Multi-band Gigabit Mesh Networks: Opportunities and Challenges

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***Abstract* — 60 GHz has attracted a lot of commercial interest due to its abundance of unlicensed frequency spectrum and the recent advances in building inexpensive transceivers. IEEE 802.11 has started a new Task Group, 802.11ad, to develop a 60 GHz PHY and MAC that can deliver at least 1Gbps MAC throughput. The 802.11ad amendment is also required to enable seamless session switch between the existing 2.4/5 GHz and the new 60 GHz radio. This paper proposes the system concept of multi-band gigabit mesh networks that can potentially satisfy the requirements set out in 802.11ad. The benefits of multi-band gigabit mesh networks are presented, including the diversity gain, range extension and spatial reuse gain. In particular, a 2-hop 60 GHz mesh is simulated for an office WLAN example to demonstrate that the spatial reuse gain can be very significant in 60 GHz mesh networks thanks to the nature of the highly directional beamformed links. Such high degree of spatial reuse can significantly improve the end to end network throughput of a multi-hop mesh network while providing reasonable range. The key challenges for the multi-band gigabit mesh are also discussed along with some open research questions for future work.**

Keywords: mmWave, 60GHz, Multi-band, Multi-channel, Mesh Networks, Gbps Wireless Networks, IEEE 802.11ad, IEEE 802.11VHT

I. Introduction

The abundance of bandwidth in the unlicensed 60 GHz band (57-66 GHz band, also known as the millimeter-wave band) has attracted more and more interest from both the research community and the industry [1-11] in recent years for short range indoor wireless communications including both Wireless Personal Area Networks (WPAN) and Wireless Local Area Networks (WLAN). Recent advances [12] of using SiGe and CMOS to build inexpensive 60 GHz transceiver components has created commercial interest to productize and standardize 60 GHz radio technology for mass market applications.

This higher frequency band comes with a larger free space propagation loss which must be compensated for by high gain directional antennas. Fortunately, high gain directional antennas are feasible to implement even for small form factor devices due to the shorter wavelengths (5 mm).

60GHz channel generally exhibits quasi-optical properties, meaning the strongest components tend to be Line of Sight (LOS). Non Line of Sight (NLOS) components do exist, mostly in the form of reflection. However, the short wavelengths in this band impose some serious challenges such as greater signal diffusion and difficulty diffracting around obstacles. 60 GHz band measurements [13] show that in general, the strongest reflected components are at least 10 dB below the line of sight (LOS) component. Even more challenging are the problems caused by obstructions. A human body walking into the path between the transmitter and the receiver can attenuate the signal by 15 dB or more and easily break the link. Common objects such as furniture, walls, doors and floors found in indoor environments can also be problematic. As a result, the practical indoor operation range at 60 GHz is likely to be limited by penetration loss instead of free space propagation loss and therefore mostly confined to a single room. In comparison, the link characteristics are very different in the lower frequency bands such as 2.4/5 GHz, where penetration loss is less, rich multi-path exists to provide diversity, and the range can reach up to hundreds of meters. Millions of users have come to enjoy the convenience of broadband wireless access thanks to 802.11-based WLAN technology (aka Wi-Fi) in the home, office and hotspots. It is commonplace for Wi-Fi users to experience link quality fluctuations and even link outage, but typically not just because someone walks by. As most wireless users don't really care about or even know the difference between RF bands, it will be natural for the users to compare their usage experience of 60 GHz products with that of Wi-Fi. While higher throughput will enhance the user experience, other factors such as ease-of-use, robustness and range will also significantly affect the experience. We believe delivering satisfactory range and robustness along with gigabit level performance is one of the most important challenges for MAC and system design at 60 GHz, and that is the motivation behind the concept of multi-band gigabit mesh networks proposed in this paper.

This paper proposes the system design concept of multi-band gigabit mesh networks and articulates why this may significantly improve the user experience with 60 GHz technology. The focus of the paper is on quantifying the benefit of such concept instead of the protocol design and implementation details.

Section II briefly surveys the multiple standardization efforts taking place today, including the newly formed IEEE 802.11ad Task Group. Section III compares the data rate and range tradeoff at 5 and 60 GHz and show the complementary nature of these bands. Such complementary nature of 2.4/5 and 60 GHz bands motivates the design concept of multi-band gigabit mesh networks. Section IV introduces the concept of multi-band gigabit mesh, presents the target usages for this concept and the benefits. Spatial reuse in 60 GHz mesh is especially significant due to the nature of highly directional beamformed links, and detailed simulation results are presented for an office scenario as an example in Section V. Section VI contrasts our proposal with some of the prior work. Section VII highlights new design and research challenges in the framework of multi-band Gigabit mesh and Section VIII concludes the paper.

II. 60GHZ STANDARD EFFORTS

Several international standard bodies have ongoing standard development efforts for 60 GHz specifications. ECMA TC48 [6, 14] has completed a 60 GHz PHY and MAC standard specification to provide high rate WPAN transport. The usage cases are high definition (uncompressed or lightly compressed) AV streaming, wireless docking station and short range sync-n-go. The IEEE 802.15.3c Task Group [7] is also in the process of developing a millimeter-wave-based alternative PHY for the existing 802.15.3 WPAN Standard 802.15.3-2003. This mmWave WPAN will support at least 1 Gbps and optionally 2 Gbps for applications such as high speed internet access, streaming content download, multiple real time HDTV video streams and wireless data bus for cable replacement.

The IEEE 802.11 working group began a new "Very High Throughput" study group (VHT SG) [10] in 2007 to investigate technologies beyond 802.11n capabilities for WLAN. The Wi-Fi Alliance (WFA) was consulted to develop the usages for VHT SG and the six categories of usages envisioned [17] include wireless display, in home distribution of video, rapid upload and download to and from a remote server, mesh or point-to-point backhaul traffic, campus or auditorium deployments, and manufacturing floor automation. Two 802.11 Task Groups have been formed toward the end of 2008 as a result of the work done by VHT SG. One of the two Task Groups, 802.11ad, is chartered to define standardized modifications to both the 802.11 physical layers (PHY) and Medium Access Control Layer (MAC) to enable operation in the 60 GHz frequency band capable of at least 1 Gbps, as measured at the MAC data service access point (SAP). The 802.11ad amendment will also enable fast session transfer between 60 GHz and 2.4/5 GHz PHYs. The fast session transfer between 60 GHz and 2.4/5 GHz PHYs will distinguish 802.11ad solution from the others including ECMA TC48 and IEEE 802.15.3c.

The system concept of multi-band gigabit mesh network proposed in this paper is largely motivated by the objectives of 802.11ad to leverage both the existing 802.11 (a.k.a. Wi-Fi) solutions in 2.4/5 GHz and the new solution in 60 GHz band to reach gigabit level performance for WLAN and WPAN applications.

III. RANGE AND PEROFRMANCE TRADEOFF IN 5 AND 60 GHZ BANDS

In order to understand the motivation and benefits of multi-band gigabit mesh networks, let us first examine the propagation characteristics and channel properties of 60 GHz band in comparison with that of 5 GHz.

