How is Energy Consumed in Smartphone Display Applications?

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ABSTRACT
Smartphones have emerged as a popular and frequently used platform for the consumption of multimedia. New display technologies, such as AMOLED, have been recently introduced to smartphones to fulfill the requirements of these multimedia applications. However, as an AMOLED screen's power consumption is determined by the display content, such applications are often limited by the battery life of the device they are running on, inspiring many researches to develop new power management schemes. In this work, we evaluate the power consumption of several applications on a series of Samsung smartphones and take a deep look into AMOLED's power consumption and its relative contributions for multimedia apps. We improve AMOLED power analysis by considering the dynamic factors in displaying, and analyze the individual factors affecting power consumption when streaming video, playing a video game, and recording video via a device's built-in camera. Our detailed measurements refine the power analysis of smartphones and reveal some interesting perspectives regarding the power consumption of AMOLED displays in multimedia applications.

Categories and Subject Descriptors
K.6.2 [**Management OF Computing and Information Systems**]: Installation Management – *Performance and usage measurement.*

General Terms
Algorithms, Management, Measurement, Performance, Design.

Keywords
OLED display, Smartphone, AMOLED, Video power.

1. INTRODUCTION
Smartphones now play a large role in almost every aspect of our daily lives, being utilized in activities such as communication, personal planning, and entertainment. Although the complexity and capabilities of these devices continues to grow at an amazing pace, smartphones are now expected to continually become lighter and slimmer. When combined with power-hungry multimedia applications, the limited battery capacity allowed by these expectations now motivates significant investment into smartphone power management research.

Multimedia applications, such as streaming video players, games, and image and video capturing tools, now comprise a considerable portion of the daily usage of smartphones. The power consumption of these applications depends heavily on the type of display technology being used, which also plays an important role in human-machine interaction. Many researches have already studied the power and performance of different display technologies [1].

Very recently, AMOLED (Active-Matrix Organic Light Emitting Diode) display panels have begun to replace conventional LCD (Liquid Crystal Display) technology in mainstream smartphones. Compared to LCD, AMOLED offers much better display quality and higher power efficiency because of its unique lighting mechanism. This unique property has led to much research involving the power evaluation and modeling of AMOLED as well as the performance variance among different AMOLED panel designs. However, due to the large variety of AMOLED panel designs and the fast pace of smartphone software development, most of this research only aims at a particular smartphone device or application. It is not clear whether there is any significant power efficiency improvement between different generations of AMOLED display technology or if it is possible to obtain an overview display power efficiency under different applications.

In this work, we evaluate the power consumption of the displays of several high-end Samsung smartphone models. In addition to this, we discuss the power modeling of different generations of AMOLED screens and conduct a detailed power analysis of several popular multimedia applications. Based on the data that was collected, we draw some interesting conclusions which may influence future research in the field. For example:

- Subsequent generations of AMOLED products do not yield the significant per-unit improvement in power efficiency that was expected. The power difference between AMOLED products is mainly realized by design metrics like size and sub-pixel.
- The power consumption of chromatic color can be efficiently reduced by implementing a dynamic color tuning technique.
- The power consumed during the video decoding process is responsible for only a small portion of the total power required for the end user to actually view the video.
- In video games, the AMOLED display's power consumption varies greatly, and it is relatively small in some cases when compared to the overall system power consumption.
- The power consumed by the AMOLED during video recording is relatively small compared to the overall power consumption.

The remainder of our paper is organized as follows: Section 2 presents previous related work; Section 3 gives our adopted methodology for power evaluation, including the devices under test (DUTs) and the test environment setup; Section 4 models the power consumptions of several different AMOLED panels on Samsung smartphones; Section 5 presents the power analysis' of video streaming players, video games, and camera recording, respectively; Section 6 concludes our work.

