Cambridge University Press
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Excerpt
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Part I

Understanding energy consumption

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1 Introduction

The last ten years has been the era of personal and social communications, with the rapid proliferation of smartphones that provide always-on connectivity with people and information. The mobile computing environment has changed over the years in many ways. Today's devices are powerful computers and sensing systems that have versatile communications capabilities, and they are capable of running native and web browser-based applications that can tap into system resources such as various onboard sensors. The devices also come in many forms and shapes, such as small and large form-factor phones, tablets, and wristwatches.

Understanding smartphone and mobile device energy consumption is a vital and challenging problem. It is vital, because the remaining operating time of a device should be understood and maximized when necessary. It is challenging, because a device consists of various hardware and software systems that work together. Various modeling, prediction, and optimization techniques are needed to engineer energy-efficient mobile systems.

1.1 Overview and the environment

Energy efficiency in mobile computing, especially in the wireless data transmission involved in mobile applications, is one of the challenges that has attracted much attention from mobile device manufacturers, application providers, and network operators. Compared with traditional telephone services, such as voice calls and short message service, executing modern mobile applications consumes much more computing and networking resources and therefore demands much more energy. However, battery technology has not developed as fast as mobile computing technology and has not been able to satisfy the increasing energy demand. This has directly resulted in a dramatic decrease in battery life, that is, the time until the next charge.

For example, the battery life of a mobile device may drop to between three and six hours, if the mobile user is using internet services such as video streaming and web browsing. Hence, energy efficiency in mobile computing, although it is a research area that has been established for more than a decade, has once again become a hot topic. A major target of this research area is to develop techniques for reducing the energy consumption of mobile devices while trying to maintain the device performance, which is

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possible because very often the devices consume more energy than is strictly necessary for a particular task.

About a decade ago when this research area was popular, the research focus was on the energy efficiency of computation [1], such as the energy consumption of microprocessors, since mobile internet services such as email were still in their early stages. Today, mobile devices, as well as application scenarios, have changed drastically.

With mobile internet services becoming popular, wireless data transmission is becoming a major source of energy consumption on mobile internet devices. Additionally, with more sensors, such as global positioning system (GPS) receivers, available on the devices, the context monitoring and its energy consumption also becomes a challenge. Hence, now is the right time to revisit energy-efficient techniques and to develop techniques to solve the existing and upcoming challenges. Indeed, the mobile systems research community has become very active in the area of smartphone energy consumption analysis and optimization with many recent proposals and results in the field.

1.1.1 A holistic approach

A holistic approach is needed to understand the energy consumption of a complex system such as a smartphone. Figure 1.1 gives an overview of the different facets that need to be considered when examining smartphone energy consumption. The energy draw of the device is determined by its physical properties and hardware components. Therefore the power profiles of the chipset, hardware accelerators, and dedicated hardware-level functions are crucial. At the device level, pertinent issues include parallelism and scheduling over multiple cores, as well as intra-device optimization. At this level, the impact of applications and processes needs to be understood by mapping software activities to hardware resources. This mapping can be done on different levels of abstraction from the process level to the system call level.

Expanding beyond the device, at the inter-device level, optimizations can be carried out across devices typically in the local communication context. This is a new and emerging area of optimization with only a few examples at the moment. A more frequently employed approach is to connect the smartphone operating system and applications to the Internet to be able to send power-hungry tasks to the fixed network for processing. This process is called offloading and it is frequently used to alleviate resource limitations at the device.

The computing environment is becoming increasingly complex and distributed. A smartphone may interact with other phones and wearable items, such as smart watches, and augmented reality devices, such as the Google Glass prototype and product. Figure 1.2 illustrates the distributed mobile environment. Smartphones typically have one or more connections with internet servers. These connections are used to synchronize the platform and application state between the mobile device and the cloud. For example, an always-on connection is used to push asynchronous updates to mobile devices. Smartphones can communicate in the local context through protocols such as Bluetooth, Bluetooth Low Energy, and Wi-Fi Direct. The local communication today

