60 GHz Multi-Gigabit Indoor WLANs: Dream or Reality?

Swetank Kumar Saha  
University at Buffalo, SUNY  
swetankk@buffalo.edu  

Viral Vijay Vira  
University at Buffalo, SUNY  
viralvij@buffalo.edu  

Anuj Garg  
University at Buffalo, SUNY  
anujgarg@buffalo.edu  

Dimitrios Koutsonikolas  
University at Buffalo, SUNY  
dimitrio@buffalo.edu

ABSTRACT

The millimeter-wave (mmWave) technology, recently standardized by IEEE 802.11ad, is emerging as an attractive alternative to the traditional 2.4/5GHz wireless systems, promising multi-Gigabit wireless throughput. However, the high attenuation and vulnerability to blockage of 60 GHz links have limited its applications (until recently) to short-range, line-of-site, static scenarios. On the other hand, the question of whether it is feasible to build general-purpose WLANs out of mmWave radios in dynamic indoor environments with non-line-of-sight links remains largely unanswered.

In this paper, through extensive measurements with COTS 802.11ad hardware in an indoor office environment, we investigate the question of whether the mmWave technology, in spite of its unique propagation characteristics, can serve as a viable choice for providing multi-Gigabit ubiquitous wireless indoor connectivity. We study the range of 60 GHz transmissions in indoor environments, the impact of antenna height, location, orientation, and distance on 60 GHz performance, the interaction among metrics from different layers of the network stack, the increased opportunities for spatial reuse, and the impact of human blockage. Our results reveal a number of challenges that we have to address for 60 GHz multi-gigabit WLANs to become a reality.

1. INTRODUCTION

We experience today an explosion in wireless network traffic driven by the rapidly growing number of mobile devices and bandwidth hungry applications. Industry research predicts that the aggregate bandwidth demands will increase by 1000x by 2020 [6]. Although intelligent spectrum adaptation in WiFi and cellular networks can offer short-term solutions, it is unlikely to completely solve the problem of high bandwidth demands in the longer term. The scalability of any solution in the lower frequency bands (LTE, WiFi, TV white spaces) is physically limited by form factor constraints, which put a hard limit to the number of antennas that can be accommodated on an AP and/or a client device, and call for alternative approaches.

One alternative approach which has recently attracted significant interest in the industry is the use of millimeter-wave (mmWave) radios in the 60 GHz band, which provides 7 GHz of unlicensed spectrum, and is supported by the new IEEE 802.11ad standard [31]. 802.11ad defines three 2.16 GHz channels and offers bitrates between 385 Mbps and 6.76 Gbps. Further, the order-of-magnitude shorter wavelengths in the 60 GHz band compared to the 2.4/5 GHz bands makes it possible to pack a very large number of antenna arrays into small factors, enabling highly directional transmissions. Narrow directional beams limit interference and allow for very dense deployments, significantly improving spatial reuse.

The caveat is the high attenuation and vulnerability to blockage of 60 GHz links. Since free-space loss scales up with the square of the carrier frequency, the propagation loss at 60 GHz is 21.6 dB worse than at 5 GHz. Furthermore, due to their small wavelength, signals in the 60 GHz band are easily blocked by obstacles such as walls, furniture, or humans. For example, a human in the Line-of-Sight (LOS) between the transmitter and the receiver can attenuate the signal by 20-30 dB [18], resulting in link outage. While the use of electronically steerable antenna arrays can theoretically overcome link outages, the overhead of re-beamforming may counter-balance the potential gains [23, 29, 21]. Moreover, directional transmissions pose a great challenge to mobility as mobile clients and APs may have to continuously re-arrange their beams.

Due to these reasons, the use of the 60 GHz technology has been limited (until recently) to short-range, (mostly) LOS, static scenarios, e.g., for HD video streaming in wireless personal area networks (WPANs) [25], wireless docking [4], or for augmenting data center networks with high capacity wireless links [5, 28, 15, 29]. These scenarios are characterized by open spaces providing direct LOS paths but largely devoid of reflective and/or obstructive surfaces and objects. The absence of phenomena such as reflection or multipath makes such environments easy to model as they exhibit near-free space propagation properties. On the other hand, the question of whether it is feasible to build general-purpose WLANs out of mmWave radios in environments with NLOS links and in the presence of user mobility remains largely unanswered.

In this paper, we investigate the feasibility of building...
general-purpose indoor 60 GHz WLANs for enterprise environments, that will offer always-on connectivity but an order of magnitude higher throughput than today's 2.4/5 GHz WLANs. Compared to WPAN or datacenter environments, the typical indoor enterprise WLAN environment is highly complex, with many objects/surfaces that can attenuate, completely block, or reflect the signal, making it harder to predict link behavior. Our main contributions and findings are summarized as follows:

(1) This paper is one of the first to investigate the feasibility of building general-purpose, indoor, 60 GHz WLANs by conducting an extensive measurement study in a typical academic office building. In contrast to previous works which measured performance at a single layer (typically PHY) using custom, non-standard compliant hardware, we investigate performance across multiple layers of the protocol stack using 802.11ad-compliant COTS devices. Although the use of commodity hardware limits our access to some PHY layer information (e.g., RSS) and our control on certain protocol features (e.g., rate adaptation, beamforming), it allows us to get a much closer idea of how the 802.11ad technology would behave when used to build full-scale WLANs. Our results differ significantly in several aspects from both theoretical modeling and experimental results reported in the past, suggesting that link characterization based on non-standard-compliant hardware or simple theoretical models cannot always provide deep insights in a complex environment.