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2. RELATED WORK

Since its development, AMOLED technology has been the topic of a great deal of research, much of which has attempted to describe and model its power characteristics. The authors of [2] presented a classic AMOLED power modeling in smartphone, which is adopted in this paper. The authors of [3] evaluated the AMOLED power model's accuracy in practical performance and helped application developers to improve the energy efficiency of their smartphone applications. OLED power model is part of the system power model. The display modeling of AMOLED has also been integrated into a system level power monitor and analyzer, as done in [8] and [9].

Power optimization schemes based on AMOLED displays have also been studied from the applications point of view. The authors of [15] reduced the power consumed while displaying an arbitrary image through the use of OLED's dynamic voltage scaling (DVS) technology, while the authors of [4] extended this DVS scheme into video streams. The authors of [7] extended the dynamic gamma correction power saving scheme for video games to the AMOLED platform. The author of [5] shows OLED screens contribute significantly to the energy consumption of web browser and then applies the optimization techniques from [6] to reduce it. These works pointed out that, while a smartphone spends most time idle when web browsing, streaming video, playing video game, and camera recording, the smartphone demands significant system resources in a continuous manner. However, we find the power contribution made by the OLED screen can be small.

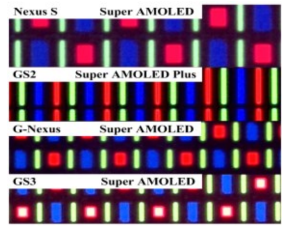
3. METHODOLOGY

3.1 Devices Under Test (DUTs)

We examined five Samsung products, including the Nexus S (released in 2010), the Galaxy S1, Nexus, and S2 (released in 2011), and the Galaxy S3 (released in 2012). During the tests, the devices ran the Android operating system and a suite of test applications. The screens of all the tested devices are all based on AMOLED technology, though they are built with different display sizes, resolutions, and technology generations, i.e., Super AMOLED, Super AMOLED Plus and Super AMOLED HD, respectively. These screens well represent the evolution of Samsung's OLED technology in recent years.

3.2 Power Evaluation Setup

Many smartphone power models have been proposed in recent research and are included in the embedded Android power monitor APIs [8][9][10]. However, these models generally have limited adaptability to the many variations of available hardware configurations, incurring inevitable run-time evaluation errors [11]. Rather than calculating power information from software, we utilized an external power monitor to directly measure the battery behavior for power consumption breakdown with a series of



(a)

Smartphone	Panel Size	Resolution
Nexus S	4.0”	480*800
Galaxy S2	4.5”	480*800
Galaxy Nexus	4.65”	720*1280
Galaxy S3	4.8”	720*1280

(b)

Fig. 1. (a) AMOLED sub-pixel matrix; (b) Smartphone AMOLED screen specs.

contrast experiments.

We adopted a mobile device power monitor produced by Monsoon Inc. for real time power measurement. It supports a sampling frequency up to 5 kHz and can be used to replace the battery as the power supply to the smartphone. The power monitor is directly connected to the smartphone and records a power histogram. During the power evaluation of the display modules, we disabled all unnecessary system services that may have caused any significant power consumption noise, including 4G and Wi-Fi network communication, background services, and power optimization applications. The contrast experiments are designed to separate the power consumption of display from that of the system, e.g., CPU and GPU. Most power consumption test are completed while the device's screen brightness is set to maximum. The specific test bench details will be presented in later sections.

