be mitigated by high gain antennas, high transmit power, and a sensitive receiver.

Due to the small wavelength at 60 GHz, it is possible to fit many antenna elements on a small platform to create high gain antenna array. An antenna array with more than 20 elements achieving a gain more than 13 dBi is feasible. With an antenna array at both the transmitter and receiver would result in over 25 dB link budget gain.

Developing a system dependent on the gain from the antenna array will require careful consideration of the antenna design. The antenna array must provide 360 degree azimuth and 180 degree elevation for coverage in a dynamic WLAN environment. This is necessary for arbitrary pointing angles between the transmitter and receiver and also to track multipath reflections for possible coverage in NLOS. Integration of the antenna array into the device must avoid human and platform obstruction that would degrade the antenna pattern. Coupling between the antenna elements must be minimized. The antenna design must also avoid large lobes in undesired directions. In order to generate the desired antenna patterns, it may be necessary to calibrate the antenna array.

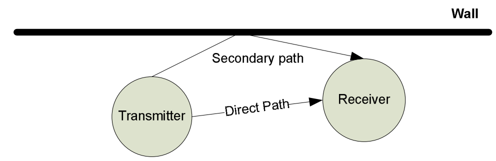

Fig.1 Multipath MAC for link robustness

B.2 MAC layer

Several MAC schemes have been proposed for the use of directional antennas in contention-based access networks such as IEEE 802.11 operating in the 2.4/5 GHz bands [5][6][7]. The major challenges addressed in these studies have focused on the well-known problems of device discovery, hidden node and deafness problems, and on achieving spatial reuse. When operating in 60 GHz, these challenges still apply but in different shape and form given that some of the assumptions at the antenna and RF level are substantially different. We do not focus on these challenges in this paper, but rather study a few other MAC challenges that are unique to multi-Gbps WLAN operating in 60 GHz.

A key challenge that must be addressed in 60 GHz is link robustness. Due to high attenuation through obstructions, the link in 60 GHz is much more susceptible to breakage than another one at 2.4/5 GHz. In addition, the use of directional antenna makes a link very sensitive to moving object or people, device mobility or just slight rotation. Hence, it is of paramount importance to design a MAC protocol that can deal with link breakages in an efficient manner. A possible solution to this problem is to design a multipath MAC, wherein a joint PHY/MAC effort can be made so that the transmitter can keep more than one path to its intended receiver(s) as shown in Fig.1. This multipath feature is possible at mmWave frequencies as a result of the radio's beamforming capabilities.

Another MAC challenge in 60 GHz is that it must support a high number of directions as compared to the number of associated devices. Most, or all, of the proposed directional MAC protocols for 2.4/5 GHz have focused on the support of at most 8 independent directions at each device. However, current mmWave standardization efforts require support for at least 32 (and in some cases 64) independent directions so that higher antenna gain can be obtained. The support of such high number of directions introduces significant challenges to the MAC, and possibly the most important of them all is the use of omni-directional transmissions for broadcast and multicast communication becomes extremely expensive given that the data rate must drop roughly proportional to the number of supported directions. Hence, the MAC design needs to minimize the use of low rate omni-directional transmissions

TABLE I

WLAN PARAMETERS FOR 5GHZ AND 60GHZ

	5GHz	60GHz
Number of antennas	4	36
Maximum EIRP (FCC)	30dBm + 6dBi (antenna gain)	40dBm
Transmit power/antenna (P_t)	24dBm	4dBm
Transmit beamforming gain (G_t)	0	15dB
Power combining gain (G_c)	0	15dB
Receive beamforming gain (G_r)	0	15dB
Modulation coding scheme	64QAM 5/6	BPSK 3/4
Minimum E_b/N_0 @ 10e-5	19dB	10dB
Aperture loss @ 1m	-48dB	-68dB
Penetration loss/drywall (L_w)	4.7dB[12]	8.8dB[13]
Penetration loss/person (L_p)	5dB[15]	14.5dB[14]

and to fully exploit high-rate directional communication not only for data, but also for control and management functions. Another key challenge is the support of an efficient contention-based random access mechanism. Random access is the basic principle for IEEE 802.11 MAC. Hence, when considering the feasibility of mmWave for WLAN applications, we also need to take into account how random access can be adapted to this new band of operation. While there are a plethora of issues to consider within the random access umbrella for mmWave, here we discuss an example concerning the slot time. In a contention-based access mechanism such as IEEE 802.11, the slot time is typically defined as:

