The Case for Visualization as a Service
Mobile Cloud Gaming as an Example

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Abstract: In recent years, significant progress has been made to improve the power efficiency of mobile devices. In particular, new GPU architectures have made it possible to run compute-intensive applications directly on battery-powered mobile devices. In parallel, research is also being conducted in the area of application offloading, the process of running compute-intensive tasks on cloud servers and delivering the results of these computations to mobile devices through their wireless interfaces. It is important to understand the power consumption implications of each of these two options. In this paper, we use *mobile cloud gaming* as an example to evaluate and compare these two alternatives (running games on the cloud or on mobile devices.) Based on this comparison, we introduce the concept of *Visualization as a Service* (VaaS) as a new model to design and implement graphics-intensive applications for mobile devices. In this model, advanced visualization capabilities (e. g., interactive visualization of high resolution videos/images) would be provided to mobile users as a service via the Internet. We show through actual hardware specifications that, despite the recent introduction of ultra low power GPUs for mobile devices, it remains far more power efficient to offload graphics-intensive tasks to the cloud. The associated latency can still be tolerated in most applications.

1 INTRODUCTION

The growth in the use of mobile devices (mobile phones, tablets, and ultra mobile PCs) is driving a phenomenal market shift. A 2013 Gartner report (Table 1) predicted that, by 2017, device shipments will reach more than 2.9 billion units, out of which 90% will be mobile devices (Milanesi et al., 2013). This growth is accompanied by an equally phenomenal boom in mobile applications. According to the research firm MarketsandMarkets, the total global mobile applications market is expected to be worth $25 billion by 2015 (up from about $6.8 billion in 2010) (MarketsandMarkets, 2010). A 2012 study by the Application Developers Alliance found that 62% of the U. S. online population owned app-capable devices and that 74% of those device owners use mobile applications. As the rendering capabilities of mobile devices improves, mobile applications are becoming increasingly graphics-intensive. This requires intensive computations that quickly drain the device's battery.

Several solutions are being developed to reduce power consumption in graphics-intensive mobile applications. Some solutions are to be used at development time while others are to be used when the application is running. The former focus on tools that help developers estimate power consumption at development time. For example, in (Thompson et al., 2011), the authors present SPOT (System Power Optimization Tool), which is a model-driven tool that automates power consumption emulation code generation. In (Hao et al., 2013), the authors use program analysis during development time to estimate mobile application energy consumption. The latter type of solutions focus on reducing power consumption of hardware components such as the GPU or NIC at run-time. Examples include the *racing to sleep* technique (that sends data at the highest possible rate), wide channels,

Table 1: Worldwide Devices Shipments by Segment (Thousands of Units) (Milanesi et al., 2013)

Device Type	2012	2013	2014	2017
PC (Desk-Based and Notebook)	341,263	315,229	302,315	271,612
Ultramobile	9,822	23,592	38,687	96,350
Tablet	116,113	197,202	265,731	467,951
Mobile Phone	1,746,176	1,875,774	1,949,722	2,128,871
Total	2,213,373	2,411,796	2,556,455	2,964,783

and multiple RF chains (Halperin et al., 2010).

A third alternative is application offloading, the process of running compute-intensive tasks on servers (often in the cloud) and delivering the results of these computations to mobile devices through their wireless interfaces. However, these wireless interfaces also may consume substantial amounts of power when receiving large amounts of data as is typical in many modern, interactive, graphics-intensive mobile applications. It is therefore important to understand the power consumption implications of the two alternatives: running the graphics-intensive application on the cloud or on the mobile device itself. In this paper, we use *mobile cloud gaming* as an example to analyze and compare these two alternatives in terms of power consumption. We show through actual hardware specifications that, despite the recent introduction of ultra low power GPUs for mobile devices, it remains far more power efficient to offload graphics-intensive tasks to cloud servers. To make our discussion concrete, we focus on two cases of mobile devices: (i) notebooks and (ii) smartphones. In both cases, we only consider gaming using the device's WiFi interface not its cellular interface. The reason for this is that the high latency and high cost make mobile cloud gaming using cellular networks (UMTS, LTE, etc.) an impractical alternative for most consumers. We will elaborate on this in Section 3.