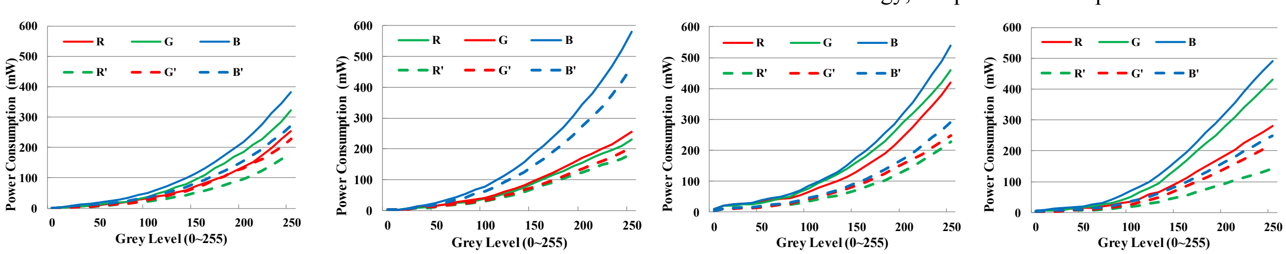
4. AMOLED DISPLAY EXPLORATION

4.1 AMOLED Power Evaluation on Sub-pixel

Different from previous research, instead of directly measuring and then comparing the power consumption of each entire screen, we attempt to normalize the displays and compare the per-unit power efficiency for different AMOLED products. Because of this we found that, in contrast to the conclusions drawn by previous research, when comparing the power efficiency between different generations of AMOLED technology:

Subsequent generations of AMOLED products do not yield the significant per-unit improvement in power efficiency that was expected. The power difference between AMOLED products is mainly realized by design metrics like size and sub-pixel matrix.

A smartphone display is composed of many individual pixels. The color of a pixel is constructed via the combination of a few basic colors (e.g., red, green, blue, or RGB), which themselves are the only colors directly emitted from the display unit via tiny sub-pixels. The display unit is defined by the arrangement of these sub-pixels, which is known as the sub-pixel matrix design. As shown in Fig. 1(a), in the AMOLED displays we tested, every pixel has three sub-pixels corresponding to the basic colors of RGB color space. Unlike LCD technology, the power consumption of an AMOLED



(a) (b) (c) (d)

Fig. 2. AMOLED screen power consumption: (a) Nexus S; (b) Galaxy S2; (c) Galaxy Nexus; (d) Galaxy S3
Solid lines are the original overall screen power consumption, dash lines are the screen power consumption normalized to 4 inch^2.

screen is highly color dependent. The power consumption of each pixel varies with the chromatic color composition that is being displayed, as not only do more intense colors require more power to display, but each individual sub-pixel has its own unique power distribution curve. Hence, various sub-pixel matrix designs are proposed to balance the lighting efficiency and display quality by adopting different alignments, area-to-area ratios, and etc. of individual sub-pixels. Fig. 1(a) illustrates the contrasting sub-pixel matrix designs of Super AMOELD Plus (based on identical RGB strips) and Super AMOLED (based on PenTile design) [12].

In many prior works involving AMOLED screens, the pixel-level power modeling is often expressed as: $P_{pixel} = f(R)+h(G)+g(B)$. This models the power consumption of a pixel as the summation of the power consumption of the individual RGB sub-pixels [2]. $f()$, $h()$, and $g()$ are the color component dependent functions and R, G, and B are the input signals, which are usually represented as a grey level of [0, 255]. In Samsung OLED products, a standard gamma correction of 2.2 is applied to the input signals in order to improve the display quality. Thus, the relationship between the power consumption of the AMOLED screen and the grey level becomes nonlinear, as shown in Fig. 2.

Fig. 2 also shows that the power models of different display modules vary significantly. One example of this is the difference between the Super AMOLED or PenTile AMOLED, used in Galaxy S3 and the Super AMOLED Plus used in Galaxy S2: the power consumption of the PenTile design in Super AMOLED is much more balanced among the different colors than the traditional RGB strips utilized in Super AMOLED Plus. In addition to this, display panels with the PenTile design also show an averagely lower power efficiency than traditional RGB strip. However, as PenTile design aligns more low power consuming green sub-pixels in the pixel matrix, it's supposed to be more power efficient. Hence, we have to also take the display panel size into consideration to compare the power efficiency.

In many existing AMOLED power measurements and models, the power consumption of a display panel is evaluated as a whole. The many different panel sizes and sub-pixel alignments available today make it very difficult to conduct a fair comparison of the power efficiency between different AMOLED technology generations. Therefore, we focused on analyzing the sub-pixel power efficiency.

