802.11ad in Smartphones: Energy Efficiency, Spatial Reuse, and Impact on Applications

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***Abstract*—We present an extensive experimental evaluation of the performance and power consumption of the 60 GHz IEEE 802.11ad technology on commercial smartphones. We also compare 802.11ad against its main competitors in the 5 GHz band – 802.11ac and, for first time, 802.11ax, on mobile devices. Our performance comparison focuses on two aspects that have not been extensively studied before: (i) dense multi-client and multi-AP topologies and (ii) popular mobile applications under realistic mobility patterns. Our power consumption study covers both non-communicating and communicating modes. We also present the first study of the power saving mode in 802.11ad-enabled smartphones and its impact on performance. Our results show that 802.11ad is better able to address the needs of emerging bandwidth-intensive applications in smartphones than its 5 GHz counterparts. At the same time, we identify several key research directions towards realizing its full potential.**

I. Introduction

An emerging class of smartphone applications, such as mobile Augmented/Virtual reality (AR/VR), Miracast, and UHD video streaming, demand 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 one of the candidate solutions to achieve the required Gbps data rates. The IEEE 802.11ad standard is touted as one of the main technologies for building the next generation of WLANs. The standard supports 2 GHz-wide channels and provides data rates of up to 6.7 Gbps, a multi-fold increase over legacy WiFi in the 5 GHz band.

Despite initial concerns about range and performance in indoor environments, several 802.11ad-compliant APs and laptops have been released over the past few years. However, before 2019, there was no commercially available smartphone featuring an 802.11ad chipset, partly due to concerns about 802.11ad's high power consumption, hardware resource usage, and antenna placement. ASUS released the ROG phone – the first smartphone featuring an integrated 802.11ad chipset – in March 2019 and the ROG II phone in September 2019.

Nonetheless, the performance of 802.11ad in smartphones remains largely unknown. While recent studies using SDRs [1], [2] or commercial-off-the-shelf (COTS) laptops, APs, and docks [3], [4], [5], [6], [7] have shown that 802.11ad works well indoors, these findings do not directly extend to smartphones for several reasons: (i) The many different ways of holding a smartphone make antenna placement a non-trivial problem. (ii) The small form factor limits the number of antenna elements in a smartphone, leading to wider beams and lower directivity gain compared to laptops and APs. (iii) The small form factor makes it much easier for the user to block the signal with their hand or body. (iv) The mobility patterns of smartphone users are much more diverse and unpredictable [8] compared to those of laptop users. Indeed, a previous study using a ROG phone [9] showed that the phone can sustain Gbps data rates, but the orientation at which the device is held significantly affects performance, the range and coverage are much lower compared to a laptop, and self-blockage during mobility can lead to link outages. However, no work has yet investigated the performance of 802.11ad in mobile devices in multi-client or multi-AP scenarios, or the impact of 802.11ad on mobile applications under realistic mobility patterns.

At the same time, legacy WiFi in the 5 GHz band has been evolving. 802.11ac, the prevalent WLAN standard today, already supports theoretical data rates up to 3.4 Gbps, although hardware constraints in smartphones limit the throughput to around 600 Mbps in practice [10], [11]. The latest 802.11ax standard (WiFi 6) [12] promises up to 6.9 Gbps, even higher than the maximum 802.11ad rate. The first 802.11ax-equipped smartphones appeared on the market in 2019. 802.11ax is viewed as a strong competitor to 802.11ad, as it offers backward compatibility with 802.11ac, together with longer range and better resilience to blockage and mobility than 802.11ad.

Besides performance, energy efficiency is highly important for mobile devices. Power consumption increases with higher PHY data rates, wider channels, and more spatial streams [13], [14], [15], [16], as well as with higher application layer throughput [17], [18], [19]. 802.11ad offers much higher data rates and uses wider channels than legacy WiFi, and the beamforming incurs an additional power cost that is absent in 5 GHz technologies. At the same time, 802.11ad supports only SISO communication, which is more power efficient compared to the MIMO used in 802.11ac/ax. Hence, it is essential to understand the different factors that affect the power consumption of 60 GHz radios and the potential energy-performance-range tradeoffs compared to legacy WiFi. Yet, the power consumption of mmWave radios remains largely unexplored, with only two prior studies that focus on laptops and APs [4], [5]. For more widespread adoption of 802.11ad, it is necessary to study 802.11ad power consumption in smartphones, where hardware resources and power management policies can be a significant performance bottleneck [10], [20].

In this paper, we fill this gap by performing an extensive experimental evaluation of the performance and power consumption of 802.11ad on commercial smartphones, and compare it against its main competitors, 802.11ac and 802.11ax. We focus on two aspects that have not been extensively studied before: (i) dense multi-client and multi-AP topologies and (ii) popular mobile applications under realistic user mobility patterns. Our power consumption study covers both non-communicating and communicating modes. We also present the first study of power saving policies in 802.11ad-enabled smartphones and their impact on performance. Our measurement dataset is available at http://bit.ly/11ad-smartphone-infocom21. Our contributions are summarized as follows:

Baseline performance in static settings (§III): Our performance comparison of 802.11ad, 802.11ac, and 802.11ax shows that, contrary to earlier concerns, the CPU in modern smartphones is not a bottleneck, and 802.11ad-enabled phones can achieve Gbps throughput in both the uplink and the downlink directions. While 802.11ax is marketed as a Gbps technology, the first generation of 802.11ax phones does not deliver Gbps throughput, *making 802.11ad the only real Gbps wireless technology on today's smartphones*.

Power consumption (§IV): We perform the first experimental study of the power characteristics of 802.11ad in smartphones. We find that the 802.11ad smartphone power consumption in non-communicating states is much lower than that of 802.11ad laptops, but higher than 802.11ac. We then show that the power saving mode (PSM) in 802.11ad smartphones puts the radio to sleep much more aggressively than legacy 802.11 implementations. It is also more complex, and we uncover, for first time, the policies that govern its operation. Finally, we study the active power consumption across different devices. Surprisingly, the 802.11ad Tx power is significantly lower than the Rx power, and the lowest among the three technologies. We also show that, for short distances, *802.11ad offers both higher throughput and lower energy cost than the 5 GHz technologies in the uplink* and higher throughput but also slightly higher energy cost in the downlink.

