60 GHz Networking: Mobility, Beamforming, and Frame Level Operation From Theory to Practice

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Abstract—Understanding the gap between theory and practice of 60 GHz networks is crucial. Theoretical models typically focus on the physical layer only and assume ideal hardware components. However, such assumptions do not hold in practice. For instance, the cost-effective design of commercial off-the-shelf products often results in hardware impairments, such as highly irregular beam shapes. Further, mobility and frame aggregation have a strong impact throughout the protocol stack. Taking these effects into account when designing 60 GHz networking mechanisms is critical. In this paper, we characterize the aforementioned effects and contribute a comprehensive dataset of real-world traces that capture them. Among other traces, our dataset includes measurements of actual beam patterns, the impact of the cases of the devices on propagation, exhaustive measurements on the degradation of link performance in case of mobility, and the behavior of aggregation at the physical layer. Our dataset is the most comprehensive study of this kind to date. As a result, our work allows researchers to take the aforementioned hardware impairments into account, which paves the way for comparable and realistic evaluations of 60 GHz networking mechanisms in the community.

Index Terms—C.2.8.c Mobile Communication Systems, C.2.1.k Wireless Communications, C.2.5 Local-Area Networks

1 INTRODUCTION

Developing robust consumer-grade devices for millimeter wave wireless networks is challenging. In contrast to 802.11n/ac networks operating in the traditional 2.4 and 5 GHz bands, devices based on the recent 802.11ad standard [1] for operation in the unlicensed 60 GHz band must overcome significant hurdles. This includes handling 2.16 GHz wide channels, using directional beamforming antennas to overcome the increased attenuation at these frequencies, and dealing with a highly dynamic radio environment [2]. Existing work studies the individual factors that such a system must address regarding both the characteristics of 60 GHz communication—fading [3], reflections [4], frequency selectivity [5]–[7], and multipath effects [7], [8]—as well as the design of hardware such as phased antenna arrays [9]. The challenge is that consumer-grade devices must be able to handle the resulting complexity of the overall system while still being cost-effective.

This has naturally led to the use of cost effective components in consumer-grade 60 GHz systems. For instance, current devices use electronic beam steering with phased arrays with relatively few antenna elements. As a result, while the transmitters use directional beam patterns, they do not fully achieve the 60 GHz vision of extreme pencil-beam focusing and negligible interference. While this is qualitatively well-known, it raises a crucial question: how large is the practical, quantitative impact of such limitations? Understanding this impact is fundamental since the aforementioned limitations may undermine common 60 GHz assumptions. This in turn is key to design protocols that can reliably operate at millimeter wave frequencies. As a quantitative analysis of these limitations is missing, related work in this area is often based on diverse assumptions. For instance, assumptions on the shape of beam patterns range from triangle-shaped sectors as in the IEEE 802.11ad standard [1] to ideal lobes as defined by theoretical formulas [10]. Neither reflects the actual shape of practical beam patterns. This also hinders the comparison of results among papers. Previous work on practical 60 GHz networks based on consumer-grade devices is limited to studying the impact of human blockage [11] and transmission range [12]. Also, existing studies do not make traces available for reuse. As a result, the following issues remain unanswered:

A. Directional communication. How directional are consumer-grade phased antenna arrays? How large is the actual impact of side lobes?
B. High spatial reuse. How close can devices operate without experiencing collisions? How strong is the impact of interfering reflections?
C. High data rates. Which coding and modulation schemes are feasible? What is the impact of data aggregation at such high physical layer rates?
D. Area-wide coverage. What is the performance of 60 GHz devices at all locations within a room to assess the operation of dense millimeter-wave deployments and study coverage issues?
E. Beamtracking under mobility. How well can existing devices track user movement and adapt their beamsteering accordingly? How beneficial would it be if devices had multiple antenna arrays, thus avoiding shadowing by the device itself?
F. Robustness under mobility. How frequent are link losses? Can nodes move out of the omni-directional discovery range of a base station due to the use of directional beampatterns for data transmission?

In this paper, we provide answers to the questions above. To this end, we use a down-converter to overhear and analyze the communication of 60 GHz devices. This gives us unprecedented insights into link utilization, beam patterns, and frame level operation. These results are based on our earlier work [13], [14], but we vastly extend it by means of a robotic measurement platform to perform the aforementioned exhaustive area-wide coverage measurements in indoor environments. Moreover, we integrate this platform with a custom hardware monitor to access firmware registers that reveal lower-layer details. Our analysis allows us to determine the key limitations of 60 GHz consumer-grade hardware, which opens the door to future work on mechanisms that address these limitations. Most importantly, we make our measurements available to the community [15] in a format which allows other researchers to build on them. This is highly relevant, as it enables realistic and comparable results. Our contributions are as follows:

1) We provide a frame level analysis of 60 GHz protocols, studying parameters such as frame length and showing that existing devices only use data aggregation if a connection requires high throughput. Otherwise, they do not aggregate, even for traffic that is not delay-constrained, thus resulting in inefficient medium usage.

2) We measure the beam patterns that our devices use. We show that the patterns suffer significant imperfections, such as high irregularity and very strong side lobes of up to −1 dB compared to the main lobe.

3) We evaluate the impact of interference due to side lobes and reflections. We find that interfering reflections from neighboring, unaligned devices may reduce the achievable TCP throughput by more than 20% of the value that would be achieved otherwise.

4) We study the performance of commercial 60 GHz devices under movement, showing that throughput decreases on average 30% compared to the static case. To this end, we perform a first-of-its-kind area-wide coverage measurement in an indoor environment.

5) We show that additional arrays on a device can improve throughput up to 4× and reduce outage by 62%. Moreover, we observe that nodes can easily move out of the discovery range of each other during on-going communication due to the use of directional beampatterns.

The paper is structured as follows. Section 2 gives an overview of millimeter wave communication. Section 3 provides details on the tested devices and our setup. In Sections 4 and 5, we present our static and mobile analysis, respectively. Next, in Section 6 we discuss the insights that we gain from our results. Section 7 concludes the paper.

