On the Potential of Fixed-beam 60 GHz Network Interfaces in Mobile Devices

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Abstract

The small form-factor and significantly high bandwidth of 60 GHz wireless network interfaces make them an attractive technology for future bandwidth-hungry mobile devices. To overcome several challenges in making such 60 GHz communication practical, beamforming is widely accepted as an integral part of 60 GHz devices. In this paper, we perform a first-of-its-kind user study to answer a rather unconventional question: can users explicitly assist *in aligning fixed-beam directional antennas on the transmit/receive side? Our measurements involving 30 users show significant promise, and lean us towards answering the question in the affirmative. The implication of these observations is in substantially simplifying the design of 60 GHz interfaces for mobile devices.*

1 Introduction

Recent years have seen a surge of interest in using mm-wave or 60 GHz radios for short range (<10 meters), multi-Gbps communication [1–3, 9, 17]. The WiGig alliance [17] envisions that 60 GHz communication will be common place in multiple deployment scenarios (Figure 1). These can be categorized into static-to-static, handheld-to-static and handheld-to-handheld communications, of which we focus on the latter two scenarios in this paper. Examples of the handheld-to-static scenarios include sync-and-go applications such as movie and music downloads from public kiosks, content prefetching for future disconnected operations, "google-in-the-pocket" by saving large amounts of user-relevant data locally, aggregation and upload of non-real-time sensor data from mobile devices, etc. Examples of handheld-to-handheld scenarios include file sharing applications between users.

For any deployment involving 60 GHz radios, directional transmission is crucial to leverage their high bandwidth potential. Directional transmission can be achieved with (a) fixed directional antennas, (b) switched-beam antennas, or (c) adaptive beamforming. These approaches ((a) to (c)) are in the order of increasing complexity, cost and power consumption, and at the same time increasing flexibility or adaptability to changing conditions; selecting the appropriate approach hence engenders a tradeoff during system design [12].

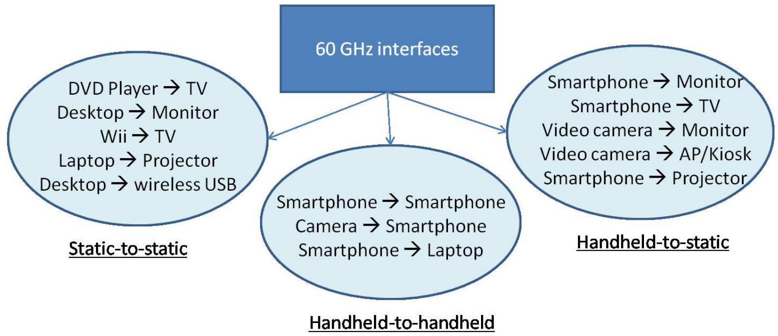


Fig. 1. Deployment Scenarios for 60 GHz wireless interfaces.

To assist in striking the tradeoff effectively, in this paper, we ask the following question: *can users assist in aligning fixed-beam antennas on the transmit/receive side for 60 GHz communications?* If the answer is yes, it could simplify the design of mobile devices by making the antenna a passive element, thereby reducing the initial cost and continuous power consumption. We ask this question based on the intuition that 60 GHz communication is predominantly line-of-sight. And for enabling short distance line-of-sight communications, our hypothesis is that human intuition (along with minimal feedback from the system) is good enough to align the transmitter receiver pairs. A challenge, however, is that at these frequencies, the wavelength is ~5mm, and hence even a small movement can cause significant signal fluctuation.

Our measurement study includes using 60 GHz radios as transmitter and receiver, with 30 users who perform repeated data transfer sessions, spanning over multiple days. The study with handheld-to-static scenario shows several interesting observations: (1) Users with little prior practice can align the antennas very well 80% of the time getting close to 1 Gbps throughput, when the distance between the transmit and receive antennas is within 1 meter. (2) Human-assisted alignment is *bimodal*; i.e. users either align very well or go completely out-of-alignment. Once mis-aligned, users correct it within a short period of time (92% of the time users re-align within 2 seconds) to achieve high throughput again, owing to the feedback provided by the system. (3) With time, users learn how to align the antennas, and hence get high throughput continuously. We make similar observations with the handheld-to-handheld scenario.

The rest of the paper is organized as follows. Section 2 provides a brief background on 60 GHz radios and directional transmission. Section 3 describes our measurement methodology. Section 4 discusses the results and their implications in detail. Section 5 discusses the limitations of this study, and Section 6 concludes with future directions.