(2) We study the performance of 60 GHz links at multiple locations and orientations (Section 5). Our results confirm that high-throughput 60 GHz communication is feasible at various setups typical of an indoor WLAN environment (corridors, halls, labs, through walls or glass). Moreover, communication is possible in the case of antenna array mis-alignment, either via beamsteering or through an NLOS link via reflection, but the performance can vary significantly depending on the location and Tx-Rx distance and can be much lower than in the case of optimal orientation.

(3) We study the impact of Tx-Rx distance on link quality indicators – RSSI, PHY data rate – and higher layer performance – TCP throughput – (Section 6). We find communication ranges much longer than those reported by previous studies with the same hardware. However, performance is unpredictable and highly dependent on the environment (type and number of reflective surfaces). In particular, we find that signal propagation in indoor WLAN environments cannot be characterized by simple log distance path loss models, which have been extensively used in 802.11ad simulators [5,28,23,30].

(4) We investigate the relationship among RSSI, PHY data rate, and TCP throughput (Section 7). We find that RSSI can only serve as a weak indicator of PHY data rate and TCP throughput and only at certain locations, but not across locations. Hence, translating signal strength to PHY data rate, a common practice in recent measurement studies [29,21], can yield inaccurate results in typical indoor WLAN environments. Further, we find that PHY data rate is not always a good indicator of higher layer performance.

(5) We examine the benefits brought by directional 60 GHz links in terms of spatial reuse (Section 8). Our results reveal that, even with imperfect hardware – wide beams and sidelobes – 802.11ad allows for much higher spatial reuse compared to 802.11ac.

(6) We study the impact of human blockage on the performance of 60 GHz links (Section 9). Our results show that human blockage, especially by humans standing near the Tx or Rx, presents a major challenge for 60 GHz links in indoor environments. However, a client served by two APs simultaneously can maintain 100% uptime and high throughput.

Overall, our results show that the 60 GHz technology can be a viable option for providing ubiquitous indoor multi-gigabit wireless connectivity, but also uncover a number of challenges that need to be addressed for this vision to become a reality.

2. RELATED WORK

60 GHz in indoor environments Our work is not the first to investigate the feasibility of 60GHz technology in indoor WLANs. Initial experimental work focused on measuring and modeling channel propagation characteristics using dedicated channel sounding hardware (e.g., [20,27,2,19,9]). A few works also measured [3], simulated [14], or studied analytically [7] the impact of human blockage in indoor environments. Tie et al. [23] studied link level performance of 60GHz links with respect to blockage and antenna orientation. However, they used custom designed non-802.11ad hardware and measured performance of IP-over-wireless-HDMI. In contrast to these works, we are using COTS 802.11ad-compliant hardware equipped with phased antenna arrays and measure performance via data transfers over real transport layer protocols (TCP/UDP).

More recently, Sur et al. [21] conducted a link-level profiling of indoor 60 GHz links, using a custom software-radio platform (WiMi). Their study offers many valuable insights, in particular about the potential capabilities and limitations of flexible beams. However, WiMi uses a small channel width of only 245 MHz and thus, it cannot achieve Gbps data rates. Hence, findings in this work are extrapolated from RSS measurements in narrow channels and they may not reflect the behavior of real 802.11ad links. Moreover, throughput values are not obtained through real data transfers but are translated from RSS and noise floor measurements in narrow channels using an 802.11ad specific rate table. In contrast, in our study we directly measure performance of COTS 802.11ad devices.

More importantly, the main limitation of all the above studies is that they target a single layer of the protocol stack (PHY, link, or transport). In contrast, our goals in this paper are to (i) measure performance across different layers using COTS 802.11ad hardware and (ii) understand the interactions between different performance metrics.
Recent work also has argued for the use of 60GHz technology to augment datacenters [5, 28, 29] and demonstrated the feasibility of this approach using both expensive proprietary devices [5, 28, 29] and the same cheap off-the-shelf hardware we use in this paper [30]. The datacenter environment, with static LOS links established on top of TOR switches, is very different from the complex indoor enterprise WLAN environment, and several of our findings are very different from the findings of these works.

**60 GHz in outdoor environments** Channel sounding measurements have also been conducted in outdoor environments [8, 20, 12]. Similarly, a few works simulated the impact of human blockage in such environments [1]. Several works have considered the use of 60 GHz technology for building outdoor mesh networks for backhaul, e.g., in 5G networks [10, 17, 16, 22]; all these proposals have only been evaluated in simulations. Finally, recent work experimentally demonstrated the feasibility of 60 GHz-based outdoor picocells [29] using both the hardware we use in this work and proprietary non-802.11ad hardware. Outdoor environments differ significantly from the ones we are concerned with, as also pointed out in [21], and several observations reported in these works do not hold for our use-case.

### 3. MEASUREMENT METHODOLOGY

#### 3.1 Hardware

Our 802.11ad link setup consists of two COTS devices: a Dell Latitude E420 laptop equipped with a Wilocity wil6210 802.11ad radio [24] and a Dell Wireless Dock D5000 [4]. The dock has an 802.11ad wireless interface and acts as an AP. Another laptop is connected to the dock through a Gigabit Ethernet interface to generate/receive TCP traffic. The use of the Ethernet interface limits the throughput in our experiments to 1 Gbps, even though the wireless link itself is capable of much higher speeds. Hence, we also use the dominant PHY data rate as an indicator of the maximum achievable throughput. The Wilocity radios do not allow us to control the PHY layer data rate and use their own rate adaptation algorithm. Beam properties (beam direction and width) are controlled by an in-built beamforming mechanism.