Spatial reuse (§V): We study the performance and energy consumption of the three technologies in dense topologies. We show that, in contrast to common belief, COTS 802.11ad devices have very poor spatial reuse, often worse than omnidirectional 5 GHz radios. We also show that, in addition to the wide, irregular beam patterns and reflections [1], [3], [21], the PSM policies in 802.11ad-enabled smartphones have an adverse impact on performance. We further confirm previous findings that the benefits of 802.11ac MU-MIMO are limited in practice [22], [23], and extend these findings to 802.11ax.

Impact on applications (§VI): We evaluate for first time the impact of 802.11ad on popular smartphone apps – mobile browsing, mobile UHD video streaming, mobile VR, and Miracast, in terms of performance and energy consumption. In the case of mobile browsing, the overly aggressive power saving policies in 802.11ad result in worse performance and increased energy consumption compared to 802.11ac/ax. *We find that disabling PSM both improves performance and reduces energy consumption*. In the case of downlink-oriented bandwidth-hungry apps (streaming, VR), 802.11ad offers much better performance than 802.11ac/ax at the cost of higher energy consumption. For uplink-oriented bandwidth-hungry apps (Miracast), 802.11ad offers simultaneously the best performance *and* the lowest energy cost.

II. Experimental Methodology

Devices. Since no device on the market features both 802.11ad and 802.11ax, we use different router-phone pairs to study each technology. To ensure a fair energy comparison between the two technologies (to the extent possible), we use the most power efficient smartphone for each technology in all our experiments. All the phones are shown in Table I. The 802.11ad devices used in this study support all 12 single-carrier MCSs of 802.11ad, with PHY data rates from 385 Mbps up to 4.6 Gbps. The 802.11ad router (Netgear Nighthawk X10) features 32 antenna elements while the 802.11ad smartphones contain 8. The 802.11ac (802.11ax) chipsets on the routers (Netgear Nighthawk X10 for 802.11ac, ASUS RT-AX88U for 802.11ax) support 4 spatial streams, MU-MIMO, channel widths of up to 160 MHz, and MCS 0-9 (0-11), yielding PHY data rates of 6.5 Mbps-3.4 Gbps (7.3 Mbps-4.8 Gbps). On the other hand, the phones support only 2 spatial streams and channel widths of up to 80 MHz, limiting the max supported 802.11ac (802.11ax) PHY data rate to 866 Mbps (1.2 Gbps).

Methodology. We use iperf3 to generate TCP traffic and log throughput every 100 ms. For each experiment, we collect 5 traces of 30-60 s each and present their mean and standard deviation. For 802.11ad, we log the Tx and Rx MCS and beamforming sectors used by the phone and the router every 100 ms. The 802.11ac and 802.11ax drivers do not export any information, and we thus set a laptop to monitor mode and capture MAC headers from which we extract the MCS, number of spatial streams, and channel width. All experiments are performed at night to avoid interference from the campus networks and human blockage in the 60 GHz band.

We measure power using two methods. For most experiments, we log voltage and current drawn by the phone from the `/sys/class/power_supply/battery` directory every 1 s for the ROG, ROG II, Mi 10, and every 0.1 s for the S10. For finer granularity, we use a Monsoon HV Power Monitor, which logs the power every 0.2 ms. We connect it to the phone by opening its back with a heat gun, unsoldering the battery from the cable that attaches it to the terminal, and soldering the Monsoon connectors to that cable. This approach only works with the ROG phone. All the power measurements are taken with the screen on, all other radios disabled, and minimal background application activity, ensuring that the base power (defined as the power consumed by the phone when the screen is on but all radios are off) is low and stable over time. All the power results are relative to the base power. Different smartphones may apply various battery aware optimizations, e.g., CPU frequency scaling or core scaling, which can have an impact on power measurements. While we have no control over such optimizations, we believe that the

TABLE I: Downlink/Uplink throughput comparison (in Mbps) with different phones and technologies.

	ROG	ROG II	S10	Mi 10
802.11ad	2100/1800	2200/1800	N/A	N/A
802.11ax	N/A	N/A	900/600	920/540
802.11ac	630/540	650/600	650/530	720/520

impact on our measurements is minimal, since we conduct all the experiments under similar operating conditions; we start each experiment with fully charged battery and the battery does not drop by more than 5% during any of the experiments.

III. Baseline Performance

Table I compares the throughput of the three technologies with each smartphone. Each phone was kept 1 ft away from the AP, facing the AP. We performed both downlink (AP-to-phone) and uplink (phone-to-AP) measurements.

Table I confirms the findings in [9] for the ROG phone and extends them to the ROG II: *both 802.11ad-enabled phones achieve Gbps data rates in both directions*. The rates are very similar to those reported for AP-laptop links in recent studies [6], [24], [25], [7], [26]. We also observe that with both phones, *the uplink performance is lower than the downlink performance*. Note that the data rates in Table I can only be sustained at very short AP-client distances, up to 1-2 ft, where the highest MCSs (10-12) are supported. At longer distances, the highest supported MCS is 8, limiting the max. 802.11ad throughput to 1.65 Gbps, lower than the values in Table I but still above 1 Gbps. The same observation was made for AP-laptop links in [6], [7], [26].

Our results show that, in spite of previous concerns [10], the CPU of modern smartphones is not a bottleneck and can easily process packets at Gbps data rates. The CPU does not run at the max. frequency and its utilization remains below 20%. We find that the key factor that enables Gbps data rates is the Linux Segmentation Offloading (GSO/GRO). With GSO/GRO disabled, the max. throughput drops to only 300-400 Mbps.

Also for the 5 GHz technologies, the downlink throughput is higher than the uplink throughput. All phones use 2 spatial streams and 80 MHz with both technologies. Thus, the higher downlink throughput with 802.11ax ($\sim$900 Mbps) compared to 802.11ac (650-720 Mbps) is due to the higher MCSs (10, 11) supported only by 802.11ax. Interestingly, while the same MCSs are used in the uplink direction, the 802.11ax throughput is similar to the 802.11ac throughput. Overall, the limitations of first generation 802.11ax smartphones (without support for 160 MHz channels and 3 or 4 spatial streams) prevent them from achieving Gbps rates, *making 802.11ad the only truly Gbps WLAN technology*.

IV. Power Consumption

A. Power in non-communicating states

We examine the power of 802.11ad and legacy 802.11ac WiFi in various non-communicating states. For high granularity measurements, we use the ROG phone and Monsoon. The results (averaged over 5 runs) are shown in Table II. For comparison, we include the results for two different generations of 60 GHz chipsets for laptops – a WiGig PCIE chipset (not fully 802.11ad-compliant) and an 802.11ad M2 chipset – from [5].

TABLE II: Power in Non-Communicating States (in mW). The results in the first two columns are reproduced from [5].