2 Background

In this section, we describe the characteristics of millimeter wave communications, and present related work in this area. Millimeter wave frequencies have been used for commercial wireless systems for several years. These first generation systems, however, were targeting mainly static or pseudo static application scenarios, like backhaul links (for example the HXI Gigalink 6451 system used in [12]) or transmission of uncompressed high definition video data [11]. With formation of the WiGig Alliance [16], the latter use case broadened to docking station applications and finally incorporated general WiFi use cases when, in 2012, WiGig was merged into the IEEE 802.11ad amendment. This amendment defines a unified millimeter wave communication standard for a variety of use cases, that include dense scenarios with indoor mobility [2]. The amendment adds so-called sector sweeps at regular beacon intervals. During a sweep, devices sequentially transmit beacons on each of their beam patterns. This allows nodes to discover each other, and determine the best pattern for communication. Within a beacon interval, devices can either use random or scheduled access. The latter avoids certain issues of random access in directional networks, such as collisions due to deafness. However, existing devices do not implement it.

Transmission Characteristics. Communication in the millimeter wave band has distinctly different communication characteristics than those of legacy ISM frequencies below 6 GHz. These differences mainly result from the increased attenuation of free space propagation and signal blockage in case of obstacles [17]. The increased attenuation of around 20-40 dB is typically overcome by highly directional antennas. These may also be used to circumvent blockage, using a propagation path via a reflection. Such reflections are possible if certain highly reflective materials are present [4]. Propagation parameters and channel models for understanding mmWave propagation have been compared and modeled by various research groups and standardization bodies [18]. Further, directional communication and blockage significantly lower the amount of interference on millimeter wave frequencies and allow for high levels of spatial reuse.

Beam Steering. With the central role of directional communication in millimeter wave systems, a device’s ability to steer its antenna beams becomes essential. As the size of antennas scales with the wave length, millimeter wave systems can integrate antenna arrays with a high number of elements even into small handheld devices. These antenna arrays allow electronic configuration of the antennas’ beam direction and provide very high directional gain. In contrast to lower frequency beamforming mechanisms, millimeter wave systems usually rely on beam steering via codebooks of predefined beam patterns that implement different directions, which reduces the complexity of the beam training process. While millimeter wave antenna arrays have been in use since first generation devices, their impact on system level network performance is not well understood, although realistic antenna patterns in mmWave cellular scenarios are being studied by means of simulations [19].

Work on Practical 60 GHz Networks. Insights into practical 60 GHz networks are limited since 802.11ad hardware is not yet widely available. At the time of writing, only two commercial wireless routers and a few mobile devices support 802.11ad. Related work uses WiGig and WiHD devices to study the performance of 60 GHz links. For instance, Zheng et al. [12] use off-the-shelf hardware to characterize 60 GHz links, dispelling a number of common beliefs regarding
millimeter wave communication. This includes showing that the range of such networks is large enough for outdoor communication, and that electronically steerable antenna arrays can deal with blockage as well as user motion. Still, in contrast to our work, they do not study and measure the beampatterns of off-the-shelf hardware nor do they perform area-wide measurements. Also, they focus on high-level metrics, while we analyze the frame level operation of WiGig and its behavior at the physical layer.

Ramanathan et al. [20] follow a different approach than [12] and, hence, us. Instead of measuring the performance of off-the-shelf devices, they use a custom-built software-defined radio that allows them to perform signal strength measurements at 60 GHz using horn antennas. Among other results, they show that different types of link breaks should be treated differently. For instance, a transmitter should change beam direction to avoid human blockage, whereas it should widen its beam to deal with mobility. Most interestingly, they show how the signal strength can be used for early detection of each type of link break. In contrast, we study actual data transmissions using hardware with electronically steerable phased antenna arrays. While [20] focuses on blockage, beam steering, and spatial reuse assuming horn antennas, we investigate topics such as reflections for range extension, data aggregation, and interference due to imperfections of commercial hardware.

**Mobility in 60 GHz Networks.** Mobility plays a key role in 60 GHz networks as even slight beam misalignments can undermine performance. By default, the 802.11ad protocol resorts to costly beam training when nodes move. Related work presents improvements on this behavior, such as short frames preceding data packets to assess the current state of the channel and react accordingly [21]. However, a holistic study that quantifies the performance loss of 802.11ad under mobility and analyzes the underlying reasons is missing. Such reasons include Modulation and Coding Scheme (MCS) fluctuations and increased Packet Error Rate (PER). While recent 60 GHz experiment platforms provide full access to such lower layer issues [22], they are not standard compliant and are based on hardware components that are very different from the ones used in commercial devices. Despite recent advances in terms of 60 GHz link robustness, mobility remains an open issue. Existing work mitigates the impact of link blockage [23], [24] but has only limited applicability to mobile scenarios. This paper reveals the key challenges of 802.11ad under mobility, as a starting point for future work.

### 3 Experiment Setup

In the following, we present the techniques that we use to obtain the 60 GHz networking trace dataset that we make available to the community. This goes well beyond simple measurements, since it includes partial reverse-engineering of the commercial systems that we consider, as well as filtering and processing the data for reuse by other researchers.

#### 3.1 Devices Under Test

We consider three different 60 GHz commercial devices (c.f. Figure 1). Our first device under test is the Dell D5000 wireless docking station. The D5000 dock is widely used in practical 60 GHz research since it was the first commercial device that largely implemented the mechanisms that later became the 802.11ad standard. It serves as a docking station for laptops with a compatible WiGig card. Broadly speaking, the dock acts as an Access Point (AP), and the connected laptop as a station. This system uses Wilocity Wil6100 “Marlon” cards, which are the precursor model of the cards used in 60 GHz routers at the time of writing. Most interestingly, these devices allow for access to lower layer information [14] such as the beampattern in use, control and data packet counters and the automatic gain control level, and are thus highly valuable for our analysis. After disassembling the D5000 dock, we found that it has a baseband chip connected to an upconverter and a 2x8 antenna array. The antenna covers a cone of 120°.

Our second device is a WiHD-compatible DVDO Air-3c system designed for transmitting HDMI data streams. The system consists of a transmitter and a receiver module that do not allow for any configuration. In terms of range and link stability, we found that the Air-3c performs better than the D5000 dock. Indoors, we could transmit video over 20 meters, even with misalignment and blockage on the direct path. Upon disassembly, we found on both sides of the link an antenna array with 24 elements placed irregularly.

Finally, our third device is the TP-Link Talon AD7200, which is the first commercial router operating in the 60 GHz band, and using the Qualcomm QCA9500 chipset which comes with a 32 element antenna array. We observe that its behavior is similar to the D5000 dock. Our lab measurements reveal that both devices use very similar chips. Due to these similarities and the aforementioned advantage of the D5000 docking station where we can access lower layer information [14] we are going to focus our study on the D5000 dock. The bandwidth of all of our three devices under test is 1.7 GHz, and they all operate on the channels defined in the 802.11ad standard. That is, their center frequencies range from 58.32 GHz to 64.80 GHz.

