Green Mobile Devices and Networks

Energy Optimization and Scavenging Techniques

Hrishikesh Venkataraman and Gabriel-Miro Muntean, Editors

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Preface

Wireless communications are evolving rapidly toward "beyond 3rd generation (B3G) and 4G systems." At the same time, multimedia transmissions, video-on-demand, gaming, etc. are becoming increasingly popular among the growing number of users. Additionally, over the past couple of years, the demand for multimedia communications and, particularly, video streaming to handheld mobile devices has grown by leaps and bounds. In particular, it is expected that by 2013, mobile phones and other browser-enabled mobile devices will overtake PCs as the most common access device worldwide. As the technology progresses, wireless devices, such as smartphones, iPhones, PDAs, etc., are offering a large number of sought-after features to customers and support for increasingly complex applications. With each passing year, the functionality and computing power of mobile devices is increasing exponentially, with more and more applications and communication technologies being added consistently to handheld wireless devices. The data rate required for supporting these services is also increasing significantly. This implies a high power requirement at the transmitting and, especially, the receiving wireless devices. However, there is an annual power improvement of only 6 percent over past years and this has not grown in tune with processing and communication technologies. This has a serious impact on the practical use of the mobile devices, especially when accessing rich media-based services. For example, the battery of an iPhone 4GS lasts a mere five hours during Internet connectivity on a 3G network.

Given the stringent requirements and the current limitations of the battery powering of mobile devices, serious efforts are required not only to improve the battery quality, but also improve the battery life. In order to achieve greater success from mobile technology over the next decades, the concept of battery recharging every one to two days has to be completely revamped. This is, of course, easier said than done. A very important question that needs to be investigated and would challenge the researchers/handset manufacturers/network operators is what kind of improvement in the battery can be achieved without significantly altering the overall performance? This is a very interesting yet a very difficult proposition. Recently, there have been several efforts to optimize the energy consumption in both devices and networks. At the level of a device receiving video content via wireless networks, the content's bit rate, frame rate, and color depth could be altered seamlessly depending on the current battery power status. Such a periodic yet a dynamic adaptive mechanism would significantly optimize the battery consumption. An important thing to ponder is that energy optimization schemes can only reduce the consumption and thereby, increase the battery life by a certain but limited amount. There should be alternate mechanisms that need to be used or proposed in order to improve the self reliance of the devices or at least significantly extend the power in the devices by generating or harvesting energy from the environment. An interesting, but challenging aspect is to look at different energy-harvesting techniques and their adaptability to be used by wireless/mobile devices and networks. In order to achieve this, significant changes have to be made in both the hardware mechanisms and software policies to adapt energy use to user requirements for the tasks at hand and to enable automatic recharge from the environment.

Significantly, at the heart of all the technology platforms and handsets introduced are networking and radio communications, thereby enabling base stations/routers/devices to support rich media services, regardless of where the users are physically located. With the latest extensive demand for high-speed Internet browsing and multimedia transmissions over the wireless networks, the focus of mobile networking has been mainly on increasing the data rate and, importantly, the system processing capacity. However, recently it has become quite evident that data rate increase and throughput maximization are not the only objectives in the next generation of wireless systems. *Tomorrow's networks should be optimized for performance and for energy efficiency as well*. A network optimized for both performance and energy implies a very different design and architecture and this is what is needed for high data rate communication to be sustainable in the future. To dramatically reduce the energy consumption of today's wireless networks, a radical new approach needs to be initiated. Hence, the next wave of energy efficient networks will not come simply from more traditional research on single aspects, such as physical layer research, but will require *holistic, system-wide, breakthrough thinking that challenges basic assumptions.*

Harvesting energy from the environment is an important aspect that can create a significant impact in the working pattern of current wireless networks. Energy harvesting can be done at the transmitters, receivers, routers, etc. However, energy harvesting in networks/base stations, etc. is still in a very nascent stage, as compared to energy harvesting in devices. This is primarily because of two reasons. Firstly, the amount of energy required by the wireless networks is very high and it is not possible to harvest such a large amount of energy at the moment. Secondly, the networks/base stations are located at one place and operated by mobile network operators, which are run by big companies. Hence, it becomes easier to power the base station through the existing electricity grid rather than harvesting energy from the environment. However, at the same time, given the increasing computational complexity and the power requirement of the base stations, extracting energy from the environment to power the operations of the base stations is an extremely relevant issue in the decades to come. In fact, in the sensor network domain, given the critical power requirement, energy harvesting for wireless sensor networks is already being carried out. It is an interesting research challenge to extrapolate the energy-harvesting mechanisms from sensor networks to wireless cellular networks.

