Power Tradeoffs in Mobile Video Transmission for Smartphones

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Abstract

In recent years, the popularity of smartphone devices has expanded their use to a plethora of applications. Smartphones are used for web browsing, gaming, general socializing, watching films or television, capturing still pictures or videos, and, of course, making voice and video calls. Mobile video streaming in smartphones is among the most popular applications. Unfortunately, it is also one of the most power-hungry and one that stretches the finite resources of a mobile device to the limit. Therefore, the quality of experience during a video session is critically dependent on the smartphone physical limitations like display size, battery capacity, transmission throughput, and processing capability. In this work, the power tradeoffs in mobile video transmission are examined. The display size and resolution along with the video quality and communication model are tested through extensive experimentation with four smartphones. The study reveals several interesting phenomena and tradeoffs. In particular, it highlights that the display size is the most important parameter that affects the average power consumption during a video session. The study also identifies situations where the display resolution affects less the power consumption than the communication technology. The conclusions from this study suggest preferred usage patterns as well as guidelines for users and developers.

Keywords: Smartphone, Wi-Fi, LTE, Video streaming, Power measurement, Android, Energy efficiency

1. Introduction

Smartphones are quickly becoming the main platform for personal communications and mobile computing. Their display resolution increases year after year, while Wi-Fi capability improves user's web browsing experience [1], enhances localization [2] and facilitates crowdsourcing [3, 4]. High-resolution displays have a strong impact on the perceived quality of the device, with experiments showing that a higher display resolution increases the user engagement, especially for multimedia and gaming sessions [5, 6].

The energy budget of a smartphone is a function of many factors, such as display technology, processor performance, power management approach, and so on [7]. A higher display resolution typically requires a higher power, and may be paired with a larger display size or with a more capable graphics processor, which, in turn, also contribute to increased energy consumption. As video streaming and downloading come to dominate the Internet traffic, video sessions inevitably consume an increasing portion of the battery energy, because of the power needed to drive the display and to transmit and process a larger amount of data compared to other applications [8].

In a smartphone, the display is on when a process demands it, while the processes that do not require the display to be active simply run in the background. Since the display energy consumption is a significant portion of the energy budget [7], applications should minimize the required time with the display on. When there is no interaction with the user, the brightness should be reduced or the display should switch back to a low-power mode. Obviously, different applications, power settings, and usage patterns give rise to variable energy requirements and battery lifetimes for the same smartphone.

The implementation of the 802.11n standard contributes to the energy budget as well. While smartphones and laptop computers may use comparable chipsets, the Wi-Fi power consumption in smartphones can be quite different. Studies have shown that popular 802.11n wireless cards can deplete a typical smartphone battery in two to three hours and can produce enough heat to quickly reach the smartphone thermal limit [9]. Therefore, an energy characterization of the 802.11n

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chipset in relation to the display usage pattern has the potential to significantly improve energy efficiency.

This work studies the power tradeoffs in mobile video transmission over four smartphones with different display characteristics. It focuses on revealing correlations between the display size, display resolution and video quality with the average power consumption of the smartphone during a video session.

The experimental results verified some expected assumption, but also revealed some interesting insights. According to the experimental results:

- The video quality does affect the average power consumption, especially as the display size increases.
- The display size affects the average power consumption more than the display resolution.
- The display resolution affects the power consumption when comparing displays with similar sizes. However, more efficient communication hardware and processor compensate for this effect during video transmission.
- Wi-Fi is more energy efficient for video communication than Long Term Evolution (LTE). The energy efficiency is further improved with Wi-Fi Direct.

The experiments were performed using four Samsung smartphones with Android operating system (OS), a windows-based computer (PC), and a router acting as an access point (AP). Two Android applications were used for video streaming and two communication protocols Wi-Fi and LTE were examined. For accurate power measurements, a precision resistor and a digital-storage oscilloscope were used. During the experiments and in order to conduct the characterization in realistic conditions, each smartphone used its own battery that discharged as expected in a real mobile video transmission session. At any event, none of the phones can be claimed to be better than the others with regard to the parameters that were measured. Rather than finding a winner, the purpose of this work is to offer insights on mobile video transmission in smartphones, and eventually guidelines for future smartphone developers.

The rest of the paper is organized as follows: Section 2 provides a brief review of the related work. Section 3 describes the experimental setup followed by the performance results and analysis in Sections 4 and 5. Finally, Section 6 concludes the paper.

2. Related work

Recent papers have examined smartphone power consumption for general TCP and UDP transmissions, categorized and modelled the power used by various subsystems, and investigated the effects of different streaming media on power requirements.