	WiGig (laptop)	802.11ad (laptop)	802.11ad (phone)	802.11ac) (phone)
ON [Not Associated]	501	1058	145	104
SCAN	2729	1756	1103	638
ON [Associated]	2351	1938	176	108
IDLE	2351	1938	1095	588
Beamforming	3100	1890	1286	N/A

ON [Not Associated] In this state, scanning is disabled and there is no Tx/Rx activity; hence, the reported power value indicates the minimum power that needs to be supplied to keep the chipset powered on. The phone's 802.11ad chipset consumes 145 mW, 41 mW more than the 802.11ac chipset but much lower than the PCIE/M2 laptop chipsets.

SCAN The 802.11ad scanning consumes 1103 mW on the phone. Again this value is much lower than the PCIE/M2 power but higher than the 802.11ac power in the same state. However, the 802.11ad scan operation takes only 1/3 of the time required for an 802.11ac scan (0.5 s vs. 1.5 s), since there are only 3 channels in the 60 GHz band as opposed to more than 20 in the 5 GHz band, resulting in lower energy consumption for 802.11ad (0.55 J) than for 802.11ac (0.96 J).

ON [Associated] In this state, the client is associated to the AP but there is no traffic, except for periodic beacons from the AP. The 802.11ac power remains at almost the same level as in the *ON [Not Associated]* state, due to the Power Saving Mode (PSM); the radio is in a low power (sleep) state during inactivity and only wakes up once every 100 ms to receive a beacon. The 802.11ad chipset on the phone consumes 176 mW in the *ON [Associated]* state, an order of magnitude lower than the power of PCIE/M2 chipsets, but 63% higher than the 802.11ac value on the same phone, possibly due to the much wider channels in the 60 GHz band.

IDLE The *IDLE* state refers to the high-power state following any Tx/Rx activity, before a PSM timeout puts the chipset to sleep. The PSM timeout of the 802.11ac chipset is 200 ms and the IDLE power is equal to 588 mW. On the other hand, 802.11ad on the phone uses a much more aggressive timeout of 15 ms but the idle power is much higher, equal to 1095 mW. The IDLE power for the PCIE/M2 chipsets is the same as the ON [Associated] power; the authors in [5] incorrectly conjectured that these devices do not implement PSM.

Beamforming Fig. 1 shows the various power states when the phone tries to re-associate with the AP after a blockage event. During blockage, the phone and the AP keep performing sector level sweeps (SLSs) to discover a working beam pair. The power consumption during this state is 1286 mW, whereas that of PCIE/M2 chipsets is 3100 mW and 1890 mW, respectively. After the blockage, the chipset remains in the *ON [Not Associated]* state for 9-10 s, before it attempts a scan and re-associates with the AP. In contrast, the work in [5] reports that the M2 chipset performs a scan right after the blockage is removed but if this scan fails, it then waits in a low power state for $\sim$4-5 s before scanning again.

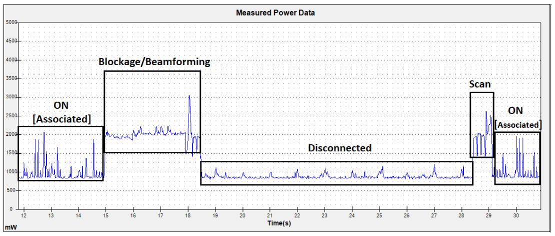


Fig. 1: Example timeline showing phone power consumption in the case of 802.11ad blockage and re-connection.

Overall, the 802.11ad chipset on the phone is much more power efficient in non-communicating states than 802.11ad M2/PCIE chipsets, but less power efficient than the phone's 802.11ac chipset. In particular, the high scanning, idle, and beamforming power are a cause of concern.

B. Power saving policies in 802.11ad

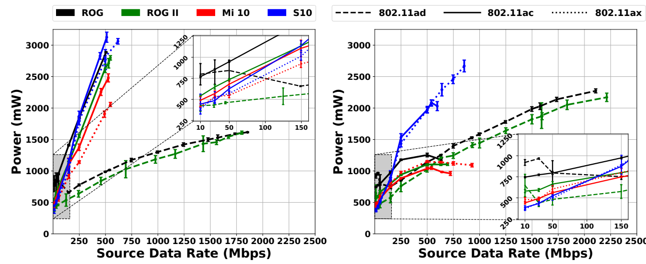
We now take a closer look at the power saving policies in different technologies. Our methodology consists of sending or receiving UDP/TCP packets of various packet sizes, varying the packet inter-arrival rate from 1 s down to 0.2 ms, and observing packet traces captured with a device in monitor mode. We find that 802.11ac and 802.11ax radios in all 4 phones implement the standard adaptive PSM [20]: the radio always goes to sleep 200 ms after the last Tx/Rx activity and wakes up at the beginning of the next beacon period.

As shown in Table II, the 802.11ad idle power consumption is much higher than the 802.11ac idle power. Consequently, both the ROG and ROG II phones, in addition to using a much smaller PSM timeout of 15 ms, implement a more complex power saving policy for 802.11ad, using three rules based on the packet inter-arrival time T_p:

Rule 1: $T_p \geq 92\ ms$: Standard adaptive PSM with a PSM timeout of 15 ms is used. The radio wakes up at the beginning of the next beacon interval or when it has a new packet to transmit.

Rule 2: $T_p \in [14\ ms, 92\ ms)$: Packets are buffered on the phone or the AP and sent at the beginning of the next beacon interval as a batch. The PSM timeout is kept at 15 ms. For the downlink, this corresponds to the standard PSM policy, where a sleeping client wakes up at the next beacon interval to receive packets from the AP in a batch. Instead, in the uplink, the standard behavior for the radio would be to wake up immediately when it receives a packet for transmission from the upper layers, rather than waiting for the next beacon. We confirm that the 802.11ac radio on the same phone does adhere to the standard. Note that this batching happens even for T_p values lower than 15 ms, where the radio should never go to sleep according to the standard.

Rule 3: $T_p < 14\ ms$: The radio follows the standard implementation for 0.5 s, transmitting or receiving one packet every T_p without going to sleep. After 0.5 s, it wakes up periodically every ΔT, sends or receives a batch of packets, and *goes to sleep almost immediately (PSM timeout less than 1 ms)*. In the downlink, this policy is similar to the static PSM implementation [20], but instead of PS POLL frames,



(a) Uplink. (b) Downlink.