Energy harvesting in devices is a relatively easy challenge. This is primarily because of the low power requirement of wireless devices. Further, a wireless device is exposed to different sources of energy in the environment, such as heat, light, mechanical keys, electromagnetic waves, audio, etc. Hence, a holistic approach would be to optimize energy harvesting through each individual mechanism and then integrate these different aspects.

This book is a first of its kind focusing solely on energy management in mobile devices and networks. It provides a detailed insight into the different energy optimization techniques and energy harvesting mechanisms in both wireless devices and networks. A unique aspect of the book is the detailed and integrated coverage of different optimization and energy scavenging techniques by different experts. This has not been dealt with before and offers a unique platform for the readers. The book is divided into two parts. The first part describes various energy optimization techniques, whereas the second part presents the energy-harvesting mechanisms.

The first part has seven chapters that focus on energy optimization techniques. Of these, the first three chapters focus on "energy optimizations in devices," while the next four chapters deal with "energy optimization in wireless networks." Chapter 1 talks about energy management and energy optimization techniques for location-based services in mobile devices. Chapter 2 explains the mechanism for energy efficient supply for mobile devices. Chapter 3 models the energy costs of different applications in wireless devices/handsets and is an extension of their previous proposed work in the same domain. In case of wireless networks, the energy consumption for the components across different wireless networks remain the same. However, the pattern of the energy consumption varies across different types of networks. Given the importance of voice communication in cellular networks, Chapter 4 talks about exploiting on–off characteristics of human speech for energy conservation in WiMAX-based systems. Further, given the amount of voice over Internet protocol (VoIP) IP services, Chapter 5 provides an insight into the quality of experience-based energy conservation techniques for VoIP services in Wireless LAN. Notably, a distributed ad hoc network represents a highly complex network in terms of both implementation and deployment. Hence, Chapter 6 explains the importance of considering multiple criteria (minimum energy, multiple relay, etc.) in a mobile ad hoc network and extends their previous work in this field. Above all, given the amount of energy optimization techniques already developed for wireless sensor networks, Chapter 7 provides a comprehensive overview of energy optimization in wireless sensor networks and how it could be potentially extrapolated for a generic wireless network.

The second part of the book includes six chapters that focus on energy harvesting techniques. Given the importance and the amount of research work being carried out for energy harvesting in wireless devices, four out of the six chapters in this section are dedicated to factors and mechanisms for different energy harvesting solutions for wireless devices. The last two chapters talk about common energy harvesting techniques in wireless networks. Chapter 8 evaluates CMOS RF DC rectifiers for electromagnetic energy harvesting in mobile devices. Further, Chapter 9 explains in detail energy scavenging techniques using a magneto inductive method, while Chapter 10 discusses the mixed signal low power techniques in energy harvesting systems. In Chapter 11, we look at designing wireless sensors with intelligent energy-aware middleware and how could this be extrapolated into futuristic wireless devices. Similarly, the last two chapters of the book, Chapter 12 and Chapter 13, provide an energy consumption profile for energy harvested wireless sensor networks and radio frequency energy harvesting/management for wireless sensor networks, respectively.

Green Mobile Devices and Networks: Energy Optimization and Scavenging Techniques can serve as a benchmark for postgraduates, future engineers, and designers in developing energy-optimal solutions and at the same time provide a deeper insight for the next generation of researchers to harvest energy from the environment for developing the next generation telecommunication systems.

The editors would like to wish the audience a happy reading time and would be happy to receive any queries from the readers.