Further, in case the link between the dock and laptop is blocked/broken, the dock automatically searches for an alternative link (e.g., through reflection) to re-establish the connection. The Wilocity radios export to the user-space the current PHY data rate and an RSSI value between 0 and 100 indicating current link quality.

Although IEEE 802.11ad specifies antenna beams as narrow as 2.86°, which can be achieved, for example, with a 10x10 antenna array [29], the Wilocity radios use 2x8 antenna arrays with a main beamwidth of 30° − 40° [30, 21]. Hence, our throughput and range measurements are probably lower bounds of the achievable performance of 802.11ad links. However, while narrow beam antennas can greatly extend range, recent work [21] has shown that they yield poor performance with client mobility and human blockage. Hence, we believe that future WLANs may use wider beams.

#### 3.2 Locations

For most of our experiments, we chose two kinds of environments/locations: Hall and Corridor, to capture the diverse scenarios that are likely to occur in a office environment. Both locations are inside an academic building (Davis Hall) at the University at Buffalo, SUNY. The building houses many faculty offices, classrooms, labs, and open student areas, representative of a dense office environment full of furniture and other objects/surfaces that can attenuate, completely block, or reflect the signal.

The first location is an open Hall thinly populated by some desks and chairs and a staircase from the floor above. This location offers better conditions for emulating free-space propagation and LOS links, reducing multipath effects and the chances of communication through NLOS links via reflection. The ceiling height is rather high and thus it does not serve as a viable reflector. The second location is a rather narrow Corridor (only 1ft wide). This environment offers ample opportunities for reflection/multipath from the walls on the side, in addition to the floor and the ceiling.

Apart from these two locations, we also studied 60 GHz link behavior through different commonly found materials (see Table 1) and some typical setups inside the building with different orientations of transmitter (Tx) and receiver (Rx) in Section 5. In addition, we performed control experiments in an outdoor open environment, devoid of objects, to better understand and explain some phenomena which we believe are characteristic of an indoor environment.

#### 3.3 Methodology

We used iperf3 to generate TCP traffic. Each experiment consists of a 10-second TCP and/or UDP session. All the results are the average of 5 sessions. All experiments were performed late night to remove the possibility of human blockage. We study the effects of client mobility on performance separately in Section 9. Unless stated otherwise, the experiment environment consists of only static objects present in the building environment.

### 4. TRANSMITTER HEIGHT

We begin by investigating the effect of dock/transmitter (Tx) height on performance as measured at the transport layer. We pick two different distances (8ft and 16ft) at each of the two locations and measure TCP and UDP throughput with different Tx height. To decide upon the optimal height for the Tx, we fix the height of the receiver (Rx) to 2’6” and vary the Tx height from 2’6” to 6’6” at the interval of 1’.

#### 4.1 Rx Orientation

In a real deployed WLAN, the AP’s location and orienta-
tion will be fixed. However, mobile clients can be assumed to have any possible orientation with respect to the AP. We will discuss in detail in Section 5.2 how the relative orientation of the Tx and Rx antenna array is an important factor in determining the link performance. For this experiment, we chose four representative orientations: 0, 4, 8 and 12 (see Table 2) for the Rx and repeat our experiments at each one of them. Orientation #0 is the optimal case when both Tx and Rx antenna array are aligned. Orientations #4, 8 and 12 are obtained by rotating the Rx by 90°, 180° and 270°, respectively, while the AP/dock orientation remains fixed.

4.2 Results

Figures 1(a) and 1(d) plot the TCP and UDP throughput achieved in the Hall for each of the four orientations and an average across all orientations for different Tx height. When both Tx and Rx are at the same height (2’6”), orientation #4 gives zero throughput, resulting in low average with a large standard deviation. As we increase the height of Tx to 3’6”, 4’6” and 5’6”, the average for all orientations approaches 800 Mbps, indicating that larger Tx height is more favorable to link performance. When the height is increased further to 6’6”, the throughput for all orientations deteriorates significantly, giving an average even lower than 2’6”. However, in contrast to 2’6” Tx height, note that 6’6” Tx height can support all four orientations.

Figures 1(b) and 1(e) plot transport layer throughput for experiments done in the Corridor. Here, the average throughput increases for heights 4’6” and 5’6” but it reduces slightly for 6’6”. The 3’6” height, which performed similarly to 4’6” and 5’6” in the hall, fails to provide connectivity at orientations #4 and #8. In this case, 5’6” seems to be optimal height providing the highest average throughput.

To further ensure that we choose the best possible Tx height, experiments at both locations were repeated with an increased distance of 16’ between the Tx and Rx. Figures 1(c) and 1(f) plot the TCP throughput for Hall and Corridor, respectively (we omit UDP results which are very similar to TCP in the interest of space). In the Hall, 3’6” provides a throughput 100 Mbps higher than 5’6” but in the Corridor, 5’6” outperforms 3’6” by more than 200 Mbps. Lastly, in the Corridor environment, 5’6” can support all four orientations while 3’6” can give non-zero throughput only for two orientations.