To accomplish this task, we first normalized the area of each individual sub-pixel to account for the size difference between sub-pixels in PenTile technology. The power consumption of the entire AMOLED screen while displaying each basic color at every grey level was then recorded and scaled to represent a screen size of 4 $inch^2$. The normalized power consumption of the sub-pixels in each scaled display is depicted as the dashed lines in Fig. 2.

Although some prior work has claimed that the power efficiency of AMOLED screens has as much as doubled between generations, i.e., from the Galaxy S2 to the Galaxy S3 [18], we found that the practical power improvement is not nearly that significant. For example, when comparing to the oldest AMOLED screen (in the Nexus S) to the latest (in the Galaxy S3), a jump of two generations, the highest pixel-level power efficiency is between only 5.7% and 29.5% improved at a grey level of 50. Interestingly, we found that the most significant factor that contributes to the power consumption difference between the different smartphone models is the sub-pixel area ratio. For example, although all the Super AMOLED display panels follow G-R-G-B sub-pixel matrix design, the sub-pixel area ratio is slightly adjusted in the different models to accommodate the specific screen size and pixel density, leading to different power models.

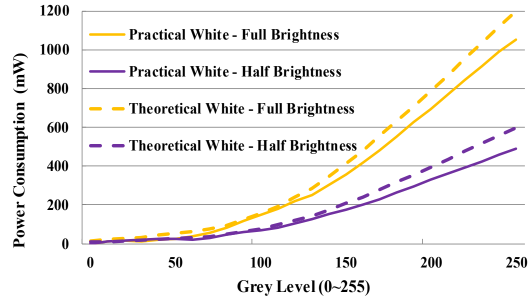


Fig. 3. System chromatic color tone remapping.

4.2 Dynamic Color Tuning

Based on the color power measurement, we also found that:

In the operation of an AMOLED screen on a smartphone, the actual displayed color and intensity may not be representative of the original raw RGB composition being sent to the screen as it may have been modified by a dynamic color tuning system in order to minimize power consumption.

The previous single color evaluation is realized by adjusting the grey level of individual RGB color component while disabling the other display channels. However, when we measured the chromatic color's power consumption in Galaxy S3, we found that it is not simply the summation of the individual RGB channels' pixel power model, which was discussed in Section 3.1.

We examined the power consumption of the AMOLED screen when its color changes from black to white. At every measured color composition, the same grey levels are applied to each sub-pixel. As shown in Fig. 3, at a grey level of 100 and above, the theoretical power consumption that is calculated by the existing simple power model is 7% to 14% higher than the practical (measured) power consumption under full brightness and 9% to 22% higher under half brightness. Similar phenomena were observed when displaying arbitrary chromatic colors, such as aqua, pink, purple, and etc.

In practice, it is very difficult to measure the power consumption of an AMOLED screen in the 24-bit RGB color space and derive a generic power model. However, it is still possible to integrate a simplified model into the smartphone for AMOLED screen power optimization. In fact, in Samsung's display system, an image processing engine called MDNIe is implemented by a designated chipset just in front of the graphic buffer to the display panel [13]. One application example of MDNIe is dynamic color tuning: the color composition being displayed on the screen can be adjusted by MDNIe to decrease power consumption while maintaining contrast levels. Hence, this system integrated dynamic color tuning has achieved power savings by color tuning effectively.

5. POWER ANALYSIS ON DISPLAY RELATED SMARTPHONE APPLICATION

5.1 Video Power Performance

Although OLED technology has substantially improved the power efficiency of displays when compared to traditional LCD screens [14], the display panel is still one of the most power-consuming components in a smartphone [15]. Applications with dynamic display contents, e.g., streaming video player, are considered as being energy-hungry by previous research.

However, in this work, we found that:

In video stream player, the AMOLED screen's power consumption is highly content dependent. The video decoding process contributes very marginal power consumption to the application.