Hrishikesh Venkataraman
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The Editors

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Gabriel-Miro Muntean, PhD, has established a strong track record in the areas of quality-oriented and performance-aware adaptive multimedia streaming and data communications in heterogeneous wireless environments. Dr. Muntean has been the co-director of a 10-person research laboratory since 2003, which is a state-of-the-art facility at the Dublin City University (DCU) Engineering building and well equipped for multimedia delivery research. He has successfully supervised three PhD and three masters for research students, and is currently supervising seven postgraduate researchers and one postdoctoral researcher. Dr. Muntean has received more than 1 million Euro of funding, having been principal investigator on two EI (Enterprise Ireland), one SFI (Science Foundation Ireland), and five IRCSET (Irish Research Council for Science, Engineering, and Technology) grants and collaborator on two other major Irish grants. In addition, he has been leading Samsung- and Microsoft-funded research projects. Dr. Muntean has authored one book, edited two, and has published five book chapters as well as 25 journal articles and more than 60 conference papers. He has been awarded four Best Paper Awards and is an associate editor for *IEEE Transactions on Broadcasting*.

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OPTIMIZATION TECHNIQUES

I

Chapter 1

Energy Management for Location-Based Services on Mobile Devices

Mikkel Baun Kjærgaard

Contents

1.1 Introduction

Location-based services (LBS) that utilize the position of mobile devices to provide user functionality, such as services for navigation, location-based search, social networking, games, and health and sports trackers, are becoming more and more important. Research has investigated such services for more than a decade now, and, recently, they also have become commercially important as they claim a large share of the mobile applications deployed on mobile phones (Skyhook Wireless, 2010).

A successful LBS must not excessively drain the battery of mobile devices. Battery capacity is a scarce resource in mobile devices because it is not increasing at the same pace as the new power-demanding features that are added to mobile devices. If users experience that a specific LBS drains the battery, they might stop using the service. It is, however, not a simple task to build low-power-consuming LBSs because such services make heavy use of many power-consuming features of mobile devices, such as the radio to receive and send data, the screen to display maps, or positioning sensors. Today's mobile devices contain several positioning sensors, e.g., a built-in GPS receiver or a WiFi radio that can be used for positioning. For a general introduction to positioning technologies, we refer the reader to LaMarca and Lara (2008). Therefore, an LBS has to take great care in how it uses device features to minimize the power consumption, especially if the service is to run continuously.

In this chapter, we characterize the power consumption of location-based services and consider profiling and modeling the power consumption of mobile device features, which is a prerequisite for most methods for minimizing the power consumption and for their evaluation. Then, we present methods for minimizing power consumption where we divide the methods into sensor management strategies and position update protocols. For example, we will present our software system EnTracked that implements several novel sensor management strategies and position update protocols that can lower the power consumption of many types of LBSs by 64 percent for a continuous moving device and by up to 93 percent for an occasionally moving device.

1.2 Power Consumption and Location-Based Services

How crucial it is for an LBS to save power depends on the usage pattern, battery recharge options, and how the service uses the phone's features. With regard to the usage pattern, an important parameter is how long a service is expected to run on a phone. The most important LBSs to minimize power consumption are those that are long running for hours or days; however, such services also provide many opportunities for applying power-saving methods. The importance of minimizing the power consumption also depends on users' recharge options because a service can be allowed to consume a lot of power if a user is able to recharge the phone when finished using the service (Banerjee et al., 2007). Due to such considerations, it might be a situation that is dependent on how important it is that a service consumes minimal power. In regards to the phone feature usage, the consumption

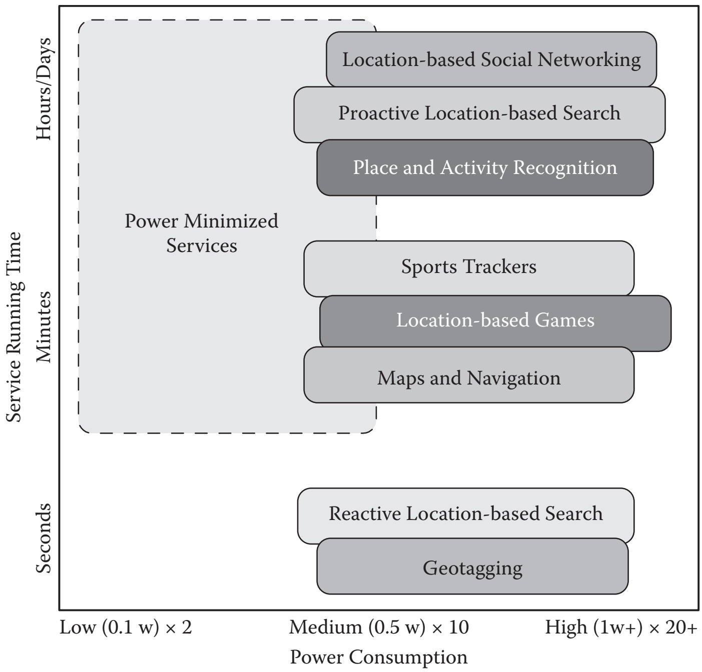

Figure 1.1 Service types grouped by service running time and power consumption with multiplicity factors for power consumption compared to a 0.05 watt standby consumption. (From Kjærgaard, M. B. 2011. *IEEE Pervasive Computing*. Forthcoming. With permission.)