This paper is organized as follows. We first give an overview of mobile cloud gaming. In Section 3, we contrast cellular-based and WiFi-based mobile cloud gaming from the perspectives of power consumption, throughput, latency, and cost. In Sections 4 and 5, we present power consumption trends in modern mobile GPUs and 802.11 network cards. In Section 6, we quantitatively evaluate and compare power consumption of a gaming session in the two previously mentioned scenarios in the context of notebooks. We repeat the same analysis for smartphones in Section 7. In Section 8, we give the conclusions from our study and suggest directions for future research.

2 WHAT IS MOBILE CLOUD GAMING?

Mobile cloud computing (MCC) is the process of offloading compute-intensive tasks from mobile devices to cloud servers (Soliman et al., 2013; Shiraz et al., 2013). The purpose is often to save power on the mobile device and/or access servers with much higher computing power. A prime example of MCC is *mobile cloud gaming* which is the process of providing video games on-demand to consumers through the use of cloud technologies. One benefit is that the cloud, instead of the user's device, carries out most of the computations necessary to play the game, e. g., complex graphical calculations. This is obviously a tremendous advantage in case the player uses a battery-powered, mobile device. Even when power is not a critical issue for the user's device, cloud gaming still provides other cloud services, e. g., storage. Cloud gaming enables power savings also on the cloud itself as it makes it possible that several players simultaneously share cloud GPUs. For example, Nvidia's VGX Hypervisor manages GPU resources to allow multiple users to share GPU hardware while improving user density and the utilization of GPU cycles (Nvidia, 2015a). To illustrate, a single cloud gaming-capable Nvidia VGX K2 unit requires 38 Watts per cloud user (Nvidia, 2015c), whereas a comparable single-user Nvidia GTX 690 consumer unit requires 300 Watts to operate (Nvidia, 2015b). In this case, cloud gaming can reduce the overall graphics-related power consumption by 87%.

3 CELLULAR-BASED VS. WIFI-BASED MOBILE CLOUD GAMING

Mobile cloud gaming may be achieved using cellular connections or WiFi connections. While both options are technically possible and relatively comparable in terms of power consumption, the WiFi option seems much more attractive when we consider throughput, latency and cost. In this section, we present results from recent studies analyzing power consumption, throughput, latency, and cost in both scenarios:

3.1 Power Consumption and Throughput

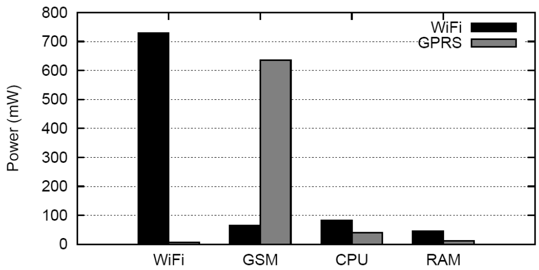


Figure 1: Power Consumption of WiFi and GSM Modems, CPU, and RAM (Carroll and Heiser, 2010).

In (Carroll and Heiser, 2010), the authors analyze power consumption of smartphones. In particular, they studied power consumption of the two main networking components of the device: WiFi and GPRS (provided by the GSM subsystem). The test consisted of downloading a simple file via HTTP using `wget`. The files contained random data, and were 15 MiB for WiFi, and 50 KiB for GPRS. While the test was not a gaming session, it still gave valuable insights. The experiments showed that WiFi achieved a throughput of 660.1 $\pm$ 36.8 KiB/s, and GPRS 3.8 $\pm$ 1.0 KiB/s. However, they both show *comparable* power consumption far exceeding the contribution of the RAM and CPU (Figure 1). The experiments also showed that, with the increase in throughput possible using WiFi, CPU and RAM power consumption also increases reflecting the increase in the cost of processing data with a higher throughput.