2 Background on 60 GHz Radios

Recent years have seen a surge of interest in using 60 GHz radios due to several reasons: (1) the rapid emergence of sophisticated mobile devices and personal area applications that demand high network bandwidth, (2) the lack of scope for such high bandwidth in other short-range technologies [5, 12], and (3) the availability of 7 GHz of license-free spectrum in the 60 GHz range, coupled with the recent breakthroughs in high-speed CMOS design [7]. Draft standards have been published by multiple industry forums [2, 17] and standards bodies [1, 9], and initial products are already available for niche applications [3].

The small wavelengths at these frequency ranges, however, imply reduced antenna aperture areas that lead to much higher path loss [7] and increased susceptibility to blockage by obstacles [15, 18]. These additional losses along with the high noise figure of 60 GHz CMOS transceiver implementations, and the low-power requirements make the feasibility of delivering Gbps speeds challenging even at distances of 10 meters. Consequently, focused transmission through beamforming is considered an integral part of 60 GHz communication [2, 17] (unlike cellular and WLAN standards where beamforming is included as an optional feature), and also receives significant research focus [11, 13, 14, 16].

In this paper, we explore the potential of *user assistance* in aligning fixed-beam antennas for focused transmission. Fixed-beam antennas are significantly simpler than adaptive beamforming antennas and consume lower power, thus making them more attractive for handheld devices.

3 Measurement Setup and Methodology

Our measurement testbed mainly consists of 60 GHz radios with fixed-beam directional antennas. Specifically, our experiments focus on answering the following questions:

1. What is the throughput achieved by users in such settings? How does it fluctuate due to users holding such a device in their hands?
2. How long does it take for users to re-align once alignment is broken?
3. Does user-assisted alignment improve over time, i.e. can users "learn" alignment over a period of time?

We consider two different application contexts: (a) when a user is interacting with static infrastructure (i.e. *handheld-to-static*), e.g. smartphone-to-display, and (b) when a user is interacting with another user (i.e. *handheld-to-handheld*), e.g. smartphone-to-smartphone.

User population: Our population mix consists of users with and without a technical background: out of our thirty users, twenty four have at least some engineering background, and the remaining are from legal/administration/janitorial departments. All users are male or female adults between 25-50 years of age.

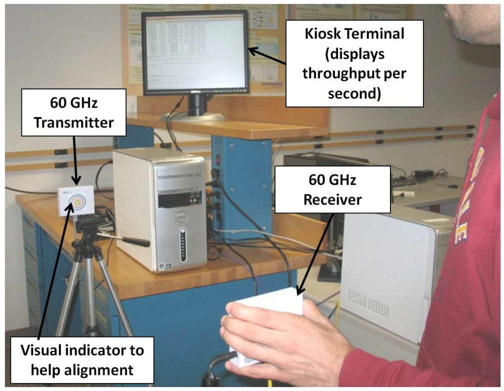


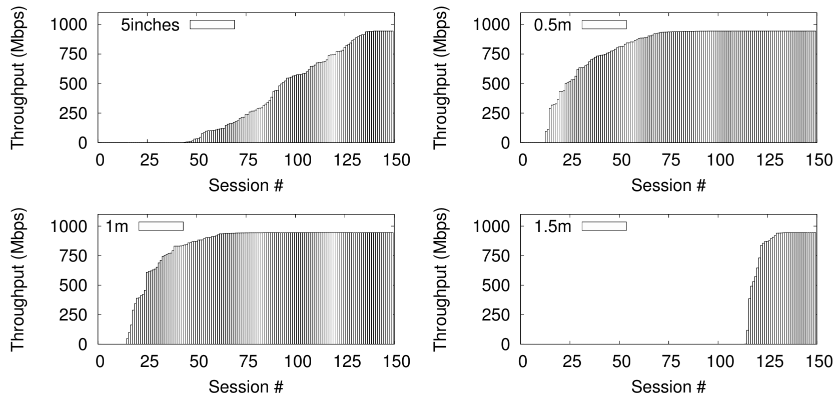
Fig. 2. Measurement setup, with tripod-mounted transmitter and handheld receiver.

Setup: Our setup is shown in Figure 2. The 60 GHz transceivers in our study are described in detail in [10]. Briefly, these transceivers operate at a carrier frequency of 60.3 GHz with a channel bandwidth of 1.6GHz. Taken together with amplitude shift-keying (ASK) modulation, a 36^o-Horizontal beamwidth (measured) antenna, and an output power of 10.4dBm, these transceivers can support a data rate of 1.25Gbps within a 7-10m range. All our experiments are however carried out within a 2m range such that packet losses are mostly due to user-induced mis-alignment. We use two Dell desktop SMP machines running Linux. We use *nuttcp v6.1.2* [4] to generate traffic at the transmitter, and *gulp* [8] for packet capture on the receiver. We also tune the kernel buffers to ensure that the bottleneck is indeed the wireless link. Packets are marked with monotonically increasing sequence numbers to enable computing different metrics.