impact depends on the power consumption of the individual features. Later sections describe how to profile the power consumption of individual phone features and give some values for a typical mobile phone.

A classification of the power consumption for different types of LBSs is shown in Figure 1.1, originally presented in Kjærgaard (2011). The classification types are inspired by the service types introduced by Bellavista, Küpper, and Helal (2008). The figure classifies service types with respect to their running time and power consumption. Running times are classified into second-long, minute-long, and hours/days-long, and power consumption into low-, medium-, and high-consuming services; a factor is given indicating the impact on the battery lifetime compared to a standby battery consumption of 0.05 watt.

The figure shows two service types that only run for seconds. Geotagging subsumes services that attach location information to other digital material, e.g., pictures, and reactive location-based searches are services that, when requested, search for information related to the user's location, for instance, about the nearest subway stations. The consumption of such services is medium to high due to the fact that the screen, communication, and positioning features are all used. Furthermore, the power consumption of such services is difficult to minimize by software means because a short, well-defined task has to be carried out. However, the impact on the battery lifetime is not significant because these services are used for a short amount of time and not frequently rerun.

Three service types are given that run for minutes. Maps and navigation involves services that can show people where they are on maps or satellite imagery and provide navigation directions to a location. Location-based games are games that use location as an element in the game play, e.g., the finding of physical caches using GPS positioning known as Geocaching or Live Pac Man, where real persons run around as monsters intending to catch the player. Sports trackers are services that can log where and when you exercise, which can be shared and analysed. Again, the consumption of such services is medium to high, but, because they run for minutes, their impact on the battery lifetime is higher. When services run for minutes, it is an advantage that they have a low consumption, but maybe not necessary, e.g., if a user is able to recharge the phone when finished. However, one problem that users might experience is that if they forget to turn a service off, it might discharge the phone without them noticing before it is too late. To avoid these issues, methods for minimizing the power consumption can be used to lower the power consumption to prolong the battery life.

In Figure 1.1, three services are shown that run for hours or days. Place and activity recognition are services that can register the whereabouts and activities of a user to, e.g., construct a daily diary or calculate a CO_2 footprint from the user's behavior. Proactive location-based searches are services that can push information to the user in the form of query results, e.g., if a user registers a search for free city bikes, the user will be notified when in the proximity of them. Location-based social networking is a service that enables the user to link location to social networking, e.g., to be notified when near friends or events. Again, the consumption of such services is medium to high, but, because the services run for hours or days, it is very important that they consume a minimal amount of power because they would otherwise have a major impact on how fast the battery will discharge, e.g., 20 times faster with a high consumption compared to standby consumption. Therefore, for long-running services, it is crucial to apply methods for minimizing the power consumption.

1.3 Profiling and Modeling the Power Consumption of Mobile Devices

As a first step in understanding the power consumption of mobile devices, one could consult their specifications. However, these will often not give the full picture because values are missing (e.g., power consumption values for central processing unit (CPU) usage) and dynamic aspects are not considered. The dynamic aspects are caused because features do not instantly power on or off, e.g., a 3G radio needs several seconds to power on before it has established a connection and the same is true

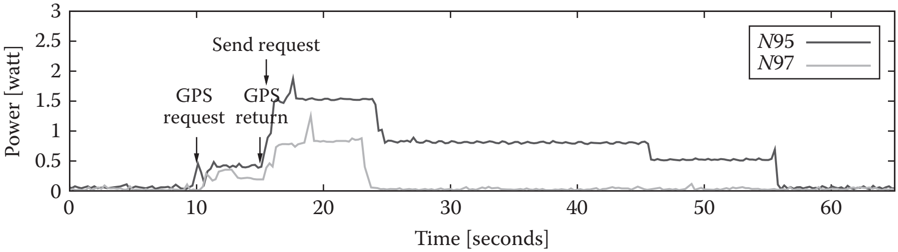

Figure 1.2 Power consumption on Nokia N95 and N97 phones for requesting a GPS position and sending the position to a remote server.

when it powers off. Therefore, the power consumed when sending data is not simply modeled as a single value for the consumption. A solution for capturing dynamic aspects is to power profile a device. To use this information to proactively minimize the power consumption of LBSs or to evaluate different design options requires that one has adequate models of the power consumption. This section discusses the profiling and modeling of the power consumption of mobile devices.