Fig. 2: Power consumption vs. source data rate with all available phones and all three technologies.

the phone sends NULL frames with the PSM bit set to 0 to notify the AP that it is awake every ΔT. The value of ΔT is much shorter than the beacon interval and becomes shorter as T_p decreases (e.g., 10 ms for $T_p \geq 1\ ms$, 4-5 ms for $T_p \in [200\ us, 500\ us]$). We conjecture that the radio on the phone "learns" the traffic pattern even in the case of downlink traffic and determines an appropriate ΔT value. For very small T_p values (backlogged traffic), ΔT approaches 0 and the radio never goes to sleep.

While the aggressive power saving policies clearly aim at maximizing the energy savings and counter-balancing the high idle power, they may have an adverse impact on performance. For example, the small PSM timeout compared to 802.11ac/ax, combined with Rule 2, may lead to RTT inflation in the case of delay-sensitive applications and poor user experience. Also, the very aggressive PSM timeout under high data rates (Rule 3) can have an adverse impact in the case of multiple competing clients, as we show in §V.

C. Active power consumption

We now evaluate the active (Tx/Rx) power consumption. Figs. 2a, 2b show the Tx (uplink) and Rx (downlink) power, respectively, as a function of the data rate for all 4 phones and all 3 technologies. We make the following observations:

First, the power consumption for a given technology varies significantly across phone models. In the case of 802.11ad, the power consumption with the newer ROG II phone is slightly lower than with the older ROG phone. For 802.11ac and 802.11ax, the power consumption is highest with the S10 phone and lowest with the Mi 10 for a given source data rate, except for very low data rates. This gap is more pronounced in the downlink. Instead, for very low data rates (10-25 Mbps), the S10 consumes the lowest power among all devices, regardless of the wireless technology.

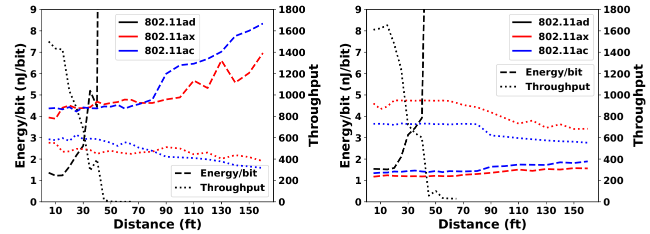
Second, 802.11ac and 802.11ax follow a typical pattern; the Tx power for a given data rate is much higher than the Rx power on all phones. On the other hand, *the trend is reversed for 802.11ad: the Rx power is higher than the Tx power*. The authors in [5] made a similar observation for an M2 802.11ad chipset. We conjecture that part of the reason for this difference is that single carrier 802.11ad requires both FFT and IFFT at the receiver for frequency domain equalization, whereas OFDM 802.11ac requires IFFT at the transmitter and FFT at the receiver. Furthermore, LDPC decoding at the data rates supported by 802.11ad is quite energy consuming.

Third, *the power consumption increases monotonically with the data rate for all three technologies and all phones for a large range of data rates*, in agreement with several power models (e.g., [17], [18]), with two exceptions: (i) the 802.11ac Rx power with all phones and the 802.11ax Rx power with the S10 plateau after 500 Mbps; (ii) the 802.11ad Tx power with the ROG and the 802.11ad Rx power with both the ROG and the ROG II exhibit non-monotonic behavior for low data rates (10-150 Mbps). *These counter-intuitive behaviors appear to be technology- rather than phone-dependent (e.g., the 802.11ad Tx power does not plateau for high data rates on any phone), suggesting that smartphone vendors employ different optimizations for different wireless technologies.*

Fourth, a comparison among the three technologies reveals that, despite early skepticism, *ultra-wideband 802.11ad radios are not extremely power hungry*. In fact, 802.11ad (on ROG II) has the lowest Tx power among the three technologies, and the margin is quite large for data rates higher than 250 Mbps (0.6-2 W). Combined with the much higher supported data rates, this makes *802.11ad the most energy efficient technology for uplink traffic*. Its Rx power is also the lowest for data rates up to about 500 Mbps, but becomes higher than that of the 5 GHz technologies for higher data rates. Under backlogged traffic, the power gap is large (950-1250 mW with 802.11ac/ax for various phones ignoring S10 vs. 2200-2300 mW for 802.11ad), but *the large throughput difference makes 802.11ad the most energy efficient technology* (1.22-1.98 nJ/bit vs. ~1 nJ/bit).

At low data rates ($< 100 Mbps$), 5 GHz technologies can be more energy efficient, since it is not necessary to activate all the VHT features (e.g., MIMO or wider channels) to support such rates. Fig. 2(b) shows that this is indeed the case when we compare the 802.11ac and 802.11ad Rx power on the same phone (for 10-50 Mbps on ROG, 10-20 Mbps on ROG II), although the gap is small (at most 200 mW). For Tx, the power still remains the lowest with 802.11ad.

Energy-throughput-range tradeoff. We have seen (§III) that 802.11ad is the only WLAN technology that can provide Gbps throughput and that 802.11ad is the least power hungry technology in the Tx state. However, there is one more factor that should be taken into account – the communication range, which is much longer for 802.11ac/ax. Our experiments with both 802.11ad phones in two indoor locations (an open space and a narrow corridor) reveal that the 802.11ad throughput drops below 1 Gbps at distances of 20-30 ft from the AP and to 0 for distances of more than 50-60 ft (open space) or 100 ft (corridor). In contrast, the 802.11ac/ax throughput remains almost unchanged for ranges up to 170 ft. We study the energy-throughput-range tradeoff among the three technologies via Figs. 3b, 3a, which plot the Tx/Rx energy/bit cost (power consumption divided by throughput) on the y-axis and the throughput in the form of a heat map, as a function of the AP-phone distance on the x-axis. The measurements were taken at an open space with the most power efficient phone for each technology – ROG II for 802.11ad and Mi 10 for 802.11ac/ax.



(a) Uplink. (b) Downlink.

Fig. 3: Energy-throughput-range tradeoff.