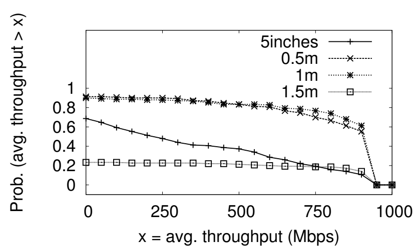
Metrics: To quantify performance, we measure *packet delivery rate (PDR)* and *throughput*, which are relevant to the target network-intensive applications. The per-second throughput is also made visible to the users on the Kiosk terminal, which helps them detect misalignment and realign better. We also measure the *re-alignment time* using the packet sequence numbers, i.e. how long it takes for users to re-align their transceivers once alignment is broken.

4 Results

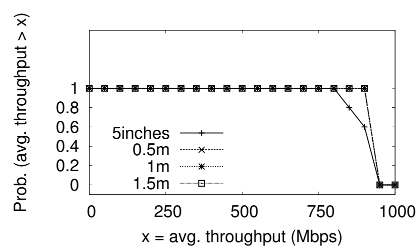
Effectiveness of User-assisted Alignment: We first conduct experiments to study the performance of user-assisted alignment in the handheld-to-static scenario. In this set of experiments, thirty users try to align the handheld receiver with the tripod-mounted transmitter, while receiving 1 GB of data (731000 UDP packets with 1470-byte payload at 1Gbps). At the receiver, we determine the start and end time of each experiment using nuttcp's control packets. These control packets utilize the wired interface between the transmitting and receiving



(a) Sorted average throughput in each session across all users.



(b) Handheld-to-static.



(c) Static-to-static.

Fig. 3. Average throughput for all users in the handheld-to-static scenario.

machines. For every user, we repeat the experiment five times (i.e. have five different data transfer sessions).

Figure 3(a) shows the sorted average throughput in each session at different distances from the static transceiver for all users. We observe that users are able to achieve much higher throughput on average at the 0.5m and 1m distances than at the 5 inches and 1.5m distances. For comparison, we also repeat the experiment multiple times with a static-to-static scenario with both the transceivers mounted on tripods and carefully aligned. Figures 3(b) and 3(c) show the average throughput distribution in the handheld-to-static setting (across all users) and the static-to-static setting respectively. At 0.5m and 1m, the graphs show that users are able to achieve high throughput (700Mbps 80% of the time), much like the static-to-static scenario. At 5 inches and 1.5m, users are unable to achieve such high throughput continuously, although the properly-aligned static-to-static scenario can achieve full throughput.

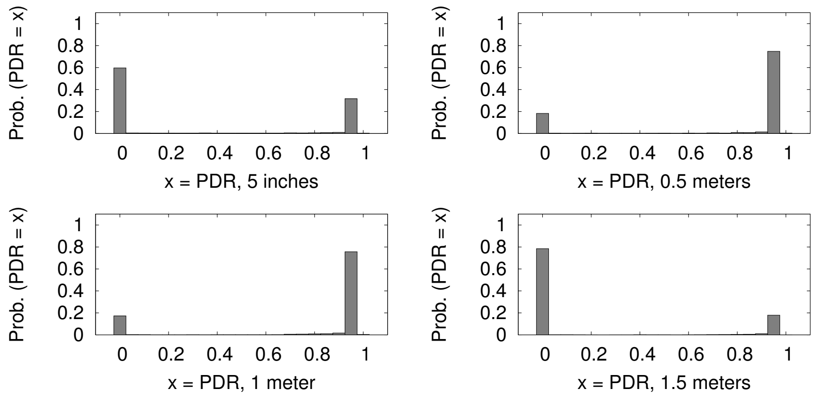
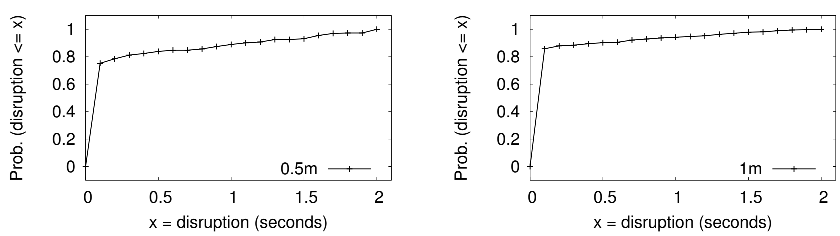


Fig. 4. PDF of PDR in the handheld-to-static scenario.