Using the log-distance path loss model [20], the average path loss $\overline{PL}(d)$ between a transmitter and a receiver separated by d (m) can be calculated as follows

$$\overline{PL}(d)[dB] = 20\log\left(\frac{4\pi d_0}{\lambda}\right) + 10n\log\left(\frac{d}{d_0}\right) \quad (1)$$

where d_0 is the close-in reference distance, λ is the wavelength,

TABLE I
PARAMETERS FOR 5GHZ AND 60GHZ

	5GHz	60GHz
Number of antennas	4	36
Maximum EIRP (FCC)	30dBm + 6dBi (antenna gain)	40dBm
Maximum 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
Aperture loss @ 1m	-48dB	-68dB
NLOS path loss exponent (n) [19]	2.6	3.5

TABLE II
MCS FOR 5GHZ

Data rate	120Mbps	180Mbps	360Mbps	600Mbps
Modulation	BPSK	QPSK	16QAM	64QAM
Code rate	3/4	3/4	3/4	5/6
E_b/N_0@BER10e-5	9.6dB	9.6dB	14.5dB	19dB

TABLE III
MCS FOR 60GHZ

Data rate	1.2Gbps	2.5Gbps	5Gbps
Modulation	BPSK	QPSK	16QAM
Code rate	3/4	3/4	3/4

and n is the path-loss exponent. The penetration loss of a non-LOS (NLOS) environment is abstracted as a larger path loss exponent. In [19], the 60GHz channel measurements show that n is approximately 3.5 for NLOS and 2 for LOS at 60 GHz; the path loss exponent is only 2.6 for NLOS at 5 GHz.

Although 60 GHz experiences much higher path loss than the 5 GHz band, the very short wavelength makes it possible to integrate a very large number of antennas (e.g. 36 antenna elements) in a very small area and use the array antenna for beamforming to compensate for the additional 20 dB of path loss due to operation at a much higher frequency. Assuming the transmitter and receiver both have N_a antennas, the transmit and receive beamforming gain can be expressed as G_t[dB]= G_r[dB]=10logN_a. Assuming 36 antenna elements on each side of the link, the beamforming gain is approximately 30 dB, which not only compensates for the additional path loss but also increases the link budget of the 60 GHz link by 10dB.

Assuming the transmit power of each antenna is P_t[dBm], the link budget of a 60 GHz link P_{LB}[dB] can be expressed as follows

$$\begin{aligned} P_{LB}[dB] &= P_t[dBm] + G_c[dB] + G_t[dB] + G_r[dB] \\ &- \overline{PL}(d)[dB] - N[dBm] - L[dB] - SNR_{\min} \end{aligned} \quad (2)$$

where G_c is the power combining gain due to the distributed power amplifiers on each RF chain, N is the noise power, L is the sum of noise figure and other implementation losses, and SNR_{min} is the minimum signal-to-noise ratio (SNR) for a specific modulation and coding scheme (MCS) that guarantees the quality of the link (e.g. bit error rate (BER) <10e-5). From (1) and (2), the transmission range d that satisfies BER<10e-5 can be derived.

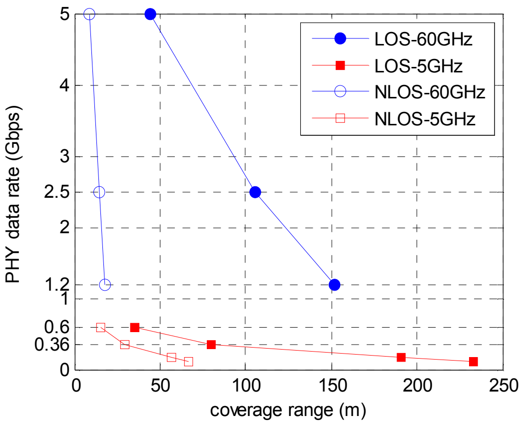


Fig. 1. Comparison of transmission ranges and data rates of 5 GHz and 60 GHz in LOS and NLOS environments using maximum transmit power per antenna (P_t = 24 dBm for 5 GHz and P_t = 4 dBm for 60 GHz)

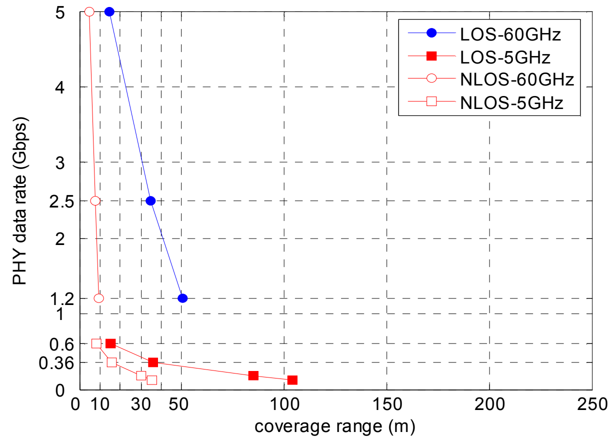


Fig. 2. Comparison of transmission ranges and data rates of 5 GHz and 60 GHz in LOS and NLOS environments using typical transmit power (P_t = 17 dBm for 5 GHz and P_t = -5.6 dBm for 60 GHz)

TABLE I shows some of the parameters of 5 GHz and 60 GHz. TABLE II and TABLE III show the MCS and PHY data rates used for numerical analysis. Using the parameters shown in Table I, II, and III, and (1) and (2), the transmission ranges of various MCS modes of 5 GHz and 60 GHz can be calculated and compared. Fig.1 shows the numerical results comparing the transmission ranges and the data rates of 5 GHz and 60 GHz in both LOS and NLOS environments based on the measurement results of [19] with the maximum transmit power per antenna (P_t = 24 dBm for 5 GHz band assuming a WiFi device and P_t = 4 dBm for 60 GHz band). It is interesting to note that in a LOS environment, 60 GHz is comparable to 5 GHz in terms of the transmission range and also has a much higher data rate. The reasons are as follows:

- the additional 20 dB path loss at 60 GHz is already compensated for by the transmit and receive beamforming gains (~30 dB)
- 60 GHz has higher EIRP (Effective Isotropic Radiated Power) than 5 GHz
- 60 GHz can use a very simple modulation scheme such as BPSK or QPSK to achieve a very high data rate (>1 Gbps) by utilizing a very wide bandwidth (~1.7 GHz), which requires very low E_b/N_0 (~10 dB) for reliable communications.

For a NLOS environment, however, the transmission range of 60 GHz quickly decreases and becomes much shorter than 5 GHz due to much higher penetration loss of obstacles between the transmitter and receiver. Considering the typical transmit power of 5 GHz and 60 GHz devices, the transmission range further decreases. Fig. 2 compares the transmission ranges and the data rates of 5 GHz and 60 GHz with a typical transmit power. For an 802.11 device, a typical transmit power per antenna is approximately 17 dBm. For a 60 GHz device, the total transmit power of a 60 GHz device is limited to 10 dBm due to the regulations in Korea, Japan, and Australia [39], which limits the transmit power per antenna to P_t=-5.6dBm for the 36 antenna case. Fig. 2 show that the transmission range of 60 GHz over a NLOS channel is less than 10 meters.

Fig.1 and Fig. 2 clearly show that the tradeoff of range and performance for 5 GHz and 60 GHz is different and complementary in nature. While 5 GHz excels in achieving larger range and robust performance in the NLOS channel, the performance of 60 GHz link is much higher with very short range but it drops off rather quickly as the range increases, especially with NLOS channel. The complementary nature of these two bands suggests a compelling reason to combine the two so to keep the best of both worlds. This is exactly the motivation behind the concept of multi-band gigabit mesh networks.

IV. Benefits of Multi-Band Gigabit Mesh

A. *Multi-band Gigabit Mesh: The Concept*

The concept of multi-band gigabit mesh is to allow the flexibility of two devices communicating with each other in either the low frequency band such as 2.4 or 5 GHz, or in the 60 GHz frequency band. Moreover, there is also the flexibility to choose a multi-hop 60 GHz path, if it is advantageous for the network performance and user experience. There are three distinct characteristics that define a multi-band gigabit mesh: 1) Some, if not all, of the devices in the mesh are capable of operating in multiple radio bands, more specifically, in a low frequency band such as 2.4 or 5 GHz (using Wi-Fi technology), and in the 60 GHz band. The network should exploit the multi-band capabilities of these devices to improve the user experience with these devices and the network in general. 2) There exists at least one multi-hop 60 GHz path among the 60 GHz devices. 3) The end to end performance between any two devices in the mesh should be above 1 Gbps measured at the MAC level.