#### 3.2 Comprehensive Trace Collection

To collect physical layer traces for our dataset and our frame level analysis, we use a VuboIQ 60 GHz Development System connected to an Agilent MSO-X 3034A oscilloscope. This setup provides traces of the analog I/Q output of the VuboIQ receiver, and thus allows us to observe the individual frames on the medium. While we undersample the signal and thus cannot decode it, the traces allow us to extract the timing and amplitude of frames by processing them offline.
in Matlab. The VubiQ frontend supports downconversion of 1.8 GHz modulated bandwidth at the common IEEE 802.11ad/aj frequencies [25]. Further, it has a WR-15 input, which we connect to horn antennas with different levels of directivity. For beampattern measurements, we use a 25 dBi horn antenna. To obtain a wide beam pattern for protocol analysis, we use the open wave guide.

Further, we obtain transport layer throughput measurements for the D5000 dock using “iperf” [26]. Specifically, we run the iperf server on the E7440 laptop, and connect a second laptop via Ethernet to the D5000 dock. We run the iperf client on this second laptop, thus generating traffic on the wireless 60 GHz link. Moreover, we reverse-engineer the Wilocity Monitor Service on the D5000 dock to obtain access to a firmware interface of the Wil6100 card that reveals lower layer information [14]. Altogether, the above setup provides detailed information of the D5000 dock at the physical, medium access control, and transport layers.

Finally, for our comprehensive performance measurements in indoor environments, we use a robotic platform that obtains all of the aforementioned traces in an automated manner on a specific set of locations within a room. In particular, we use a Kobuki Turtlebot II robot to move the E7440 laptop along a grid of points within a large conference room. The robot uses a camera to follow a line marked on the floor and stops at fixed intervals to measure performance. At each location, it repeats this measurement for eight different rotation angles, covering an overall angular range of 360°. Except for our mobility analysis, we perform all measurements while the robot is static. We place the D5000 docking station next to a wall but pointing towards the room to recreate a realistic location of an AP. As a result, we obtain a comprehensive measurement database for the entire room area and virtually any orientation of the laptop. This gives us unprecedented insights into the practical performance of 60 GHz networks, since earlier work is limited to individual locations within a room.

4 Static Analysis

In this section we describe the results of our static analysis. We first present our findings on protocol operation and aggregation. Second, we analyze the beamforming of the D5000 dock. Third, we investigate the impact of reflections. Finally, we study the coverage of the D5000 in a wide area.

4.1 Protocol Analysis

Measurement Setup. To gain insights into the protocol operation of our 60 GHz devices, we use the VubiQ receiver as described in Section 3. To overhear the frames of both the transmitter and the receiver, we use the open wave-guide of the VubiQ system [1]. For the Dell D5000 dock case, we use Iperf to generate TCP traffic. This traffic is transmitted from the laptop to the docking station via the 60 GHz wireless link. For the wireless HDMI case, we transmit a high definition video signal. We use Matlab to post-process the traces, and obtain insights into frame and burst lengths. The latter allows us to analyze data aggregation.

Beacon and Discovery Frames. All of our 60 GHz devices transmit periodic control frames. Specifically, they transmit discovery frames to establish new links, and beacon frames to maintain an existing connection. Table 1 shows their periodicity. We observe that systems transmitting real-time video signals, such as the Air-3c, send beacon frames much more frequently than the Talon router. This allows them to maintain a very high quality of service in case of link impairments. Since the Talon router is not specifically designed for streaming, the beacon interval is larger.

Dell D5000 Dock. We observe that the communication of the Dell D5000 dock consists of three phases, namely, device discovery, link setup, and data transmission. These three phases match the Beacon Transmission Interval (BTI), the Association Beamforming Training (A-BFT), and the Data Transmission Interval (DTI) of 802.11ad, respectively. In the first stage, the D5000 dock transmits the aforementioned discovery frames. Figure 2(a) shows an example of such a frame. In the second stage, a complex association and beamforming process takes place. Our frame level analysis of the third stage shows that data transmission is divided into frame bursts. These bursts are equivalent to Beacon Intervals (BI) in 802.11ad, and their maximum length is 2 ms. Each burst begins with two control frames, which have a different amplitude than the subsequent series of data and acknowledgment frames, as shown in Figure 2(b). Outside the bursts, the channel is idle except for the regular beacon exchange between the docking station and the notebook (c.f. Fig. 2. Frame structure of the Dell D5000 docking station system.

<table>
<thead>
<tr>
<th>Frame type</th>
<th>Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5000/ Talon Discovery Frame</td>
<td>102.4 ms</td>
</tr>
<tr>
<td>WiHD Discovery Frame</td>
<td>20 ms</td>
</tr>
<tr>
<td>D5000 Beacon Frame</td>
<td>1.1 ms</td>
</tr>
<tr>
<td>Talon Beacon Frame</td>
<td>102.4 ms</td>
</tr>
<tr>
<td>WiHD Beacon Frame</td>
<td>0.224 ms</td>
</tr>
</tbody>
</table>

TABLE 1
D5000 dock, Talon, and WiHD frame periodicity
Table 1. We also investigate the impact of data aggregation. Figure 4 gives an intuition on the relevance of data aggregation at very high rates such as in 802.11ad. To study this issue, we measure the length of data frames for different TCP throughput values. We control the TCP throughput by adjusting its window size in Iperf. Figure 4(a) depicts the CDF of the frame lengths for each throughput value. The CDF reveals that most frames are either short (around 5 µs) or long (15 to 20 µs). That is, we can divide them into two categories. The length of long frames varies more than the length of short frames, which is due to different levels of aggregation. The highest level we observe corresponds to a frame duration of 25 µs. Further, the amount of long frames increases with throughput—the higher the traffic load, the higher the level of data aggregation.

Moreover, we investigate the level of medium usage for increasing throughput values. Surprisingly, Figure 4(b) shows that, beyond a relatively low throughput value, all oscilloscope traces contained data frames. That is, the transmitter transmitted continuously. We observed that this throughput increase at constant medium usage is due to a higher level of frame aggregation. That is, WiGig can scale throughput from 171 Mbps to 934 Mbps by simply increasing the amount of data in each frame, and thus vastly reducing the overhead due to medium access. According to Figure 4(a), WiGig only needs to aggregate 25 µs of data to achieve this massive improvement. For comparison, 802.11ac must aggregate 8 ms of data to achieve only a 2x improvement [27]. This is due to the much larger bandwidth of 802.11ad compared to 802.11ac. Any idle time due to MAC overhead translates into huge throughput losses. In addition, we verified that the transmitter used the same MCS for all traffic loads in Figure 4(a). That is, the throughput increase is not due to the use of a higher MCS. This is expected, since the MCS is typically not adapted to the link load but to the link quality.