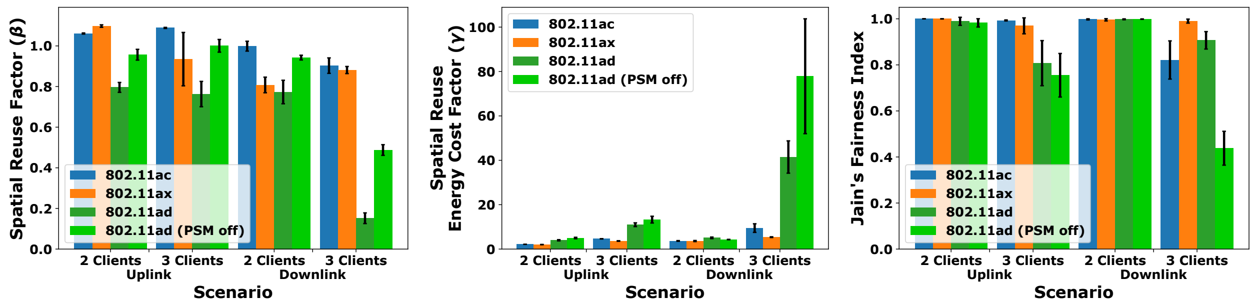
Fig. 3a shows that *802.11ad is the preferred technology for short distances up to a few 10s of ft in the uplink case, combining faster data rates* ***and*** *lower energy cost*. In the downlink case (Fig. 3b), the answer is not immediately clear. For very short distances, 802.11ad has the highest throughput but 802.11ax is the most energy-efficient technology. Thus, there is a *tradeoff between speed and energy efficiency* and the preferred technology depends on which one of these metrics has priority over the other. *For longer distances, 802.11ax becomes the preferred technology in both directions, followed by 802.11ac*, whereas 802.11ad performs very poorly both in terms of throughput and energy efficiency.

The low 802.11ad Tx power consumption makes the technology ideal for novel uplink-oriented, bandwidth-intensive applications, such as Miracast. However, the high Rx power consumption raises a concern for traditional downlink applications, such as streaming or VR. It also suggests that we may have to revisit recent 5/60 GHz bundling proposals [26], [11] to make them energy-aware.

V. Spatial Reuse

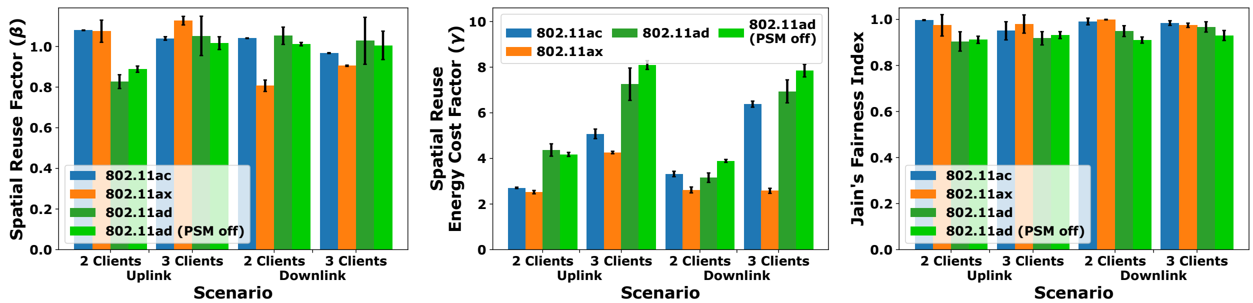
We evaluate the ability of the three technologies to share the medium efficiently. We consider single-AP, multi-client topologies with 2 or 3 clients associated to the same AP and multi-AP topologies with 2 or 3 APs and 1 client per AP. We use the spatial reuse factor β [1], defined as $\beta = \frac{Sum\ rate\ of\ concurrent\ links}{Average\ rate\ of\ isolated\ links}$. Ideally, n coexisting links achieve $\beta = n$, when there is no mutual interference. Lower β values indicate interference and reduced spatial reuse, and $\beta < 1$ indicates collisions and reduced performance compared to the case of isolated links. We also calculate Jain's Fairness Index (FI) [27], which takes values between 1/n and 1, with higher values indicating better fairness. To study the impact of interference on energy consumption, we define a spatial reuse energy cost factor γ as: $\gamma = \frac{Sum\ E_b\ of\ concurrent\ links}{Average\ E_b\ of\ isolated\ links}$, where E_b is the client energy per bit cost (§IV). Similar to β, n coexisting links ideally achieve $\gamma = n$. However, there is no upper bound for γ unlike β; $\gamma > n$ means that the energy cost increases compared to the case of isolated links.

Single-AP, multi-client topologies. In the uplink case shown in Fig. 4, the 5 GHz technologies achieve β and FI very close to 1, indicating fair sharing but no spatial reuse. In the 3-client topology, the CSMA overhead is more pronounced in the case of 802.11ax – the faster of the two technologies. In contrast, 802.11ad performs poorly, achieving β below 0.8 with both 2 and 3 clients. For 3 clients, we also observe unfairness, with an FI equal to 0.8. The inability of the 802.11ad clients to efficiently share the medium has an impact on the energy cost too, especially in the 3-client case. The value of γ for 802.11ad



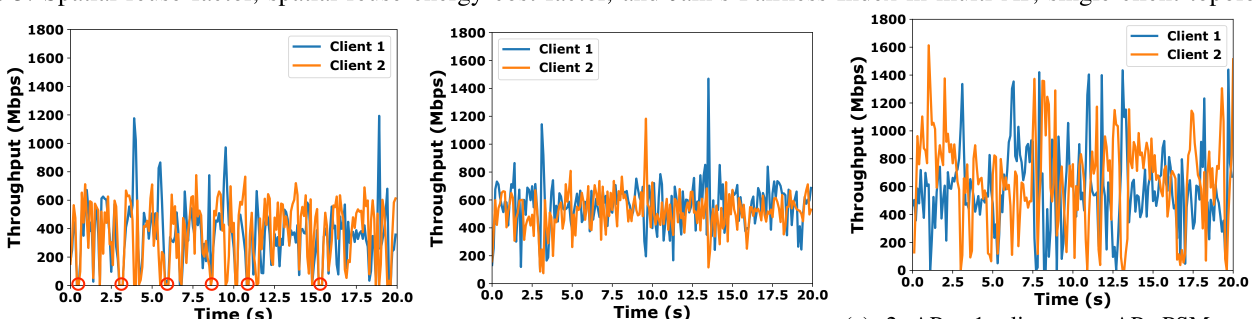
(a) Spatial reuse factor β. (b) Spatial reuse energy cost factor γ. (c) Jain's Fairness Index.

Fig. 4: Spatial reuse factor, spatial reuse energy cost factor, and Jain's Fairness Index in single-AP, multi-client topologies.



(a) Spatial reuse factor β. (b) Spatial reuse energy cost factor γ. (c) Jain's Fairness Index.

Fig. 5: Spatial reuse factor, spatial reuse energy cost factor, and Jain's Fairness Index in multi-AP, single-client topologies.