3.2 Latency

In the context of mobile cloud gaming, latency refers to the timespan between a user's action and the corresponding reaction (Lampe et al., 2013), e. g., time between the action of pressing a button and seeing a character in the game move as a result of that action. High latency is a real challenge in mobile cloud gaming. Wireless connections (WiFi and cellular) and even wired residential end host round trip times (RTTs) can exceed 100 ms (Lee et al., 2014). To many gamers, this is the point when a game's responsiveness becomes unacceptable. A recent effort to reduce latency in mobile cloud gaming is Outatime, a speculative execution system for mobile cloud gaming that is able to mask up to 250 ms of network latency (Lee et al., 2014). It produces speculative rendered frames of future possible outcomes, delivering them to the client one entire RTT ahead of time.

While latency is an issue in both cellular-based and WiFi-based mobile gaming, WiFi connections typically have much less latency than cellular connections (Lampe et al., 2013).

3.3 Cost

Cost is also a major factor in favor of WiFi-based mobile cloud gaming. For example, in (Lampe et al., 2013), the authors give an analytical assessment that shows that the cost (from cellular data transfer) of a gaming session of one hour would be about 2.36 Euros without including the likely additional usage fee to be paid to the cloud gaming provider.

As we may conclude from the previous discussion, WiFi-based mobile cloud gaming is currently more practical than cellular-based mobile cloud gaming. We, therefore, limit our discussion to this option in the remainder of this paper.

4 POWER CONSUMPTION TRENDS IN MODERN MOBILE GPUs

It is currently generally true that GPUs offering a good rendering capability consume much power for operation and cooling. To illustrate the current power consumption trends of mobile GPUs, we list in Table 2 some modern notebook GPUs and their respective power consumptions. The table suggests that playing a game on a notebook equipped with one of the listed GPUs may not be a viable option. For example, the Dell Precision M6700 mobile workstation (which Dell touted as the "world's most powerful 17.3" mobile workstation") is equipped with the Nvidia Quadro K5000M GPU. The configuration can pull 98 Watts of power when running on battery under a heavy CPU or GPU load. This means that it would be possible to drain the system battery in about an hour (Notebook Review, 2015). Even with this limited ability to support long running, compute-intensive applications, this configuration costs more than $2K. Better battery life may be possible but with much more expensive configurations. Efforts are underway to develop mobile devices with power efficient computing components (e. g., multicore CPUs and ultra low power GPUs) and batteries that can run compute-intensive applications (e. g., games and

Table 2: Energy Consumption of Some Modern Notebook GPUs

GPU Card	Power Consumption (W)
NVIDIA GeForce GTX 680M SLI	2 x 100
AMD Radeon HD 7970M Crossfire	2 x 100
NVIDIA GeForce GTX 680MX	122
NVIDIA GeForce GTX 675M SLI	2 x 100
GeForce GTX 680M	100
Quadro K5000M	100
AMD Radeon HD 7970M	100

other graphics-intensive applications) for many hours. For example, Nvidia is introducing Tegra 4, a mobile GeForce GPU with up to 72 custom cores, a quad-core ARM Cortex-A15 processor with a fifth Companion Core that further improves performance and battery life. According to Nvidia, a battery of a capacity of 38 watt-hours would be sufficient to operate a Tegra 4 mobile device running a gaming application between 5 and 10 hours. This corresponds to a power consumption (for the entire device) of 4 to 8 Watts (Hruska, 2013). However, mobile devices with these high-end configurations will remain beyond the reach of average users for the foreseeable future.