B. *The Target Usages for Multi-band Gigabit Mesh*

Looking across the various standard efforts for 60 GHz, it is clear that the superset of the usages addressed by these efforts really span across WPAN and WLAN. Let's consider the requirements of these usages in terms of range, channel condition and link robustness, and see which usages can benefit from the concept of the multi-band gigabit mesh networks.

- *Very short range (<1 meter) with LOS guarantee*

The first set of usages operate at a very short range (<1 m) with a LOS condition almost always guaranteed. One such usage example is sync-n-go. Sync-n-go refers to the usage of rapidly transferring data from one device to another. It may be downloading a multimedia file like HD (High Definition) movie from a Kiosk to a handheld device; it may also be exchanging photos between two peer to peer devices such as cell phones. The speed is the key to make this usage compelling, especially when the amount of data is huge. Sync-n-go typically does not involve a range beyond 1 meter, and so the user has greater control to help position the devices so that they are in range with LOS toward each other. This set of usages is generally considered the least challenging from range, link budget and channel condition's point of view. This category of usages does not need multi-band gigabit mesh to achieve satisfactory user experience and so such usages are *not* the target applications of multi-band gigabit mesh networks.

- *Medium range (1-10 meters), without LOS guarantee*

The second set of the usages operate at medium range (1-10 meters, within one room) with reasonable probability of LOS but no guarantee. Even if there is a clear LOS path, movement of people or objects may easily disrupt the LOS path and so it is expected that NLOS links would be heavily used for these usages. Some examples include: i) Wireless HDMI (High-Definition Multimedia Interface) [11] to replace the HDMI cable between a TV and other video devices with a high rate 60 GHz link. This may be used in the home, a conference room or an auditorium. ii) Wireless docking in the office: The wireless docking station may be embedded into a display or monitor or may be a fixed standalone device. Mobile devices such as laptops or MID (Mobile Internet Devices) are connected wirelessly to the docking station when in the office. Other fixed devices such as keyboard, mouse, printer, and storage device (e.g., a hard drive) may be plugged into the docking station either via a wired interface (e.g., USB) or wirelessly. iii) Densely deployed 60 GHz WLAN: 60GHz APs mounted on the ceiling to deliver Gbps connectivity to many stations on an office floor.

Fig. 2 shows that it is feasible to deliver 1.2 Gbps PHY rate at the range of 10 meters under NLOS condition in 60 GHz. This may translate into 1 Gbps MAC rate if the MAC efficiency is 84% or more. But the actual range would greatly depend on the reflection surface materials and obstacles in the path. Lower MAC efficiency would also lower the achievable MAC performance below the targeted 1 Gbps. So it could still be challenging to deliver 1 Gbps MAC rate at 10 meter range in some indoor environment. A multi-hop path in 60 GHz may allow shorter distance for each single hop link and hence may increase the possibility of LOS for each single hop link. As the distance between the transmitter and the receiver increases, the likelihood of blockage with people moving about in the room also dramatically increases. While it is generally expected that 60 GHz radio will build in antenna tracking and re-training capability upon link breakage, concept such as multi-band mesh networks can help to provide additional diversity and robustness, and minimize the impact of 60 GHz link outage on the user experience.

- *Long range (>10 meters), NLOS*

As Fig. 2 shows that it may be very challenging to achieve transmission range beyond 10 meters for NLOS 60 GHz channel. Even more challenging than the distance is the obstruction caused by walls, doors, windows, furniture and other clutters commonly found in indoor environments. Such severe obstructions make it extremely difficult to cover a larger room or multiple rooms with a single hop 60 GHz link. For example, to provide full house coverage with multiple rooms, doors and floors, a multi-band mesh network is a must-have in order to meet the basic expectations of coverage. With multi-band mesh, it becomes possible to provide coverage comparable to lower bands and higher peak throughput in part of the house. The user may experience different levels of performance when moving about the house, but that is nothing new since the user would have experienced similar effect even with 802.11n products, albeit at a less profound level.

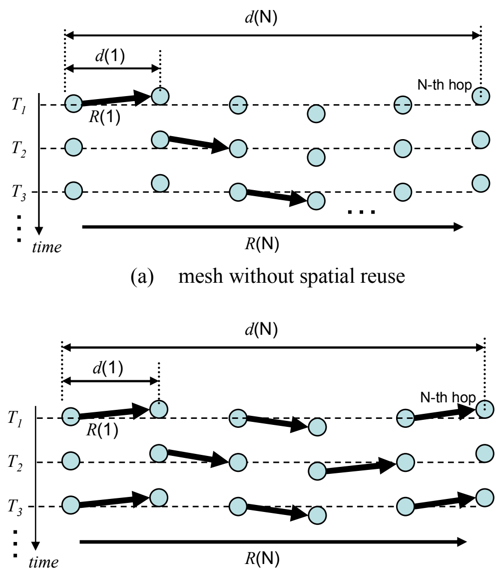
So in summary, the target usages for the multi-hop gigabit mesh networks are any usage that requires a distance of more than 1 meter without LOS guarantee.

C. *The Benefits of Multi-band Gigabit Mesh*

We've already touched on some of the benefits of multi-band gigabit mesh networks in the previous discussion; here we examine them more closely. The first benefit is the diversity gain, which may be due to the flexibility to switch between different bands, or the flexibility to choose different path within the 60 GHz mesh. Another major benefit is range and spatial reuse performance gain provided by the 60GHz mesh. While there may exist spatial reuse gain in any mesh network in any band, the spatial reuse gain in 60 GHz mesh networks is much more significant due to the nature of highly directional beamformed links in 60 GHz. Detailed simulation results are provided in the next section for an office mesh deployment scenario to illustrate the extend of spatial reuse gain.

- *Multi-band diversity gain by switching between bands*

1) *Data plane*: The multi-band aspect refers to the fact that the wireless system consists of multi-band wireless devices which are capable of operating in both the lower frequency bands (e.g., 2.4 and/or 5 GHz) and a higher frequency band (60 GHz). This combines the coverage and link robustness benefit offered by the lower frequency bands with the high rate benefit offered by the 60 GHz band as illustrated in Fig. 1 and Fig. 2. In other words, a data link would be carried over 60 GHz whenever possible (e.g., when the receiver is within reach at 60 GHz), and would fall back to 2.4/5 GHz when the 60 GHz link breaks.



(b) mesh with spatial reuse and perfect scheduling

Fig. 3. Illustrations of the link schedules in a linear topology multi-hop mesh with and without spatial reuse (source to destination is separated by N hops)

2) *Control plane*: Diversity gain can also be achieved in the control plane as well as the data plane. Most of the 60 GHz WPAN specifications employ TDMA (time division multiple access) to access the shared medium efficiently between different devices [6][7][11]. Although TDMA has higher efficiency in utilizing the medium compared to a random access scheme, it needs a scheduler that schedules the traffic in the network and the scheduling control messages need to be exchanged between the scheduler and the devices before the actual data transmissions to their target devices. When the scheduling messages are lost due to the link breakage between the devices and the scheduler in the 60 GHz band, the devices can fall back to the lower bands and maintain the control plane with the scheduler and continue to exchange data with their target devices in the 60 GHz band with minimal interruption.

Another example to leverage multi-band integration in the control plane is to facilitate faster link establishment in one band when a link is already established in another band. For example, device discovery in 60 GHz can be time-consuming due to the directivity of 60 GHz link. One 60 GHz device looking for other 60 GHz devices needs to employ some kind of omni-communication because there is no prior knowledge of the existence and the direction of the other devices. Having a link already established in 2.4 or 5 GHz enables some information about the other multi-band devices to be communicated more quickly in 2.4 or 5 GHz band to speed up the discovery process in the 60 GHz band.

