A First Look at 802.11ad Performance on a Smartphone

Shivang Aggarwal, Arvind Thirumurugan, Dimitrios Koutsonikolas
University at Buffalo, The State University of New York
{shivanga,athirumu,dimitrio}@buffalo.edu

ABSTRACT

We present the first, to our best knowledge, measurement study of 802.11ad on a commercial smartphone. We explore a number of different aspects including range and coverage, performance under various mobility patterns, and impact on power consumption. We find that, although the performance is generally inferior to that of a laptop, the phone can sustain Gbps rates and the power consumption is not prohibitively high. Overall, our results show that, in spite of earlier concerns, 802.11ad can be a viable candidate technology to address the needs of emerging bandwidth-intensive applications in smartphones.

ACM Reference Format:
Shivang Aggarwal, Arvind Thirumurugan, Dimitrios Koutsonikolas. 2019. A First Look at 802.11ad Performance on a Smartphone. In *3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems (mmNets'19), October 25, 2019, Los Cabos, Mexico.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3349624.3356766

1 INTRODUCTION

An emerging class of smartphone applications, such as mobile Virtual reality (VR), Augmented reality (AR), and live 4K/8K video streaming, demand multi-Gbps speeds from the underlying wireless network. The 14 GHz of unlicensed spectrum around 60 GHz have attracted ample attention from both academia and industry as a candidate solution for providing the required multi-Gbps data rates. IEEE 802.11ad is one of the standards that govern the use of this spectrum and is touted as the primary technology for building the next generation of WLANs.

Despite early concerns regarding the range and performance in indoor environments, a number of 802.11ad compliant devices such as access points (APs) and laptops have been released in the market over the past few years. However, until last year, there was no commercially available smartphone with an 802.11ad chipset. Manufacturers have had several concerns with putting an 802.11ad chipset on a phone such as heavy power consumption, hardware resource usage [7], and antenna placement [1]. After a number of early failed attempts and promises [4, 5], this year ASUS finally released the ROG (Republic of Gamers) phone with an integrated 802.11ad chipset.

Nonetheless, the performance of 802.11ad in smartphones remains unknown. Although a number of recent studies using software-defined radio (SDR) based solutions or COTS laptops (e.g., [6, 9, 10, 15]) have shown that 802.11ad indeed works well indoors (the range is much longer than initially predicted and beamforming in COTS devices is efficient enough to minimize periods of low connectivity), it is not clear if these findings can be extended to smartphones for a number of reasons. First, antenna placement becomes a non-trivial problem as there are more than one ways of holding a small device such as a smartphone. Second, the small form factor of the phone exacerbates the blockage problem, as it becomes much easier for the user to block the antenna with their hand. Lastly, there is a concern about the energy consumption in smartphones in case of high speed data transfers over a significant period of time.

In this paper, we use the ROG phone to conduct the first experimental study of 802.11ad on a smartphone. We focus on performance aspects affected by unique smartphone features, e.g., the antenna array placement or the client mobility patterns, and compare the performance against that achieved by 802.11ad laptops in previous studies. We also evaluate the phone's power consumption under Gbps data rates.

Our results show that, even though the phone's performance is in general inferior compared to laptops, 802.11ad still works well enough considering the ROG phone's 802.11ad chipset is meant to be used primarily as a docking solution. Further, our results suggest that a smartphone with a general purpose 802.11ad solution can indeed hold up well in most realistic scenarios and reliably sustain Gbps speeds, thus enabling this new era of high bandwidth demanding smartphone applications.