2.1. Communication modes and power

The power usage of various transmission modes, especially Wi-Fi 802.11n or 802.11a/c, Bluetooth, 3G, and 4G, have been studied extensively. Previous research has investigated features of 802.11n, including throughput, reliability, and power, across many usage scenarios, and methods to provide detection of the types of interference present have been examined [10]. On the subject of interference, the challenges of achieving good signal separation for multiple, orthogonally-tuned 802.11n radios in close proximity to one another were highlighted [11]. Therefore, in setting up tests for 802.11n, care must be taken when selecting channels, because the presence of nearby tranceivers on different channels can affect the measured performance.

The energy usage in different operating modes can be studied by directly measuring the power consumption, or by using models to match and extract similar information. As an example, the energy consumption of Wi-Fi data transmission can be estimated through deterministic power modelling [12]. State machines for separate smartphone components were used to model energy consumption instead of the statistical methods employed elsewhere. Another approach to modelling the power consumption [13], which relies on application-layer parameters that are readily available to developers (e.g. throughput), does not yet translate well between devices and requires a training dataset to be collected for real-world usage.

Examining Wi-Fi and Bluetooth using TCP and UDP transmission, the thresholds for optimizing throughput and power consumption were calculated and the criteria for switching (or not switching) between them were defined [14]. Specifically, it appears that Wi-Fi power consumption scales with throughput, and, for the considered file sizes, there is little benefit in switching to a Bluetooth connection at any time. However, for audio streaming and in the face of nearby interference, Bluetooth appears to be a better choice, although audio quality over Bluetooth may suffer when compared to Wi-Fi.

The relative energy requirements for various smartphone sensors (including cellular modems) can also be investigated based on the *triggered sensing* concept [15]. In the stand-by time ranking of the smartphone communication modes, first is the idle cellular modem, followed by the idle Bluetooth interface, and last is the idle Wi-Fi interface. Since it has been found that there is little benefit to switching to Bluetooth if a Wi-Fi connection is present, we can concentrate on the comparison between Wi-Fi and LTE.

2.2. Measuring smartphone power

The power consumption in smartphones depends on the characteristics of the wireless standards, it varies in the sleep, idle, and active modes, and it is contingent on the use of features like the *race-to-sleep* protocol. Models were proposed for the 802.11g [16] and the 802.11n/ac protocols [17]. This is especially relevant because in modern smartphones Wi-Fi transmission and reception are a major power sink. Several papers [17, 13, 18, 19] used the Monsoon Power Monitor instrument and the iPerf software tool to emulate and record a battery's voltage and current supplied to the smartphone during various network tests. Furthermore, a PC was used as an access point to provide the server-side of the connection [18]. The downside of using the Monsoon Power Monitor for collecting data is that it stands in for the battery and so the work's accuracy becomes dependent on the model used by the control system in the Monsoon.

The possibility of using the smartphone microprocessor's *dark silicon* (i.e. those parts of the microprocessor that are gated in order to stay within the power envelope) was investigated by strictly controlling the power budget for each sub-system and by de-pipelining the code to minimize transitions imposed by the software being executed [20]. The results suggest the potential for possible energy savings by using energy-aware software development protocols for application developers. However, it is clear that the mapping between energy consumption (or savings) and battery discharge (or charge) is not linear due to the discharge characteristics of modern lithium-ion or lithium-polymer batteries [21]. Therefore, particular care should be taken when measuring or predicting energy usage in smartphones. It also highlights the difficulty in using models determine the power budget for each subsystem in the smartphone.

While examining smartphone power usage at a component or a service level yields insight into which blocks or operations should be highlighted when optimizing power, it is also helpful to investigate how some of the more popular end-user applications affect the power consumption. Indeed, it is no surprise that video streaming and downloading are, or will soon be, the majority of traffic on the Internet [22]. The battery level can be an input to an adaptive process for streaming video [22]. This approach shows merit, although the nonlinear battery discharge characteristics must be taken into account [21]. While using the battery-level as an input to video streaming is a good step, the display is also identified as a major consumer of power, therefore any investigation into reducing power during streaming video should carefully examine the display power characteristics for potential savings [7].

Finally, the battery power measurements highlight the need for both instantaneous power measurements, as well as a method for keeping the battery in place during the measurements (as opposed to using a bench-top power supply), because of its characteristics as it discharges under load [21]. A method for calculating the current drawn by the smartphone under test while the battery is installed uses a low-value (0.1 Ω) shunt resistor and differential probes [23].