Figure 5(a) shows the impact of the link length on the physical layer rate. The longer the link, the lower and more unstable the data rate. While Figure 5(a) depicts the link rate, in Figure 5(b) we show the average Iperf throughput at increasing distances. We observe that the throughput is approximately stable up to a certain distance d and then falls abruptly. This distance d varies significantly for different experiments. Thus, while the individual experiments exhibit the aforementioned abrupt behavior, the average falls gradually. We do not observe results beyond 900 Mbps because the Gigabit Ethernet interface at the docking station limits the achievable throughput. This is also the case for the Talon router. We conclude that the MCS drops gradually with distance to about 1 Gbps but then falls abruptly. In our experiments, the range of the Talon router was even higher, reaching up to 40 meters in an indoor corridor scenario. Our measurements suggest that such long links are feasible due to constructive interference from reflections.

DVDO Air-3c. Next, we analyze the frame flow for the DVDO Air-3c WiHD system. We observe the same communication stages as for the D5000 dock. When analyzing the data transmission stage, we found the beacon frame frequency to be much higher than for the D5000 system.
we rotated the notebook by 20° with respect to the laptop. Figure 7(c) shows the resulting docking station beampattern as an overlay. We observe that the gain of the main lobe is 10 dB below the gain that we measure when the devices face each other. That is, beamforming towards the boundary transmission area of the antenna array significantly reduces link gain. Also, we observe a much higher number of side lobes as strong as −1 dB with respect to the main lobe.

**Quasi Omni-Directional Search.** Implementing omni-directional antenna patterns is a major challenge for millimeter wave communication [28]. However, this kind of pattern is crucial for device discovery and beam-training [2]. The Dell D5000 system sweeps 32 different quasi omni-directional patterns during device discovery (c.f. Figure 2(a)). Figure 8 shows four out of these 32 beampatterns. The irregularities of the beampatterns are a natural result of our measurement setup—since we manually move the Vubiq receiver along the 100 measurement positions, small deviations are inevitable. Nevertheless, Figure 8 clearly depicts the rough shape of the lobes. While the HPBW can be as wide as 60°, each pattern contains several deep gaps that may prevent communication with devices at the corresponding angles. These gaps are due to the limitations of consumer-grade phased antenna arrays. However, probing multiple such patterns during device discovery mitigates the impact of such gaps, and allows the dock to cover the entire azimuth. The remaining 28 patterns are comparable in terms of directional focus and received signal power.

### 4.3 Reflections

**Reflection Analysis.** Next, we analyze the impact of reflections in a realistic wireless setting. This addresses the common assumption that the 60 GHz multi-path environment is very sparse compared to the 2.4/5 GHz case, and that reflections result from quasi-optical propagation in the direction of transmission. To this end, we set up a single 60 GHz link in an empty conference room, either using the D5000 dock or the WiHD system. We then measure the energy received from all possible directions at six different locations \{A . . . F\} in the room, as shown in Figure 9. To this end, we mount the Vubiq receiver with a highly directional horn antenna on a programmable rotation device and place it at each of the six locations. At each location, we then measure the incident signal strength for all directions and assemble the result to an angular profile. If no reflections occur, we expect to receive energy only from the direction in which the 60 GHz devices are located. For instance, at location A, we should only observe energy coming horizontally from the right and from above. Additional lobes in the angular profile indicate reflections. To analyze the impact of different materials, we perform the experiments in a room which has brick, glass, and wood walls. Figure 9 depicts the angular profiles that we measure for the D5000 dock. We perform the same experiment also for the WiHD system but we do not show the corresponding figure due to space constraints. In both cases, most angular patterns have at least two clearly identifiable lobes, each pointing to one side of the 60 GHz link. We observe energy from both ends of the link because the receiving end not only receives data frames but also transmits the corresponding acknowledgments. A significant number of angular
patterns feature additional lobes that signal reflections off the walls. In contrast to common assumptions regarding 60 GHz communications, the lobes show a significant amount of incidence energy. For instance, the angular pattern at position $F$ in Figure 9 has a lobe directly pointing to the lower wall. Geometrically following the reflection of the signal off the nearby window suggests that this lobe is due to the transmissions of the laptop. Further, the angular pattern at position $B$ features a lobe pointing towards the wooden wall. This lobe arises from a second order reflection that originates at the D5000 dock, and bounces off both the glass wall as well as the wooden wall. This second order reflection has a signal strength that is comparable to the line-of-sight (LOS) path, because the gain from the antenna array in the direction of the reflection is higher than in the direction of the LOS. This compensates the additional path loss in the reflected case. This finding is highly relevant since current millimeter-wave networking models often assume that the strong attenuation at 60 GHz results in at most first order reflections. While having second order reflections translates into better coverage, they also cause more interference. Thus, including this effect in the evaluation of 60 GHz systems is crucial. Compared to the D5000 dock, the WiHD system shows similar effects. However, the angular patterns feature more and larger lobes than in Figure 9. This suggests that the WiHD system is less directional, and thus produces more reflections. As a result, the negative impact on spatial reuse is even higher.

**Communication via Reflections.** While the above results show that reflections are significant, we also perform a case study to analyze to what degree those reflections help to extend the coverage of a network if the LOS is blocked. To this end, we set up a link parallel to a glass wall using a D5000 dock and its corresponding laptop. Additionally, we place an obstacle in between both. Figure 10 depicts our setup. We then measure the angular energy profile at the receiver to verify that the LOS path is actually blocked, and that all energy arrives via the reflection off the wall. Figure 10 validates this—the angular energy profile does not include any lobe on the LOS. Finally, we use Iperf to measure the achievable rate on such a reflection. We obtain 550 Mbps ($\pm 18$ Mbps with 95% confidence) which is more than half of what we measure on LOS links. Thus, communication via reflections is feasible and achieves significant data rates. Earlier work [12] shows similar findings but lacks validation via an angular profile.