2 EXPERIMENTAL SETUP

Devices. The Asus ROG Phone [2] is the only commercially available smartphone with an 802.11ad chipset. Additionally, it houses an 802.11ac chipset. The phone is powered by a Snapdragon 845 octa-core processor with an 8GB RAM and

mmNets '19, October 25, 2019, Los Cabos, Mexico

ACM ISBN 978-1-4503-6932-9/19/10...$15.00
https://doi.org/10.1145/3349624.3356766

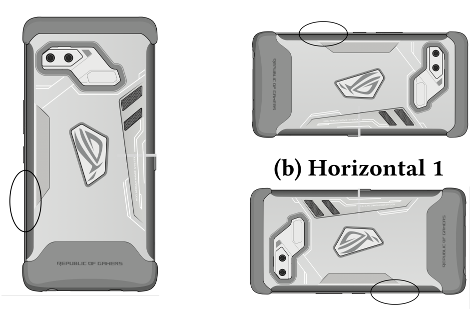
a 4000 mAh battery. The phone is marketed as a gamer's phone and the intended use of the 802.11ad chipset is to cast the phone's screen via an 802.11ad dock. However, in this paper we evaluate it as a general purpose 802.11ad phone.

All our experiments are performed with a Netgear Nighthawk X10 Smart WiFi Router [3], which includes an 802.11ad chipset along with an 802.11ac chipset. The router is connected to a server-grade desktop via a 10-Gigabit ethernet cable.

Methodology. For all our measurements, we use iperf3 to generate TCP traffic. We take multiple traces of 60 seconds for each case unless mentioned otherwise. Along with the TCP throughput, we log the transmitter and receiver MCS and beamforming sectors used by the phone as well as the router every 100 ms, and voltage and current drawn by the phone every 1 s.

3 BASELINE PERFORMANCE

In our recent study [10] using off-the-shelf 802.11ad routers (including the Nighthawk router we use in this paper) and laptops, we showed that, in contrast to a common belief, 802.11ad achieves excellent indoor range, with Gbps speeds often supported at distances longer than 100 ft. In this section, we examine if the smartphone can support similar ranges. We perform measurements in the same two locations described in [10] for a direct comparison between the two client devices (laptop and smartphone): a wide open space (lobby) with a high ceiling and a few desks and chairs, and a long, narrow (5 ft) corridor, completely free of any objects, with dry wall on both sides. We repeat the measurements with three different phone orientations, since the device orientation directly affects the position of the phone's antenna array with respect to the AP and hence, the beamforming process and the sector selection. The antenna array position and the three orientations are shown in Fig. 1. In both locations and for all three orientations, we keep the AP at a height of 6 ft and the phone at a height of 3.5 ft with the back of the phone facing the AP, and perform measurements in both the uplink and downlink direction.



(a) Vertical (b) Horizontal 1 (c) Horizontal 2

Figure 1: Asus ROG Phone Orientations and Antenna Placement.

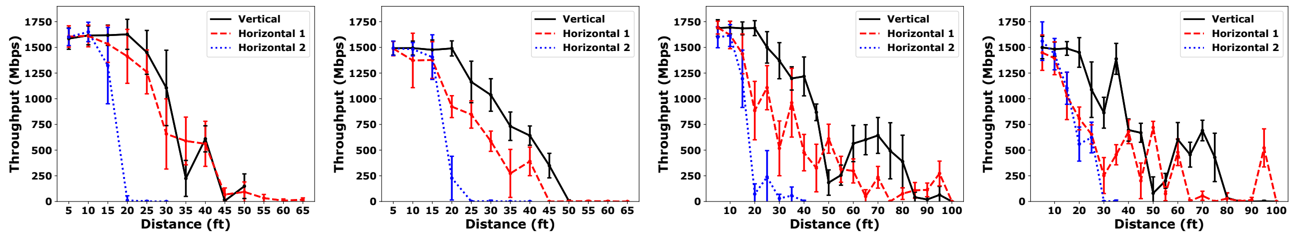
In the lobby (Figs 2a and 2b), for orientations Vertical and Horizontal 1, we observe a gradual drop in throughput as the distance increases from 5 ft to about 45-50 ft. After 50 ft, in the Vertical orientation the phone cannot establish a connection to the AP while in the Horizontal 1 orientation, it is able to successfully connect to the AP up to 65 ft (although the throughput is lower than 100 Mbps). In case of the Horizontal 2 orientation, we observe a very sudden drop in throughput from 15 ft to 20 ft and after 30-40 ft, the phone cannot connect to the AP. We also observe that for all three orientations the performance in uplink is generally worse than in downlink. Finally, we note that the range is lower compared to that achieved by a laptop; e.g., in [10], we reported Gbps performance up to 80 ft in the same location.