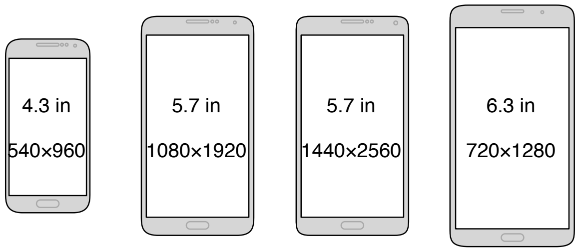
3. Experimental setup

3.1. Smartphone features

The four different models of smartphones used in the experiments were the Samsung Galaxy S4 mini I9190 (Mini), the Samsung Galaxy Note 3 N9005 (Note 3), the Samsung Galaxy Note 4 N910W8 (Note 4), and the Samsung Galaxy MEGA 6.3 I9200 (MEGA). These smartphones were selected in order to test different display sizes and resolutions while maintaining compatible chip sets and operating systems. Fig. 1 shows the different display sizes and resolutions, and Table 1 provides the key features of each smartphone. The Wi-Fi chipsets are popular among other smartphone manufacturers as well. The batteries are lithium-ion with nominal voltage around 3.8 V.

3.2. Power consumption measurements

The setup sketched in Fig. 2 was used to characterize the power consumed by the smartphones during the various tests. Power consumption measurements are typically done by replacing the smartphones' batteries with a dedicated source-measurement unit [18] or with a laboratory bench-top power supply, a shunt resistor and voltage metering equipment [23]. However, the laboratory sources do not replicate the battery voltage changes in relation to the current dynamic variations and to the battery state of charge. Therefore, to conduct the characterization in more realistic conditions, the smartphones' batteries were used, and, in order to ensure measurements' consistency, the battery state of charge was maintained between 75% and 95%, while



(a) Mini. (b) Note 3. (c) Note 4. (d) MEGA.

Figure 1: Screen size and resolution of the smartphones tested.

Model	Mini	Note 3	Note 4	MEGA
Android version	4.4.2	5.0	5.1.1	4.4.2
Wi-Fi (802.11) protocols	a/b/g/n	a/b/g/n/ac	a/b/g/n/ac	a/b/g/n/ac
Display diagonal (mm)	108	145	145	160
Display area (cm^2)	42.0	75.7	75.7	92.2
Display resolution (pixels)	540×960	1080×1920	1440×2560	720×1280
Battery nom. voltage (V)	3.8	3.8	3.85	3.8
Battery capacity (mA h)	1900	3200	3220	3200
Battery capacity (W h)	7.22	12.16	12.40	12.16

Table 1: Smartphone specifications.

the battery temperature was monitored to be between 25°C and 30°C.

While keeping the battery in its housing inside the smartphone, the current absorbed by the phone was measured by exposing the circuit node between the phone's and the battery's negative terminals by means of two pieces of vinyl-coated copper foil tape inserted between the two aforementioned terminals, thereby splitting the two terminals and allowing the insertion of a shunt resistor.

A digital-storage oscilloscope Tektronix DPO 4104 was used to monitor the smartphone voltage on channel 1, $V_1(h)$, and the resistor voltage on channel 2, $V_2(h)$. The oscilloscope was controlled through a software interface developed in LabVIEW 2015, and the waveforms were captured to time series files. The oscilloscope was configured to sample the voltages at a rate of 10 S/s, with channel 1 configured to 1 V/div and channel 2 configured to be 50 mV/div. Measuring the voltage across the resistor allows the subsequent calculation of the current sourced by the battery as

$$I(h) = -\frac{V_2(h)}{R}\,, \tag{1}$$

where h is the time index, and the resistance, R, was

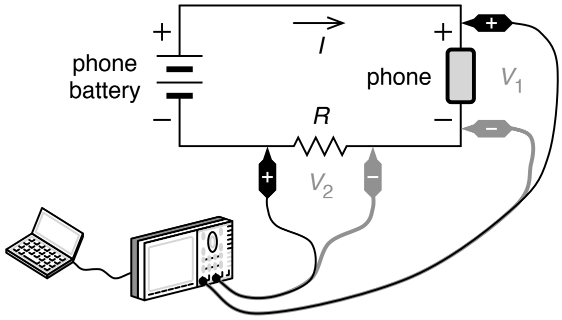


Figure 2: Setup for measuring the power supplied by the battery to the smartphone.

chosen to be 237 mΩ, which is a value that still provides enough bits for accurate measurement while allowing enough headroom to capture the full voltage range.

The instantaneous power is calculated for each sample using

$$P(h) = V_1(h)\, I(h) = -\frac{V_1(h)\, V_2(h)}{R}\,, \tag{2}$$

and the average power is then found by taking the mean of the instantaneous power time series

$$\overline{P} = \frac{1}{n} \sum_{h=1}^{n} P(h)\,, \tag{3}$$

where n is the number of samples collected over the course of the test.

Wi-Fi 802.11 connectivity for the smartphones was provided either by direct connection to a Dell Precision Tower 3620 for streaming via a Plex Media Server, or via a D-Link DIR-605L access point (AP) for streaming via YouTube. Access to the 4G cellular network was provided by Telus Mobile. Movies of various lengths were selected from YouTube and streamed either from YouTube or the Plex Media Server.