A general observation from these experiments is that performance over 60 GHz indoor links is heavily affected by a number of factors – location, orientation, Tx height, Tx-Rx distance – and it is highly unpredictable; e.g., changing the Tx height by just 1’ can improve or deteriorate TCP/UDP throughput by several hundreds of Mbps. Hence, it is very hard to pick an optimal height for all possible locations, antenna orientations, and link distances. Overall, our experiments suggest that 5’6” performs better in general, although in some cases 3’6” shows better performance. We decided in favor of 5’6” since previous studies have concluded that larger Tx height results in propagation characteristics closer to the Friis model [21] as it reduces the chances of multipath caused by reflections from the floor. Also, from a perspective of deployment of WLANs, a larger height for the AP is desirable for a larger coverage distance/area. For the rest of the experiments, unless stated otherwise, we use 5’6” as the height of the transmitter.

5. PERFORMANCE ACROSS LOCATIONS AND ORIENTATIONS

Table 1: Measurement Locations

| Location# | Distance | Description |
|-----------|----------|-------------|
| 0         | 8’6”     | Hall        |
| 1         | 16’      | Hall        |
| 2         | 8’6”     | Corridor/Sym. |
| 3         | 8’6”     | Corridor/Asym. |
| 4         | 16’      | Corridor/Asym. |
| 5         | 8’6”     | Wall        |
| 6         | 8’6”     | Glass       |
| 7         | 8’6”     | Corner      |
| 8         | 8’6”     | Lab         |
| 9         | 24’      | Lab         |

Table 2: Measurement Orientations

| Orientation# | Rx | Tx | Orientation# | Rx | Tx |
|--------------|----|----|--------------|----|----|
| 0            | →  | ←  | 8            | ←  | ←  |
| 1            | →  | ←  | 9            | ←  | →  |
| 2            | →  | ←  | 10           | ←  | →  |
| 3            | ←  | ←  | 11           | ←  | ←  |
| 4            | ←  | ←  | 12           | ↓  | ←  |
| 5            | ←  | ←  | 13           | ↓  | ↓  |
| 6            | ←  | ←  | 14           | ←  | ↓  |
| 7            | ←  | ←  | 15           | ↓  | ↑  |

In this section, we study the impact of location and antenna array orientation on the performance of 60 GHz links. In addition to the Hall and Corridor locations, we study the performance in a number of other setups inside the building, representative of typical scenarios in an office environment, e.g., through different commonly found materials (e.g. wood, glass) or around corners, with different Tx/Rx orientations. We followed a methodology very similar to that in [23] and performed multiple experiments at each of the locations with same 16 different Tx/Rx orientations as in [23] (see Table 2 and Figure 4(b) in [23]). There is at least one setup for each location where the transmitter and receiver are placed rather close to each other (around 8 ft). This ensures that we measure the best case performance, when the signal does not attenuate severely as a function of distance. At a few locations, we also present results for longer distances for comparison.

5.1 Impact of location

Figures 2(a), 2(b), 2(c) plot the average RSSI, the selected PHY rates, and the average TCP throughput at each of the 10 locations. We consider both orientation #0, which represents the case when both the Tx and Rx antenna arrays are fully aligned, and the average across 16 orientations.

Figures 2(d) and 2(e) show that orientation #0 provides near best possible performance (RSSI between 80 and 100, TCP throughput between 800 and 900 Mbps) at all locations, except one (Location #7). In fact, the standard deviations
are negligible, indicating that the mean RSSI and throughput were sustained across multiple runs. Location #7 is a rather special case, where the Tx and Rx are placed around the edges of a corner, in a manner that there was no LOS path possible between them. Hence, similar to the findings in [23], we observe that high-throughput 60GHz links can be established through materials such as walls or glass. Although the signal does attenuate when it passes through such materials (Figure 2(a)), Figure 2(b) shows that, in the case of optimal antenna orientation, an NLOS link through a wall was able to sustain rates of 1540-3080 Mbps 80% of the time and an NLOS link through glass was able to sustain a rate of 2310 Mbps 95% of the time.

In contrast, the performance averaged across all orientations is much lower than for Orientation #0; RSSI (Figure 2(a)) and TCP throughput (Figure 2(c)) never cross their halfway mark (50 or 400 Mbps, respectively). Among setups with similar environment but different Tx and Rx distances (Locations #0 and #1, #3 and #4, #8 and #9), the setup with the smallest distance always performs better. Further, the extremely large standard deviations suggest very large performance variation at a given location for different orientations. This can be attributed to some orientations resulting in zero throughput, not even allowing a connection establishment between the sender and receiver. For example, in the presence of a wall or a corner between the sender and the receiver, non-zero throughput was achieved only at 3 orientations each. Even worse, in the case of Location #9 (a relatively long link in a research lab filled with “clutter” [2], i.e., objects that do not directly block the LOS between the Tx and the Rx, such as office furniture, soft partitions that do not extend to the ceiling, and lab equipment), Orientation #0...
was able to sustain high data rates (1925 Mbps or higher for 85% of the time) and high throughput, but no link was established for any of the remaining 15 orientations. Although [2] found that attenuation due to clutter decreases as we move from 2.5 GHz to 60 GHz, our results show that clutter can have a severe impact on 60 GHz performance, except in the case of very short distances or perfect antenna orientation. **Remarks** Overall, these results confirm that high-throughput 60GHz communication is feasible at various locations typical of an indoor WLAN environment but strongly point to the importance of the relative orientation between the Tx and Rx antenna arrays. Although communication is possible in the case of antenna array misalignment, either via beamsteering or through an NLOS link via reflection, the performance can vary significantly depending on the location and Tx-Rx distance and can be much lower than in the case of optimal orientation.