In the corridor (Figs 2c and 2d), the Horizontal 2 orientation achieves similar range and performance as in the lobby. However, for the other 2 orientations, the results are quite different. The range has increased to 100 ft and the throughput does not drop linearly with distance but exhibits large variations even at locations 5 ft apart, due to the waveguide effects in the narrow corridor (also found in [10]). On the other hand, similar to the lobby, the performance in uplink is again in general worse than that in downlink. Again, the phone's range is lower compared to the laptop's range. In [10], we reported Gbps throughputs up to a distance of 155 ft with a laptop whereas the phone cannot connect to the AP at distances longer than 100 ft.

Remark: The 802.11ad range on the phone is much lower than on a laptop. Additionally, performance in the uplink is lower than in the downlink. Nonetheless, Gbps speeds are still feasible at distances of several tens of ft.

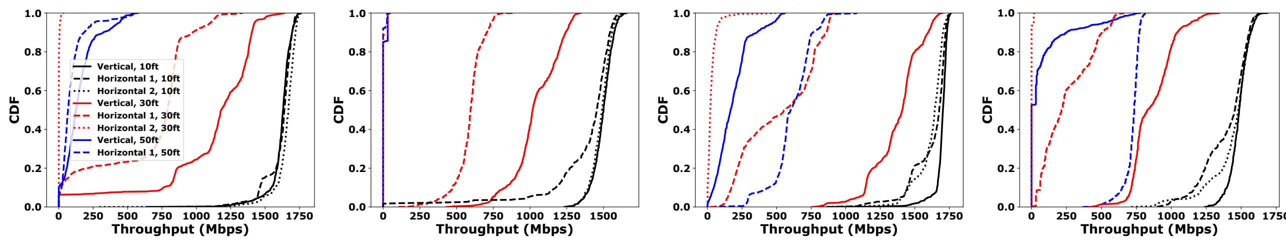
To dive deeper into these results, we pick 3 representative positions – 10 ft, 30 ft, and 50 ft – and analyze them in further detail. We start by looking at the throughput CDFs for all 3 orientations in both the lobby and corridor (Fig. 3). At 10 ft, the Vertical and Horizontal 2 orientations sustain MCS 8 more than 90% of the time in both the downlink and uplink direction; as a result, the throughput stays above 1500 Mbps and 1250 Mbps for downlink (Figs 3a, 3c) and uplink (Figs 3b, 3d), respectively, 90% of the time. The Horizontal 1 orientation sustains MCS 8 for 70-80% of the time still achieving high throughput but comparatively lower than the other 2 orientations. On the other hand, Horizontal 2's throughput is nearly zero around 80-90% of the time in all cases at 30 ft (with MCS either 0 or 1 more than 95% of the time) and fails to connect at 50 ft. In contrast, the throughput for the Horizontal 1 and Vertical orientations varies substantially at 30 ft spanning a range of more than 500 Mbps in all cases – a result of both the orientations using at least 3-4 different MCSes. At 50 ft, in the lobby, both working orientations have near zero uplink throughput while the downlink throughput remains below 250 Mbps 90% of the time with MCS 0 and 1 being used almost all the time. In the corridor, the Horizontal 1 orientation performs much better as the throughput stays between 500 and 750 Mbps 90% of the time with MCS up to 6.

Remark: The orientation at which the phone is held has



(a) Lobby, Downlink. **(b) Lobby, Uplink.** **(c) Corridor, Downlink.** **(d) Corridor, Uplink.**

Figure 2: Throughput over distance.



(a) Lobby, Downlink. **(b) Lobby, Uplink.** **(c) Corridor, Downlink.** **(d) Corridor, Uplink.**

Figure 3: CDF of throughputs at 10, 30, and 50 ft for the 3 orientations.

a great impact on the network performance at different distances. Horizontal 2 works well only at short distances. Vertical performs well at short and medium distances but its performance drops at longer distances. Finally, Horizontal 1 performs worse than Vertical in short and medium distances but supports the longest range.