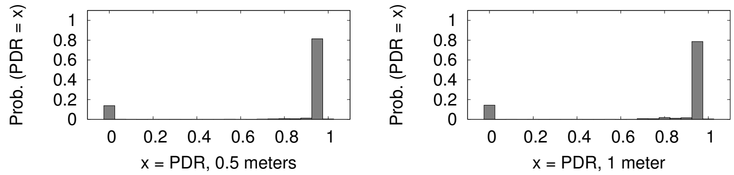
(a) 0.5m

(b) 1m

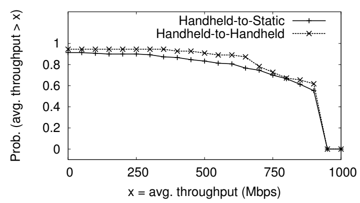
Fig. 5. CDF of connectivity disruption durations due to mis-alignment.

To understand the underlying packet loss behavior due to mis-alignment by users, we plot the probability density function (PDF) of the PDR (discretized into 5% buckets) at different distances in Figure 4. The hardware we use drops packets locally if the link is not aligned, as determined by PHY-layer pilot signals. The PDR is computed in 100ms intervals. Surprisingly, we observe a *bimodal* packet loss distribution—packet loss is either negligible and PDR is close to one, or all packets in the interval are lost. Further, the low average throughput at 5 inches and 1.5m is explained by the high frequency with which PDR is zero in both these cases (60% of the time at 5 inches and 80% of the time at 1.5m).

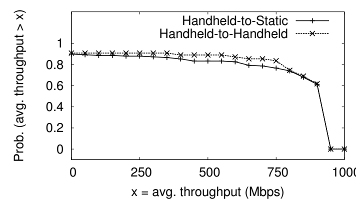
At 1.5m, we observe that users find it hard to align the transceivers with the visual input we provided. Many users requested for additional input either in the form of a laser-pointer or in the form of device vibration (common in today's smartphones). We believe that the high packet loss at 5 inches is due to the well-known receiver saturation problem [6]. This hypothesis is confirmed



(a) PDF of PDR in the handheld-to-handheld scenario



(b) 0.5m



(c) 1m

Fig. 6. PDR and average throughput comparison.

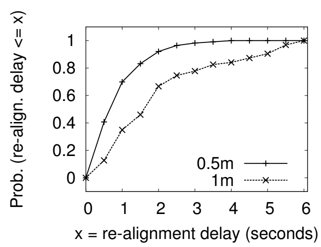
by holding the transceiver slightly higher or lower than the intuitive alignment height that reduces the received signal; we observe increased throughput by doing so. Independently, some users observed this behavior over time and used it to improve their throughput at 5 inches. We made similar height adjustment for the static-to-static scenario in Figure 3(c).

The bi-modal loss behavior has the advantage that it simplifies the feedback given to applications and users. In practice, users are more likely to be able to understand (and adopt) systems with simpler feedback.

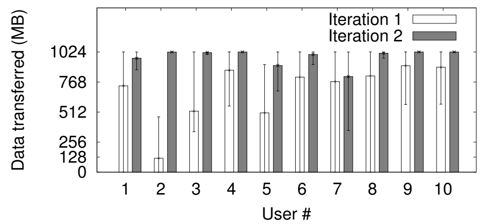
Figures 5(a) and 5(b) show the distribution of connectivity disruption (intervals greater than 10ms in which no packets were received) across all users. The graph shows that 80% of the time, disruption is only about 100ms. Such fine-timescale disruptions can be handled by backoffs and retransmissions at the MAC layer, thereby avoiding their exposure to higher layer protocols like TCP.

These results show that there is a region in which users can comfortably align fixed-beam 60 GHz transceivers, which should be taken into consideration when designing systems using such transceivers.

Handheld-to-handheld scenario: Figure 6 shows the result of the same experiments with both transceivers being handheld. We run this experiment with 12 different pairs of users. We observe that the PDR and throughput behavior is similar to the handheld-to-static scenario—the PDR is bimodal and the throughput distribution is similar.



(a)



(b)

Fig. 7. (a) Re-alignment delay in seconds, and (b) two iterations of data transfer (in MB) showing learning behavior at 0.5m.