We examined a set of pure video streams without audio track and analyzed the composition of the application's power consumption. We also conducted a breakdown of the screen's power consumption over each functional component. To better represent typical display content differences, we followed YouTube's video category and selected four types of video streams: music videos, sports, gameplay videos, and news reports. All of the video clips tested are selected and downloaded from YouTube. Most of these video streams are between 2-3 minutes in length and vary between 1000 and 2500 frames.

5.1.1 Power consumption with different display contents

Because of the previously discussed color-dependent power model associated with AMOLED pixels, the display content directly determines the power consumption of an AMOLED screen. We evaluated 50 local video streams in each category on a Samsung Galaxy S3 in the field study. All of the video streams were encoded with a bit rate of 0.8 Mbps without a sound track. The refresh frame rates and display areas were configured differently to evaluate the system decoding performance. The overall power consumption of the device was recorded while at the same time monitoring the individual component power breakdown.

The average power consumptions of each category of video are shown in Table 1. In full screen tests, videos are stretched to fill the entire screen, while in original size tests the videos are displayed on the screen in a letterbox with a resolution of 640x360 (the rest of the space on screen is black). The original size test is used to simulate the small display windows embedded in other application's UI's, e.g., Facebook and YouTube.

Table 2 gives the contrast test results, which are measured by disabling the display output and allowing it to only display a black screen. In these tests, the power consumption of the device is only influenced by the video processing and other background operations. As expected, the contrast values are not dependent on the display content and are almost identical for different content samples with the same decoding configuration. By subtracting the power consumption in Table 2 from corresponding items in Table 1, we can derive the power consumed by the display panel itself.

Our results show that the most power consuming video content category is Sports. At 60fps and 30fps, the AMOLED screen consumes 29% and 32% of total smartphone power, respectively. Such high power consumption comes from the bright color tone and complex textures, which require high luminance and balanced color tuning. As a comparison, the least power consuming video content category is music video, which consumes only 15% and 17% of total smartphone power at 60fps and 30fps, respectively.

Table 1. Video stream power consumption (mW)

Video	1280x720 (full screen)		640x360 (full screen)		640x360 (original size)	
	30fps	60fps	30fps	60fps	30fps	60fps
Music	786.4	975.8	682.9	783.7	594.9	698.1
Sports	960.4	1172.1	855.3	953.2	652.4	751.9
Game	869.0	1061.2	786.5	889.1	628.2	730.8
News	901.3	1124.3	802.7	915.7	612.3	725.5

Table 2. Contrast power consumption (mW)

Video	1280x720 (full screen)		640x360 (full screen)		640x360 (original size)	
	30fps	60fps	30fps	60fps	30fps	60fps
Music	646.9	820.8	543.8	648.2	544.8	649.4
Sports	646.8	823.2	542.5	644.3	548.7	649.0
Game	644.3	820.6	543.5	643.7	548.0	648.8
News	647.5	822.1	545.2	644.2	548.2	649.0

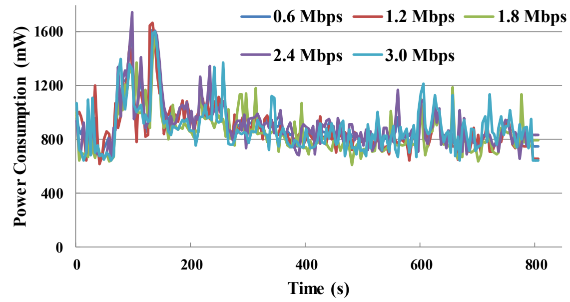


Fig. 4 System chromatic color tone remapping

Our results also show that the power consumption of the AMOLED screen decreases considerably when the resolution of the displayed video stream degrades: the ratio of the power consumed by the AMOLED screen to that of the entire smartphone decreases to between 7% and 15%. This indicates that while streaming an online video, AMOLED screens consume quite a small portion of the overall smartphone power, especially when compared to the potential power cost of network, which can require up to 2W.