Next we evaluate the choice of the Tx and Rx sectors made by both the phone and the AP and the impact on performance. In case of the Rx sectors, we make a similar observation as in [10]: the Rx sector on the phone (in downlink) and on the AP (in uplink) never changes. We draw the same conclusion here as in [10], that both the phone and the AP use a quasi-omni beam pattern in Rx mode. In contrast, the TX sector selection is very stable on the AP (fixed TX sector most of the time) but quite unstable on the phone. Even at 10 ft, the phone selects up to 4-5 different Tx sectors. This behavior is amplified at longer distances. At 30 ft, for the Horizontal 2 orientation, more than 10 different Tx sectors are selected in both the lobby and the corridor, as the phone keeps looking (unsuccessfully) for a strong link. For the Horizontal 1 and Vertical orientations, we majorly see 2-3 Tx sectors being used at this distance and hence we see a much better performance when compared to the Horizontal 2 orientation (Figs 2, 3). At 50 ft, for the 2 working orientations we notice many more (sometimes >10) sectors being chosen and a much worse performance.

Remark: The beamforming protocol on the phone performs much worse than on the AP, resulting in lower uplink performance.

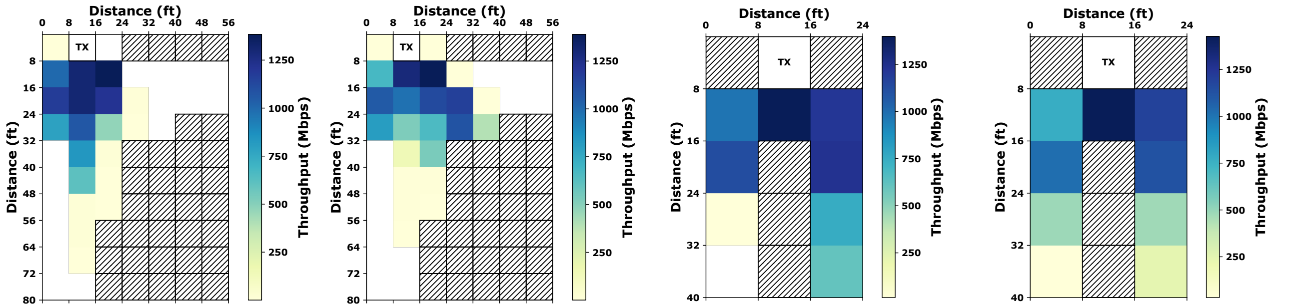
4 COVERAGE

In the previous section, we only evaluated the impact of distance between the phone and the AP. In this section, we consider both the distance and angular separation. We perform the experiments in 2 locations: the lobby and a lab. We divide the floor in both locations into 8 ft by 8 ft squares and take throughput measurements at the center of each square. Since the Horizontal 2 orientation yielded very poor performance in the previous experiments, we only do experiments with the Vertical and Horizontal 1 orientations from now on.

Figs 4a and 4b plot the results for the lobby. We observe that the range changes significantly when angular separation is introduced. The range drops sharply on the left side of the AP to 32 ft from 72 ft in front of the AP, while on the other side a connection can be sustained up to a much longer distance (56 ft) for both orientations. This is because of reflections from the wall on the right side of the lobby. Overall, coverage is much worse as compared to what was observed in [10], especially at narrower angles of separation.

We also observe that each of the 2 orientations in the lobby works better in different positions. The Horizontal 1 orientation can establish a connection and achieve higher throughputs at wider angles while the Vertical orientation can achieve much higher throughputs at narrower angles. For example, the Vertical orientation can barely achieve 10-20 Mbps at the right-most position where it gets a connection whereas at the same position Horizontal 1 yields more than 1 Gbps throughput. On the other hand, when the angular separation is zero, the Vertical orientation can achieve Gbps rates for longer distances than the Horizontal 1 orientation (40 ft vs. 24 ft).