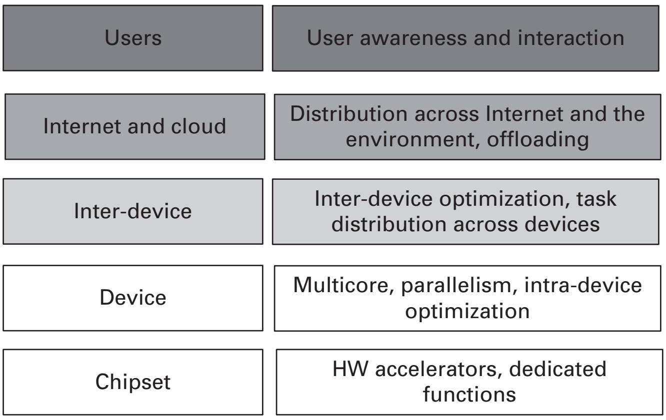

Figure 1.1 A holistic view of smartphone energy consumption

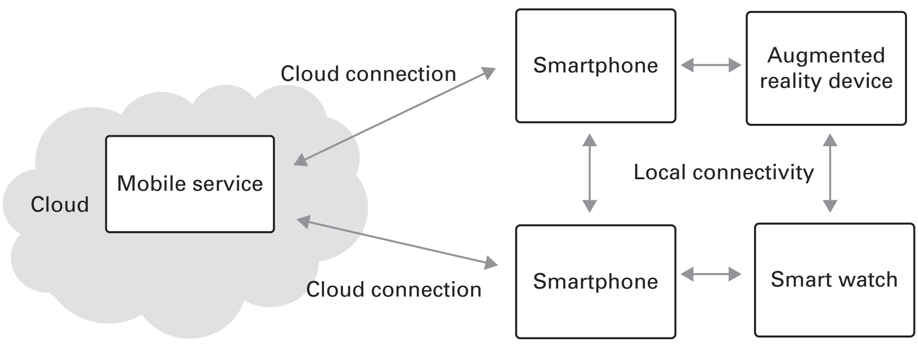

Figure 1.2 Overview of the mobile environment

is still quite limited, but with the advent of wearable devices, such as smart watches, and augmented reality devices, this is expected to change. This environment will be a fertile ground for new innovative applications that sense and interact with users in myriad ways; however, it also presents many challenges including energy efficiency, user interaction, security, software configuration, and communications.

Finally, we have the user and groups of users that carry the devices and interact with their software and hardware. Ultimately, the way people interact with the devices has a very large impact on the use of hardware resources and thus the overall energy consumption. In addition, the system can give recommendations to users on how to improve the energy efficiency of the system. This can be achieved through options that the users can set, such as the backlight and connectivity modes, or by recommending software updates or software-use strategies. For example, on the Samsung Galaxy S4, users can control the battery use by adjusting the power-saving mode settings. These settings relate to the CPU, screen, background color, and haptic feedback. Indeed, the term human–battery interaction (HBI) has recently been coined to describe how users charge and discharge the smartphone battery and manage the settings relating to battery use [2]. Thus we have to factor in the human element to understand the real-life energy consumption of smartphones.

1.1.2 Stakeholders

Figure 1.3 presents the key stakeholders for feature phones and smartphones. Feature phones, or GSM phones, are closed embedded devices that typically do not support extensive third-party software. Today the differences between feature phones and smartphones relate specifically to the extent of the application ecosystem, the hardware and software subsystems available for applications, and advanced operating system features such as multitasking. The stakeholders have an interest to ensure that the devices and the ecosystem around the devices function properly and that the devices are energy efficient. Today this is much harder to ensure given the complexity of the devices and their capabilities, as well as the huge numbers of applications using the device capabilities in unpredictable ways.

The stakeholders have different interests and requirements:

- End users require the mobile devices to have long operating times without affecting usability and performance.
- Device manufacturers are responsible for the smartphone hardware integration into a complete product and sometimes also the mobile platform. Each hardware component needs to be optimized for energy efficiency; but this is not enough, the combinations of components in runtime usage also need to be considered and optimized.
- Telecom equipment manufacturers, such as Nokia Solutions and Networks (NSN), Ericsson, and Huawei, develop wireless network technologies, such as the 3G and 4G cellular networks. Energy efficiency is a key requirement for these networks both for the mobile devices and the infrastructure.