To truthfully model the power consumption of a phone, one has to consider dynamic aspects in addition to the consumption of individual features. To illustrate these aspects, Figure 1.2 shows two power profiles of a Nokiaâ N95 and a Nokia N97 phone running a Python script that every 60 seconds invokes the GPS to produce a single position fix, opens a transmission control protocol (TCP) connection to a server over the 3G radio, sends the position fix, and then closes the connection. It can be seen from the figure that the single steps are not executed instantly, and that it takes some seconds for the GPS to produce a position fix and to send the position fix. Furthermore, after sending, both the 3G radio and the GPS keep consuming power for a while. Finally, the different phones also have different delays and power levels associated with their features.

The ability to accurately model the power consumption and delays is important for three reasons. Firstly, without a model, we cannot make informed decisions about what actions to take to minimize the power consumption. Secondly, if we do not have a model of the delays, we do not know how much time to reserve for delays at runtime to update positions within required accuracy limits. Thirdly, it might be too laborious to evaluate different options for power saving for each step in the design process by deploying the software on a phone, mimic real behavior (e.g., a walking tour outdoors), and measure the power consumption. As an alternative, a model for power consumption allows simulation of the power consumption without deploying the software, which enables a faster development process. A drawback of such models is that they depend on the estimation of device-dependent parameters as already illustrated in Figure 1.2. Therefore, there is a tradeoff between the model's accuracy with regards to the number of parameters that the model takes into account and the practicability of using the model, in terms of the effort to profile the parameters for a new device.

1.4 Device Model

In the following, we present a device model originally proposed in our previous work (Kjærgaard et al., 2009) consisting of two parts: (1) a power model that describes the power usage of a phone, and (2) a delay model that describes the delays, for instance, when requesting a phone feature, e.g., the time it takes for a GPS to return a position. The model considers a subset of the phone features relevant for position tracking using GPS and inertial sensors. If needed, the model could be easily extended with additional variables to also consider WiFi, Bluetooth, and GSM positioning. Furthermore, the basic model assumes that no CPU heavy tasks have to be considered, but they could be factored in given a mapping between, e.g., the size of the input of the task and the resulting power consumption. For interactive user applications, one also would need to take into account the power usage of features such as the computations for the application logic, keystrokes, camera use, and screen use.

In the models, we consider the following phone features:

- Accelerometer (a)
- Compass (c)
- GPS (g)
- Radio idle (r)
- Radio sending (s)
- Background (I_p)

For each feature, the variable used to reference the feature later in the text is given in brackets. Background is not strictly a feature, but is included in the power model to cover the background consumption of the phone.

The power model consists of two functions defined in the equations below: the power function *power* and the consumption function $c_{d,p}$ where d is a feature's power-off delay and p its power consumption.

$$power(a_t, c_t, g_t, s_t, c_t) = I_p + c_{gd,gd}(g_r) + c_{rd,sd}(r_t) + c_{rd,sd}(s_t)$$

$$c_{d,p}(x) = \begin{cases} p & if\ x <= d \\ 0 & if\ x > d \end{cases}$$

The equation uses the variables a_t, c_t, g_t, r_t, s_t for the different features listed in the above list to denote their last usage. Each variable denotes at time step t, the number of seconds since the feature was last powered off (a variable is zero if the feature is in use in the current time step t). Since the idle power consumption is constant, no variable i_t is introduced. Furthermore, the parameters a_p, c_p, g_p, r_p, s_p, I_p denote the power consumption of a feature, e.g., 0.324 watt for a Nokia N95 internal GPS. The parameters a_d, c_d, g_d, s_d, r_d denote the number of seconds until a feature is powered off after last usage, e.g., 30 seconds for a Nokia N95 internal GPS. More example values for the different features will be provided in a later example for a Nokia N95 phone, but also can be found in Kjærgaard (2010).