SlotTime =aCCATime + aRxTxTurnaroundTime + aAirPropagationTime + aMACProcessingDelay

where aCCATime is the time required to perform clear channel assessment; aRxTxTurnaroundTime is the time required for Tx/Rx turnaround; aAirPropagationTime is the propagation time and aMACProcessingDelay is the MAC processing delay. For random access to be efficient, the slot time needs to be smaller than the frame transmission time. In 2.4/5 GHz, this is the case since the slot time is either 9 or 20 µsec and the frame sizes are in the order of milliseconds. However, in mmWave it is significantly more challenging since the frame transmission times are as small as a few microseconds due to the very high data rate. On the other hand, aCCATime will be much longer since a device may have to sweep around in all directions to perform carrier sense. Hence, the slot time (15-30µsec in some estimates) in 60 GHz will end up being larger than the frame transmission time. Therefore, the performance of existing random access mechanisms over mmWave may be severely compromised if this key challenge is not efficiently addressed.

III. FEASIBILITY OF USING 60GHZ FOR WLAN

In this section, we analyze the feasibility of using 60 GHz for WLAN, including the transmission range, the spatial reuse opportunity, range extension techniques, and 2.4/5 GHz and 60GHz multi-band integration options.

A. 60GHz and 5GHz Transmission Range Comparison

The wide coverage range is one of the key requirements for a WLAN. TABLE I compares a number of parameters of a 60GHz WLAN and a 5GHz WLAN that determines the transmission range.

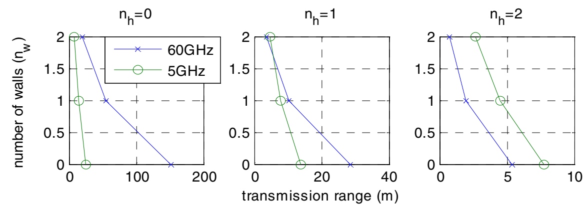

Fig. 2 Transmission range comparisons between 5GHz and 60GHz (n_h is the number of people in the transmission path)

Let's first assume that the PHY data rate of a WLAN has to reach 1.2 Gbps. It is nontrivial to achieve that in 5 GHz band due to limited bandwidth. For example, one way to reach this with the current 802.11n in 5GHz band is to increase its bandwidth from 40MHz to 80MHz and to use at least four antennas at both transmitter and receiver sides for spatial multiplexing with short guard interval and the highest modulation and coding scheme, i.e. 64QAM with code rate r=5/6. However, transmitting across multiple rooms separated by dry walls is not so difficult in 5GHz band.

In contrast, the 60 GHz WLAN can easily achieve 1.2 Gbps with a simple modulation scheme such as BPSK by utilizing 1.7 GHz wide bandwidth. The simpler modulation scheme requires lower E_b/N_0 to achieve the same bit error rate (BER) performance. For example, BPSK requires 9dB less E_b/N_0 to reach 10e-5 BER than 64QAM in AWGN. Thanks to much shorter wavelength of 60 GHz than that of 5 GHz, it is feasible to integrate a large number of antenna elements within a small area and use them for transmit and receive beamforming to compensate the additional 20 dB aperture loss compared to a 5 GHz channel. The fact that the maximum EIRP (Effective Isotropic Radiated Power) allowed in the 60 GHz band is 4 dB higher than that of the 5 GHz band also helps increase the 60 GHz link budget. However, the 60 GHz WLAN suffers from much higher penetration loss compared to the 5 GHz WLAN.

The transmission ranges of 5GHz and 60GHz WLANs can be calculated with the parameters shown in TABLE I. Using the partition based path loss model [9] as shown in (1), the average total path loss of a specific site $PL(d)$ can be calculated as the sum of the log-distance path loss model and the partition attenuation factors (PAF), which are the penetration losses due to the drywalls (L_w) and the people (L_p) in between the transmitter and the receiver in our case.

$$PL(d)[dB] = PL(d_0)[dB] + 10n\log\left(\frac{d}{d_0}\right) + \sum PAF[dB] \quad (1)$$

where n is the path-loss exponent of the site, d is the transmitter-receiver separation, and d_0 is the close-in reference distance. A number of 60 GHz measurement campaigns show that the path loss exponent for a LOS environment is approximately n=2 [10][11]. Using this result in (1) and using the parameters from TABLE I, the link budget can be easily calculated and converted into the transmission range.