(a) 1 AP, 2-clients, PSM on: throughput of both clients simultaneously drops to 0. (b) 1 AP, 2-clients, PSM off: throughput no longer drops to 0. (c) 2 APs, 1 client per AP, PSM on: throughput of one client drops to 0, the other one peaks.

Fig. 6: Example throughput timelines in multi-client and multi-AP topologies.

is 3.97 with 2 clients and 10.97 with 3 clients. In contrast, the 5 GHz technologies achieve a γ value very close to 2 in the 2-client topology. In the 3-client topology, the energy cost increases for 802.11ac/ax as well (γ values of 4.6 and 3.6), but much less compared to 802.11ad.

In the downlink case, the AP ensures perfect sharing, but MU-MIMO for 802.11ac/ax has the potential to improve spatial reuse. Surprisingly, β is equal to or less than 1 for both technologies, showing that *MU-MIMO not only does not help, but in most cases hurts performance and potentially fairness* (3 clients, 802.11ac). We also tested a total of 20 2-client and 20 3-client random topologies; β was above 1 in only 55% (10%) of 2-client (3-client) topologies, with median/max. values of 1.05/1.25 (0.85/1.15). Our results confirm recent studies [22], [23], which found that MU-MIMO in practice often performs worse than SU-MIMO with 802.11ac, due to naive grouping algorithms used in COTS APs that do not consider the inter-user interference. We extend these findings to 802.11ax, showing that contrary to expectation, its performance is even more affected than 802.11ac. For 802.11ad, β is the same as in the uplink case in the 2-client topology but much lower in the 3-client topology, where all 3 clients starve (average throughputs of 32-65 Mbps only). As a result, the energy cost also increases drastically in the 3-client topology for 802.11ad, as shown by the very high value (41) of γ.

The poor performance of 802.11ad in multi-client topologies, and especially the starvation of all three clients in the downlink, is highly counter-intuitive. While deafness [28] in the uplink can occasionally result in collisions, in the downlink the AP should be able to coordinate the access to the medium. Upon closer inspection of the traces, we noticed intervals of several tens of ms where the throughput of all clients drops to zero simultaneously (see e.g., Fig. 6a for a downlink 2-client topology). By inspecting packet traces collected with another router configured in monitor mode, we found that the PSM implementation (see §IV) in the 802.11ad chipsets is responsible for the poor performance.

Each 802.11ad client goes to sleep aggressively when it remains idle for a few ms, e.g., when the AP is serving another client, and sends a NULL frame with the power management bit set to 1 to notify the AP. Yet, the AP often tries to deliver a new data frame to such a client later, instead of buffering it for the next beacon interval, either because it did not receive the NULL frame (due to a collision), or because it had already pushed more packets for this client to its transmission queue. Since the client does not respond with a MAC layer ACK, the AP falsely thinks that the link is broken after several retries. It triggers beamforming to recover the link, and keeps performing SLSs for the rest of the beacon period; it also stops forwarding traffic to other clients, and prevents them from sending TCP ACKs (it responds with Denial-To-Send (DTS) frames to every RTS). As a result, all TCP sessions experience timeouts and cut their windows. Only after the client wakes up at the beginning of the next beacon period and responds to the beamforming messages, the AP finally resumes traffic to all clients. The phenomenon is more pronounced in the 3-client downlink case, where we count 80-100 TCP retransmissions over each 1-min experiment.

Multi-AP, single-client topologies. In the uplink case (Fig. 5), 802.11ac/ax again achieve very good sharing but limited spatial reuse. Their energy costs are higher compared to the downlink case. 802.11ad performs similar to the single-AP case with 2 clients in terms of all three metrics, but is better with 3 clients, albeit still worse than 802.11ac/ax, especially in terms of the energy cost. In the downlink scenario, β drops for 802.11ax; recall from §III that the 802.11ax downlink throughput is higher than the uplink, hence, the same idle time due to carrier sensing and back off will incur a higher penalty. In contrast, 802.11ad performs much better than in the single-AP case, with both 2 and 3 clients, achieving β equal to or better than the 5 GHz technologies and similar fairness. However, once again, it does not achieve any spatial reuse, and its energy cost is higher than that of 802.11ac/ax.

The lack of spatial reuse for 802.11ad in the multi-AP case is due to the wide, irregular beam patterns created by the phased arrays in COTS devices (also observed in [1], [3], [21]). By inspecting packet traces, we found several instances, where the APs respond to RTSs from clients with DTS frames, preventing the from transmitting for a long period of time, because they sense the medium busy due to transmissions from other APs/clients. The interaction between the medium access and PSM has another adverse impact; indeed, while the sum of the average throughputs is always close to the capacity (resulting in β values close to 1), the instantaneous throughput of each client exhibits very large variations, sometimes dropping down to 0 but not simultaneously for all clients (Fig. 6c). We found that after receiving a DTS, sometimes a client goes to sleep and hence, it cannot receive any packet for the remainder of the beacon period. If the AP does not receive the NULL frame, then again it starts performing multiple SLSs, as in the single-AP case. Here, other AP-client pairs can continue their own transmissions and hence, we do not see instances where the throughput of all clients simultaneously drops to 0. However, multiple SLSs still interfere with other transmissions and reduce the overall capacity.

We repeated all the experiments with 802.11ad clients with PSM disabled. In the single-AP, multi-client topologies, disabling PSM indeed improves performance and eliminates the throughput drops to 0 (Fig. 6b), but it reduces the fairness. In particular, we find that in the downlink case with 3 clients, two of the clients starve (throughputs below 30 Mbps) while the middle one achieves on average 400-500 Mbps. The energy cost also increases, particularly in the the downlink case with 3 clients. Conversely, in the multi-AP, single-client topologies, disabling PSM results in a slight decrease in β (except for the uplink, 2-client case), since the problem of interference due to wide beams remains and contention becomes higher when all clients remain awake.

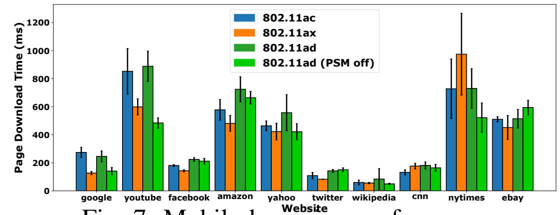


Fig. 7: Mobile browsing performance.