3.3. Video selection

For the video selection process a popular video trailer was chosen. The video was selected after experimentation with videos with different length in order to examine the effect of video length on the average power consumption, as explained in Section 4.1.1. The chosen video has a length of 78 s.

For the YouTube experiments, the video was played in each smartphone with the following video qualities: 240p, 360p, 480p, and 720p.

The same video was used from the server for the server experiments, with slightly different quality in order to meet the requirements for all the smartphones.

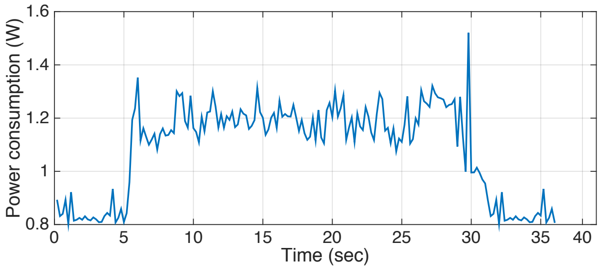


Figure 3: Instant power consumption of a short video session.

Hence, for the server experiments, the video had the following qualities: 270p, 320p. 480p, and 800p.

3.4. Experimental procedure

For every smartphone, there were four experimental sessions. Every session had a video streaming for one of the following:

YouTube over Wi-Fi. The smartphone is connected to the AP. The YouTube application is used to stream the selected video to the smartphone.

Streaming over Wi-Fi Direct. The smartphone is connected to the PC directly through Wi-Fi. An FTP server is used to stream the video from the PC to the smartphone over Wi-Fi.

YouTube over LTE. The smartphone is connected to YouTube over LTE. The YouTube application is used to stream the selected video to the smartphone.

Streaming over LTE. The smartphone is connected to a video server at the PC over LTE. The server streams the video to the LTE network and from there to the smartphone.

The power measurement starts 5 s before each session and stops 5 s after the video is finished. All the processes and applications on the smartphone are off. Bluetooth, GSM (when measuring Wi-Fi) and Wi-Fi (when measuring GSM) radios are disabled, with minimal background application activity.

An example power trace for a 25-s video session is shown in Fig. 3. This is the instantaneous power consumption of MEGA for a video in 720p. The increase of the power after 5 s, when the video streaming starts, and the decrease of the power after 30 s, when the video streaming concludes, are both clearly visible.

The Android driver does not allow the user to configure any 802.11n parameters while the AP uses an 802.11n adapter. All the experiments have been conducted in a laboratory environment during night in order to minimize interference from other wireless devices. During the experiments, the same desktop background was used for all the phones, the display was set to the maximum brightness, and the loudspeaker was set to full volume.

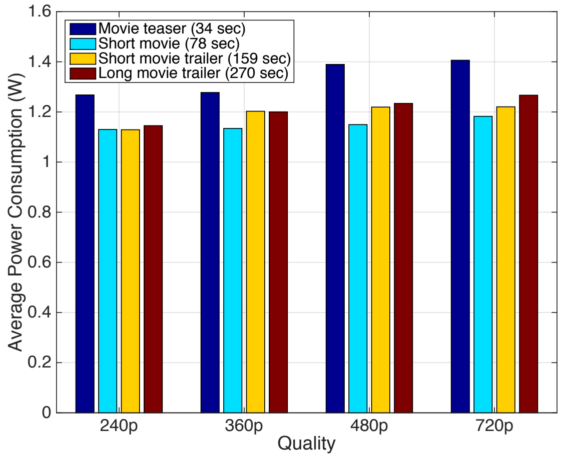


Figure 4: Average power consumption of videos with different length on MEGA.

4. Experimental results

4.1. Video length, quality and encoding

Since the smartphone technical characteristics, such as CPU and memory performance, affect the average power consumption, in the first part of the experiments, the same smartphone was used to examine the effect of video length, quality and encoding.

4.1.1. Video length

The effect of the length of the video on the average power consumption of the smartphone was examined. Using the smartphone MEGA, four different mp4 videos were selected:

1. Movie teaser with a duration of 34 s.
2. Short movie with a duration of 78 s.
3. Short movie trailer with a duration of 159 s.
4. Long movie trailer with a duration of 270 s.

The videos are selected from a dataset [24] designed to examine the effect of the video format on the Quality of Experience (QoE) of the user. Each video belongs to a different type [25].

As shown in Fig. 4, the average power consumption varies for videos with the same format and different

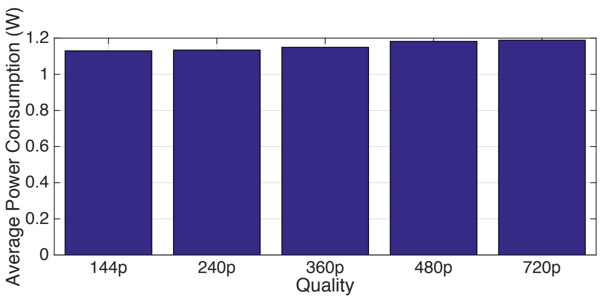


Figure 5: Average power consumption of videos with different quality on MEGA.