Fig. 2 shows the numerical results of the transmission range comparisons between the 5 GHz and 60 GHz. The

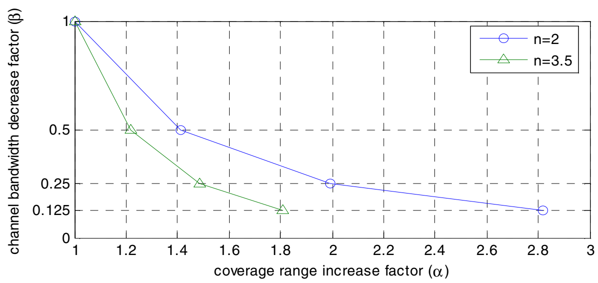

Fig. 3 Coverage range as a function of channel bandwidth

results show that when there are only obstacles with very low penetration loss such as drywalls in the transmission path, the 60 GHz WLAN outperforms the 5 GHz WLAN. However, as the number of obstacles with high penetration loss (e.g. a human body) increases in the transmission path, the 5 GHz WLAN starts to outperform the 60 GHz WLAN. This is because the 60 GHz WLAN starts to suffer from the shorter transmission range than the 5 GHz WLAN as the large PAF dominates the path loss. Given that an AP operates from the ceiling for many operational environments (e.g. office and hot spots), LOS or only light obstructions can be expected for good percentage of time and thus good coverage can be expected for such environments. Home, however, may be more difficult due to many NLOS situations between the rooms and floors with higher penetration losses (e.g. >10dB). Therefore, other measures may be needed to provide sufficient coverage range in NLOS environments.

B. Range Extension

Some approaches to extend range for 60 GHz WLAN include: mesh networking, narrowband operation, and multi-band integration.

Mesh networking can improve the coverage range of 60 GHz WLANs through multi-hopping [8]. Users would access WLAN through the nearest 60 GHz AP, which would serve as the entry/exit point to the 60 GHz mesh infrastructure. As the user moves about in the network, it changes its entry/exit point. The advantage of mesh networking is that it provides a seamless solution, but it may require a potentially large number of 60 GHz APs to be deployed densely and that the throughput performance available to the user falls with the number of hops traversed by a link [8].

Another approach to improve the coverage range is to exploit channelization. Existing standardization bodies developing 60 GHz WPAN systems (ECMA TC48, IEEE 802.15.3c) divide the worldwide 60 GHz band into four non-overlapping channels (availability varies per country) of 2.16 GHz each, supporting data rates in the order of 5 Gbps. For 60 GHz WLAN, narrower channel bandwidths would allow an increase in the power spectral density and hence coverage range, at the expense of lower data rates. As the channel bandwidth, BW, is decreased by the channel bandwidth decrease factor β ($0<\beta<1$), to β·BW, the SNR at the receiver is increased by $\delta[dB]=10\log(1/\beta)$, which increases the coverage range by a factor of α as follows

$$\alpha = 10^{\left(\delta/10n\right)} \tag{2}$$

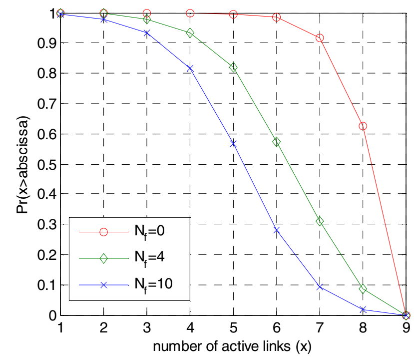

Fig. 4 Distribution of a number of simultaneous active links

where n is the path loss exponent. Fig.3 shows how the coverage is impacted as different channel bandwidths are considered and for different path loss exponent n. Therefore, it seems possible to find an operating point where > 1Gbps data rate is supported while approaching a WLAN-like coverage.

A multi-band WLAN that can operate at both the microwave band (2.4/5 GHz) and mmWave band (60 GHz) could be employed to leverage the longer range in 2.4/5 GHz, and the use of the 60 GHz band would take place on an opportunistic basis. In other words, a data link would be carried over 60 GHz whenever possible (e.g., receiver within reach), and would fall back to 2.4/5 GHz once it is out of range in 60 GHz. The topic of multi-band integration is further discussed in Section III.D.

While these approaches have been described separately, a practical solution may involve a combination of them.

C. Beamforming and Spatial Reuse Evaluation in Office Environments

Although the main purpose of beamforming is to compensate the additional 20dB path loss of 60GHz compared to 5GHz, beamforming also allows potential spatial reuse gain in a dense networking environment (e.g. office with many cubicles, each has its own WPAN) by mitigating interference to and from adjacent networks and allowing concurrent communications without interfering with each other.