- *Multipath diversity gain by switching path within 60GHz*

There may exist different paths between a pair of 60GHz devices that intend to communicate. For example, there may be a single hop path and a 2-hop path between a transmitter and a receiver. If the single hop path is broken due to obstacles such as a person walking by, another path such as the 2-hop path may be taken to get around the obstructions. It is also possible that the 2-hop path is a concatenation of two direct LOS links

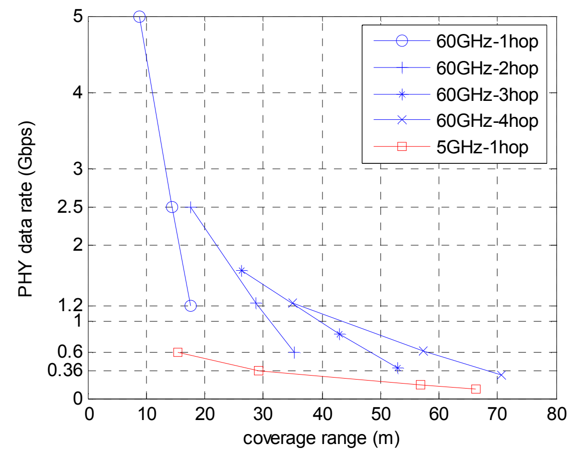


Fig. 4. Comparison of transmission ranges and data rates of 60 GHz multi-hop mesh and a single hop 5 GHz for NLOS environments using maximum transmit power per antenna

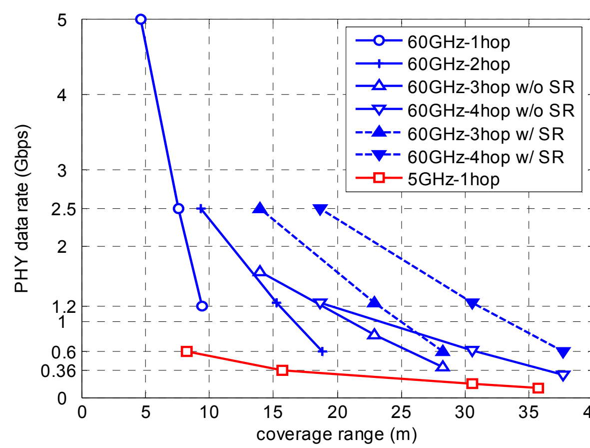
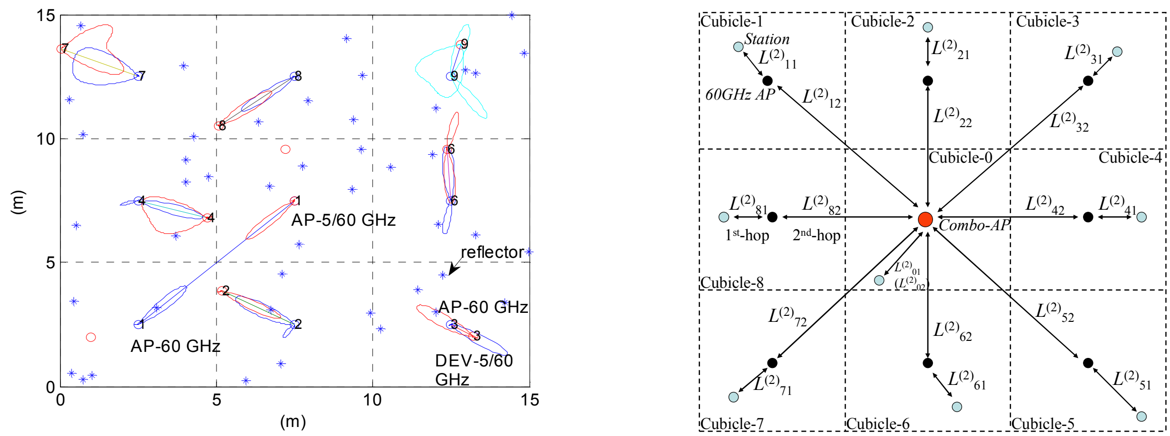


Fig. 5. Comparison of transmission ranges and data rates of 60 GHz multi-hop mesh with and without the spatial reuse (SR) and a single hop 5 GHz for NLOS environments using typical transmit power per antenna

and such a path is better than a single hop NLOS path. So having an option of taking the multi-hop path can also be considered as another aspect of the diversity gain

- *Range extension by the 60 GHz mesh*

Let's first consider the range extension benefit alone without considering spatial reuse gain achievable within the mesh. As illustrated in Fig. 3(a), for a linear topology of mesh without considering any spatial reuse possibility, if the number of hops between the source and the destination is N, the coverage range $d(N)$ increases by N; but the effective end to end data rate $R(N)$ decreases by N [27], without taking into account the overhead associated with creating and maintaining the mesh network. Fig 4 shows a very simplistic comparison of multi-hop (2~4 hops) 60 GHz mesh links with a single hop 5 GHz link for NLOS environments in a linear topology network such as shown in Fig 3(a). Similar comparisons can be done for LOS (not shown here). The important finding from Fig. 4 is that a 4-hop 60 GHz link still significantly outperforms a 1-hop 5 GHz link while the range remains comparable. While a single hop link in 60 GHz can achieve 1.2 Gbps or above for a range of 18 meters, a multi-hop link can achieve 1.2 Gbps or above



(a) 9-cubicle network topology with 5 reflectors/cell (b) network topology diagram of the 2-hop mesh network

Fig. 6. A network topology of 2-hop mesh network for a dense office

for a range of 36 meters, effectively doubling the range while still maintaining Gbps level performance. Note that two factors that would affect the mesh performance are not yet accounted for in Fig 4, namely, the MAC overhead in the mesh, and the spatial reuse due to highly directional beam formed links. While the MAC overhead may reduce the actual performance, on the other hand, the spatial reuse may significantly increase the performance, as discussed below.

- *Spatial reuse performance gain within the 60 GHz mesh*

With the spatial reuse benefit, the effective throughput of the 60 GHz multi-hop mesh can be improved significantly. Since a large number of antenna elements are used in the 60 GHz devices, a very narrow beam can be formed in a particular direction with very high gain and thus the mesh can have a good chance of having multiple active links simultaneously without interfering with each other. Assuming full spatial reuse and perfect scheduling in the mesh, for example, for the linear topology mesh as shown in Fig. 3(b), half of the segments of the multi-hop link can be active simultaneously regardless of the number of hops. Therefore, the effective end to end data rate $R(N)$ can be expressed as $R(N)=R(1)/2$ for the linear topology. Fig.5 compares the PHY data rate and the transmission range of the multi-hop (2~4 hops) 60 GHz mesh links with and without exploiting the spatial reuse benefit for NLOS environments using the typical total transmit power (10 dBm). Considering a partial spatial reuse gain, imperfect scheduling in a real network, and the actual deployment scenario, the effective end-to-end PHY rate of the linear topology mesh will fall somewhere in between the solid and dashed lines shown in Fig.5. More realistic bound of the spatial reuse is shown in the next section by simulation of an office WLAN deployment example.

V. SIMULATION STUDY ON SPATIAL REUSE OF A 60 GHZ OFFICE MESH

A. *Simulation Scenario and Assumptions*

To further quantify the spatial reuse performance in a mesh for a realistic deployment scenario, let's consider the example of a multi-band WLAN mesh for office environments as shown in Fig. 6. The office area WLAN is comprised of devices in nine cubicles. There are two kinds of APs in this network: 60 GHz-only-APs, each covering a small area such as one cubicle; and a combo-AP that operates in both 5 and 60 GHz and hence can cover the larger area of all nine cubicles. The combo-AP also serves as the 60 GHz AP for the center cubicle. This combo-AP has a wired connection such as Gigabit Ethernet, acting as the connectivity gateway to the external network for all the devices in this office WLAN. The other eight 60 GHz-only APs do not require wired Ethernet connections on the ceiling as they can communicate with the combo-AP using 60 GHz links. Through these eight 60 GHz-only APs and one combo-AP, all the stations in the office area can form a 2-hop mesh network in 60 GHz.