**Interference from Reflections.** The above reflection analysis allows us to assess the existence and strength of reflections. In addition, we use a second setup to determine the impact of those reflections on data transmissions. In particular, we set up two geometrically non-interfering 60 GHz links close to a metal reflector, as shown in Figure 11. To eliminate the influence of side lobes on the measurement, we position shielding elements close to the WiGig devices. Further, we make sure that we do not block the reflected signal resulting from the metallic surface behind the WiHD receiver. We then analyze the coverage area of this reflection using the VubIQ transceiver to ensure that the docking station is located inside. Finally, we perform a TCP throughput measurement from the laptop to the docking station using iperf. By switching on and off the WiHD devices, we evaluate the impact of the reflection on the WiGig connection. For the iperf connection, we set a TCP window size of 250 KByte such that it fully loads the underlying Ethernet link, which the docking station tunnels over the 60 GHz wireless link. The WiGig tunneling manages to provide full gigabit speed...
for the Ethernet link. This almost completely saturates the link because the D5000 system tries to minimize the delay of the Ethernet traffic. That is, instead of aggregating data to reduce the medium usage, the transmitter sends a larger number of packets. Due to this high medium usage, we expect the link to be very sensitive to interference effects.

The results in Figure 11(b) show that interference indeed has a strong impact in our setup. We observe that the TCP throughput increases significantly after about 90 seconds, which is when we power off the WiHD link. The performance degradation due to the WiHD reflection is about 200 Mbps compared to the interference-free transmission. Further, we observe that the throughput fluctuates strongly for the case with interference. Most probably, these variations result from attempts of the D5000 dock to adapt to the high interference by switching among MCS levels. The average throughput reduction is about 20%, but reaches up to 33%.

### 4.4 Area-Wide Coverage

While our above analysis focuses on specific scenarios, in the following we consider a comprehensive measurement campaign within a large conference room. The size of the room is $21.5 \times 10.5 \text{ m}^2$. As discussed in Section 3.2, we use a robot carrying the E7440 laptop to perform measurements on the physical, medium access control, and transport layers at a large number of locations and orientations within this room. The robotic automation is key to tackle the complexity of this very large measurement campaign. The measurement locations are the 117 intersections of a $13 \times 9$ grid marked on the floor. The intersections are at a distance of 0.8 meters both horizontally and vertically. At each location, the robot repeats the measurement in eight equally spaced directions to cover the full 360° azimuthal range. As a result, we obtain a comprehensive set of 936 measurements. This dataset is highly valuable to the community since it is the first systematic 60 GHz networking trace collection within a room. Researchers can easily use the traces to evaluate the performance of 60 GHz protocols regarding, e.g., rate adaptation, mobility, and handovers in indoor environments.

We place the D5000 docking station at grid intersection $(0, 0)$, which we define at the midpoint of the top wall of the room, as shown in Figure 12. While we collect a wide range of information including MCS, PER, and the identifier of the beampattern in use, in Figure 12 we only depict the throughput results as a heatmap due to space constraints. As expected, the WiGig link achieves the highest throughput when the E7440 laptop is close to the D5000 dock. However, even when the E7440 laptop is facing the D5000 dock, throughput is not symmetric across the otherwise empty room. Still, when the laptop is facing the docking station at $+45°$ or $-45°$, such as in Figures 12(b) and 12(h), the coverage area is clearly shaped towards the right and the left half of the room, respectively. Interestingly, we still achieve significant throughput when the laptop is facing away from the D5000 dock, as depicted in Figure 12(e). This shows that the antenna radiates a significant amount of energy through a back lobe. Given the location of the antenna in the laptop lid, under regular usage this back lobe points towards the person using the laptop and thus may not be usable for communication. All in all, we conclude that the coverage of commercial 60 GHz hardware is highly irregular, and thus strongly differs from theoretical models. This behavior is an immediate result of the irregular shape of the beampatterns that we observe in Section 4.2.

### 5 Mobile Analysis

In the following, we analyze the impact of mobility on consumer-grade 60 GHz devices in indoor environments. To this end, we use the comprehensive grid measurement set discussed in Section 4.4 as a baseline and compare it to the performance under mobility.

#### 5.1 Experiment Design

Since we recorded the robot-assisted grid measurements under static and controlled conditions, they reflect the optimal performance of the link at a certain location and orientation. To ensure this, we reset the devices prior to each measurement, thus forcing them to perform a full beamsweep and find the best possible beampattern. In contrast, in this section we move the E7440 laptop at walking speed along a number of different paths on the grid while performing the same measurements as in the static case. Naturally, the performance is lower since the link must continuously adapt to the changing environment at each location. By comparing the static performance at the grid intersections along which we move with the corresponding mobile performance, we can assess the ability of the WiGig/802.11ad protocol to handle mobility. For instance, under mobility the E7440 laptop may not always use the best beampattern or MCS and thus achieve suboptimal performance in terms of throughput.

We define a number of mobility paths along the grid. Figure 13 shows four examples of such trajectories, out of a total dataset of 15 trajectories. The arrows indicate the orientation of the E7440 laptop during the movement. In most cases the arrows follow the movement, such as in Figure 13(a). However, we also consider other cases for which the E7440 laptop is always facing the D5000 dock regardless of the direction of movement, such as the trajectory in Figure 13(b). This allows us to assess the impact of device rotation while moving. We repeat each trajectory at
least three times to avoid measurement artifacts. Moreover, we record each trajectory both forward and backward but always sticking to the orientation of the E7440 laptop as depicted by the arrows in Figure 13. This allows us to study, for instance, whether the rate control of the E7440 laptop adapts well to both decreasing and increasing signal quality.

### 5.2 Mobility Results

Our mobility experiments show a significant performance degradation compared to the static case. As a first step, we average the performance of all trajectories compared to the corresponding static measurement data. Table 2 gives an overview of our results. We observe that the overall throughput in the mobile case is on average 30% lower than in the static case. At the same time, the number of control packets increases by 31.71%. In other words, the WiGig link must invest a significant amount of overhead into maintaining the link while moving, and still suffers a significant throughput loss. Most interestingly, the PER before retransmissions for data traffic increases by three orders of magnitude from virtually zero to close to 0.5%. This shows that the link suffers significant impairments during movement, suggesting that the rate control and the beamtracking algorithms cannot keep up with pedestrian movement. We conclude that future work must focus on mitigating the aforementioned 30% performance drop.