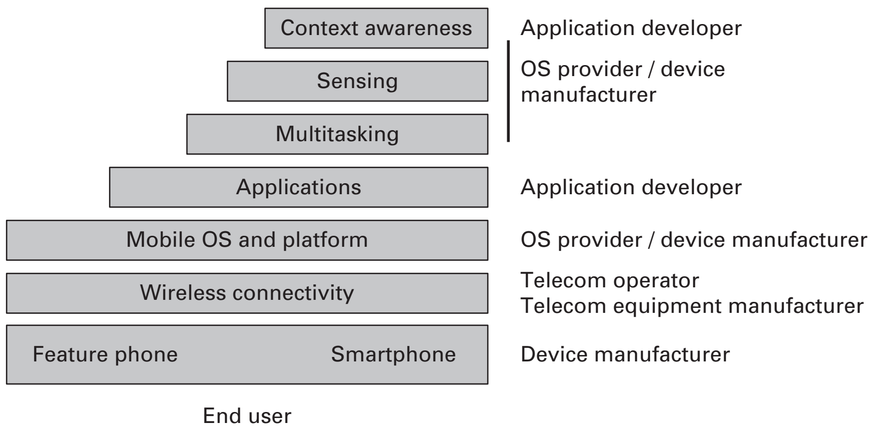

Figure 1.3 Key stakeholders in smartphone development

- Telecom operators are interested in keeping the end users satisfied and offering high-quality services. Therefore operators have an interest in ensuring that harmful applications are not run on the phones and that the network usage is efficient. On the other hand, mobile phone energy consumption is not the primary concern of mobile network operators. Operators are indirectly addressing mobile phone energy consumption through the configuration and deployment of wireless access networks.
- Platform providers are responsible for the operating system and many of the middleware components inside the mobile platform. For example, Google, Microsoft, and Mozilla develop mobile platforms that are then used by third parties. Energy efficiency is a key requirement for the OS and the middleware. The current mobile platforms employ various solutions to monitor and control energy consumption.
- Application developers aim to create the best possible applications for end users. Low energy consumption is one requirement for a good application. The end users would not consider purchasing an application that drains their battery in one hour if there are competing applications that work much longer. Therefore the mobile developer is interested in ensuring that the overall energy consumption of the application is in line with expectations and that there are no energy- or performance-related software bugs.

1.2 Smartphone hardware and software

From the hardware perspective, the modern smartphone is a general purpose computing device and a sensing system that consists of the essential components of a computer with dedicated signal processing and radio subsystems as well as a battery. The rechargeable battery stores energy that is discharged when powering the device. The software part of the device consists of the operating system (OS) including the device drivers, the middleware and libraries, and mobile applications running on top of the OS and middleware.

Compared to the feature phone, the smartphone has gained a lot in terms of software and hardware complexity. Early feature phones, or GSM handsets, were closed systems that did not support third-party software on the devices. These devices were designed for two specific tasks: voice communication and simple text messaging. For such devices it is relatively straightforward to develop energy-consumption models and then optimize the devices based on the models. In contrast, smartphones support third-party software and have many new functions, such as multiple radios and communication techniques: TCP/IP, web and email, FM radio, GPS reception, music and video playback, and so on.

Table 1.1 presents example smartphones and their characteristics (adapted from [3]). We observe that many of the smartphone properties are evolving at an exponential pace. The cellular technology evolution can be seen through five-year leaps. The downlink speeds have improved by a ten-fold factor at every leap. The display size is increasing in powers of two and the size of the software on the device is increasing in powers of ten, with the latest generation having a preset footprint of several gigabytes and the capacity

Table 1.1. Evolution of mobile phones

	1995	2000	2005	2010	2015
Cellular generation	2G	2.5–3G	3.5G	Transition towards 4G	4G
Standard	GSM	GPRS	HSPA	HSPA, LTE	LTE, LTE-A
Downlink (Mb/s)	0.01	0.1	1	10	100
Display pixels (× 1000)	4	16	64	256	1024
Comms modules	–	–	Wi-Fi, Bluetooth	Wi-Fi, Bluetooth	Wi-Fi, Bluetooth LE, RFID
Battery capacity (Wh)	1	2	3	4	5

for tens of gigabytes of user content. The battery capacity in terms of watt-hours is increasing linearly.

Battery technology has not developed as fast as smartphone power requirements, making energy a limited resource. Battery capacity is determined and limited by its chemical properties. Thermal limitations must also be taken into account in the design of smartphones and other battery-powered mobile devices. Without active cooling the power consumption of a small device is limited to approximately 3 watts [4]. Battery capacity can be increased with physically larger batteries; however, this would lead to larger devices which is not a desirable solution. Indeed, alternative solutions are highly sought after by academia and industry.

An important part of the added value of the devices comes from the application-centered ecosystems, in which third-party developers develop and distribute mobile applications through application stores or similar marketplaces. The mobile application market started its tremendous growth in 2008 with the advent of the Apple App Store and since then hundreds of thousands of mobile applications have been made available in various stores and distributed to mobile devices.

Interest in the energy consumption of devices has shifted from the energy-efficient design of feature phones for a small number of basic tasks to the overall energy optimization of smartphones that run arbitrary third-party software. In addition to energy-efficient hardware, the OS and platform developers need to consider the energy consumption of the device and its components to be able to optimize energy consumption in specific usage scenarios.