5 POWER CONSUMPTION TRENDS IN MODERN NOTEBOOK NICs

The original 1997 release of the IEEE 802.11 standard operated in the 2.4 GHz frequency band and provided a data bit rate of 1 to 2 Mb/s. The standard release approved in February 2014 (known as 802.11ad) operates in the 2.4/5/60 GHz frequency bands and provides a data bit rate of up to 6.75 Gbit/s. While higher bit rates often translate into higher power consumption, this is less true in recent ultra-low power 802.11 standards. For example, today's fastest 3 antenna 802.11n device can achieve 450 Mbps. A single antenna 802.11ac device can achieve a similar bit rate with similar power consumption. This means that a typical tablet with single antenna 802.11n 150Mbps WiFi can now support 450 Mbps with 802.11ac without any increase in power consumption or decrease in battery life (Netgear, 2012).

6 GRAPHICS-INTENSIVE APPLICATIONS: GPUs VS. NICs

To assess the benefits of using a mobile GPU versus offloading to the cloud, we consider gaming as it is a typical example of graphics-intensive mobile applications. Specifically, we consider four modern games that rely heavily on GPUs. We compare two scenarios in terms of power consumption. In the first scenario, the game is run entirely on the mobile device and uses only its GPU. In the second scenario, we consider an execution where the game is run on a cloud server and the mobile device only receives and renders sequences of frames produced by the server. We analytically evaluate power consumption in these two scenarios and show that, with modern wireless technology, offloading is a far better alternative to running graphics-intensive applications using the device's GPU. To make the comparison even more in favor of the GPU-based alternative, we ignore the power consumption of the device's disk. We assume that, when a graphics-intensive application is run on a mobile device, most of the power is consumed by the device's GPU. This is becoming increasingly true with the wide availability of mobile devices with solid-state disk drives.

To compare power consumption in the two scenarios, we first present a simple model that captures the interactions between the player and the gaming application. We will assume that, during a given gaming session of duration t, the player takes an action after every r seconds in average. We call r the *reactivity* of the player. To respond to the player's action, the application generates a video stream of length v seconds.[1] So, during the entire session, the application generates t/r video sequences whose length is v seconds each. In total, the application generates tv/r seconds of video during the given gaming session.

6.1 Scenario 1: Gaming Using the Mobile Device's GPU

To assess the power consumed by a notebook's GPU in a gaming session, we used the benchmark presented in (NoteBookCheck, 2014). The benchmark

[1]This is to simplify our discussion. In practice, the application likely generates two video sequences of different lengths in response to two different actions.

has a large number of notebook GPUs and a number of popular games. For each combination of game and GPU card, the benchmark gives the average number of frames per second (fps) that the GPU card achieves with four different resolution levels: Low (L), Medium (M), High (H), and Ultra (U). The benchmark considers that a frame rate of 25 fps is sufficient for fluent gaming. For the purpose of this study, we considered four GPU cards and four 2014 games, namely GRID Autosport, Watch Dogs, Titanfall, and Thief. Table 3 gives the frame rates obtained in the given combinations[2]. The resolutions in the table are as follows: Low (1024x768), Medium (1366x768), High (1920x1080 for the first two games and 1366x768 for the last two games), and Ultra (1920x1080). Table 3 also gives power consumption for the four GPU cards.

As an example, consider a mobile device equipped with a GPU of type Nvidia GeForce GTX 850M. As shown in Table 3, this GPU card will consume between 40 and 45 Watts in one hour. We will show that offloading to the cloud (Scenario 2) brings an order of magnitude reduction in terms of the power consumed by the mobile device.

6.2 Scenario 2: Mobile Cloud Gaming

We now evaluate the required data bit rate that the NIC card of a notebook would have to support to achieve the same game fluency (i. e., 25 fps) for one of the four GPU cards of Table 3. As an example, consider again the Nvidia GeForce GTX 850M (which is the best of the four GPUs in terms of power consumption.) For the game GRID Autosport and for low resolution, the Nvidia GeForce GTX 850M is able to support 166.65 fps which is: 166.65 x 1024 x 768 x 8 = 1048471142.4 bits/second (assuming a color depth of 8 bits/pixel). Thus the NIC card would have to operate at a bit rate of about 1.05 Gb/s. A similar computation for the Ultra high resolution level gives us a bit rate of: 34.7 x 1920 x 1080 x 8 = 575631360 bits/second. Thus, to support the same gaming fluency at the Ultra-high resolution level, the NIC would have to operate at 575 Mb/s. Note that the required bit rate at the Ultra-high resolution level is almost half of that of the required bit rate at the low resolution level because the GPU supports a lower frame rate at the Ultra-high resolution level. To support these bit rates, the mobile device's NIC would have to be 802.11ad compliant. The 802.11ad standard is able to support bit rates up to 6.77 Gbit/s.