The results from the lab are plotted in Figs 4c and 4d. Here, the performance is mostly symmetric with respect to location for the Horizontal 1 orientation, which is expected,



(a) Lobby, Vertical **(b) Lobby, Horizontal 1** **(c) Lab, Vertical** **(d) Lab, Horizontal 1**

Figure 4: Coverage in Lobby and Lab with different orientations. The shaded region in the lobby shows inaccessible areas, such as walls and other rooms. The shaded region in the lab shows areas occupied by furniture.

since the lab environment is also symmetric. Surprisingly, for the Vertical orientation, the performance differs based on which side of the lab the phone is in. Note that because of the antenna placement on the phone (Fig. 1a), when the phone is on the right side of the AP, the antenna points towards the wall and the phone is able to sustain a connection and close to Gbps performance because of reflections from the wall. For example, for the furthest position on the left of the AP in Fig. 4c, the phone cannot even establish a connection while on the other side it gets a throughput of 600Mbps.

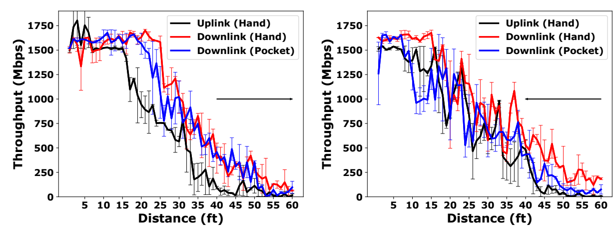
Remark: Coverage with a phone is in general lower compared to with a laptop and heavily depends on the device orientation, in addition to location and AP-client angular separation.

5 MOBILITY

In this section, we evaluate the performance of the phone under typical mobility scenarios where the phone may be in the user's hand or pocket. This is the first study, to our best knowledge, that evaluates the performance of 802.11ad over realistic mobility patterns, as all previous works used either laptops (e.g., [6, 8, 10]) or bulky SDRs (e.g., [9, 15]), and hence were limited in terms of performing realistic motion.

We perform the experiments in the lobby and the corridor and consider the following 3 scenarios: (a) moving away from the AP, starting in front of the AP while facing away from the AP, (b) moving away from the AP, starting in front of the AP while facing the AP, and (c) moving towards the AP, starting at a distance of 60 ft (lobby)/80 ft (corridor). We repeat these measurements with the phone in the user's hand (emulating a video call) and in the user's pocket (where the phone may be performing a large download). In all cases, the user moves at a speed of 1 ft/s and the phone is held or kept in the pocket in the Vertical orientation.

In the lobby, while moving away from but facing towards the AP (Fig. 5a), we observe that the phone can sustain throughputs above 1.5 Gbps up to 15 ft when held in the hand, in both the uplink and downlink direction. Surprisingly, very similar performance is observed even when the phone is in the pocket (downlink). After 15 ft, the uplink



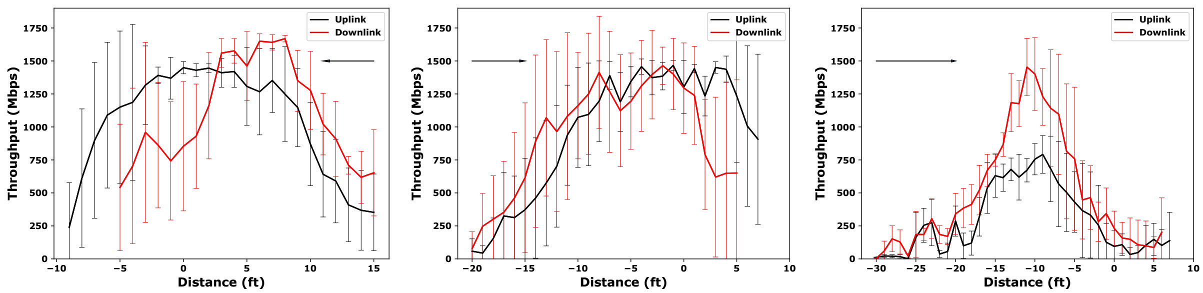
(a) Away from the AP. **(b) Towards the AP.**

Figure 5: Mobility in Lobby while facing the AP.

throughput drops very sharply and is always lower than the downlink throughput. Again, keeping the phone in the pocket results in similar performance to (or only slightly lower than) holding it in the hand for the whole duration of the motion. When moving towards the AP (Fig. 5b), the uplink throughput remains very low up to 45 ft, with a maximum of around 100 Mbps, but becomes comparable to the downlink throughput for shorter distances. Here, both the uplink and downlink throughputs exhibit much higher variations over distance compared to the moving away case. We see similar results in the corridor (the graphs are omitted due to space limitations).