Moreover, we simulated approximately 200 video streams under each category to obtain the power consumption statistics of AMOLED screens. Our simulated results show that power consumption of the AMOLED screen is between 74.6mW and 374.2mW during full screen viewing and 37.2mW to 90.7mW during original size viewing. When compared to the contrast power consumption shown in Table 2, we propose that:

The power consumption of an AMOLED screen is highly content dependent and may have relatively little impact on the overall power consumption of video streaming applications.

5.1.2 Video stream decoding cost

We also analyzed the power consumption of the video decoding process. The impact of display resolution, frame rate, and encoding bit rate are included in our analysis.

Similar to the experiments presented in Section 4.1.1, two display resolutions of 1280x720 (full screen) and 640x360 are adopted in our tests. For the same display content, bit rate, and fps, the observed video decoding power consumption is almost identical when the stream is stretched to full screen from 640x360 and when it is viewed at original, letterboxed size. This means that the full screen pixel stretching in the display buffer consumes very little power for low resolutions. However, a large power rise (~ 100mW) is observed if the resolution increases from 640x360 to 1280x720, as shown in Table 2. This is due to the significant power required during the decoding process for high-resolution video.

The largest power consumption difference occurs when the frame rate changes. The increase in the system power consumption at a fast frame rate comes from extra workload placed on the CPU. For example, the power consumption of the decoding process at 60 fps and a resolution of 640x360 is about 100mW higher than that of one at 30fps. When the resolution rises to 1280x720, the difference becomes even more pronounced at 200mW.

We also tested 50 complex CG videos with the same content, time length, frame rate and resolution but different display quality, i.e., the bit rate. In our tested videos, the bit rate varies from 0.6 Mbps to 3.0Mbps. Although the videos share the same resolution, the low-quality ones include many mosaics and the corresponding video compression can be easier, which led to the lower bit rate. However, we found that the low bit rate and aggressive compression do not introduce any significant changes in power consumption: as is shown in the power track example in Fig. 4, there are almost no power differences between the different bit rates. Combined with our previous tests, this led us to the conclusion that higher display resolutions incur a much more significant increase in power consumption than an increased bitrate. Therefore, we propose that:

Fast frame rate and high resolution introduce significant video decoding power consumption. However, when compared to the whole system, this power portion is not significant.

5.2 Game Power Performance

Due to the large volume of graphic computation on CPU/GPU and high display quality requirement, video games have become one of the most power-consuming application types in smartphones. We also measured the game power performance, based on the above observation, we propose that:

Smartphone games consume a large amount of power. This power is mainly consumed by background computation while significant extra power may be required by user interaction. However, the AMOLED power consumption is generally small in comparison.

We first measured the power consumptions of 20 of the most popular games from the Google Play store on the Galaxy S3 platform. To enable easy interaction, most of the games are composed of big objectives with bright colors. This generates an increase in the power consumption of the AMOLED display. Our measurements show that the power consumption of the whole smartphone is generally within the range of between 1140mW and 1750mW when user interaction is disabled.

Some video games require user interaction that involves frequent sensor operations (e.g., tilt to move or touchscreen input). For instance, the power consumption of the device while playing Angry Birds and Fruit Ninja was increased to 1640mW and 2220mW, respectively, during normal operations. Compared to other applications like web browsing (with a power consumption in the range of 600mW to 1500mW) and video players, these video games require large amounts of power. The display power required with each of another 200 Android video games was simulated with the Galaxy S3 AMOLED power model. The simulations were made with official game trailer videos from YouTube. The average power consumption of the AMOLED was between 50.3mW~446.4mW.