The focus of our simulation study is on the spatial reuse aspect of the 60 GHz mesh. We implemented a 60 GHz MATLAB simulator that can quantify the spatial reuse gain in this 60 GHz office mesh network.

1) *Simulation scenario*: The network is comprised of nine cubicles each with dimensions of 5×5×3 (width × length × height in meters). All the APs are placed on the ceiling with the height of 3 meters. Each cubicle has one station that is placed randomly within its boundary and 1 meter above the floor level (assuming the stations are on a desk). For 2-hop data transmission in 60 GHz, a station in a cubicle first transmits data to its 60 GHz AP in the first hop, and in the second hop the 60 GHz AP communicates with the combo-AP. In order to make the system design simpler for 2-hop data transmission in the 60 GHz band, a station in one cube routes its data only through the 60 GHz AP above the station's cubicle.

2) *Channel model*: The channel model for the first hop between a station and its 60 GHz AP is modeled as NLOS (path loss exponent n=3.5 [19]) to capture the obstacles in the office environment, and the channel model for the second hop between the 60 GHz AP and the multi-band 5/60 GHz AP is modeled as LOS (n=2 [19]) since APs are installed on the ceiling and hence unlikely to encounter obstacles.

3) *Reflector model*: Very strong specular reflectors (such as metallic bookshelves or cabinets commonly found in the office) are modeled by randomly placing them in each cubicle between the height of 1~2 meters. It is assumed that a signal ray is reflected by the reflector only once without any signal

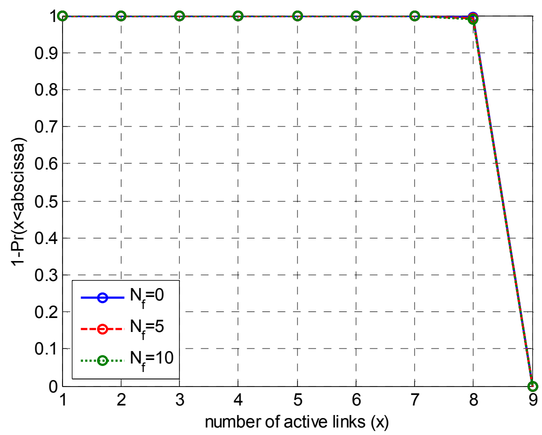


Fig. 7. Distribution of the number of simultaneous active links in 60 GHz 2-hop mesh network (all the stations and the APs use the 6x6 square array antenna)

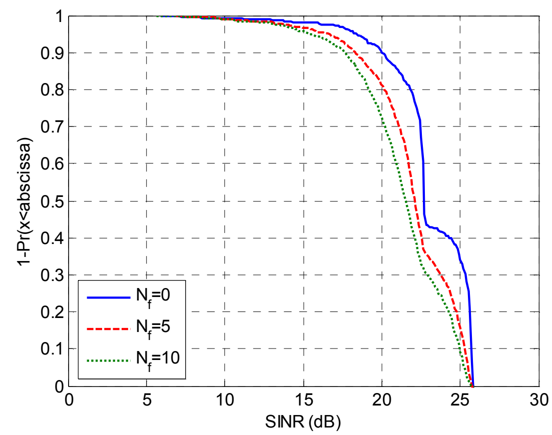


Fig. 8. Distribution of the SINR of the 2nd hop links between one of the 60 GHz AP and the combo-AP for the two-hop mesh (all the APs using the 6x6 square array antenna)

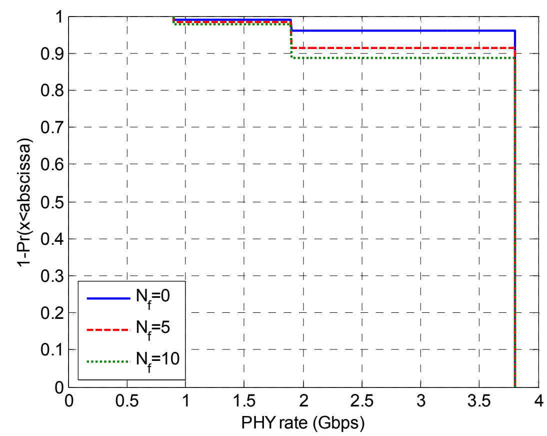


Fig. 9. Distribution of the PHY rate of the 2nd hop link between one of the 60 GHz AP and the combo-AP for the two-hop mesh (all the APs using the 6x6 square array antenna)

attenuation to capture only the first order reflections. By varying the number of reflectors (N_f= 0, 5, and 10) in a cubicle the effect of a multi-path environment can be simulated.

4) *Antenna model:* All the APs are equipped with a 6x6 square array antenna (36 antenna elements) and the stations are equipped with a 6x6 or a 4x4 square array antenna considering the fact that there are more limitations such as form factors and cost for the stations than the APs. The adjacent antenna elements are separated by a half wavelength. The total transmit power of each array antenna is fixed to 10 dBm. Each antenna element is assumed to be an ideal isotropic radiator. The orientation of the array antenna is randomly rotated in the x, y, and z-axis.

TABLE IV
MCS AND DATA RATES [11]

MCS mode	MCS1	MCS2	MCS3
Modulation	QPSK	QPSK	16 QAM
Code rate	1/2	2/3	2/3
Data rate	0.952 Gbps	1.904 Gbps	3.807 Gbps

5) *PHY Data rates*: Depending on the SINR of each link, the data rate can be chosen from three different MCS modes shown in Table IV. For the simulations, the SINR thresholds are set to 5.5 dB, 13 dB, and 18 dB for MCS1=0.952 Gbps, MCS2=1.904 Gbps, and MCS3=3.807 Gbps, respectively to have BER lower than 10e-5.

B. Metrics to Measure Spatial Reuse

Several metrics are used to measure spatial reuse in the 60 GHz mesh. The first metric is the number of simultaneous active links in the network.

The notation $L_{ij}^{(2)}$ is used to denote the link in this 2-hop office mesh network, the superscript $^{(2)}$ denoting the 2-hop path between the stations and the combo-AP, with the cubicle index i = 0,1,…,8 denoting the location of the station where the data communication is initiated or destined, and the hop index j=1,2 distinguishing if it is the first or the second hop. This is shown in Fig. 6(b). Note that for the center cubicle there is only a single hop from the station to the combo-AP, while for the other cubicles there will be a 2-hop path. Just for the convenience of notation, the center cubicle is assigned with index i=0; and so effectively $L_{01}^{(2)} = L_{02}^{(2)}$. Therefore, there are totally 17 distinct links in this office network, denoted as $\{ L_{ij}^{(2)} : i = 0,1,\ldots,8 ; j=1,2 \}$. For the rest of this subsection, the set of links between the stations and the 60 GHz-APs, $\{L_{i1}^{(2)} : i = 0,1,\ldots,8\}$, is referred to 1st hop links, and the set of links between the 60 GHz APs and the combo-AP, $\{L_{i2}^{(2)} : i = 0,1,\ldots,8\}$, referred to 2nd hop links.

Note that only one of the 2nd hop links can be active at any given time. So theoretically there cannot be more than 9 simultaneously active links in this mesh network, and the only possible set of 9 simultaneously active links is $\{L_{i1}^{(2)}: i = 0,1,\ldots,8\}$. If the number of active links is no more than 1, there is effectively no spatial reuse in the network. So the number of simultaneous active links is a very intuitive metric to indicate the degree of spatial reuse. But it is not the most accurate one as it does not reflect the quality of these active links. Therefore another metric, the aggregated end to end PHY throughput in the mesh, is introduced as a more accurate measurement of the mesh performance at the PHY level.