As a next step, we study a number of individual trajectories to highlight particular effects caused by mobility. For instance, in Figure 14 we depict a trajectory that starts in the lower-right corner of the empty conference room and ends in front of the docking station located at position (0, 0). Both at the beginning and at the end of the trajectory, the mobile device is roughly pointing towards the docking station. However, at about half of the distance, the device follows a short horizontal trajectory, and thus points in a direction which is parallel to the docking station. In the static case, the impact of this horizontal segment is negligible. As we observe in Figure 14, TCP throughput remains at about 800 Mbps throughout the trajectory, and the number of control packets is minimal. However, for the mobile case, we clearly see the impact of the horizontal trajectory. The throughput drops to zero for about two seconds and, simultaneously, the number of control packets shoots up to more than 6000 packets per second. That is, as soon as the device enters the horizontal segment, the connection to the docking station drops due to beam misalignment. As a result, the laptop initiates a full sector level sweep which results in the large number of control packets that we observe in Figure 14. The

### Table 2

<table>
<thead>
<tr>
<th>Throughput</th>
<th>Static</th>
<th>Mobile</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>790.7 Mbps</td>
<td>606.8 Mbps</td>
<td>-30.29%</td>
</tr>
<tr>
<td>Num. of Control Pkts</td>
<td>603.3 pkts</td>
<td>883.6 pkts</td>
<td>31.71%</td>
</tr>
<tr>
<td>Ratio Control/Total</td>
<td>2.42%</td>
<td>3.19%</td>
<td>31.81%</td>
</tr>
<tr>
<td>Control Pkt Error Rate</td>
<td>0.02%</td>
<td>0.36%</td>
<td>94.11%</td>
</tr>
<tr>
<td>Data Pkt Error Rate</td>
<td>0.0004%</td>
<td>0.45%</td>
<td>99.92%</td>
</tr>
</tbody>
</table>
static case suggests that the orientation of the device does not hinder a reliable connection. Hence, this experiment shows that the poor performance of the connection is due to the limited beam-tracking and the inefficient beam-sweep of the device. Moreover, we observe that the \(30\%\) throughput loss in Table 2 is indeed just an average. The instantaneous loss can easily reach \(100\%\) as in Figure 14. We observed such outage in multiple of our mobility traces.

Figure 15 depicts a similar analysis to that of Figure 14 but focuses on the MCS. Specifically, the black lines show the MCS index variations for three different trajectories. The higher the MCS index, the higher the physical layer rate is. As a reference, the gray bars show the MCS index for the static case at the grid locations along which the device moves in the mobile case. Note that, while the bars have a certain width for readability, the value of each bar refers to the discrete position value on the x-axis. In contrast, the black lines represent the continuous evolution of the MCS index for the mobile case. The white diamond markers indicate the locations at which the dock, the laptop, or both devices switch beampatterns. Figure 15 shows that the static case often operates at higher MCS values than the mobile case. This is expected since beam misalignment is very frequent under mobility. For instance, when moving along the second trajectory in Figure 15, the device resorts to the most robust MCS at position five due to a suboptimal beampattern change and does not recover until about four seconds later when it reaches position nine. During those four seconds, the device performs frequent but unsuccessful beam searches. In the third trajectory, MCS drops are present throughout the trace. However, in this case, we observe that the device continuously attempts to switch back to a higher MCS. Sometimes it succeeds for a brief interval but then immediately must fall back to lower MCSs. We also observe that MCS changes are often correlated with beampattern changes. This re-confirms that the impact of mobility that we analyzed at the transport layer in Figure 14 stems from the fluctuations at the physical layer. Interestingly, the first trajectory in Figure 15 depicts cases where the MCS chosen under mobility is slightly higher than in the static case. That is, the continuously changing channel conditions of the mobile case can trigger the rate adaptation mechanism to behave more aggressively than in the static case, which increases the PER.

In Figure 16, we perform a similar comparison as in Figure 15 but for all of our trajectories. In addition to the MCS index, we also consider the beampattern index. To this end, we perform a piecewise constant interpolation of the static grid data to obtain a continuous MCS and beampattern value along each trajectory. We then compute the percentage of each trajectory during which the static and the mobile case result in different MCS and beampattern indexes. In other words, we quantify how much the behavior of the devices deviates from the optimal static behavior as a result of mobility. We observe that the difference in terms of percentage is rather high. For the MCS index, the difference of static and mobile is about \(70\%\). While the second trajectory in Figure 15 shows that for some specific cases the difference can be lower, generally this does not hold. Moreover, the CDF in Figure 16 shows that the difference is beyond two MCS index steps for half of the cases. Regarding the beampattern index, we observe that the laptop selects a suboptimal sector roughly \(70\%\) of the time. For the docking station, this value increases up to about \(80\%\). The reason for this slight difference between the laptop and the docking station is unclear, but is likely due to the specific implementation details of the beam-tracking and beam-searching mechanisms of these devices. While the mismatch in terms of beampattern index is significant, it is difficult to assess the exact impact on the communication. Essentially, the devices only reveal the index number of the current beampattern, but not to which beamshape each index number refers to. From our measurements, we concluded that successive index values do not translate into adjacent beampatterns. Even if the index numbers of the mobile and static cases do not match, the beampatterns might be similar. Still, the poor results in terms of throughput (c.f. Figure 14) and physical layer rate (c.f. Figure 15) suggest that this is not the case.

Finally, Figure 17 depicts a more detailed analysis of beampattern selection. We consider two trajectories (a) and (b), as in the left part of the figure. Both are horizontal, but...
TABLE 3

Performance for multiple antenna arrays on trajectories of Figure 13

<table>
<thead>
<tr>
<th>Throughput</th>
<th>One Array</th>
<th>Two Arrays</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td># Control Pkt</td>
<td>651.5 Mbps</td>
<td>740.65 Mbps</td>
<td>13.68%</td>
</tr>
<tr>
<td># Data Pkt</td>
<td>827.9 pkts</td>
<td>733.6 pkts</td>
<td>-11.40%</td>
</tr>
<tr>
<td>Ratio Control/Total</td>
<td>3.10%</td>
<td>2.72%</td>
<td>-12.30%</td>
</tr>
<tr>
<td>Control Pkt Error Rate</td>
<td>0.22%</td>
<td>0.20%</td>
<td>-10.00%</td>
</tr>
<tr>
<td>Data Pkt Error Rate</td>
<td>0.61%</td>
<td>0.26%</td>
<td>-56.64%</td>
</tr>
<tr>
<td>MCS Changes</td>
<td>19.5</td>
<td>18</td>
<td>-7.26%</td>
</tr>
<tr>
<td>BP Changes at TX</td>
<td>18.25</td>
<td>17</td>
<td>-7.00%</td>
</tr>
<tr>
<td>BP Changes at RX</td>
<td>20.25</td>
<td>18.16</td>
<td>-11.00%</td>
</tr>
</tbody>
</table>

Average throughput/outage up to eight arrays on random trajectories.

