On the Feasibility of Indoor IEEE 802.11ad WLANs

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***Abstract*—In this work, we argue against the common belief that millimeter-wave (mmwave) technology is not a viable option for building general purpose *indoor* WLANs due to the high directionality and susceptibility to blockage of 60GHz links. Our initial experiments, with commodity 802.11ad hardware, present a very encouraging picture, as far as range and blockage by commonly found materials in indoor WLAN environments is concerned. We observe that, while a typical indoor environment presents unique challenges in terms of presence of obstacles, it also provides communication opportunities with multiple available paths between the sender and receiver through the abundance of reflective surfaces. Our results clearly indicate that previously reported observations regarding 60GHz links inside datacenters or outdoor picocells do not apply to an indoor WLAN setup and thus motivate further work towards building multi-Gigabit indoor 802.11ad WLANs.**

I. Introduction

The millimeter-wave (mmwave) technology, standardized by the recent IEEE 802.11ad specification, has emerged as an alternative to the traditional 2.4/5GHz wireless systems, promising multi-Gigabit throughput. However, the special propagation characteristics of high frequency radio waves centered around 60GHz have limited its applications to being a replacement for high-speed wired links in line-of-sight (LOS) scenarios such as datacenters or home networks. The high directionality of 60GHz links and their susceptibility to blockage have led to the assumption that mmwave radios are unsuitable for NLOS topologies common in general-purpose home/enterprise WLANs.

In this work, we try to show the feasibility of using mmwave links in a scenario very different from the typical use cases in the literature which were characterized by large open spaces providing direct LOS [1] paths but largely devoid of reflective and/or obstructive surface 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, a typical home/enterprise WLAN environment presents a much higher complexity, with many objects/surfaces that can attenuate, completely block, or reflect the signal making it harder to predict the link behavior. Our work experiments with such an environment and presents results indicating that even the currently available commercial hardware can provide reasonable performance in a typical indoor WLAN setup.

Related work Our work is not the first to investigate the feasibility of 60GHz links indoors. In [2], Tie et. al. study link level performance of 60GHz links with respect to blockage and antenna orientation. However, they use custom designed non-802.11ad hardware and measure performance of IP-over-wireless-HDMI; in contrast, we use off-the-shelf 802.11ad hardware and measure performance of real transport layer protocols: TCP/UDP. Recent work has also argued for the use of 60GHz technology to augment datacenters [1] or to build outdoor picocells [3]. These scenarios are very different from the one we are concerned with and we show that observations reported in these works do not hold for our use-case.

II. Experimental Methodology

In our initial experiments, we found that our hardware can provide indoor connectivity upto 165 feet. However, in this work we focus mainly on studying the impact of location and/or antenna orientation. We conducted experiments at 10 different locations/setups inside the Computer Science building of the University at Buffalo. We followed a methodology very similar to that in [2] and performed multiple experiments at each of the locations with same 16 different orientations of the Rx and Tx antenna as in [2] (see Table I and Figure 4(b) in [2]). The chosen setups are diverse and represent the wide variety of scenarios that would typically occur in an office environment. 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 few locations, we also present results for longer distances for comparison.

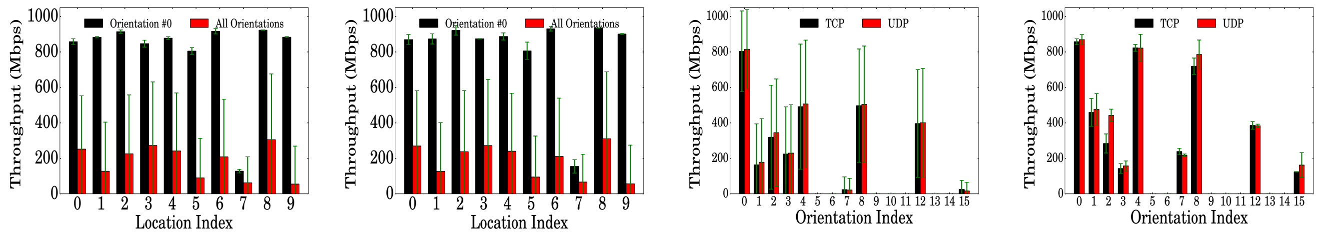
TABLE I. Measurement Locations and Orientations

L#	Distance	Description
0	8’6”	Open Space
1	16’	Open Space
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

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

Our 802.11ad link setup consists of two commercially available devices: a Dell Latitude E420 laptop equipped with a Wilocity wil6210 802.11ad radio and a Dell Wireless Dock D5000 (AP). Another laptop is connected to the dock through a Gigabit Ethernet interface to generate/receive TCP/UDP traffic. The use of the Ethernet interface limits the transmission/reception speeds to 1 Gbps, even though the wireless link itself is capable of much higher speeds.