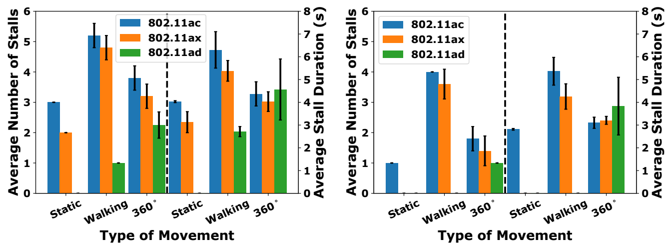
Our results show very limited spatial reuse among COTS 802.11ad devices due to the wide, imperfect beams of practical phased arrays. Even worse, the PSM implementation in this first generation of 802.11ad mobile devices interacts poorly with medium access, causing very large throughput variations in the case of multi-AP topologies and starvation in the case of multi-client topologies. Although disabling PSM indeed improves the performance in single-AP topologies, we note that this is not a viable solution for mobile devices. We remark that the design of more efficient power management schemes is highly important for future work.

VI. Impact on Applications

We consider 4 popular smartphone applications – browsing, video streaming, VR, and Miracast – with different characteristics and investigate the impact of each wireless technology on application performance and device energy consumption.

Mobile browsing. With the phone 6 ft away from the AP, we use Chrome to access 10 popular websites of size 6-16 MB with an empty cache and measure the page load time using the Chrome DevTools. Note that the total page load time consists of the content download time and the rendering time. The rendering time depends on the complexity of the website. Even though for complex websites (e.g., Yahoo, CNN, NY Times) it can be 6x-100x longer than the downloading time, for most of the websites we consider, the download time is comparable and sometimes even longer than the rendering time. Since analyzing the rendering time is out of scope of this work, we focus on the download time in the remainder of this section. To obtain fine granularity in the power measurements (since the download time can be less than 1 s), we use a ROG phone with Monsoon for the 802.11ad and 802.11ac measurements. For 802.11ax, we use an S10 phone but do not measure the power consumption due to lack of support for Monsoon.

Fig. 7 shows that for most websites, 802.11ax achieves the shortest download time. On the other hand, the download time



(a) QP 20. (b) QP 25.

Fig. 8: Video streaming performance.

TABLE III: Energy consumption in video streaming (Joules).

QP	Static			Walking			360°		
	ac	ax	ad	ac	ax	ad	ac	ax	ad
20	77	76	92	99	95	104	90	88	111
25	57	58	75	75	72	79	67	67	75
30	34	48	43	42	42	54	43	46	58

with 802.11ad is longer than with 802.11ax for 8/10 websites and the longest among the three technologies for 6/10 websites, in spite of the much faster data rates. The gap sometimes is substantial (up to 300 ms). The energy consumption is also higher than with 802.11ac for 8/10 websites by 10-71%. We found that the reason for the poor performance with 802.11ad is again the aggressive PSM policy, which results in RTT inflation. Indeed, Fig. 7 shows that with PSM disabled, the download time with 802.11ad improves in most cases (by up to 400 ms) and becomes comparable or even lower than 802.11ax for 6/10 websites. Interestingly, the energy consumption for 802.11ad *decreases* with PSM disabled for 9/10 websites by up to 44%, and becomes lower than with 802.11ac for 5/10 websites, since the reduction in the download time with PSM off more than compensates for the power savings with PSM on. *Our results highlight again the need for improved 802.11ad power saving policies that do not compromise performance*.

Mobile UHD video streaming. We use a 4K, 50 FPS, 20 s video from the Derf's collection under Xiph [29], encoded at 3 different QP levels: QP 20 (bitrate 1.3 Gbps, SSIM 0.97), QP 25 (775 Mbps, 0.91), and QP 30 (311 Mbps, 0.84). We host the videos on a local server attached to the AP, in order to remove the Internet bottleneck, and use ExoPlayer to stream them to the ROG II (802.11ad) and Mi 10 (802.11ax/ac) phones. We consider three different scenarios: (i) a static user sitting 10 ft away from the AP, (ii) a user walking towards and away from the AP at a speed of 3 ft/s, and (iii) 360° rotation, where the users sits 10 ft away from the AP and moves the device and their body emulating watching a 360° video. As expected, all three technologies can stream the lowest of the three qualities without any stalls. Hence, we only plot the number of stalls and average stall duration for QP 20/25 (Figs. 8a, 8b).

These figures show that *802.11ad is the only technology that can stream all three QP levels without any stalls in the static case*. With 802.11ax, the user experiences on average 2 stalls of 3 s when streaming the highest quality. Finally, 802.11ac can only stream the lowest of the three qualities without stalls.

Motion worsens the performance for all technologies. Still, *802.11ad streams the medium quality video without any stalls when the user is walking and provides the lowest number of stalls compared to 802.11ac/ax in all scenarios*. This is thanks to the much higher data rates that allow the player to buffer enough frames to mask temporary idle periods due to self-blockage. We also observe that different mobility patterns have different impact on the three technologies. 360° motion has a higher impact on 802.11ad; indeed, even though the average number of stalls is lower with 802.11ad, the average stall duration is higher than with 802.11ac/ax, because device and/or body rotation results in self-blockage and/or misalignment between the fields of view of the AP and client [24]. The use of omni-directional antennas in 802.11ac/ax mitigates the impact of device/body rotations. However, in the case of walking, the rate adaptation makes multiple incorrect decisions, which result in performance degradation [30].

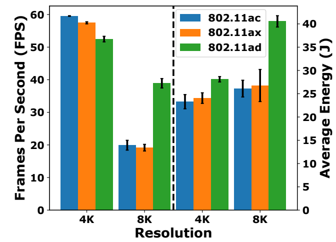


Fig. 9: Mobile VR evaluation.

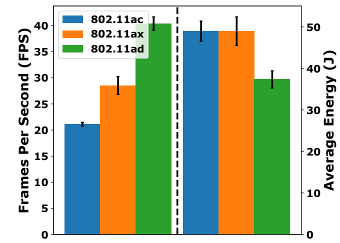


Fig. 10: Miracast evaluation.

Table III shows that the energy consumption with 802.11ad is higher than with 802.11ac/ax. However, the gap is small (4-36%), since the much higher 802.11ad throughput compensates for the higher Rx power compared to 802.11ac/ax.