Both metrics are presented in the form of CCDF (Complementary Cumulative Distribution Function) curves, generated from Monte Carlo simulation of 1000 runs. For each run, the stations and the reflectors are placed randomly within

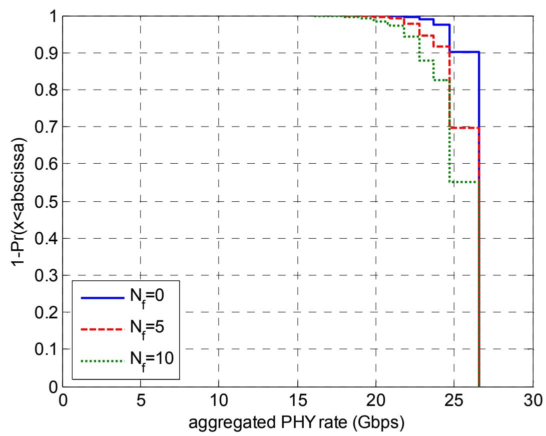


Fig. 10. Distribution of the aggregated PHY rate of the 1st hop links between the stations and the 60 GHz APs for the two-hop mesh (all the stations and the APs using the 6x6 square array antenna)

the cubicles and the antenna array is oriented randomly. It is assumed that a link can be active only if the SINR of the link is above the lowest SINR threshold (i.e. 5.5 dB) and if the link does not lower the SINR of the preexisting active links below the lowest SINR threshold.

C. Simulation Results with 6x6 Antenna Array

Fig. 7 shows the distribution of the number of simultaneous active links in the network with all the APs and the stations using the 6x6 square antenna array. The way to determine the number of simultaneous active links in each run of simulation is to first randomly pick a 60 GHz AP to form a 2nd hop link with the combo-AP; then determine which and how many of the 1st hop links can be activated successfully with the chosen 2nd hop link. The order of activation among the 1st hop links is random in each run. The simulation results show that eight links are almost always active and the number of reflectors (N_f = 0, 5, and 10) does not cause much change on that. Remember that there can be only one 2nd hop link active at any given time, say $L_{12}^{(2)}$. This means all the rest of 7 cubicles (index i = 2 to 8) can still be actively transmitting or receiving from their 60 GHz-only AP at the same time. Fig. 7 shows that extremely high degree of spatial reuse is obtained in this scenario. This is possible because all the APs and stations are using an antenna array with a large number of antenna elements (i.e. 36) which provides very high transmit and receive beamforming gain (~30 dB) and very narrow beam width, the distance between a station and the AP in its cell is very close, and the beams pointing to or from the APs on the ceiling do not interfere with each other.

While the number of reflectors does not impact the number of active links, it does affect the quality of these links. Fig. 8 shows the SINR distribution of the 2nd hop links $\{L_{i2}^{(2)} : i = 0,1,\ldots,8\}$ (that is, links between one of the 60 GHz APs and the combo-AP on the ceiling). As the number of reflectors increases, interference from the other active first hop links in the network increases and thus the SINR of the 2nd hop link between the APs decreases. The SINR distribution in Fig. 8 is converted into the distribution of the PHY rate of the 2nd hop links in Fig. 9. The results show that for the moderate number of reflectors (N_f =5), the 2nd hop links can maintain the highest MCS (i.e. 3.8 Gbps) for more than 90% of the time. Since there

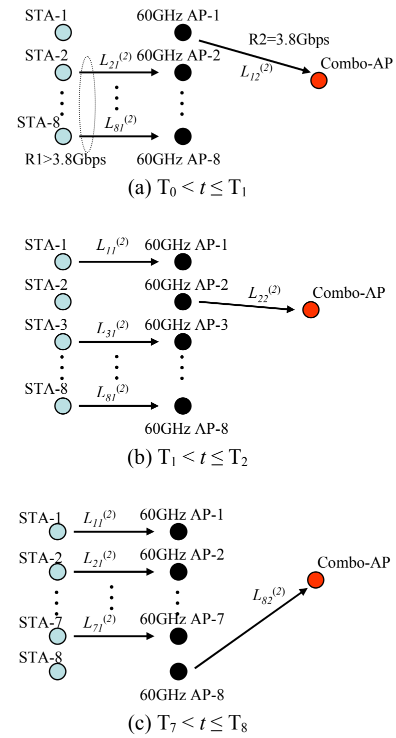


Fig. 11. Illustration of the two-hop mesh operation over the time $T_0 < t \le T_8$ achieving the end-to-end throughput close to the maximum PHY rate of the 2nd-hop link

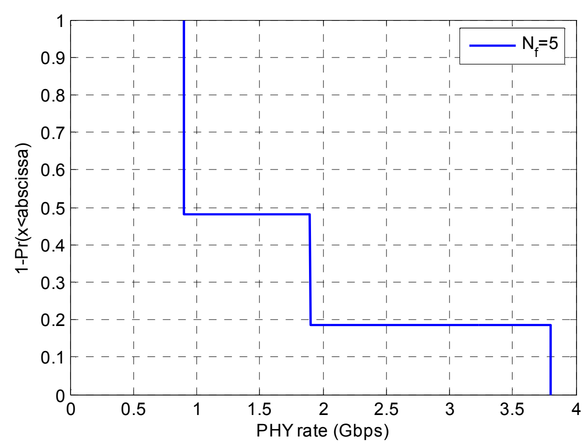


Fig. 12. Distribution of the PHY rate of the one-hop link between one of the stations and the 60 GHz AP both using the 6x6 square array antenna

can be only one active 2nd hop link at any given time, Fig. 9 effectively shows the aggregated throughput of the 2nd hop link at the combo-AP in the network.

Let's now consider the aggregated PHY rate of 1st hop links in Fig. 10. The aggregated PHY rate is defined as the sum of all the active links' PHY rate. Similar to the situation with the 2nd hop, as the number of reflectors increases the aggregated PHY rate of the 1st hop links decreases due to increased interference between each other. However, the aggregated PHY rate for the 1st links is still extremely high, over 20 Gbps most of the time. This is because of the extremely high degree of spatial reuse among the 1st hop links.

Now consider the end to end aggregated PHY rate in the 2-hop mesh. Fig. 7 and Fig 9 shows that the 2nd hop link can

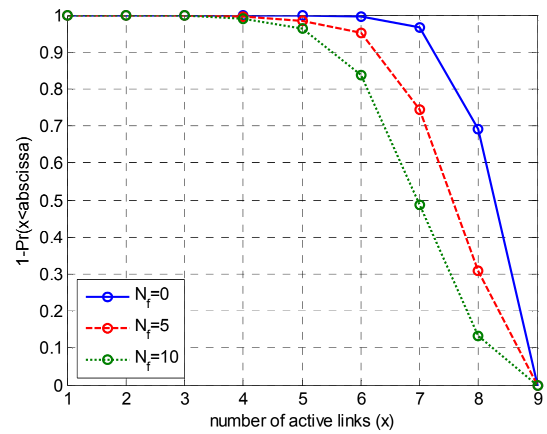


Fig. 13. Distribution of the number of simultaneous active links in 60GHz 2-hop mesh network (the stations with 4x4 square array antenna and the APs with 6x6 square array antenna)