(a) follows \( y = 1.6 \) m while in (b) the laptop is further away at \( y = 4 \) m. Moreover, the laptop is facing the docking station in both trajectories, as the arrows in Figure 17 indicate. We consider two metrics, namely, how often the beampattern changes during each trajectory, and how many different beampatterns does a device use during each trajectory. Note that the former can be very large even if the latter is very small in case a device is continuously fluctuating between a few beampatterns only. Figure 17 shows that the number of beampattern changes is roughly similar for both trajectories. However, the number of beampatterns among which the device fluctuates is smaller for (a) than for (b). The reason is that the devices are closer to each other in case (a), and thus experience a higher SNR. Basic mobility mechanisms typically trigger a beam retraining when the SNR falls below a certain threshold. As expected, this happens less often for (a) than for (b). In case (a), the devices can communicate even if the main lobes of the chosen beampatterns are not pointing to each other due to the significant sidelobes of practical beampatterns. Thus, we conclude that sidelobes can be beneficial to deal with mobility since they may enable communication even in case of suboptimal beamsteering.

5.3 Multiple Antenna Arrays

Existing consumer-grade 60 GHz devices typically feature a single antenna array. For instance, both the Dell D5000 dock and the TP-Link Talon AD7200 have one antenna array facing forward and covering roughly 120°. This inherently limits the coverage area of the devices and may cause significant performance degradation under mobility. For instance, a device moving on trajectory (a) in Figure 13 suffers poor performance or even link loss (c.f. Figure 14) when traveling along the x-axis, that is, in parallel to the docking station. A natural solution to this issue is using two or more antenna arrays per device. In our above example, if the E7440 laptop were equipped with an antenna array facing sideways, it could switch to that array while moving along the x-axis, as depicted for trajectory (b) in Figure 13.

In this experiment, we emulate such additional antenna arrays on the E7440 laptop. To this end, we combine multiple measurements of the same trajectory with different device orientations. While this approach does not fully account for the antenna switching overhead, it provides a rough estimate of the benefit of using multiple antenna arrays in a device. Table 3 shows a comparison of the average performance for a device with two antenna arrays compared to the single array case. We observe that throughput increases on average 13.68% while the ratio of control packets to data packets decreases by 12.3%. This clearly shows that additional arrays can provide a significant benefit. Since the overall link quality is better, the PER for both control and data packets decreases, too. The difference in the case of control packets is only 10% because such traffic is transmitted at the most robust MCS defined in 802.11ad. However, for data packets, which are transmitted at higher MCSs, the PER decreases on average 56.64%. Table 3 also shows that MCS and beampattern selection are more stable with two arrays. Essentially, using a second array facing sideways prevents low link quality and thus avoids that the rate and steering control algorithms cause unnecessary fluctuations.

In Table 4 we extend our analysis to up to eight arrays. We use random trajectories that may include areas with no coverage. As a result, the throughput values in Table 4 are lower than in Table 3. The icons show the relative placement of the antennas. As expected, the higher the number of antennas, the higher is the throughput. However, we observe that the antenna placement does play a significant role. For instance, placing a second antenna on the left side of the device results in better throughput than placing it on the right side. This is due to the case of the laptop that we use as a client. The case shadows the left side but does not block the right side. Thus, adding a second array on the left side is more beneficial. We observe an equivalent effect for outage.

5.4 Link Robustness

Our area-wide static measurement results in Figure 12 show that the E7440 laptop is not able to connect to the D5000 dock in a significant number of locations. Interestingly, during our mobile measurements we observe that the E7440 laptop stays connected at those locations if it associated to the D5000 dock while in one of covered areas in Figure 12. The underlying reason is that the devices use wide beampatterns during device discovery, and thus their discovery range is smaller than their communication range. In other words, devices can maintain a connection when moving into some of the light areas in Figure 12 because the beampatterns used for communication are more directional than the ones used for device discovery. To investigate this effect, we measure the throughput for three trajectories along the x-axis of our measurement grid. Specifically, our trajectories follow the line \( y = 5 \) meters, and each of them considers one out of three device orientations as seen in Figure 18. The three orientations of the E7440 laptop are as follows: facing the D5000 dock, facing left, and facing right. We then compare our result to the throughput that we measure in the static case (c.f. Section 4.4), for which we reset the connection prior to each measurement and are thus limited by the discovery range of the D5000 dock. Figure 18 shows our results. As expected, for the static case the laptop cannot connect to the dock at the edges of the trajectory for all three
orientations. In contrast, for the mobile case facing the dock, the laptop achieves a throughput of at least 500 Mbps at all locations. For the other orientations, the throughput of the mobile case decreases to zero at the locations where the dock is outside the 120° coverage area of the laptop.

6 Discussion

We use two methodologies that allow us to gain new fundamental insights into the operation of 60 GHz networks, and which make our results stand apart from related work. First, we analyze commercial 60 GHz devices with the VubIQ system to understand their behavior at the physical layer. Second, we use a robot-assisted technique to obtain a first-of-its-kind coverage map of such consumer-grade devices. This allows us to obtain a large trace dataset that captures the behavior of 60 GHz networks. Most importantly, we partially reverse-engineer the Wilocity Monitor Service to allow unprecedented access to a firmware interface of the Wil6100 card. We use the resulting traces to draw general conclusions, in contrast to existing work, which mainly focuses on specific use cases. Next, we discuss the insights that we gain from the above methodologies and derive design principles for the development of 60 GHz networks.

Antenna patterns. We observe that the antenna patterns of consumer-grade 60 GHz devices not only exhibit significant side lobes due to a cost-effective design but also very much depend on the specific location of the antenna array on the device. This partly invalidates current assumptions regarding channel access at the MAC layer—in scenarios where devices with certain beampatterns do not interfere, others may cause collisions. As a design principle, we derive that 60 GHz networks should implement multiple MAC behaviors and choose the one which is most suitable for the beampatterns of the individual devices in the network. Also, devices should use more directional beampatterns, since current implementations do not exploit the gains that these antenna arrays can achieve. In order to do so, manufacturers may need to redesign the shape and placement of the antenna array within the device. At the same time, having these COTS 60 GHz devices implementing so wide patterns enables these first-of-a-class devices to have a robust link without requiring very accurate beam training or realignment in case of mobility. However, this may need to be reconsidered in future hardware generations. Devices will perform poorly in case of multiple parallel links if they are not able to synthesize narrower beampatterns, generating interference and reducing spatial reuse.