Mobile VR. We use the ROG II (802.11ad) and Mi 10 (802.11ax/ac) to experiment with the Viking Village app, which has been used in recent VR studies (e.g., [10], [31]). We follow the state of the art Furion [10] that prefetches the surrounding pre-rendered panoramic frames from a local server based on the client's current view and does not perform any quality adaptation. Since the ROG/ROG II phones are not VR-ready, we pre-encoded a 24 s, 60 FPS Viking Village scene at two different resolutions (4K, bitrate 264 Mbps; 8K, bitrate 1.1 Gbps), based on a specific trajectory, and we wrote a client app that requests frames over a TCP connection based on this trajectory. The app runs on a phone placed in a Google Cardboard VR headset, while the user wears the headset and moves their head and body. To support 60 FPS, each frame should be available for displaying at most 16.66 ms after being requested. Hence, we estimate the FPS metric by counting the number of frames that are available on the client at least 16.66 ms before their hypothetical display time.

Fig. 9 shows that the 5 GHz technologies can support the 4K resolution using Furion, achieving almost 60 FPS. 802.11ad performs slightly worse (52 FPS) and increases the energy consumption by 16-22%, since it is more impacted by body and head rotation. Indeed, mobility triggers multiple beamforming events within a 24 s period (10-15 different sectors are used in each experiment) and the MCS often drops all the way down to 1. However, *4K is the upper limit for 5 GHz technologies*; at 8K (this is a hypothetical scenario, as today's smartphone screens do not support 8K resolution), 802.11ac/ax only achieve 23/24 FPS, since the sub-Gbps bandwidth provided by these technologies cannot support the high 8K data rates. On the other hand, 802.11ad supports 38 FPS – a 658-65% improvement, although still below the target 60 FPS. Nonetheless, this result is encouraging, since *the technology does provide the required bandwidth and multi-AP [24], [32] or relay-based [33], [34] setups, bundling 60 GHz and 5 GHz interfaces [26], [11], or intelligent interface switching [25] combined with quality adaptation could provide resilience to self-blockage*.

Miracast. This is the default usage scenario of 802.11ad on the ROG and ROG II phones. We played the Asphalt Legends Racing Game on the ROG II phone while casting the phone's screen to a 4K TV, using the ASUS WiGig dock, and collected a 30 s packet trace using tcpdump. The average frame rate is 42 FPS and the uplink throughput varies between 500-700 Mbps. The trace also includes many proprietary small packets sent by the dock to the phone between frames, which limit the total channel capacity. Since there are no similar docks available for the 802.11ac and 802.11ax technologies, we replay this trace between the Mi 10 (802.11ax/ac) or ROG II (802.11ad) phone and a desktop, connected via the RT-AX88U or Nighthawk X10 router, to emulate Miracast over each technology. We move both phones in a similar pattern to when the game is actually being played, while sitting in a chair.

Fig. 10 shows that 802.11ac/ax fail to support the required frame rate, delivering on average only 21 FPS and 28 FPS, respectively. Recall that the 802.11ax max. uplink throughput is around 550 Mbps only, similar to 802.11ac. Here, *802.11ad is the only technology that can meet the application demands and, at the same time, the most energy-efficient technology*, consuming 25% less energy compared to 802.11ac/ax, thanks to the much lower Tx power (Fig. 2(a)). Compared to VR, the amount of motion is limited (since the user is sitting in a chair and only moves the phone in their hands). Although mobility still triggers beamforming several times within the 30 s period (the phone uses 6-12 different sectors), the MCS rarely drops below 4 (1155 Mbps), which is sufficient to support the required application layer throughput.

VII. Related Work

mmWave performance and power consumption. There is a large body of work on 60 GHz performance characterization using either SDRs [1], [35], [36], [33], [37], [8], [2] or WiGig-based hardware [38], [3], [39], [4], which are not fully 802.11ad-compliant, and more recently, 802.11ad-compliant COTS APs and laptops [5], [24], [25], [40], [32], [6], [7], [41], [21], [26], [11]. In contrast, our study explores performance of 802.11ad on smartphones, considering realistic smartphone user mobility patterns. Additionally, with the exception of [33], [8], [11], all previous works focus on PHY, link, or transport layer performance under backlogged traffic. In contrast, our work is one of the first to study the impact of 802.11ad on popular mobile applications. In contrast to performance, the power consumption of mmWave radios has not been studied extensively. There are only two works [4], [5] that studied experimentally the power consumption of WiGig/802.11ad PCIE/M2 radios. **mmWave in smartphones.** To our best knowledge, the only other work that studied the performance of 802.11ad in a COTS smartphone is [9]. This paper expands [9] in the following ways: (i) We provide a detailed characterization of the 802.11ad power consumption in COTS smartphones. (ii) We compare the performance and power consumption of 802.11ad against those of 802.11ac and, for first time, 802.11ax, using a variety of mobile devices. (iii) We explore performance and power consumption under multi-client and multi-AP scenarios as well as under popular mobile applications and uncover the impact of 802.11ad power saving policies on performance. Recently, Narayanan et al. [42] conducted the first measurement study of 5G mmWave using smartphones. Since the characteristics of cellular networks are very different from those of WLANs, their study is orthogonal to ours, focusing on topics such as comparison among different carriers, 5G-4G handoffs, location-based performance estimation, and impact on HTTP/2 and HTTP/3 performance. **Sub-6 GHz WiFi in smartphones.** There is a large body of work on the power consumption of 802.11a/b/g/n/ac in smartphones, e.g., [43], [14], [17], [44], [16], [15], [19]. Our work is the first to conduct an experimental evaluation of the performance and power consumption of the new 802.11ax standard. **802.11 PSM.** Several works have studied PSM in legacy 802.11, identified issues, and proposed improvements, e.g., [45], [20], [46]. To our best knowledge, this is the first work to explore in detail PSM in 802.11ad-enabled mobile devices.

VIII. Conclusion

We presented an extensive experimental evaluation of the performance and power consumption of 802.11ad on commercial smartphones. We also compared 802.11ad against its main competitors in the 5 GHz band – 802.11ac and, for first time, 802.11ax, on mobile devices. We showed that 802.11ad is currently the only WLAN technology that truly offers Gbps data rates, and, for uplink-oriented, bandwidth-intensive applications, it simultaneously provides the best performance and lowest energy cost among the three technologies. On the other hand, we found that 802.11ad-enabled COTS devices achieve poor spatial reuse due to the wide, irregular beam patterns of their phased arrays. We also showed that the overly aggressive power saving policies of 802.11ad in smartphones have an adverse impact on the performance and energy consumption in dense topologies and in the case of delay-sensitive applications. Our study identified several key research directions towards fully realizing this potential of 802.11ad in smartphones, such as intelligent interface switching, energy-aware algorithms for bundling 5 GHz and 60 GHz interfaces, and performance-aware power saving policies.

Acknowledgements

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