To evaluate the spatial reuse gain, we implemented a MATLAB simulator for an office environment with 3×3 cubicle layout where each cubicle has dimension of 3m×2m (width×length). Within each cubicle, we randomly placed a transmitter and a receiver and assumed that the transmitter and the receiver are pointing their beam toward each other and all the stations in the cubicles are operating in the same frequency channel. Each station has 36 antenna elements (a 6×6 square antenna array) and the position of each antenna array is randomly rotated in x, y, and z-axis for each station. We also modeled reflectors that capture the 60GHz propagation characteristics of specular reflections in a cubicle and placed them randomly in each cubicle to measure the spatial reuse gain in a multi-path environment. The transmit power of each antenna element is set to 0 dBm. The required minimum SINR for each link is set to 5.5 dB for approximately 1 Gbps PHY data rate operation.

The simulation results are shown in Fig. 4. The distribution of the number of simultaneous active links in the office environment is measured by changing the number of reflectors (N_f) per cubicle. The simulation results show that when there are no reflectors, there can be more than 7 simultaneous active links for 90% of the time. As the number of reflectors increases, the number of simultaneous active links decreases because the reflected signals cause more interference to the data reception of the adjacent networks. The simulation results show that even for N_f=4, there can be more than 4 simultaneous active links for 90% of the time, which shows that the spatial reuse gain can be achieved by beamforming even in a multi-path office environment.

D. Integration of 2.4/5 GHz and 60GHz

Today, nearly every computer and portable device is shipped with a WLAN interface operating at 2.4GHz, 5GHz, or both. The introduction of a new 60 GHz wireless interface will drive the need to investigate if and how to best integrate 2.4/5 GHz and 60 GHz radios, so as to achieve the form factor, power, and cost targets demanded by today's competitive market for wireless devices. Here we explore architectural options for radio integration within the networking protocol stack.

Integration at the PHY layer is often too difficult, given the disparate characteristics between the 2.4/5GHz and the 60GHz bands. Hence, integration at the MAC and link layers becomes the most promising candidates. Broadly speaking, depending on the usage models and requirements, different levels of integration between 2.4/5GHz and 60GHz radio may include: i) Handover, ii) Upper MAC, and iii) Full MAC.

Handover integration is a type of coarse integration which happens above the MAC layer, typically at the link layer. It does not entail major PHY/MAC modification per se, but hooks may have to be defined for an efficient joint operation between the radios (e.g., fast context transfer between radios). This type of integration allows both 2.4/5 GHz and 60 GHz radios to operate simultaneously with no service interruption. Since the integration happens above the MAC, handover between radios takes place over a longer time scale (order of 100s of ms to seconds), which may be an issue for some latency sensitive applications and for fast mobility support.

Typically, the implementation of a MAC layer is divided into lower and upper MAC. Lower MAC functions include those requiring accurate timing and fast response (e.g., RTS/CTS and DATA/ACK exchange in IEEE 802.11) and are primarily implemented in hardware. Upper MAC functions usually do not have stringent timing requirements (e.g., association, several security functions, channel time allocations) and hence are typically handled in software. As a result, this can be taken advantage of when considering the integration of 2.4/5GHz and 60GHz radios.

The upper MAC integration entails changes to the MAC for joint operation across 2.4/5GHz and 60 GHz bands, but these modifications are primarily confined to software changes. As opposed to the handover integration, the time scales for the upper MAC integration is typically in the order of tens of milliseconds. The 2.4/5GHz and 60GHz may not be able to operate simultaneously and protocol complexity is increased at the software level, but no significant hardware changes are needed.

Finally, full MAC integration is the fine integration which happens down to the lower MAC, resulting in both the lower and upper MAC being entirely integrated across frequency bands. This type of integration entails major MAC modification and radios are likely unable to operate simultaneously in different bands.

IV. CONCLUSIONS AND FUTURE WORK

In this paper, we described the usage models and the requirements of a multi-Gigabit WLAN and identified the challenges associated with the PHY and MAC layers. The transmission range analysis showed that it is feasible to use the 60GHz band for a WLAN operation in a lightly obstructed environment. With a beamforming technique, the simulation results showed that the beamforming can provide spatial reuse gain in a dense networking environment that improves the capacity of the overall network. We also proposed a number of options to extend the coverage range of a 60GHz WLAN and also the 2.4/5GHz and 60GHz integration options that will allow reliable WLAN operation over a fragile 60GHz channel.

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