[2]The missing value in the last row corresponds to a test that could not be run because the GPU card could not support a sufficiently acceptable frame rate.

To evaluate the power consumed by the device's wireless networking card during the considered gaming session, we will assume a model of a wireless networking card that consumes ρ_{tx} watts when in transmit mode and ρ_{rx} watts when in receive mode. With single-antenna 802.11 devices, the devices cannot send and receive simultaneously. This normally implies that one has also to take into account the cost of frequently switching the device's radio between the transmit and the receive mode. This, however, is changing as mobile devices are now increasingly being equipped with MIMO (multiple-input and multiple-output) technology enabling the use of multiple antennas at both the transmitter and receiver. In fact, Mobile Experts predicts that the use of MIMO technology will reach 500 million PCs, tablets, and smartphones by 2016 (Madden, 2011). As a result, we will only take into account power consumption due to transmission, reception, and idling. We will note the power consumption of the radio during idling by ρ_{id}.

Let μ_t and μ_r be the transmission and reception rates respectively. Let l be the length of the packet sent to the application when the player takes an action. The time needed to transmit this packet is then: l/μ_t. Let t be the length of the entire gaming session (in seconds). During the time t, the device transmits t/r times where r is the player's reactivity (defined earlier). The total time during which the device transmits is therefore:

$$\frac{tl}{r\mu_t}\,\mathtt{secs.} \tag{1}$$

The corresponding power consumption during the period of time t is:

$$P_{tx} = \frac{\rho_{tx} t l}{r\mu_t} \tag{2}$$

To evaluate the power consumed by the device's receiver, recall that our model assumes that, to respond to each player's action, the application generates a video stream of length v seconds. The devices spends v/μ_r seconds to receive each of these video streams. Since we have t/r of these video streams during the considered time period of length t, the device's NIC receives video streams during:

$$\frac{tv}{r\mu_r}\,\mathtt{secs.} \tag{3}$$

Let P_{rx} be the power that the device's NIC consumes to receive the t/r video sequences. P_{rx} can be given by:

$$P_{rx} = \frac{\rho_{rx} t v}{r\mu_r} \tag{4}$$

Table 3: Average Frame Rate of Some Combinations of GPU cards, Games, and Resolutions

GPU Card	GRID Autosport				Watch Dogs				Titanfall				Thief			
	L	M	H	U	L	M	H	U	L	M	H	U	L	M	H	U
GeForce GTX 770M (75 Watts)	199.6	130.3	92.6	46.5	80.7	66.1	27.7	19.8	60	60	59.3	48.3	57.1	51.3	46.8	26.6
GeForce GTX 860M (60 Watts)	192.15	109.65	88	47.2	71.2	60.7	27.7	18.9	60	60	59.5	42.4	60.5	52.7	44	23.95
GeForce GTX 850M (40-45 Watts)	166.65	99.33	68.3	34.7	61.8	52.3	20.75	14.7	60	59.7	53.25	34.3	46.45	39.6	36.65	18.2
GeForce GTX 765M (50-75 Watts)	191.9	130.7	74.1	34.8	81.3	56.9	21.1		60	59.7	54.3	35.6	58.2	43.1	37	19.1

Table 4: Power Consumption for the Intel Dual Band Wireless-AC 7260 802.11ac, 2x2 Wi-Fi Adapter (Hewlett Packard, 2013)

Mode	Power (mW)
Transmit	2000
Receive	1600
Idle (WLAN associated)	250
Idle (WLAN unassociated)	100
Radio Off	75