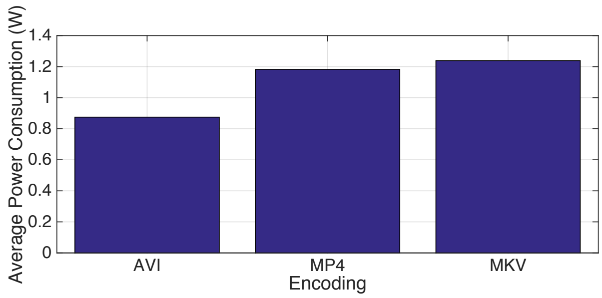


Figure 6: Average power consumption of videos with different encoding on MEGA.

duration. For instance, the movie teaser, which is the shortest video, has the highest average power consumption. This is expected, since the videos have different visual and audio features that contribute to the total power consumption. Hence, the video length cannot be used as an indicator of the average power consumption, while the video features affect the average power consumption. Therefore, the average power consumption is not directly related to the video length.

4.1.2. Video quality

The effect of the video quality on the average power consumption was examined next. A short .mp4 movie trailer was used, in the following five video formats: 144p, 240p, 360p, 480p, and 720p.

As shown in Fig. 5, the video quality does affect the average power consumption. As the video quality improves on the same smartphone device, the average power consumption increases as well.

4.1.3. Video encoding

The effect of the video encoding on the average power consumption was also considered. The experiment used the same video in 480p in the following encodings: mp4, mkv, and avi.

As shown in Fig. 6, the video encoding affects the average power consumption. When the video is in avi encoding, the average power consumption is lower than in the other two encodings. At the same time, when the video is in mp4 or mkv encoding, the average power consumption is similar.

4.2. Maximum throughput experiments

The performance of the Wi-Fi chip was tested with both UDP and TCP. The throughput was measured using iPerf, a standard network performance measurement tool [26], when the smartphones were connected to the PC through an AP, and when they were connected directly to the PC. Every smartphone acted as a server, while the PC acted as a client.

The four smartphones, the PC and the AP were close to each in other to minimize the interference and ensure a strong connection. there were four sessions for each smartphone: TCP mode when connected to the AP, UDP mode when connected to the AP, TCP mode when connected directly to the PC, and UDP mode when connected directly to the PC.

iPerf recorded the data every second. At the beginning of every session an idle waiting period of 120 s took place to stabilize the smartphone network connection when TCP or UDP are tested. For UDP, the smartphones were set to forward the data at a rate of 54 Mb/s, the theoretical 802.11g link bandwidth, to achieve the maximum available link throughput. After the waiting period, the measurements lasted for 300 s in each session. The two sessions for every smartphone were repeated three times and the average values of the experiments were computed. The results are shown in Table 2a for the AP and in Table 2b for the direct connection.

As shown by Tables 2a and 2b, overall the direct connection with the PC has better performance, as expected. At the same time, Note 4, which has a newer chipset, has a better performance than the other three smartphones in both TCP and UDP mode.

Similarly, the LTE performance of the smartphones was tested. For the LTE experiments, the same network provider was used at the same location. As the results in Table 2c show, Note 4 has the best performance overall. This is due to the better LTE chip that this smartphone has.

4.3. Measuring YouTube over Wi-Fi

The average power consumption for video streaming from YouTube over the AP to the smartphone was mea-

	Mini	Note 3	Note 4	MEGA
TCP	25.2	31.7	40.7	28.6
UDP	24.8	31.3	41.2	28.4

(a) Throughput (Mb/s) when downloading through Wi-Fi via the AP from the PC.

	Mini	Note 3	Note 4	MEGA
TCP	42.9	45.7	70.7	43.6
UDP	38.9	44.7	51.6	44.6

(b) Throughput (Mb/s) when downloading directly through Wi-Fi from the PC.

	Mini	Note 3	Note 4	MEGA
Download	36.0	44.0	56.2	38.7

(c) Throughput (Mb/s) when LTE is used.

Table 2: Throughput measurements.

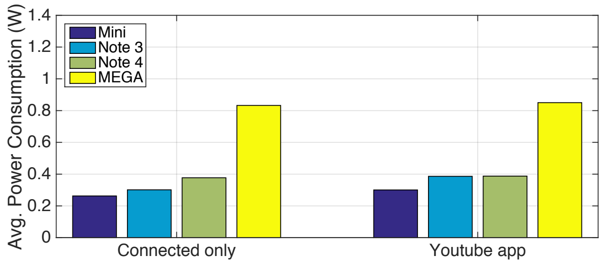


Figure 7: Base case for Wi-Fi.