### 5.2 Impact of Tx/Rx orientation

We now take a closer look at the performance of each of the 16 orientations. Figures 3(a), 3(b), 3(c) plot the the average RSSI, the selected PHY rates, and the average TCP throughput at each orientation, averaged across all locations. We also consider separately Location#0, which represents the best-case scenario (LOS over 8 ft).

Figure 3 shows that orientations #0, as expected, performs the best among all orientations. Interestingly, orientations #4, #8, and #12, i.e., cases where the Tx points directly towards the Rx location, as in the best scenario, but the Rx is rotated by 90°, 180°, or 270°, give very similar and significantly higher throughput than all other orientations, indicating that the Tx position is more critical to performance. On the other hand, orientations #1, #2, and #3 where the Rx is fixed facing the Tx location and the Tx is rotated in 90° intervals are characterized by throughputs lower than 450 Mbps, and rather large standard deviations. Even worse, for any given Tx orientation except the one directly facing the Rx location (#0, #4, #8, #12), all Rx orientations except the one directly facing the Tx location give extremely low or zero performance. E.g., consider orientations #1, #5, #9 and #13, where Tx orientation is fixed, in Figures 3(a), 3(c), among them, only orientation #1 gives non-zero RSSI/throughput.

The heavy impact of antenna orientation may initially sound counter-intuitive for Wilocity radios, since they are equipped with electronically steerable antenna arrays. However, practical 802.11ad phased antenna arrays cannot generate homogeneous beams across all directions [13]: this has been recently verified experimentally in [21].

**Orientation/link asymmetry** One additional observation from Figures 3(a), 3(b), 3(c) is that, at Location #0 (Hall), orientations #4 and #12, which are symmetric w.r.t the Tx position, do not give similar throughput. The same observation can be made about orientations #1 and #3, which are symmetric w.r.t the Rx position. To eliminate the impact of environmental asymmetry (there are still walls in the Hall although far from the Tx-Rx link, as well as furniture), we looked at the results at Location #2 (a Corridor with walls of the same material on both sides). The result was similar (we omit it here due to space limitation). Further, [21] showed that 60 GHz links exhibit link asymmetry (downlink and uplink throughput are different when the Tx and Rx use different beamwidths). These orientation and link asymmetries make it extremely hard to predict and/or accurately model performance in indoor environments.

**Outdoor experiments** In case of Tx/Rx antenna array misalignment (orientations other than #0), communication can be achieved either via beamsteering which allows for realignment of the main beam or over an NLOS link through reflection. Since the Wilocity radios neither allow us to control the beam steering process nor provide any information about it, we resorted to outdoor experiments in order to obtain a better idea about the factor that allows communication at different orientations. Specifically, we repeated the experiments for all 16 orientations at an outdoor open space devoid of reflective and/or obstructive surfaces and objects. Only four orientations (0, 4, 8 & 12), where the Tx faces the Rx gave non-zero throughput.

**Remarks** The results show that COTS 802.11ad devices can establish Gigabit links even with imperfect Tx/Rx orientation. In indoor environments, the presence of multiple reflective surfaces creates additional opportunities via NLOS links, although the throughput of such NLOS links is typically much lower compared to the throughput of LOS links. We conclude that Tx orientation is more important in determining the performance and the possibility of a connection. On the other hand, orientations where neither of the Tx or Rx antenna point toward the other’s location, are not suitable for communication at all. Further, due to the complex indoor environment, symmetric properties cannot be assumed.

### 6. IMPACT OF DISTANCE

In the last section, we only focused on the relative orientation of Tx and Rx antenna arrays and hence most experiments were conducted with Tx and Rx very close to each other, to avoid the effects of severe signal attenuation of the 60 GHz radio signal. However, for mmWave technology to be a viable option for building WLANs, it is necessary to examine how channel quality indicators, RSSI and PHY data rate, and the corresponding transport layer throughput, vary with the distance between the transmitter and the receiver. Figures 4, 5 plot the RSSI, the PHY rate distribution, and the TCP throughput over distance at the two main locations: Hall and Corridor.

**Range** A common belief is that 60 GHz’s range is too short even in free space due to the very short wavelength and highly directional antennas are required for communication at longer distances. Figures 4 and 5 disprove this belief, showing that long ranges can be achieved even with radios designed for short-range indoor applications which use relatively wide beams and have lower EIRP (23 dBm) than
maximum allowed by FCC (40 dBm) \[29\]. The Corridor measurements show that RSSI exhibits large oscillations\(^2\) but does not drop with distance beyond 40 ft (Figure 5(a)) and a PHY data rate of 2310 Mbps can be supported at a distance of 170 ft (Figure 5(b)). The Hall measurements show a different picture, closer to what one would expect, with RSSI gradually dropping with distance up to 75 ft (Figure 4(a)) but even in this case, the link was able to support a rate of 1540 Mbps or 1925 Mbps roughly 70% of the time at a distance of 130 ft (Figure 4(b)). These ranges are much longer than the values reported recently with the same hardware (770 Mbps at 72 ft in a datacenter \[30\], 385 Mbps at 72 ft and 2310 Mbps at only 33 ft in an outdoor environment \[29\]).