Energy problems have increased with the growth of the smartphone and tablet markets and with the phenomenal success of mobile software. Smartphone users are frequently asking for advice on how to improve the operating time of their devices, and there are many mobile applications for tracking energy usage of the devices. The general advice for smartphone users is to turn off extra functionality such as Wi-Fi or GPS, dim the background light, and avoid the use of applications that consume a lot of energy. Concern over energy consumption has also resulted in new kinds of bugs, called energy bugs (ebugs), that are software or hardware errors that manifest in excessive energy consumption [5].

Indeed, the above concerns and requirements toward energy efficiency have resulted in the rise of battery-monitoring applications and overall interest in detecting unusual energy behavior of applications and hardware components.

Given that heavy battery use may discourage consumers from downloading and using an application, application developers have become interested in optimizing their application design for energy efficiency. This is a new field and, although some tools exist, there is no well-established technique for analyzing the energy consumption of mobile applications.

> In this book, our central tenet is that smartphone energy consumption can be significantly reduced by focusing on the design of applications, middleware, and the OS taking the underlying hardware into account. Thus it is central to understand the higher-level activities of the applications, what happens within the software stack, and how those activities map to hardware resource consumption.

1.2.1 Increased capabilities of smartphones

The increasing coverage of mobile broadband networks has been accompanied by a significant boost in the capabilities of mobile devices. Feature phones and personal data assistants (PDAs) are being replaced by smartphones and sub-notebook form-factor tablet devices, such as Apple's iPad series, Samsung's Galaxy Tab, and other Android tablets. The new devices are equipped with high-performance processors, large-volume storage, multiple network interfaces, high-resolution displays, and rich sensors. All these capabilities together make it possible for mobile devices to handle much more complex tasks. It has opened a door to mobile applications that require heavy computation, high-speed data transmission, and rich context information.

Table 1.2 presents example smartphones and their capabilities. The ARM processors dominate the smartphone market and almost all current smartphones use ARM-based CPUs. The clock speed of the devices has increased over the years: more than tripled from 2008 to 2013. In addition, the battery capacity has increased, but as mentioned above the capacity has fallen behind the other capabilities.

The sensing capabilities of smartphones have also increased over the years. Today's smartphone has many ways to probe the internal and external operating environment. Internal sensors monitor the status of the battery, CPU, and wireless networks. External sensors monitor and estimate the orientation and acceleration of the device, the location, physical proximity, compass direction, temperature, atmospheric pressure, humidity, and user gestures. Box 1.1 outlines the sensors on the Samsung Galaxy S4 smartphone. This smartphone has an interesting solution for controlling the onboard sensors. The device uses an Atmel AVR microcontroller-based sensor hub for managing the sensors in real time.

Table 1.2. Example smartphones and their characteristics

Device	CPU	Clock speed	Issue	Year	Battery
Apple iPhone 3G	ARM11	412 MHz	Single	2008	1219 mAh
Nokia N97	ARM11	434 MHz	Single	2009	1500 mAh
Nokia N900	TI ARM Cortex-A8	600 MHz	Dual	2009	1320 mAh
Apple iPhone 4	ARM Cortex-A8	800 MHz	Dual	2010	1420 mAh
Samsung Galaxy Nexus	TI ARM Cortex-A9	1200 MHz	Dual	2011	1750 mAh
Apple iPhone 5	Apple A6	1300 MHz	Dual	2012	1440 mAh
Nokia Lumia 920	Qualcomm APQ8055 (Snapdragon S4)	1500 MHz	Dual	2012	2000 mAh
Samsung Galaxy S4	Qualcomm Krait: ARM Cortex-A15 and ARM Cortex-A7	1600 MHZ Cortex-A15 and 1200 MHz Cortex-A7	Quad	2013	2600 mAh

Box 1.1 Samsung Galaxy S4 sensors

- Accelerometer
- Gyroscope
- Proximity
- Compass
- Barometer
- Temperature
- Humidity
- Gesture

Example of context-awareness: The Motorola Moto X[a] released in August 2013 is based on the Qualcomm Snapdragon S4 pro (1.7 GHz dual-core Krait CPU), quad-core Adreno 320 GPU, a natural language processor, and a contextual computing processor. The device has a 2200 mAh battery and runs the Android 4.2.2 OS extended with context-awareness support. Specifically, the new feature of the phone is continuous audio sensing with the Google Now product. The device can wake at any time to hear the user's voice and react to the command and the surroundings. Indeed, context awareness is now being introduced to mobile applications and operating systems. This places even greater requirements on the energy efficiency of the software and hardware to keep the operating times of the devices reasonable.

[a] www.motorola.com/us/shop-all-mobile-phones/Moto-X/FLEXR1.html accessed January 6, 2014.