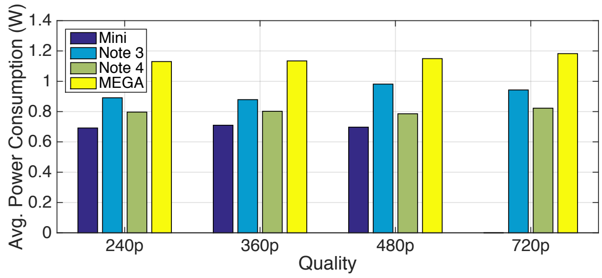


Figure 8: YouTube streaming over Wi-Fi through AP.

sured. Two base cases were examined:

Connected only, in which the smartphones are connected to the internet through the AP and have the same background on the display, and

YouTube app, in which the smartphones are connected to the YouTube application only with no other buffering nor other video playing.

In both cases, there are no other applications running in the smartphone. The results are shown in Fig. 7.

When the smartphones are connected to the Wi-Fi, the main unit that draws energy is the display. Hence MEGA, with the largest display, consumes the most energy. While Note 3 and Note 4 have the same display size, Note 4 consumes more energy, because its display resolution is higher. Mini, with the smallest display size and the lowest resolution, has the lowest power consumption. Every smartphone, when connected to YouTube, consumes more power than in idle conditions due to the YouTube application.

Next, the average power consumption during video streaming was measured. The results are shown in Fig. 8. Since Mini cannot stream in 720p, there are no results for this smartphone.

As the video quality increases, the average power consumption increases in all the smartphones. MEGA, with the biggest display has the highest average power consumption, although its resolution is lower than Note 3 or Note 4. The display size affects the average power consumption more than the resolution. In smartphones with same display size, Note 4 has lower power consumption than Note 3 although it has a higher resolution. The reason for this is the newer chipset. Note 4 has a better wireless performance and a better processor than Note 3, hence, it receives the streamed video faster with better overall power consumption. Note 3 has the second highest average power consumption, in contrast with the previous results, when only the connectivity was measured. Finally, Mini again has the lowest power consumption due to the small display size.

4.4. Measuring streaming over Wi-Fi Direct

The average power consumption for video streaming between the server and the smartphone through Wi-Fi Direct was measured. At the beginning, the average power consumption of the connection with the server and the video stream application was measured. In both cases all the smartphones have the same background on their display. Fig. 9 shows the results.

Although Mini cannot display the 800p format, the video with this quality was streamed to the device and the device downgraded the format to the suitable level. Hence, the average power consumption between 480p and 800p for Mini is slightly different because of the downgrade process, but the quality is similar. Alike the previous session, the average power consumption is related to the smartphone display. The bigger the display

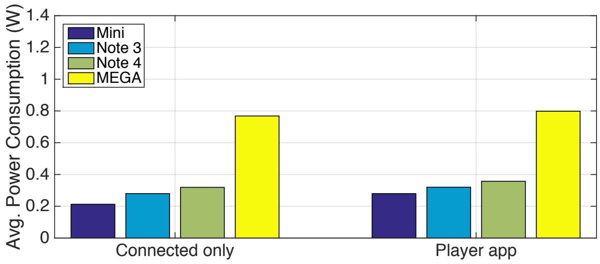


Figure 9: Base case for Direct.

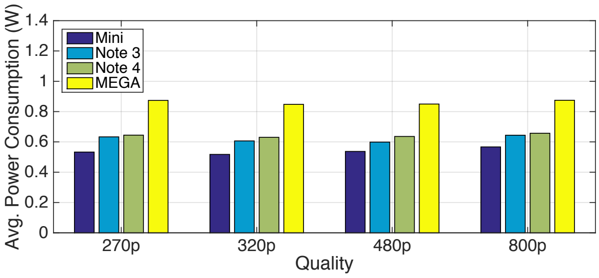


Figure 10: Server streaming over Direct.

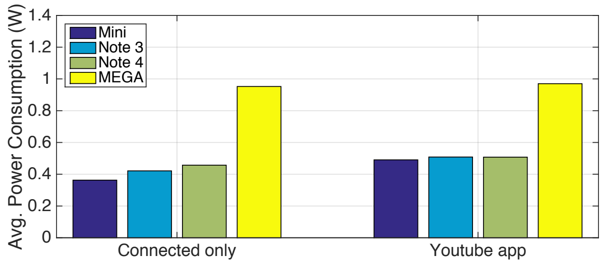


Figure 11: Base case for LTE.