**RSSI vs. distance** Recent experimental work \[5, 28, 29, 30\] observed that the attenuation of 60 GHz signals with distance follows closely the Friis model in LOS scenarios, both in stable datacenter and outdoor picocell environments. The validity of the free-space propagation model has led to the use of simple RSS-based rate adaptation algorithms in simulators \[5, 28, 23, 30\] and the use of RSS as a direct indicator of the PHY data rate \[29, 21\]. We discuss the validity of the Friis model in indoor WLAN environments in this section and the relationship between PHY data rate and RSSI in Section 7.

In Figure 3 (Hall), we observe that the distance axis can be divided in 3 distinct regions. For distances up to 20 ft, RSSI remains close/equal to 100 and the link can sustain the highest PHY data rate almost 100% of the time (Figure 4). The next region is between 25 ft and 75 ft where RSSI decreases with distance. Lastly, distances between 80 ft and 130 ft are characterized by extremely large RSSI oscillations; RSSI drops to zero at several distances and then rises again, often to high levels. Although we cannot confirm it, we believe these link outages are the result of multipath. We also hypothesize that such “dead zones” might have led researchers previously \[29, 30\] to conclude a much shorter range for the Wilocity radios. It is possible that narrower beams can eliminate dead zones at the cost of higher vulnerability to blockage and mobility \[21\]. Investigating this tradeoff is part of our future work.

In Figure 5 (Hall), we observe a different behavior, characterized by 4 distinct zones. RSSI shows a decreasing trend with distance only for very short distances (5-15 ft), remains almost stable for distances 20-40 ft, exhibits very large variations and non-monotonic behavior but non-zero values for distances longer 40-110 ft, and finally exhibits “dead zones” at distances longer than 110 ft.

Overall, the large variability of RSSI with distance indicates the presence of strong multipath in typical WLAN environments.

**PHY data rate vs. distance** Figure 4(b) and 5(b) show that for most distances there are 2 or 3 dominant data rates, and the lowest rate of 385 Mbps is used at least 10% and up to 60% of the time, even in the case of very short distances/high RSSI (with the exception of very short distances in the Hall). This observation suggests highly time-varying channels and/or inability of the rate adaptation algorithm

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\(^2\)Due to a phenomenon known as waveguide effect \[19\].
to converge to a single rate (note that the experiments were performed in a stable environment with no human presence).

In the Hall experiments (Figure 4(b)), we still observe a monotonic decrease with distance and RSSI; lower data rates dominate at longer distances/lower RSSI values. In contrast, there is no such monotonicity in the corridor.

Figures 6(a) and 6(b) compare the measured dominant rates against the theoretically computed rates from (1). We observe that the conservative models which account for reflection losses significantly underestimate the data rate; if we assume a 15/7 dB loss, only the control data rate (27.5 Mbps) can be supported for distances longer than 30/65 ft. On the other hand, assuming zero loss due to reflections results in overestimation of the data rate for short distances (up to 30 ft) and underestimation for long distances in both environments, potentially due to a combination of multipath and waveguide effects. Overall, we observe that PHY data rate cannot be predicted from simple propagation models in indoor WLAN settings.

Remarks The results in this section show that RSSI does not drop monotonically with distance. This observation suggests
that, in contrast to observations made by previous works in indoor datacenter or outdoor picocell environments, propagation in typical indoor WLAN environments does not follow simple propagation models from the literature due to the presence of strong multipath, and calls for new propagation models in 802.11ad simulators. The rate adaptation logic cannot converge to a single rate most of the time even in the case of high RSSI indicating a weak (if any) correlation between the two metrics. PHY data rate and throughput show a weak correlation with distance in certain environments (Hall) and no correlation in other environments (Corridor).

7. RELATIONSHIP AMONG RSSI, PHY DATA RATE, AND THROUGHPUT

In the previous section, we saw that distance cannot serve as a strong indicator of link quality (RSSI, PHY data rate) and higher layer throughput. In this section, we take a closer look among the three metrics – RSSI, PHY data rate, and TCP throughput – and investigate whether one of them can be used as a strong indicator of the other. In particular, we examine whether (i) RSSI can be used to predict PHY data rate and/or TCP throughput and (ii) PHY data rate can be used to predict TCP throughput.

**PHY data rate, throughput vs. RSSI** Since RSSI varies during a 10 sec iperf 3 session, we had to consider a finer time granularity to investigate the relationship between RSSI and PHY data rate/TCP throughput. We divided each session in 100 ms intervals and selected only those intervals where a particular RSSI value was observed at least 90% of the time. We then grouped the dominant RSSI values observed in the selected intervals in bins of 100 units. Figures 7(a) and 7(b) plot the PHY data rate distribution and the average TCP throughput over RSSI in the Hall. Figures 8(a) and 8(b) repeat the same graphs in the Corridor.

We first focus on PHY data rate. Figures 7(a) and 8(a) show that RSSI can serve as a (weak) indicator of PHY data rate at a given location; for most RSSI values, there is a dominant data rate appearing more than 60% of the time. The situation is better in the Hall where we also observe a monotonic relationship between the two metrics – higher dominant data rates for higher RSSI values. However, the picture changes when we compare the two locations. For the same RSSI bin, the observed data rates can be very different at the two locations. For example, for low RSSI (20-30), the data rate remains constant at 385 Mbps in the Hall but can take the values of 770 Mbps or 962 Mbps 40% of the time in the Corridor. As another example, for very strong RSSI (90-100), the data rate in the Corridor takes its lowest value (385 Mbps) 50% of the time.