In both the lobby and the corridor, while moving facing away from the AP, we always lose connection within the first 5-10 seconds. Therefore, we are not able to report any meaningful results. In this case, the body completely blocks the signal between the AP and the phone and neither of them are able to find a working transmission sector even through reflections, except for very short distances.

We also report here the outage time, i.e., the percentage of time the throughput was zero at any given distance. In the lobby, for scenario (b) (Fig. 5a), we find that the downlink outage time when the phone is held in the hand is at most 25% for distances longer than 50 ft. When the phone is in the pocket, the average outage time goes up to 60% for similar distances. In contrast, the uplink outage time increases sharply to above 80% and exceeds 20% even for shorter distances of 30-40 ft. In scenario (c) (Fig. 5b), the uplink outage times are similar but the downlink times are even lower compared to scenario (b) – below 15% when



(a) Westbound, 5 ft from AP. **(b) Eastbound, 5 ft from AP.** **(c) Eastbound, 15 ft from AP.**

Figure 6: Lateral Mobility.

the phone is in the hand and below 25% when it is in the pocket. In the corridor, outages are much more frequent for all three cases in both directions, starting at 15-35 ft when moving towards and at only 5 ft when moving away from the AP. Additionally, the downlink outage times are much higher and often similar to the uplink ones. As a comparison, in [10], we reported downlink outage times as high as 80% with the same Nighthawk router and a laptop in the lobby but at distances longer than 140 ft. On the other hand, we saw no outage till 70 ft while with the phone outages start at 30-45 ft.

Remark 1: The poor performance of the phone's beamforming protocol adversely affects the network performance during motion.

Remark 2: A layer of cloth, surprisingly, does not block the millimeter-wave signal between the phone and the AP.

Next, we perform experiments while moving laterally with respect to the AP. We repeat the measurements moving eastbound and westbound once at a longitudinal distance of 5 ft from the AP and once at a distance of 15 ft. In all experiments, we start walking from the furthest lateral distance where we can get a connection and keep walking till we lose the connection.

Fig. 6a shows the throughput when the phone is 5 ft away from the AP and moving westbound (antenna pointed away from the AP). Before crossing the AP, downlink performs much better than uplink, yielding 300-400 Mbps higher throughput. Just as we are about to cross the AP, the downlink throughput drops from around 1.5 Gbps to 750 Mbps within 3-4 ft of motion and then the connection is lost after a further 5 ft of motion. On the other hand, in uplink, the phone loses connection just 5 ft further as well but it can sustain much higher throughput before. We also notice that the standard deviations are very high and we observe that the individual traces are quite different from one another. For example, at the starting point, we see the initial throughput varies from around 1.2 Gbps for one trace to less than 100 Mbps for another. This is the artifact of the rate adaptation incorrectly choosing an MCS lower than it can actually sustain. We make similar observations towards the end of the run where in some traces the throughputs can be as high 1 Gbps while in others as low as 50 Mbps.

At a longitudinal distance of 15 ft, while moving westbound, the phone was not able to establish a connection to the AP even when it was laterally in front of the AP, as the combined effect of the body blockage and longer distance cause a much larger signal attenuation.

Figs 6b an 6c show the results while moving eastbound. In this case the phone's antenna points in the direction of the AP and hence we can achieve connection even at a longitudinal distance of 15 ft. At a longitudinal distance of 5 ft, we are able to get a connection 20 ft away laterally. Here, both uplink and downlink can achieve Gbps throughputs on both sides of the AP. Another observation is that the range of motion is longer in this case than when we moved in the opposite direction. For instance, moving westbound we were only able to cover a distance of about 20 ft in downlink, whereas in this case we are able to maintain connection for 25 ft. Similar to the westbound motion, the standard deviations are again very high.