The device's NIC is in the idle mode when it is not transmitting and not receiving. This occurs during:

$$t - \frac{tl}{r\mu_t} - \frac{tv}{r\mu_r} \texttt{secs.} \tag{5}$$

The power consumed by the device's NIC while idling is therefore:

$$P_{id} = \rho_{id} t (1 - \frac{l}{r\mu_t} - \frac{v}{r\mu_r}) \tag{6}$$

Let $P_{NIC}(t)$ be the power consumed by the wireless NIC during the t-second gaming session. $P_{NIC}(t)$ is then:

$$\begin{aligned} P_{NIC}(t) &= P_{tx} + P_{rx} + P_{id} \\ &= \frac{\rho_{tx} tl}{r\mu_t} + \frac{\rho_{rx} tv}{r\mu_r} + \rho_{id} t (1 - \frac{l}{r\mu_t} - \frac{v}{r\mu_r}) \end{aligned}$$

In practice, one must consider values for ρ_{rx} that accommodate high reception rates (for high definition gaming) and values for ρ_{tx} that correspond to low transmission rates since the user's actions usually translate into short packets.

To illustrate, we consider the case of an HP EliteBook Folio 1040 G1 Notebook PC. This notebook is equipped with the Intel Dual Band Wireless-AC 7260 802.11ac Wi-Fi Adapter whose power consumption is given in Table 4) (Hewlett Packard, 2013). Assume that the NIC card is 80% of the time in reception mode, 10% of the time in transmit mode, and is idle (but associated) 10% of the time. If we apply our power model to this WiFi adapter, power consumption in one hour would be (approximately):

$$\begin{aligned} P_{NIC}(t) &= P_{tx} + P_{rx} + P_{idle} \\ &= 0.1 \times 2000 + 0.8 \times 1600 + 0.1x250 \\ &= 1505 \texttt{ milliwatts} \end{aligned}$$

assuming the highest Rx and Tx power levels.

Considering the examnple of a notebook equipped equipped with a GPU of type Nvidia GeForce GTX 850M (Section 6.1), we can estimate that, in one hour, the GPU card will consume about betwee 0.8x40 W and 0.8 x 45 W, i.e., between 32W and 36W, assuming a GPU ustilzation of 80% similar to our assumption of the NIC card being in the Rx mode 80 % of the time.

From the results obtained in the two scenarios, it is clear that using the wireless networking interface in a gaming session consumes much less power than using a modern GPU card installed on the same device. Specifically, the power consumed using the wireless card would be around (1505 / 34000) x 100, i.e., around 4.42% of the power consumed by the on-device GPU.

7 MOBILE CLOUD GAMING USING SMARTPHONES

We now compare power consumption between GPU-based gaming and cloud-based gaming on smartphones.

7.1 Power Consumption of GPU-based Gaming on Smartphones

In (Kim et al., 2015), the authors measured power consumption of a Qualcomm Adreno 320 GPU in a Google Nexus 4 smartphone. They used two games in their tests: Angry Birds (2D game) and Droid Invaders (3D game). The authors report results for a gaming session that lasted 560 seconds for Angry

Table 5: Frame Rates for the Adreno 320 GPU on a Google Nexus 4 and on a Samusung Galaxy S4 using the Manhattan Benchmark (GFXBench, 2015)

Smartphone Model	GPU	Resolution	Frame Rate
Google Nexus 4 (LG E960)	Adreno 320	1196 x 768	9.2
Google Nexus 5	Adreno 330	1794 x 1080	10.1
Samsung GT-I9507 Galaxy S4	Adreno 320	1920 x 1080	5.4
Samsung GT-I9515 Galaxy S4 Value Edition	Adreno 320	1920 x 1080	5.1
Samsung Galaxy S4 Active (GT-I9295, SGH-I537)	Adreno 320	1920 x 1080	5.1
Samsung Galaxy S4 (GT-I9505, GT-I9508, SC-04E, SCH-I545, SCH-R970, SGH-I337, SGH-M919, SPH-L720)	Adreno 320	1920 x 1080	5.1

Birds and 505 seconds for Droid Invaders. Throughout the two gaming sessions, power consumption remained approximately at around 1750 mW for Angry Birds and at around 2000 mW for Droid Invaders. We will use the average of these two numbers (1875 mW) as an estimate of the average power consumption of both 2D and 3D games.