Finally, we analyzed power utilized by background computation while playing the open-source video game Quake 3 on the Android platform. Although it is an old game, it still offers reasonable game complexity and display quality on present smartphone platform. By modifying the code, we were able to obtain the power breakdown

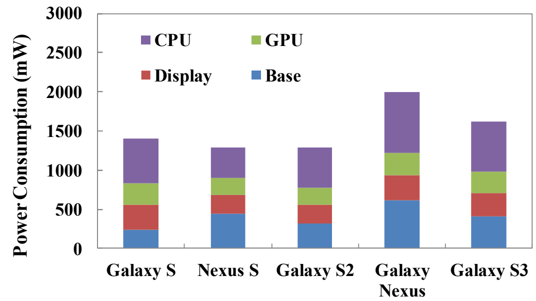


Fig. 5 Power component breakdown example of video game.

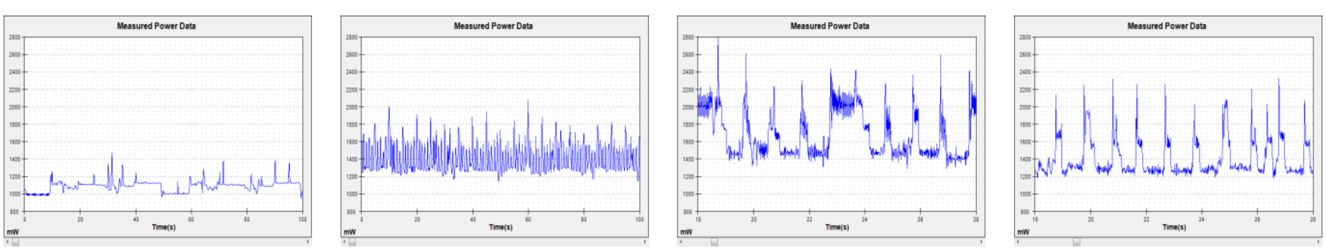
of the game over different hardware models. We chose five different smartphone models to cover the existing GPU/CPU configurations and display panel designs, as shown in Fig. 5. Although some models share the same chipset, e.g., the popular GPUs – PowerVR and Adreno (e.g., Galaxy Nexus uses PowerVR and ARM9; Galaxy S2 and S3 use Adreno and the CPU from Qualcomm), a variance in power performance is still observed. For example, the power supporting necessary background system services varies between 1245mW and 2140mW, which is much higher than the normal power level of other applications, such as streaming video players. The ratio between the power consumption of the AMOLED screen (typically 237mW to 363mW) and the whole smartphone reduces to between 15% and 22%. Fig. 5 also shows that CPU's generally consume more power than GPU's. In the Galaxy S and S2, the contribution of the CPU to total power consumption can be up to 40%.

5.3 Camera Power Performance

Besides streaming video players and video games, camera recording is another important display-related application on smartphones [17]. As has been studied before, camera recording incurs a surprisingly high power cost. However, the performance with the AMOLED display is not yet evaluated in this regard. In our experiments, we found that:

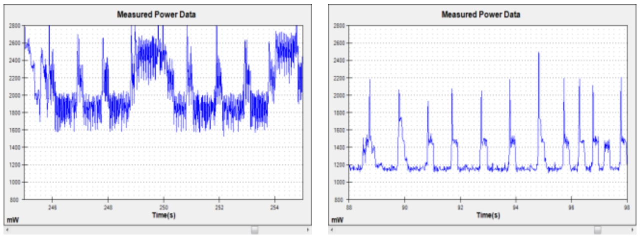
The AMOLED display's power contribution is relatively small compared with that of the rest of the system during camera recording. Possible power reduction may be achieved by optimizing the internal data transformation.

To arrive at this conclusion, we measured the power consumption of camera recording applications. Most of the measured smartphone cameras have a very high resolution of 6 to 8 megapixels and are capable of recording HD videos at up to 1080p. Four test modes are included in our measurements: 1) contrast mode, where the camera works as normal but the AMOLED screen is disabled; 2) preview mode, where we only use camera for preview but not recording; 3) high quality recording, where the video resolution is 1280x720; and 4) low quality recording, where the video resolution is 640x360. To exclude the power variance



(a) (b) (c) (d)

Fig. 6 Galaxy S2 camera recording power histogram: (a) Preview mode; (b) Low quality recording; (c) Zone-in of the power histogram of high quality recording; (d) Zone-in of the power histogram of low quality recording.