When we are 15 ft away from the AP (Fig. 6c), we observe that the range of motion is significantly higher than in the other cases (>35 ft). The reason is that because of the larger longitudinal distance from the AP, the angular separation for the same lateral distance decreases. On the other hand, the throughput values are much lower on average than in the other cases. For example, in the uplink case, the maximum throughput throughout the run is less than 750 Mbps.

Remark: The position of the antenna with respect to the AP greatly affects the range of motion and the performance.

Lastly, we perform an experiment where we attempt to evaluate how the phone performs in a micro-mobility [13] scenario. In this experiment, the user is sitting on a chair 10 ft from the AP and is playing a racing game on the phone using the phone's 802.11ad link to cast the screen via a dock to a TV. The phone initially is held in the Horizontal 1 orientation and, while the game is played, the phone is moved around in random positions. We perform 3 runs. The average throughput during these runs is 1.29, 1.38, and 1.33 Gbps with a standard deviation of 184, 161, and 284 Mbps. The throughput varies slightly throughout each run but generally stays above 1 Gbps.

Remark: The phone performs well in micro-mobility scenarios (the default usage scenario for the ROG phone).

6 POWER CONSUMPTION

We evaluate the power consumed by the phone for two orientations at 3 different distances (10, 30, and 50 ft). We log the current and voltage values from the `/sys/class/power_supply/battery` directory on the phone. We report the power consumption values after taking out the phone's base power consumption. At 10 ft, the average uplink/downlink power consumption is 1194 mW/1948 mW for the Vertical orientation, with uplink/downlink throughputs of 1.45 Gbps and 1.56 Gbps. We see similar values for the Horizontal 1 orientation. At 30 ft, the average uplink/downlink power consumption is 1452 mW/2174 mW for the Vertical orientation, with uplink/downlink throughputs of 1.05 Gbps and 1.4 Gbps, and 1113 mW/1872 mW for the Horizontal 1 orientation, with uplink/downlink throughputs of 702 Mbps and 822 Mbps. We conjecture that the higher power values at 30 ft compared to 10 ft in spite of lower or comparable throughputs are due to a higher number of beamforming operations [11]. In all cases, we surprisingly see that the power consumption for data reception is much higher than for data transmission (a similar trend is observed at 50 ft as well). Although we do not have an explanation, we note that a similar observation was made in [11] using a laptop. We also performed an experiment where we charged the battery to 100% and ran a 20 minute long data transfer in both the uplink and downlink directions separately. The battery percentage dropped by only 5%/7% in the uplink/downlink case.

7 RELATED WORK

There has been a large body of work performing 60 GHz channel measurements using SDRs (e.g., [9, 15]) or WiGig-based hardware (e.g., [8, 12]), which are not fully standard compliant. In the case of SDRs, there are often additional issues such as the use of horn antennas instead of antenna arrays and the limited bandwidth [15]. More recent studies (e.g., [6, 10, 11, 14]) use standard compliant COTS APs and laptops to obtain a deeper understanding of 802.11ad link characteristics and lower layer operations. However, the use of laptops does not allow for a realistic evaluation of mobility patterns and offers limited insights into the power consumption aspects that are important in the context of mobile devices. In contrast, our work is the first to evaluate 802.11ad performance and power consumption on a real smartphone under typical scenarios that a smartphone user encounters in day-to-day operation.

8 CONCLUSION

We conducted the first measurement study of 802.11ad on a commercial 802.11ad-compliant smartphone. We focused on aspects such as the range and coverage of the device in typical indoor environments. We found that the phone, although weaker in terms of range than a laptop, does work well in particular orientations. We also conducted experiments in mobile scenarios typical of a smartphone user and found that the beamforming performs suboptimally and can severely affect network performance. Nonetheless, given that this phone was built for a specific 802.11ad application, we believe that future phones with more generic 802.11ad solutions will improve in these aspects. We also found that the 802.11ad power consumption is not prohibitively high despite earlier concerns. Overall, our results suggest that 802.11ad can be a viable solution to enable new bandwidth-intensive applications in smartphones.