7.2 Power Consumption of Cloud-based Gaming on Smartphones

To compare power consumption of cloud-based gaming with GPU-based gaming, we first need to evaluate the NIC bit rate that would be necessary to provide a gaming experience comparable to the one achieved through GPU-based gaming. For this, we used results from the GFXBench 3.0 benchmark, a cross-platform OpenGL ES 3 benchmark designed for measuring graphics performance, render quality and power consumption on several types of devices including smartphones. In particular, the benchmark has battery and stability tests that measure the devices battery life and performance stability by logging frames-per-second (fps) performance and expected battery running time while running sustained game-like animations (GFXBench, 2015). We focused on results for the Adreno 320 GPU on a Google Nexus 4, which is the same configuration used in the GPU-based scenario of the previous section.

Table 5 shows the frame rate for several tests using the Manhattan benchmark (GFXBench, 2015). Row 1 of the table shows that the Adreno 320 GPU on a Google Nexus 4 achieved a frame rate of 9.2 fps. Considering this frame rate and the given resolution (1196 x 768), the NIC bit rate that would be necessary to achieve a similar gaming experience can be derived as: 9.2 x 1196 x 768 x 24 (bits/pixel) = 202810982.4 bps $\approx$ 203 Mbps.

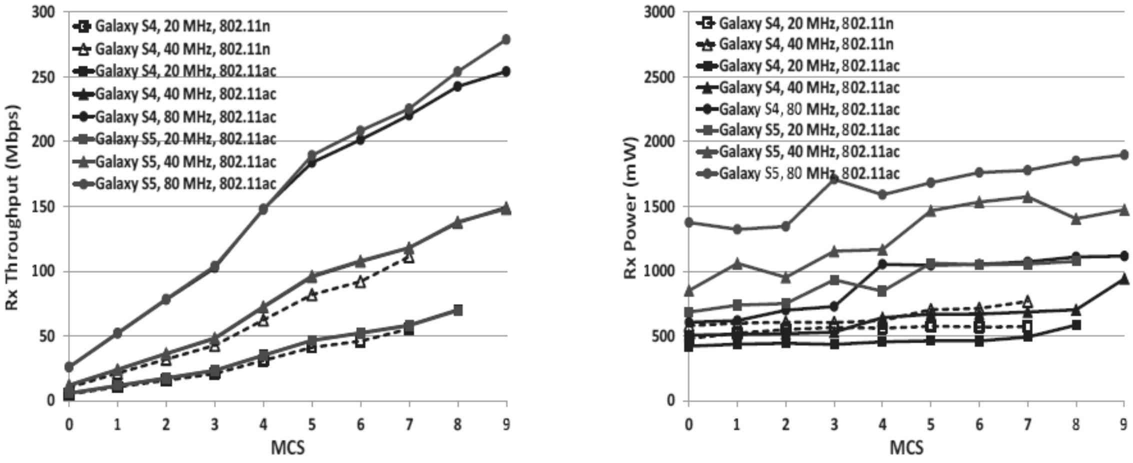
We now turn to evaluating the power needed on the NIC to sustain this bit rate. For this, we use the results from (Saha et al., 2015) where the authors experiment with a variety of smartphones supporting different subsets of 802.11n/ac features. In particular, the authors measured throughput and power consumption in a Galaxy S4 using different configurations. Based on their findings for the Galaxy S4 used in the experiment, only 802.11ac offers Rx throughput levels sufficient for the considered gaming bit rate (of 203 Mbps). Figure 2 (reproduced from (Saha et al., 2015)) shows that the best Rx throughput with 802.11ac was about 250 Mbps. Power consumption in this case was about 1100 mW.