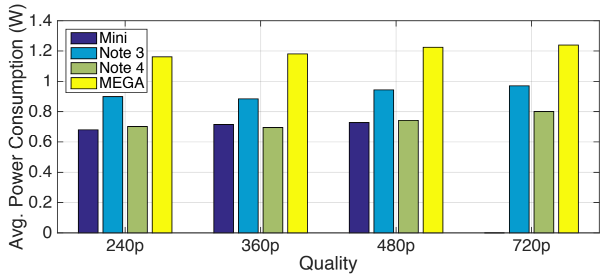


Figure 12: YouTube streaming over LTE.

the higher the average power consumption. Furthermore, the average power consumption of every smartphone in this base case of direct communication is almost the same as the average power consumption of the base case of Wi-Fi over AP communication.

Then, the average power consumption during video streaming was measured. The results are shown in Fig. 10. MEGA has the highest power consumption overall, since it has the biggest display. For Note 3 and Note 4 the performance is similar, while in most cases Note 4 has slightly higher average power consumption than Note 3. In this experiment, there is no application running for the video streaming, hence, although Note 4 has a better Wi-Fi chip, the video processing application is similar to that of Note 3. Note 4 does not take advantage of the better CPU performance in the direct video streaming and since it has better resolution than Note 3, it also has higher average power consumption.

4.5. Measuring YouTube over LTE

The average power consumption for video streaming from YouTube over LTE to the smartphone was measured. In the base scenario, two cases were examined:

Connected only, in which the smartphones are connected to the LTE network only and have the same background on the display, and

YouTube app, in which the smartphones are connected to the YouTube application over the LTE with no other application running.

The average power consumption for the two cases and for every smartphone is shown in Fig. 11.

All the smartphones consume slightly more energy when the YouTube application is running. The average power consumption follows the smartphone display size. As the size increases, the average power consumption increases as well. In the smartphones with the same display size, the higher resolution of Note 4 increases the average power consumption over that of Note 3, when there is no other application running in the background. When the YouTube application is running, these two smartphones have almost the same average power consumption. This is probably because of the better processor of Note 4. In comparison with the Wi-Fi average power consumption from the previous section, all the smartphones consume a bit more energy when they are connected over the LTE network.

Next, the average power consumption for the YouTube video streaming over LTE was measured. The results are shown in Fig. 12. Since Mini cannot display the videos in 720p there are no results for Mini in that quality.

As shown in Fig. 12, all the smartphones increase their average power consumption in comparison with the base case. However, the smallest increase happens in Note 4. Since this smartphone has the best pro-

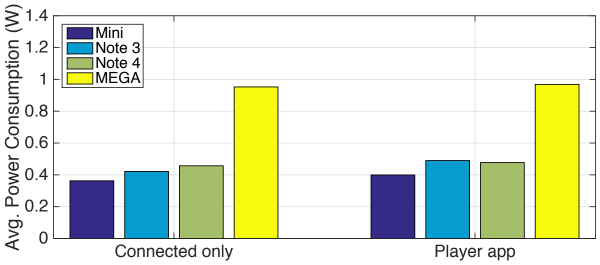


Figure 13: Base case for LTE over server.

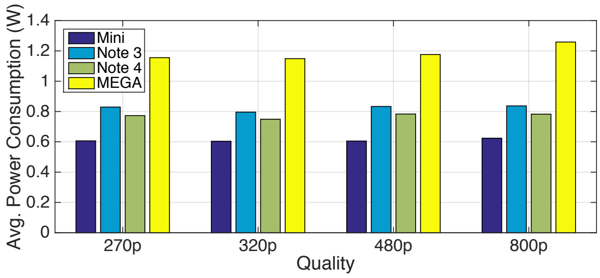


Figure 14: Server streaming over LTE.

cessor, while the average power consumption still increases, it does not increase at the same rate as the other smartphones. For this reason, although in the base case Note 4 consumes more power than Note 3, during video streaming Note 3 consumes, on average, more power than Note 4. Hence, although Note 4 has a higher resolution, the better processor makes the average power consumption of this smartphone better than that of Note 3, which has the same display size, lower resolution but older processor.

4.6. Measuring streaming over LTE

The last experiment measures the average power consumption for video streaming from the video server to the smartphone over LTE. In the base scenario, the two cases are:

Connected only, in which the smartphones are connected to the LTE network only and have the same background on the display, and

Player app, in which a video player application is loaded to the smartphone, but the video is not buffering nor playing yet.

The results are shown in Fig. 13.

Since in both this experiment and the previous one with the YouTube over LTE, the smartphones are connected to the same LTE antenna, the performance results of the ‘Connected only’ case in Fig. 13 are identical to those of Fig. 11. However, for the ‘Player app’ case, the average power consumption for every smartphone, although it is higher than the ‘Connected only’ case, it is lower than the ‘YouTube app’ case. Since in this experiment a video player is used, the extra power consumption is only due to the player application. Hence, if the player application consumes less power than the YouTube application, the average power consumption for every smartphone is lower.