9 ACKNOWLEDGEMENTS

This work was supported in part by NSF grants CNS-1553447 and CNS-1422304.

REFERENCES

[1] [n. d.]. *802.11ad will vastly enhance Wi-Fi - Qualcomm.* https://www.qualcomm.com/media/documents/files/abi-research-802-11ad-will-vastly-enhance-wi-fi.pdf

[2] [n. d.]. *ASUS Republic of Gamers (ROG) Phone.* https://www.asus.com/us/Phone/ROG-Phone/

[3] [n. d.]. *Netgear Nighthawk® X10.* https://www.netgear.com/landings/ad7200

[4] [n. d.]. *New ASUS ZenFone 4 Pro is first with Gigabit LTE and multi-gigabit 802.11ad Wi-Fi.* https://www.qualcomm.com/news/onq/2017/09/21/new-asus-zenfone-4-pro-first-gigabit-lte-and-multi-gigabit-80211ad-wi-fi

[5] [n. d.]. *SiBEAM Captures World's First 60GHz Millimeter-Wave Smartphone Design Win in Letv's Flagship Smartphone, Le Max.* https://www.businesswire.com/news/home/20150519005350/en/SiBEAM-Captures-Worldś-60GHz-Millimeter-Wave-Smartphone-Design

[6] Hany Assasa, Swetank Kumar Saha, Adrian Loch, Dimitrios Koutsonikolas, and Joerg Widmer. 2017. Medium Access and Transport Protocol Aspects in Practical 802.11ad Networks. In *Proc. of IEEE WoWMoM.*

[7] Zeqi Lai, Y. Charlie Hu, Yong Cui, Linhui Sun, and Ningwei Dai. 2017. Furion: Engineering High-Quality Immersive Virtual Reality on Today's Mobile Devices. In *Proc. of ACM MobiCom.*

[8] Thomas Nitsche, Guillermo Bielsa, Irene Tejado, Adrian Loch, and Joerg Widmer. 2015. Boon and Bane of 60 GHz Networks: Practical Insights into Beamforming, Interference, and Frame Level Operation. In *Proc. of ACM CoNEXT.*

[9] Swetank Kumar Saha et al. 2017. X60: A Programmable Testbed for Wideband 60 GHz WLANs with Phased Arrays. In *Proc. of ACM WiNTECH.*

[10] S. K. Saha, H. Assasa, A. Loch, N. M. Prakash, R. Shyamsunder, S. Aggarwal, D. Steinmetzer, D. Koutsonikolas, J. Widmer, and M. Hollick. 2018. Fast and Infuriating: Performance and Pitfalls of 60 GHz WLANs Based on Consumer-Grade Hardware. In *Proc. of IEEE SECON.*

[11] S. K. Saha, T. Siddiqui, D. Koutsonikolas, A. Loch, J. Widmer, and R. Sridhar. 2017. A detailed look into power consumption of commodity 60 GHz devices. In *Proc. of IEEE WoWMoM.*

[12] Swetank Kumar Saha, Viral Vijay Vira, Anuj Garg, and Dimitrios Koutsonikolas. 2016. A Feasibility Study of 60 GHz Indoor WLANs. In *Proc. of IEEE ICCCN.*

[13] Li Sun, Souvik Sen, and Dimitrios Koutsonikolas. 2014. Bringing Mobility-Awareness to WLANs using PHY layer information. In *Proc. of ACM CoNEXT.*

[14] Sanjib Sur, Ioannis Pefkianakis, Xinyu Zhang, and Kyu-Han Kim. 2017. WiFi-Assisted 60 GHz Wireless Networks. In *Proc. of ACM MobiCom.*

[15] Sanjib Sur, Vignesh Venkateswaran, Xinyu Zhang, and Parameswaran Ramanathan. 2015. 60 GHz Indoor Networking through Flexible Beams: A Link-Level Profiling. In *Proc. of ACM SIGMETRICS.*