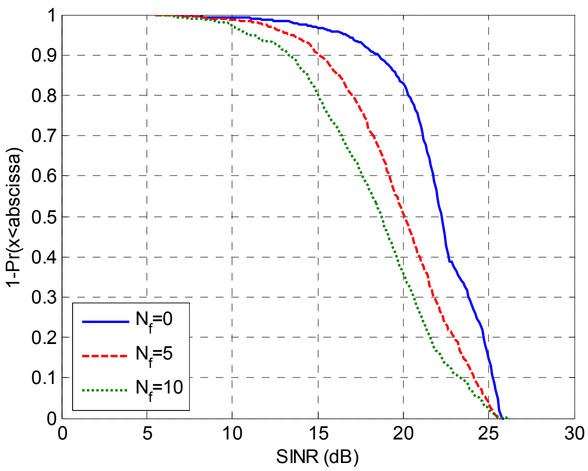


Fig. 14. Distribution of the SINR of the 2nd-hop link between one of the 60 GHz AP and the combo-AP for the two-hop mesh (all the APs using the 6x6 square array antenna)

maintain the highest data rate (3.8Gbps) more than 90% of the time while seven other 1st hop links are active simultaneously. This is illustrated in Fig. 11. In Fig. 11(a), at one time instance ($T_0 < t \le T_1$), the seven 1st hop links $\{L_{i1}^{(2)} : i = 2,3,4,5,6,7,8\}$ may be active simultaneously with the 2nd hop link $L_{12}^{(2)}$. Fig. 11(b) shows the next time instance ($T_1 < t \le T_2$) when $\{L_{i1}^{(2)} : i = 1,3,4,5,6,7,8\}$ and $L_{22}^{(2)}$ 2nd-hop are the simultaneously active links. Fig. 11(c) shows another time instance ($T_7 < t \le T_8$) when $\{L_{i1}^{(2)} : i = 1,2,3,4,5,6,7\}$ and $L_{82}^{(2)}$ are the simultaneously active links. Since the aggregated throughput of the 1st hop links (shown in Fig. 10) is much higher than the 2nd hop (shown in Fig. 9), and one of the 2nd hop links can be almost always active simultaneously with seven other 1st hop links (shown in Fig. 7), the end to end throughput is basically determined by the 2nd hop link throughput. So the end to end throughput distribution should look like the throughput distribution of the 2nd hop shown in Fig. 9 as well. That is, 90% of the time the end to end throughput can reach 3.8 Gbps.

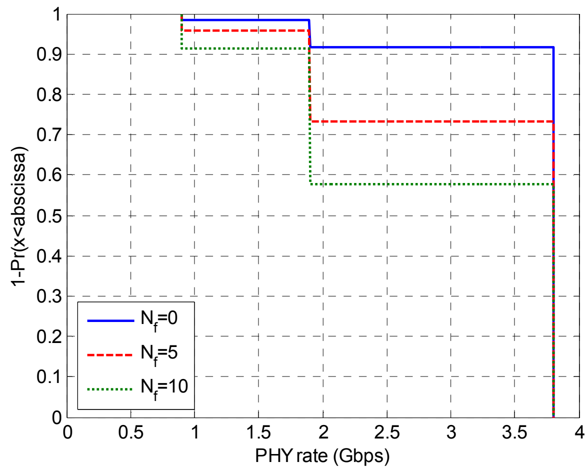


Fig. 15. Distribution of the PHY rate of the 2nd hop link between one of the 60 GHz AP and the combo-AP for the two-hop mesh (all the APs using the 6x6 square array antenna)

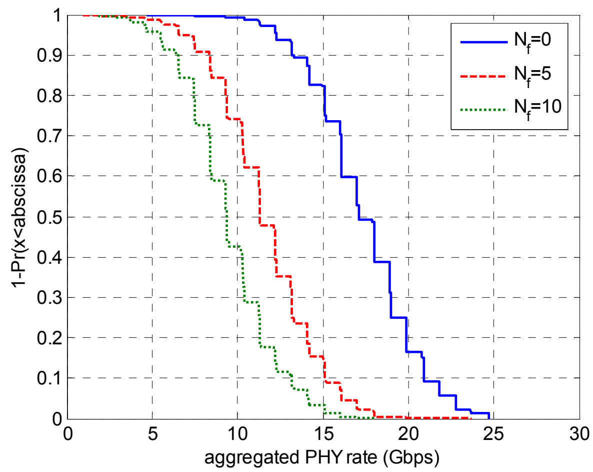


Fig. 16. Distribution of the aggregated PHY rate of the 1st hop links between the stations and the 60 GHz APs for the two-hop mesh (the stations with 4x4 square array antenna and the APs with 6x6 square array antenna)

It is remarkable that a two-hop mesh network reaches the highest data rate (3.8 Gbps) that is ever achievable by a single link, thanks to the high degree of spatial reuse. It can be shown that such 2-hop network actually outperforms a one hop network where there is only one 60 GHz AP serving all the stations in the 9 cubicles. Fig. 12 shows the distribution of the PHY data rate of such single hop links for N_f=5. The results show that such one hop link can achieve 3.8 Gbps only 19% of the time, which is much worse than the two-hop mesh. This is because the path loss exponent is higher between the station and the AP due to more obstacles compared to the 2nd hop link between the 60 GHz AP and the combo-AP in the two-hop case and the distance between the station and the AP is longer.

Another remarkable insight one may gain from this example is that even though the aggregated PHY rate for the 1st hop links can be over 20 Gbps most of the time, it does not translate directly into the end to end throughput for the mesh, because the 2nd hop is the bottleneck of the network. This is typical of a network with star or tree like topology, and congestion and flow control is a well known and well studied

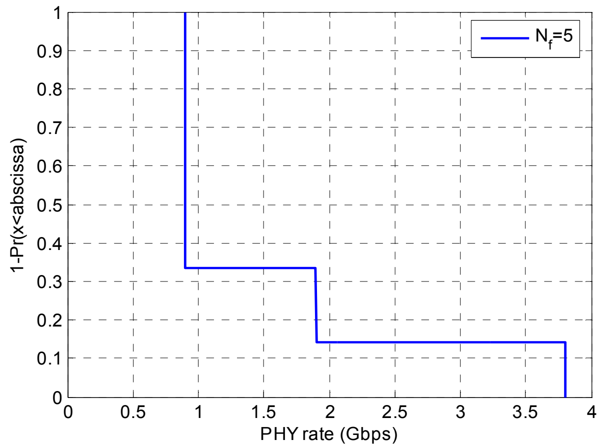


Fig. 17. Distribution of the PHY rate of one-hop link between one of the stations and the 60 GHz AP (the stations with 4x4 square array antenna and the APs with 6x6 square array antenna)

problem in mesh network literatures [31-34]. However, this problem becomes even more severe in our example because of the spatial reuse with highly directional links in 60 GHz. Without proper congestion control, much of the huge spatial reuse potential is wasted. So this example demonstrates the need to further study effective congestion and flow control that can maximize the return of spatial reuse.

D. Simulation Results with 4x4 Antenna Array at the Stations

Now suppose the stations in the two-hop network have only 16 antenna elements (a 4x4 square array antenna), which might be more realistic considering the small form factor of the stations and the cost constraint. As the number of antenna elements decreases, not only the link quality degrades due to the decreased beamforming gain but also interference to and from the other active links increases due to the wider beam width.

Fig. 13 shows the effect of the decreased number of antenna elements at the stations on the spatial reuse gain. The spatial reuse gain decreased significantly comparing to Fig. 7 where the stations are equipped with 36 antenna elements. However, more than five links can still be active simultaneously more than 90% of the time, which is still very high spatial reuse gain.

Fig. 14 and Fig. 15 show the effect of the decreased number of antenna elements on the SINR and the PHY rate of the 2nd hop links. Comparing to Fig. 8 and Fig. 9, although more interference from the stations degrades the quality of the link, the link can still support the highest data rate for more than 70% of the time with a moderate number of reflectors (N_f=5).

Fig. 16 shows the aggregated PHY rate of the 1st hop links. Comparing to Fig. 10, the PHY rate is significantly lower with 4x4 antenna array at the stations. However, the results show that the aggregated PHY rate is still sufficiently higher than the 2nd hop PHY rate in Fig. 15. This is because 100% of the time at least 3 links (i.e., one 2nd hop link and two 1st hop links) can be active simultaneously as shown in Fig. 13, and so the end to end PHY throughput is still determined by the 2nd hop. So the end of end PHY throughput with 4x4 antenna array at the stations has similar distribution as shown in Fig. 15.