We now look at the throughput. Figure 7(b) shows that RSSI can serve as a reliable although coarse-grained indicator of throughput in the Hall. We clearly distinguish 3 regions – high throughput region (600-900 Mbps for RSSI higher than 70), medium throughput region (400-700 Mbps for RSSI between 40 and 70), and low throughput region (0-300 Mbps for RSSI lower than 40), with only one “grey zone” (RSSI 60-70 and 70-80). The picture is very different in the Corridor. Instead of distinct regions, here we observe a monotonic increase of the average throughput with RSSI. However, the standard deviations are very large (100-200 Mbps) except in the case of very high RSSI values. We also observe that, for the same RSSI, throughput, similar to the data rate, can be very different in the two locations, making prediction different across locations.

**Throughput vs. PHY data rate** Similar to RSSI, the PHY data rate also varies during a 10 sec iperf 3 session. Hence, we used a similar methodology to investigate the relationship between PHY data rate and TCP throughput. We selected only the 100 ms intervals where a particular data rate was reported at least 90% of the time. Figures 7(c) and 8(c) plot the average TCP throughput over the PHY data rate in the Hall and Corridor, respectively.

A first observation from these figures is that some data rates are never selected consistently over a 100 ms period. The two highest data rates result in high throughput values and small standard deviations in both locations. However, for the remaining data rates, throughput varies significantly with standard deviations often higher than 200 Mbps. In the Hall, higher data rates typically result in higher throughput ranges. On the other hand, in the Corridor, several data rates have overlapping throughput ranges. Overall, the PHY data rate cannot serve always as a good indicator of throughput.

**Remarks** The results in this section show that RSSI can only serve as a weak indicator of PHY data rate and TCP throughput and only at certain locations, but not across locations. This observation has two immediate implications. First, translating signal strength to PHY data rate, a common practice in recent measurement studies [29, 21], can yield inaccurate results in typical indoor WLAN environments; the same observation is true for legacy 802.11 (e.g., [26, 11]). Second, simple RSS-based rate adaptation algorithms, which have been used in recent simulation studies [5, 28, 23, 30], may not be effective; more intelligent algorithms may be required in complex environments. Further, PHY data rate is not always a good indicator of higher layer performance.

8. SPATIAL REUSE

One of the major advantages of the 60 GHz technology is spatial reuse, thus enabling efficient use of the channel airtime. Although the use of directional links makes it harder for sensing-based MAC (CSMA/CA) to work as desired, it allows for concurrent transmissions on the same channel. In this section, we use three representative topologies to look at the degree of spatial re-use allowed by our hardware which uses wide beams of $30^\circ - 40^\circ$.

Each topology consists of three links inside our lab, which houses 22 cubicles and is full of office-like furniture (chairs, desks, computer systems etc.). Each of the links is setup at a
height of 4 ft and a LOS path exists between the Tx and Rx. In topology 1 (Figure 9(a)), the links are placed parallel with separation of 8 ft. between consecutive links. For topology 2 link 2 is perpendicular to links 1 and link 3. Topology 3 is emulates a case where multiple users are co-located and are serviced by three different APs. All three links operate on the same channel. For each topology, we measure TCP throughput of each individual link when it is operating alone and when all three links are active at the same time. To quantify the degree of spatial re-use, we use the spatial reuse factor $\beta$ introduced in [21], which is equal to the sum throughput of concurrent links divided by the average throughput of isolated links$^3$.

Table 3 summarizes the results. Topology 1, where links are distant enough that side lobes do not cause interference, provides for maximum spatial reuse. Topology 2 provides the least spatial reuse as Links 1 and 3 get around 60% of their isolated throughput. In topology 3, spatial reuse is better than in topology 2, even though the receivers of the three links are located very close to each other. On the other hand, spatial reuse for 802.11ac is close to 1 as it does not allow for concurrent transmissions.

Table 3: Spatial Reuse Factor ($\beta$)

| Topology 1 | Topology 2 | Topology 3 | 802.11ac |
|------------|------------|------------|----------|
| $\beta$    | 2.95       | 2.16       | 2.78     | 0.92     |

Remarks: The results demonstrate a large advantage of 802.11ad over legacy WiFi. Even with imperfect hardware using wide beams and sidelobes, spatial reuse is much higher than in the case of 802.11ac. This result combined with the higher data rates of 802.11ad compared to 802.11ac and the very small form factors of mmWave technology make 802.11ad a strong candidate for delivering the multi-fold throughput increase in future WLANs.

9. IMPACT OF HUMAN BLOCKAGE

The inability of 60 GHz links to pass through human body without suffering severe attenuation, owing to the small wavelength of the carrier wave, is often described as one of the major challenges for the mmWave technology. A human in the LOS between the transmitter and the receiver can attenuate the signal by 20-30 dB [18], resulting in link outage. [29] found that in outdoor picocell settings the impact of static pedestrians is limited in a very small area around the user due to the base station height (6 m). However, the impact of groups of moving pedestrians becomes heavier. Recent studies in indoor settings [23, 21] showed that human blockage remains a major challenge, and becomes worse due to the long re-connection times of existing 802.11ad hardware. We investigate the severity of this problem through two sets of experiments.

9.1 Controlled experiment

We performed experiments in the Hall and Corridor with controlled human placement and motion. We study the blockage caused by both permanent human obstruction of the LOS.
link and transient motion which disrupts the link temporarily. We are primarily concerned with measuring the reconnection time and throughput degradation.