Re-alignment time: Once connectivity breaks due to mis-alignment, we measure how long it takes for users to align back. We ran experiments in which ten users were asked to re-align their receiver after explicit (and sudden) alignment changes to the transmitter. To carry out these alignment changes, we rotate the transmitter at random instances of time when data transfer is taking place. After each rotation, we wait for the user to re-align the handheld receiver (and stabilize the throughput), and then initiate the next re-alignment sequence. Such a methodology ensures that the drop in PDR or throughput was specifically due to the explicitly induced re-alignment. Figure 7(a) shows the CDF of the realignment delay from these experiments. At 0.5m, we see that users are able to re-align their transceivers within 2 seconds 92% of time and take atmost 4 seconds to re-align. At 1m, we see that the re-alignment delay is slightly higher. This experiment also gives us an idea of the initial alignment time for users.

Improvement in alignment over time: We repeat our first experiment of 1 GB data transfer with 10 users with lowest throughput. We compare the total data transferred in their two iterations in Figure 7(b). At 0.5m, users are able to transfer 5-764% more data in Iteration 2. Even at 1m, seven out of the ten users could improve the average amount of data transferred from 7-140% (results not shown here). We attribute this improvement to users "learning" to improve their alignment over time by figuring out the sensitivity of the device to mis-alignment.

In summary, at close enough distances, we observe that users are able to align fixed-beam antennas well, thereby motivating their consideration for adoption in power- and complexity-constrained mobile handheld devices.

5 Discussion and Limitations

Fixed-beam antennas are also useful in static-to-static scenarios in a managed deployment, as long as line-of-sight is ensured. Alternately, handheld-to-static and

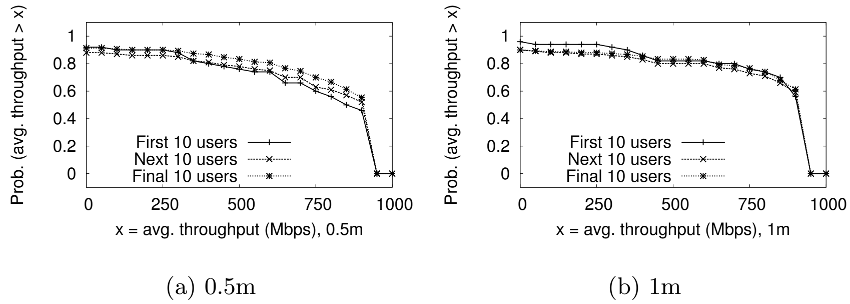


Fig. 8. Throughput distribution for different numbers of users (handheld-to-static).

handheld-to-handheld can be converted to a static-to-static scenario by aligning the devices on a stable platform. Nevertheless, the particular scenario instantiated with a given pair of devices is mainly a matter of users' convenience.

Like most user studies, this study is also done on a small set of users. To understand the sensitivity, we use the data obtained for Figure 3, and plot the throughput distribution with different numbers of users. In Figure 8(a) and Figure 8(b), we see that the throughput distribution does not change much beyond 10 users, thereby indicating that small number of users can provide sufficiently representative results.

Unfortunately, we did not have access to the internals of the current hardware to tune the channel bandwidth, transmit power, antenna beamwidth, and the modulation and coding schemes. While this limitation does not affect the general observations in our study, we believe that future work should explore the sensitivity of user alignment to the above parameters. Further, the paper relies on conventional wisdom that fixed-beam antennas are more cost- and power-efficient than adaptive beamforming antenna systems; as hardware becomes more accessible, future work should explore quantifying the cost and power benefits.

6 Conclusion and Future Directions

This paper focuses on answering the following question: *Can users explicitly assist* in aligning fixed-beam directional antennas on the transmit/receive side of a 60 GHz communication link? Our study reveals three useful conclusions: (1) Users can align the antennas very well 80% of the time getting full throughput at reasonable distances. (2) When mis-aligned, users correct it within a short period of time to achieve full throughput again. and (3) With time, users learn how to align the antennas, and hence get near full-throughput continuously. Using fixed-beam antennas can significantly simplify 60 GHz interfaces on mobile devices, thereby making them cheaper and energy-efficient—both of which are attractive benefits to mobile equipment manufacturers.

The work raises several interesting questions: What are the design considerations for a MAC to mask off the effects of mis-alignment? Can such a MAC ensure that traditional higher-layer protocols are completely unaffected? While the user attempts to align the antennas, can another omni-directional antenna or a wider beamwidth antenna allow for low rate communication, to ensure that the user sees more graceful throughput degradation? We plan to explore these directions in our future work.

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