We used iperf3 to generate TCP and UDP traffic. Each experiment consists of a 10-second TCP session followed by a 10-second backlogged UDP session. All the results are the average of 5 sessions. All experiments were performed late night to remove the possibility of human blockage; study of the impact of human blockage is reserved as future work. This



(a) TCP throughput across locations. (b) UDP throughput across locations. (c) Throughput across orientations (All locations). (d) Throughput across orientations (Location #0).

Fig. 1. Average TCP and UDP throughput for different locations and orientations.

work only deals with static objects present in the building environment. The wireless cards report the PHY data rate chosen by the internal rate-adaptation mechanism and an RSSI value between 0 and 100. We also obtain the application layer throughput every 0.1 second from iperf3.

III. TCP/UDP Performance across Locations

TCP Performance Figure 1(a) shows the average TCP throughput achieved at each of the 10 locations, both for orientation #0, which represents the case when both the Tx and Rx antenna arrays are fully aligned, and the average across 16 orientations. We observe that orientation #0 provides for near best possible performance (between 800-900 Mbps) at all locations, except one (Location #7). In fact, the standard deviations are negligible, indicating that the mean throughput was 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. Further, similar to the findings in [2], we observe that high-throughput 60GHz links can be established through materials such as walls or glass. In fact, for orientation #0, both glass and wall give throughput comparable to that of open space or corridor.

In contrast, the throughput averaged across all orientations never crosses the halfway 400 Mbps mark. Further, the extremely large standard deviations suggest very large throughput 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.

Lastly, between setups with similar environment but different distances between Tx and Rx (e.g., Location #0 and #1), the one with the smaller distance always performs better.

UDP Performance Figure 1(b) shows that UDP performance mirrors very closely the corresponding TCP performance observed before. For orientation #0, this suggests that TCP did not suffer high packet loss or re-ordering and was able to utilize the full bandwidth available. Interestingly, the average UDP throughput across all orientations also matches closely TCP throughput, indicating that even with orientations that failed to provide maximum throughput, link layer retransmissions were enough to recover losses (if any) and TCP did not have to cut down its congestion window.

These observations 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.

IV. TCP/UDP Performance across Orientations

We now look more closely at the performance of each of the 16 orientations. Figure 1(c) plots the average TCP and UDP throughput at each of the 16 orientations averaged across the 10 locations. Orientation #0, as expected, performs the best among all orientations. Interestingly, orientations #4, #8, and #12, cases where the Tx points directly towards the Rx location, as in the best scenario, but the Rx is rotated by 90^o, 180^o, or 270^o, give very similar and significantly higher throughput than all other orientations, indicating that the Tx position is more critical to performance. Orientations #1, #2, and #3 present situations where the Rx is fixed facing the Tx location and the Tx is rotated in 90^o intervals. These three orientations are characterized by throughputs lower than 450 Mbps, and rather large standard deviations, which means that the throughput in such orientations depends on the location and environment (presence of reflective surfaces, etc.). 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 throughout. E.g., consider orientations #1, #5, #9 and #13, where Tx orientation is fixed. Among them, orientation #1 gives high throughput while others give zero throughput.

Lastly, to further investigate the effect of orientations, Figure 1(d) plots the throughput over all orientations for Location #0, where maximum number of orientations give non-zero throughput. Orientations #4 and #12, which are symmetric w.r.t the Tx position do not give similar throughput for this particular location. Same observation can be made about orientations #1 and #3, where the Tx position is symmetric with respect to a fixed Rx position.

We conclude that Tx orientation is more important in determining the throughput 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. In general, large standard deviations in throughput indicate a larger problem of providing predictable performance guarantees at the application layer, for all location and orientation combinations.

References

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