Then, the average power consumption for video streaming between the server and the smartphone when connected in LTE was measured. The results are shown in Fig. 14. Once again for Mini the video with quality 800p was streamed to the device and then downgraded.

The average power consumption is the highest for MEGA, which has the biggest display. The second highest is for Note 3, and the third for Note 4. Once again, the better communication chip and processor unit of Note 4 make it more energy efficient than Note 3 when the video application is running.

Overall, the average power consumption when connected to the server and streaming the video is higher than the base case, but it is lower than streaming the video over YouTube.

5. Discussion

The experimental results have shown that the display size contributes more to power consumption than the display resolution. In all the experiments, the smartphone with the largest display consumes the most power. Hence, the power consumption during a video streaming session is most affected by the display size.

When the display size is the same, the processor unit, the communication chip, and wireless or LTE card, play an important role in the total power consumption. When there is no video streaming, the smartphone with the highest resolution consumes more power. However, during video streaming, a more efficient wireless or LTE card can overcome the resolution difference. In the case of Note 3 and Note 4, in the base scenario Note 4 consumes more power than Note 3 due to the higher resolution. However, during the video streaming tests the higher throughput, both in Wi-Fi and in LTE, helped Note 4 to overcome the difference and finally to consume less energy overall.

For video streaming over Wi-Fi, a direct connection is more power efficient than the connection through an AP. A higher throughput can be achieved, while there is no need for extra applications running in the background.

For video streaming over LTE, again a direct connection is more power efficient. The devoted video server

Format	Protocol	Mini	Note 3	Note 4	MEGA
240p	Wi-Fi	0.6917	0.8910	0.7966	1.1301
	LTE	0.6994	0.8991	0.7715	1.1613
360p	Wi-Fi	0.7099	0.8789	0.8020	1.1342
	LTE	0.7157	0.8837	0.7945	1.1805
480p	Wi-Fi	0.6973	0.9814	0.7854	1.1495
	LTE	0.7272	0.9430	0.7933	1.2248
720p	Wi-Fi	n/a	0.9426	0.8225	1.1824
	LTE	n/a	0.9696	0.8310	1.2392

Table 3: Average power consumption (W) of Wi-Fi and LTE for the YouTube application.

Format	Protocol	Mini	Note 3	Note 4	MEGA
270p	Wi-Fi	0.5330	0.6731	0.6447	0.8737
	LTE	0.6564	0.8294	0.7715	1.1553
320p	Wi-Fi	0.5175	0.6064	0.6302	0.8477
	LTE	0.6039	0.7961	0.7493	1.1488
480p	Wi-Fi	0.5371	0.5988	0.6359	0.8498
	LTE	0.6053	0.8333	0.7835	1.1760
800p	Wi-Fi	0.5669	0.6440	0.6571	0.8747
	LTE	0.6101	0.7769	0.7827	1.2583

Table 4: Average power consumption (W) of Direct and LTE for the video player application.

provides better throughput and decreases the delay time at the smartphone.

A comparison between the communication methods showed that LTE consumes more energy than Wi-Fi for video streaming. Especially for Wi-Fi, the Wi-Fi Direct is the most energy efficient communication method for video streaming, according to the experimental results.

The detailed results for the YouTube application for every smartphone are shown in Table 3. It is clear that the LTE consumes slightly more power than the Wi-Fi.

Similarly, Table 4 shows the results between Wi-Fi Direct versus LTE with the video player application. Again, the Wi-Fi is more energy efficient, while a comparison between Wi-Fi and Wi-Fi Direct shows that the Wi-Fi Direct has the lowest power consumption.

For the LTE methods, the devoted server consumes less power than the YouTube application.

Using the tables 3 and 4, it becomes clear that there is a hierarchy of power consumption in the from display size, to display resolution, to finally the processor/communications subsystem. So, with some efficient wireless card or LTE card it seems, from our experiments, to be more effective use of energy to transmit the streaming video data as quickly as possible. Additionally, considering the display size as it relates to the phone's power consumption, selecting a more efficient display for a given size can provide immediate power saving benefits to the phone designer.

6. Conclusion

This work presents a study on the power tradeoffs in mobile video transmission. The power consumption of four smartphone devices was examined. The smartphones were selected to have different display size and resolution. The transmitted video had four different qualities while the power consumption was measured during Wi-Fi and LTE sessions.

The experimental results show that the smartphone display affects the most the average power consumption during a video session. The extensive experimentation revealed a number of other useful insights such as the importance of the Wi-Fi chip in smartphones with same screen size and different resolutions. Understanding the display size, resolution, processor/wireless card interplay of power consumption in the phone provides useful information when designing phones, streaming services, and phone applications that consume those resources.

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