Table 6: Power Consumption (in mW) in Non-Communicating Modes. (Saha et al., 2015)

Configuration	PSM	Idle
802.11n, 20 MHz, SS	24 ± 16	398 ± 7
802.11n, 40 MHz, SS	25 ± 5	413 ± 2
802.11ac, 20 MHz, SS	22 ± 9	374 ± 7
802.11ac, 40 MHz, SS	20 ± 9	425 ± 3
802.11ac, 80 MHz, SS	19 ± 10	529 ± 11

The authors did not provide measurements for the throughput and power consumption in transmit mode with 802.11ac. They, however, measured throughput and power consumption in transmit mode with 802.11n. Figure 3 shows their results. In particular, the results show that that it is possible to achieve a Tx throughpout of more than 40 Mbps with as little power as 800 mW. Note that, in a cloud-based gaming session, a Tx throughout of 40 Mbps is typically sufficient. The authors also measured power consumption of the Galaxy S4 when it is in non-communication modes, i.e., power saving mode (PSM) or idle. Their results (Table 6) show that the highest 802.11ac power consumption in PSM was 31 mW and that the highest 802.11ac power consumption when idle was 540 mW. The relatively high idle mode power consumption of larger channel widths (80 Mhz) has also been observed by other studies (e. g., (Zeng et al., 2014)).

Based on all the previous results from (Saha et al., 2015) and assuming that, in a cloud-based gaming session, the device's 802.11 adapter spends 80% of the time receiving, 10% of the time transmitting, and 10% of the time idle, the total power consumed in one



(a) Rx throughput. (b) Rx power consumption.

Figure 2: 802.11ac Throughput and Power Comparison for Galaxy S4 and Galaxy S5 with a Channel Width of 20/40/80 MHz and FA on. (Saha et al., 2015).

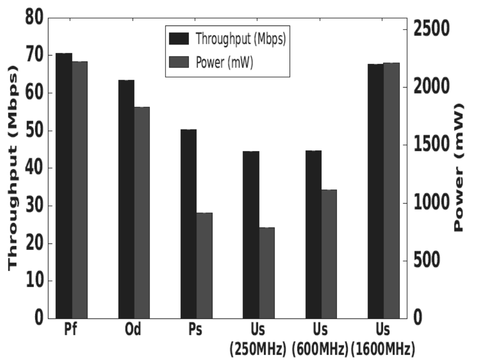


Figure 3: Comparison of Different CPU Governors/Frequencies for Galaxy S4 (802.11n) (Saha et al., 2015)

hour by the 802.11 adapter would be:

$$\begin{aligned} P_{NIC}(t) &= P_{tx} + P_{rx} + P_{idle} \\ &= 0.1 \times 800 + 0.8 \times 1100 + 0.1 \times 540 \\ &= 1014 \texttt{ milliwatts} \end{aligned}$$

Comparing power consumption in the two scenarios: using GPU-based gaming (which is 1875 mW as derived in Section 7.1 and cloud-based gaming (which is 1014 mW as derived in this section), we conclude that, in the considered smartphone configuration, cloud-based gaming can potentially result into a power saving of about 46%.

8 CONCLUSION

We presented a comparative analysis between two scenarios of mobile gaming, one that relies entirely on the GPU of the mobile device and one where the gaming application runs on the cloud. We analytically evaluated and compared power consumption in these two scenarios. Based on our analysis, we argue that the idea of Visualization-as-a-Service (VaaS) is a viable computing model that enables the users of mobile devices with limited power capabilities to still use long running graphics-intensive applications. In this model, advanced visualization capabilities would be provided to users as a service via the Internet.

Two research directions are worth studying: (i) the impact of protocol (TCP/UDP/IP) overhead and (ii) the impact of the CPU overhead for processing the large number of packets typical in cloud gaming. We believe that considering these two types of overhead will provide a more accurate assessment of the benefits of cloud-based gaming over GPU-based gaming.

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