(a) (b)

Fig. 7 Galaxy S2 camera recording power histogram: (a) 3264x2448; (b) 320x240.

introduced by the AMOLED screen itself, the smartphone cameras record the same video test benches projected to a screen, including pure black, still picture, and the videos from typical categories. Except for the auto focus, other additional effects are disabled.

A typical power histogram of Galaxy S2 smartphone in preview mode is shown in Fig. 6(a). Note that the power consumption of the AMOLED screen can be derived by subtracting the power utilized during contrast mode from the power consumption in preview mode. In recording modes, the power consumption of the smartphone increases, as shown in Fig. 6(b). The power variances among the different display contents are barely recognized and dominated by the video processing with some impacts from recording quality. For a 4-minute camera recording, the average power consumption is 1400mW and 1650mW with the low- or high-quality recording, respectively. Out of the total power consumption, the portion of the AMOLED screen accounts for 170mW and 180mW in the low- or high-quality recording, respectively. Here the frame rate is 30fps. The power difference incurred by the resolution up-scaling is 250mW=1650mW–1400mW, which is quite small compared to the overall.

However, the zone-ins of the power histograms of each recording mode in Fig. 6(c) and (d) show periodic spike patterns. The highest spikes in the low and high-quality recordings are around 1620mW and 2050mW, respectively. Also, the spike pattern during low-quality is more regular than that in high-quality recording.

We believe the difference of camera spike patterns in the two types of video recordings is introduced by the constraints on data communication. Since the camera buffer capacity is limited, the power consumption due to data transfer in the high-quality recording becomes more apparent when the frame size increases. We also tested the camera recording application with the resolutions of 3264x2448 and 320x240, as shown in Fig. 7. Distinct spike pattern difference are observed in these two tests. As expected, the spike pattern during the 3264x2448 resolution recording becomes prominent.

The power breakdowns of the camera recording application on different smartphone models is shown in Fig. 8. The contributors to the total power consumption include encoding process, camera device, display and base power consumption. Since the display content captured from the real environment generally have a very low luminance, the power consumption of the AMOLED screen is only 200mW to 400mW. The power consumption of video encoding, which is greatly impacted by the internal data communication, varies significantly among the different models.

Hence, with the tested results, we reached the conclusion that the power consumption of the AMOLED display only accounts for a small part of the device's overall power consumption when recording video from the camera.

6. CONCLUSION

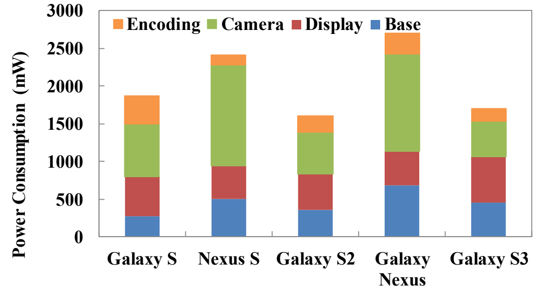


Fig. 8 Power component breakdown in camera recording.

In this paper, we evaluated the power consumption of various display-related applications on smartphones. We first refined the power analysis of AMOLED display by considering design metrics such as sub-pixel area and matrix. We then conducted the AMOLED screen power analysis in the smartphone applications of a streaming video player, video game, and camera recorder. A wide selection of display content was tested during our experiments running on several representative Samsung smartphone platforms. We found that the AMOLED screen power model is heavily affected by sub-pixel matrix design while the power efficiency over the unit area is almost the same. We also found that the power consumption of the AMOLED screen while watching a video is much less than expected while decoding process power consumption is also not significant. In video games, the power consumption of the AMOLED screen varies significantly and power optimization should focus on the CPU side. Finally, camera recording incurs surprisingly high power consumption, which is constrained by the internal data transformation, with the AMOLED display accounting for only a small portion of overall power cost.

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