At each location, we tried four different Tx-Rx distances (8’6”, 16’6”, 24’6”, and 32’6”). At each location, we considered two kinds of blockage: mobile and static. In the former, a person walks in random fashion along the LOS path between the Tx and Rx. If the link breaks as a result of such motion, the human moves away from the link to allow it to recover. In the latter, a person stands permanently between the Tx and Rx, forcing the Tx to find an alternate NLOS path. In cases where the link does not break in spite of the blockage, we measured the throughput degradation caused due to human presence. Table 4 summarizes our findings, plotting the average values over 5 experiments. A zero reconnection time indicates that the link did not break; in that case, the value in brackets indicates the observed TCP throughput. An infinity (∞) value means that the Tx was unable to re-establish the link even several minutes after introducing the blockage.

Table 4: Reconnection time and throughput in case of human blockage (M:mobile, S:Static).

|       | 8’6” | 16’6” | 24’6” | 32’6” |
|-------|------|-------|-------|-------|
| Corridor |      |       |       |       |
| M      | 0    | 0     | 0     | [728] |
| S      | [573]|       | |       |
| Hall   | 15.34| 15.42 | 16.07 | 16.61 |

In the Corridor, the link was resilient to transient human obstruction for distances upto 24’6”. For a Tx-Rx distance of 8’6”, the link did not break even in the presence of permanent human blockage. Note though that throughput, which was always higher than 800 Mbps before the appearance of the human, dropped significantly in some cases. For larger distances, the Tx failed to find an alternative path in the presence of permanent human blockage. Note that in order to simulate the worst case, the person in most cases stood very close to the Tx or Rx making it harder for the Tx to search for a new path. On the other hand, human blockage introduced mid-way between the Tx and Rx failed to break the link. Lastly, for even greater distance (32’6”), the link failed under human mobility and it took upto 16.6 seconds for it to be established again.

The results in the Hall are very different. The link broke under human mobility for all distances and reconnection times were in the range of 15.34 to 15.67 seconds, similar to the Corridor case, and much longer than the values reported in [23][29]. The absence of any reflective surface in the immediate vicinity of the Tx made it harder for Tx to quickly find an alternative path when it was blocked momentarily. In case of static blockage, the Tx failed to find a NLOS path in all cases.

Remarks The results of the controlled experiments indicate that a static human near the Tx or Rx presents a much bigger challenge compared to transient blockages introduced by human motion. Nonetheless, the reconnection times are extremely high when considered in the context of multi-Gbps throughput. One potential way to address this problem is beam dilation, although [21] showed that it only works under high SNR scenarios. Hence, there is a need for faster, more efficient rebeamforming algorithms, potentially combined with mechanisms that distinguish the cause of link outage (human blockage or client mobility), as different approaches work better in each scenario [21].

9.2 In the wild experiment

The controlled experiments gave an insight into the challenges arising out of the presence of humans into the environment. However, two questions remain unanswered: (i) how often would such blockages occur in a typical WLAN and (ii) can serving a client with multiple APs (similar to the BS picocloud scenario in [29] for 60 GHz outdoor picocells) help mitigate this problem? To answer these questions, we used a methodology similar to that of [29] since Wilocity radios do not allow switching between APs on-the-fly. We deployed three links in our lab, very close to each other, emulating a single client which can potentially connect to any of the three docks/APs, in a topology very similar to that of Topology 3 (Figure 9(c)) for a period of 15 hours. The 15 hour experiment period included both night hours and day hours of the following day. We recorded per second TCP throughput for each of the three links.

Figures 10(a), 10(b), and 10(c) present the CDF of throughput in three cases when one, two, or three APs are considered to be deployed. In the first case, where we assume that only one of the 3 APs was available for connection to the client,
we see that each of the links was blocked/disconnected (zero throughput) for less than 5% of the time and two of the links maintained a throughput between 600 and 700 Mbps most (around 70%) of the time. However, throughput above 800 Mbps was achieved for less than 5% of time by each link.

When considering 2 APs, we have 3 possible combination of APs. Further, for each combination, we plot both the best throughput achieved out of the two APs and the worst one for comparison. Interestingly, all the three combinations gave a 0 percentage of disconnection time, indicating that two APs would have been sufficient for maintaining 100% uptime.

For the 3-AP case, we show the best and worst throughput CDFs. If a client were to connect to the best AP all the time, it would never experience disconnection and would maintain a median throughput of around 680 Mbps.

**Remarks** Our 15 hour experiment showed that the presence of humans in a typical office environment does not have a significant impact on connectivity but can cause a significant throughput degradation. However, using 2 APs per client can provide 100% uptime and high throughput.

10. CONCLUSIONS

In this paper, we investigated the feasibility of building general-purpose indoor multi-gigabit 60 GHz WLANs by conducting an extensive measurement study in a typical academic office building using commercial 802.11ad hardware. We studied the range of 60 GHz transmissions in indoor environments, and the impact of antenna height, location, orientation, and distance on 60 GHz performance at multiple layers of the protocol stack. We explored the interaction between link layer indicators and transport layer throughput. We also studied spatial reuse opportunities and the impact of human blockage. Our results indicate that the 60 GHz technology can indeed be a viable option for building multi-gigabit WLANs but there are several challenges that need to be addressed before 60 GHz WLANs can be realized in practice.

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