The delay model contains functions that capture the delay for any feature that has a significant associated delay. Features that have none or negligible delays are modeled as they instantly perform their task. In a mobile phone, it is mainly the GPS and the radios that have request delays when powering on associated with them, which can be modeled as two functions—$req_g(g_t)$, $req_s(s_t)$—that describe the request delays for the GPS and for activating the radio for sending.

1.4.1 Example: Modeling the Nokia N95 Phone

In the following, we take a Nokia N95 phone as an example and explain how we parameterize the model for this phone and present results for how well the model fits with actual device measurements.

The Nokia N95 8GB is a 3G phone with an internal GPS module and a triaxial accelerometer, both of unspecified brand, and a 1,200 mAh battery. The phone runs the Symbian 60 operating system version F1. To measure the power consumption of the phone, we used the Nokia-developed tool Nokia Energy Profiler version 1.1 (Nokia, 2011). The Nokia Energy Profiler tool has been built by Nokia to enable developers to analyze the power consumption of mobile applications and it supports a power sampling rate of up to 4 Hz. To measure the delays and power consumption of different features, several Python scripts have been developed that enable and disable features and measure various delays. The Python scripts run on the N95 with the aid of the Python Interpreter for S60, version 1.4.4 (Pys60 Community, 2011) and the included libraries that provide access to phone features, such as the internal GPS and the triaxial accelerometer. The internal GPS supports a sampling rate of 1 Hz and the triaxial accelerometer, a sampling rate of around 35 Hz. To make measurements involving sending data using the phone's 3G radio, a TCP/IP server was implemented in Java and deployed on a server connected to the Internet with a public IP address to which the phone was able to connect.

To determine the power parameters a_p, g_p, r_p, s_p, I_p, we have collected a number of power consumption traces with a N95 phone with different features enabled and disabled. Before each trace collection and before all of our other experiments, the phone was fully charged to counter the influence of the nonlinear voltage decrease of batteries (Brown et al., 2006). First, the Nokia Energy Profiler application was started, then the Python interpreter was started with a Python script that enabled or disabled certain features for a specific amount of time. The total script running time was five minutes for these measurements. Then the Python interpreter was closed and the Nokia energy profiler was stopped. The power consumption trace

Table 1.1 Power Consumption for Features of the Nokia N95

Feature	*Average Power [milliwatt]*
Background (l_p)	62
Accelerometer (a_p)	50
GPS (g_p)	324
Radio idle (r_p)	466
Radio sending (s_p)	645

collected with the Nokia energy profiler was exported to a file. These traces were trimmed to remove the consumption logged while the Python script was not running and when the screen was powered on. The average feature consumptions were calculated from the trimmed traces and are listed in Table 1.1. In the model, we use the average values for the parameters.

The request delays modeled by the two functions $req_g(g_t)$ and $req_s(s_t)$ have been measured using the same experimental setup. Firstly, the GPS request delay for assisted GPS was measured as the time between requesting a GPS measurement and the moment when a position was returned. The radio request delay was measured as the difference between the GPS timestamp and the reception timestamp on a remote server. A more detailed discussion of the measurements can be found in (Kjærgaard et al., 2009).

$$req_g(d)\begin{cases} 1 & if\ x <= 30 \\ 6 & if\ x > 30 \end{cases}$$

$$req_g(x)\begin{cases} 0.3 & if\ x <= 6 \\ 1.1 & if\ x < 6 \end{cases}$$

Following a similar experimental approach, the power-off delay, which is the time a feature takes to power off after the last usage, also has been measured and is listed in Table 1.2. The results indicate that the power-off delay for the GPS and