The above results are compared to the one-hop scenario in Fig. 17 and it shows that the one-hop case also suffers from the decreased beamforming gain and now the link can support the highest data rate for only 14% of the time (vs. 73% of the time with two-hop mesh in Fig. 15). So even with the 4x4 antenna array, a 2-hop mesh still outperforms the one hop network in this office WLAN example and maintains the end to end PHY throughput close to the highest PHY rate of the 2nd hop for majority of the time. This shows that the stations can have less number of antenna elements than the APs but still enjoy the end to end throughput performance benefit by employing mesh.

VI. PREVIOUS WORK

Multiple research projects in Europe [8, 9] have been focusing on the design of a holistic wireless system that provides higher performance for WLAN. One such example is the European Information Society Technologies (IST) Broadway project [8, 16] which targeted specifically for a WLAN with the hybrid dual frequency system design concept based on HIPERLAN/2 at 5 GHz and a fully ad-hoc extension at 60 GHz. The usage scenarios envisioned include hotspot coverage, public Internet access, high density dwellings and flats deployment, corporate and campus environments. However, IST limited its bandwidth in the 60 GHz band to no more than 240 MHz and hence the maximum data rate achievable was only 720 Mb/s, substantially below 1 Gbps.

Conceptually what it is proposed in this paper is similar to the approach taken by the IST Broadway project but there are three important distinctions that lead to a substantially different solution: i) Broadway is based on HIPERLAN/2 and there is very tight integration of 5 GHz and 60 GHz at the RF front end. Our work is based on the 802.11 MAC to maximize reuse and integration with existing 802.11 solutions at 2.4/5 GHz. ii) Broadway limited its channel width at 60 GHz band to no more than 240 MHz and hence the max link data rate was only 720 Mb/s. The latest PHY proposals in both ECMA TC 48 [7] and IEEE 802.15.3c [8] use a much wider channel (close to 2 GHz) for obtaining multi-Gbps PHY rates. Similar assumptions are taken here at the PHY to ensure multi-Gbps data rate capabilities. The MAC efficiency can be deeply affected by the operating PHY rate [1, 18] and so MAC throughput does not always scale linearly with the PHY rate. It is important to re-examine and sometimes re-design the MAC protocol when the PHY rate is substantially increased. iii) It was assumed in Broadway that only infrastructure devices such as APs used directional antenna at 60 GHz and all stations used an omni-directional antenna. Our work assumes that it is feasible to employ directional antennas for stations such as laptops, or MIDs. This allows a significant spatial reuse benefit and can affect the design substantially in both the PHY and MAC layers.

VII. DESIGN CHALLENGES OF MULTI-BAND GIGABIT MESH

This section presents high level considerations of the system design concept of multi-band Gigabit mesh networks and the new research challenges within that framework.

A. Integration Architecture to Support Seamless Session Switch

The concept of multi-band integration is straightforward but the design and implementation are non-trivial. One of the important design questions is where in the protocol stack such integration should happen - at the RF front end, baseband, MAC, or above the MAC?

The answer partly depends on how similar or different the radio stack (antenna, PHY, MAC, etc.) would look like across the bands. Given the very different channel properties of the 60 GHz band, the antenna, RFIC and baseband design for the 60 GHz would be quite different from that of 2.4 or 5 GHz band [38]. We also have strong reasons to believe that the media access mechanism for 60 GHz would be quite different from the CSMA/CA based media access mechanism for Wi-Fi in the 2.4 and 5 GHz bands, as explained below.

First and foremost, the current design of CSMA/CA assumes that devices in the same physical proximity can carrier sense and overhear each other because of the omni-directional antenna typically used in 2.4 and 5 GHz bands and so all communications can be assumed to be broadcast at the physical level. This is no longer the case in 60 GHz, because high gain directional antenna would be employed in order to reach decent range. This directivity fundamentally violates the assumption of CSMA/CA and so direct reuse does not make sense.

Another reason that we may consider to modify the 802.11 MAC is that current 802.11 MAC does not provide strong QoS guarantee, which may be acceptable for Internet connectivity type of applications but not acceptable for high performance media applications such as wireless display. Media access such as TDMA (Time Division Multiplex Access) that can provide better QoS assurance is probably needed. While TDMA typically is used successfully for licensed band applications such as cellular networks, it is relatively unproven for unlicensed band applications such as 60 GHz. The main difficulty with TDMA in unlicensed band is to cope with the interference from independent overlapping networks without causing instability in the networks. The fact that 60 GHz links typically employ directional communication between devices can somewhat mitigate such a problem as directional communication helps lesson the probability of interference and hence improves space reuse as evidenced from our simulation results shown in this paper.

For these reasons, we believe media access mechanism for 60 GHz would be quite different from that of existing Wi-Fi at 2.4 and 5 GHz. This begs the question of how these different media access mechanisms be reconciled or integrated in the multi-band framework. Such reconciliation needs to be investigated carefully in order to design a reasonable integration architecture that can support seamless session switch between different bands.

B. Radio concurrency

Depending on how tightly the 60 GHz radio and 2.4/5 GHz radio are integrated, a multi-band device may or may not be able to operate in different bands concurrently. Therefore it is important to have the flexibility of allowing both configurations to function in the network. If two radios can be used concurrently, it opens up the possibility of using both bands to further optimize the performance for the device and the network beyond what a single radio can provide. On the other hand, full concurrent operations may increase hardware cost and may consume too much power for the mobile devices. If two radios are not to operate simultaneously for a long period of time, then how and when to switch from one band to another is also an interesting question to consider.

C. Multi-hop Multi-band Mesh Challenges

Some of the issues with directional ad hoc networks such as medium access control, neighbor discovery and routing have been well studied [22-30], albeit for lower frequency bands. It is necessary to reevaluate the ideas and applicability for higher frequency bands, with realistic antenna patterns and higher PHY rates. Some concepts might be more readily applicable than others. For example, congestion control [31-34] is a well recognized problem in multi-hop ad hoc networks. As demonstrated in our office WLAN example in Section V, the congestion problem could be even more pronounced for some topology like star- or tree- like networks, and the un-even spatial reuse gain in different part of the network may actually worsen the congestion at certain point of the network. How to address congestion and flow control in such highly directional networks is a new research topic. The concept of network coding [35] has shown promise to combat performance issues such as congestion. But such a concept may be challenging to apply in a directional mesh because network coding leverages omni-directional broadcast which is a very expensive operation at 60 GHz; so further study might be needed in that area as well.

The topic of multi-channel ad hoc networks has been studied somewhat in the past [36-37], however, most of the work assumes homogeneous channels within the same band. Multi-band mesh works across characteristically very different bands, and so imposes a new set of problems to solve but we have seen very little work done on this yet.

Power consumption is another aspect that needs to be carefully studied in the context of multiband mesh. For example, as pointed out earlier, radio concurrency may have negative impact on power while boosting the performance. Another important factor to consider is how much power the radio consumes when operating in different band.

VIII. Conclusion and Future Work

The industry is positioning 60 GHz radio as a high performance radio that is capable of delivering gigabit performance in a wide range of usage scenarios. 60GHz represents a technological opportunity This means that 60 GHz radio has to live up to expectations similar to Wi-Fi since most users are familiar with that experience. In this paper we point out that one of the key challenges in meeting those expectations is to improve range and robustness at 60 GHz. This paper proposes the system design concept of multi-band gigabit mesh networks to meet that challenge and quantify its potential benefits in range extension and spatial reuse with analysis and simulation results. The integration of 60GHz radio with the existing 2.4/5GHz band WiFi radio presents an opportunity to provide a unified technology for both gigabit WPAN and WLAN, thus further reinforcing the technology convergence that is already underway with the widespread adoption of Wi-Fi technology [40]. Much more work need to be done in order to prove the feasibility of this concept with a detailed protocol design. Our current analysis and simulation do not take into account the MAC overhead associated with the mesh creation and maintenance, and we would like to take that into account in our further study to tighten the performance bound. We also want to continue to investigate the topics discussed in the last section to provide a complete solution for multi-band gigabit mesh networks.

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