Reflections. We show that 60 GHz signals may cause interference even after reflecting twice off walls. As a result, MAC layer designs which exploit the sparsity of 60 GHz signals to increase spatial reuse may incur unexpected collisions. Such designs are often based on geometric principles, that is, the beampattern and range of a node define its area of interference. As a design principle, we derive that such protocols should extend this geometric approach to include up to two signal reflections off walls or obstacles, as we see from our measurements that these second order reflections can still be strong. Also, it is possible to take advantage of these reflections for user localization.

Interference and spatial reuse. We observe significant interference in scenarios with two or more 60 GHz links, even in cases for which the parallel operation of the links should be feasible. This also includes interference via reflectors. As a result, spatial reuse drops dramatically in the systems that we analyze. The underlying reason is that devices need to carrier sense each other, leading to backoff and increasing the channel idle time. As a design principle, we derive that more directional patterns should be used to improve spatial reuse, as well as implementing medium access control approaches that take this into account and are thus more efficient than traditional carrier sensing.

Aggregation. Our analysis reveals that 60 GHz aggregation provides large throughput gains at much smaller timescales than legacy systems. For instance, while 802.11ac achieves a $2 \times$ gain with a frame length of 8 ms (c.f. Table 1 in [27]), 802.11ad achieves a $5.4 \times$ gain by aggregating only up to 25 $\mu$s due to its very high data rates. Hence, the impact of aggregation on delay is much smaller for 802.11ad, while reducing dramatically channel usage time. As a design principle, we derive that the frame length should not only depend on the desired throughput and delay, but also on how many nodes share the medium. If many nodes share it due to, e.g., wide beampatterns, a higher aggregation level helps to provide channel time for all nodes.

Range. We show that the range of 60 GHz links often varies significantly between experiments (c.f. Figure 5(b)) due to, e.g., differences in temperature and humidity. As a design principle, we derive that devices may need to adjust their transmit power to control interference even in quasi-static scenarios, such as wireless backhaul networks. Performing power control will also lead to energy savings when the links are close to each other.

Coverage. Although 60 GHz communication experiences less multi-path effects than 2.4 GHz or 5 GHz communication, our area-wide measurements reveal that coverage cannot be modeled based on geometric principles only. Even in an empty room, we do not observe a cone of coverage as often suggested in earlier work. The underlying reasons are (a) the irregular beampatterns of consumer-grade 60 GHz hardware, and (b) the impact of antenna placement. For instance, the antenna of the D5000 dock is located at the right side of the device case. As a result, in Section 4.4 we observe...
that the left part of Figure 12 tends to suffer from less coverage than the right part. This suggests partial shadowing due to the device case. The same issue would arise with external adapters (e.g., 802.11ad USB dongles), since their orientation would also be critical for coverage. Thus, we conclude that coverage models for 60 GHz networks must not only take into account the room geometry and obstacles, but also the physical characteristics of the transmitter and the receiver. This means that the AP placement and orientation play a very important role for such 60 GHz wireless networks. Placing APs on a wall or in a corner instead of in the middle of the room may result in better performance due to the placement of the antenna array in current devices and their difficulty for beam steering into extreme angles. Placing an AP in the center of a room requires full 3D beam steering in azimuth and elevation angle, whereas current phased arrays typically have limited steerability particularly for the elevation angle.

**Mobility.** The performance gap in terms of the impact of indoor mobility on throughput is on average 30% for 802.11ad and traffic below 1 Gbps. Beyond beampattern misalignments, the underlying reasons include MCS fluctuations, higher PER, and 30% higher control traffic overhead. While our setup does not allow us to infer how this performance gap behaves beyond 1 Gbps due to the use of Gigabit Ethernet, we expect it to be more pronounced, requiring the development of faster beamtracking techniques, such as the one in [30].

**Multiple antenna arrays.** Our coverage analysis shows that existing 60 GHz devices radiate energy in unexpected directions, such as backwards or sideways. However, connections in such directions are strongly impaired and may often cause significant harm due to strong MCS and beam-pattern fluctuations. Hence, even if transferring communication to a second antenna array on the device involves a certain overhead and is not strictly necessary, we expect it to pay off. Moreover, since the device already has significant information regarding the angle at which its communication partner is located, a full beam training is unnecessary. Also, manufacturers should take this into account when designing their devices, as the antenna placement and the number of antennas plays an important role in terms of performance.

**Discovery range.** We observe that the discovery and communication ranges of the Dell docking station system differ significantly. This suggests that the dock and the laptop use quasi-omni directional beampatterns during the discovery phase to keep beam training overhead to a minimum, and directional beampatterns during the data communication phase to improve performance. The 802.11ad standard recommends such quasi-omni beam training for efficiency. Instead of requiring each side to perform a full beam sweep for each of the sectors of the other side, the standard allows one side to remain in quasi-omni mode during the sweep. The process is repeated for each side, which means that beamtraining only requires two full beam sweeps. A natural limitation of this approach is that nodes cannot perform beamtraining if both nodes need to use a directional beampattern to be in range. To achieve both efficient beamtraining and large discovery range, future work should focus on more efficient beam sweeping. For instance, nodes could perform partial sweeps based on the expected location of their communication partner, or they could leverage signals received via side-lobes. Given the strong side lobes of consumer-grade 60 GHz antennas that we observe in Section 4.2, the latter is a highly promising approach for practical network deployments.

### 7 Conclusion

We present an in-depth analysis of consumer-grade off-the-shelf 60 GHz systems. Our goal is to investigate the impact of the cost-effective designs of such devices. While these effects are often qualitatively well-known, we quantify them in order to provide a practical intuition on how important they are. This contributes crucial insights for the design of 60 GHz networking protocols. In particular, we investigate the impact of data aggregation, beam patterns, reflections, interference, and mobility. We conclude that, while some common 60 GHz assumptions hold (e.g., data aggregation), others become critical for consumer-grade devices (e.g., impact of side lobes). We capture all of the above characteristic behaviors of 60 GHz networks in an exhaustive dataset of traces which we make available to the community [15]. This dataset enables researchers to perform more realistic and comparable evaluations of 60 GHz networking mechanisms.

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