Table 1.2 N95 Power-off Delays for Features

Feature	*Average Time [seconds]*
GPS	30.0
Radio idle	31.3
Radio sending	5.45

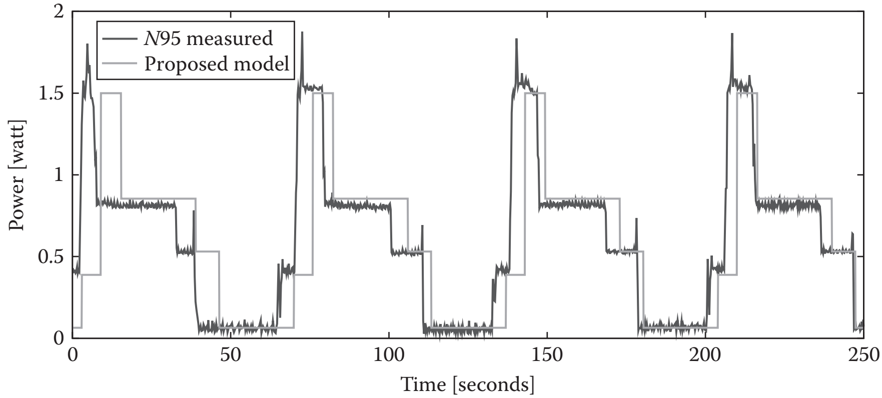

Figure 1.3 Comparison of consumption measured on a Nokia N95 with the modeled consumption. To improve readability, the curve for the proposed model has been shifted in time to not directly overlap with the measured curve.

for radio idle is around 30 seconds and a little below 6 seconds for radio sending. The power-off delay for radio idle is relative to when radio sending has powered off to idle mode.

To validate the proposed device model, we now compare the power consumption for periodic tracking calculated with the device model to the power consumption of traces collected on an N95 phone. Figure 1.3 plots data from the collected trace for 60 seconds periodic tracking, overlaid with the predicted power consumption of the device model. We can see how the proposed model closely matches the real power consumption. Therefore, this model can be used to inform the design of our tracking techniques toward minimizing the power consumption.

1.5 Methods for Minimizing the Power Consumption

This section reviews methods for minimizing the power consumption of LBSs. When considering methods for minimizing the power consumption, we have to consider how the services are distributed. Figure 1.4 outlines a conceptual model, which differentiates between local services running on mobile devices and remote services running in the cloud (Hayes, 2008). The local services will request positions from an API (application program interface) on the device, which means that the used power for positioning can primarily be linked to on-device sensors and processing. Exceptions to this are positioning methods that depend on server assistance, e.g., A-GPS and WiFi positioning. The remote services, on the other hand, will request positions from an API residing in the cloud, which means that the used power for positioning in addition to the on-device consumption results

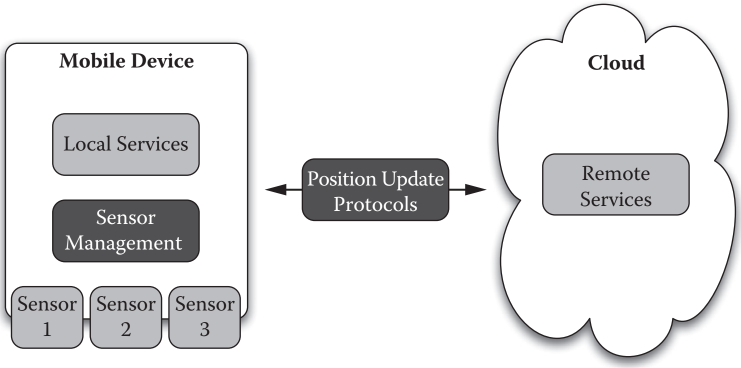

Figure 1.4 Overview of sensor management strategies and position update protocols.

from the radio's consumption for wireless connectivity. Therefore, it makes sense to differentiate between remote and local services, which also affect properties, such as position latency and privacy. If many remote services are interested in monitoring the position of a device, a dedicated tracking service might be deployed that is responsible for monitoring the device and for forwarding position updates to other remote services.

We, furthermore, divide the responsibility of handling service requests into on-device sensor management strategies and position update protocols (residing both on the device and in the cloud). Sensor management strategies decide how to use available position sensors to estimate the current position. Position update protocols control the interaction between the device and remote services. Such a division enables a flexible combination of different sensor management strategies and position update protocols and better overall performance by optimization of either subproblem.

After presenting relevant sensor management strategies and position update protocols, as a case, we will present our software system EnTracked that implements several novel sensor management strategies and position update protocols that can lower the power consumption of many types of LBSs by 64 percent for a continuous moving device and by up to 93 percent for an occasionally moving device.

1.5.1 Sensor Management Strategies

Sensor management strategies decide how to use available position sensors to estimate the current position. Sensor strategies could be implemented considering relevant properties, such as power consumption, positioning accuracy, the positioning availability in different environments (e.g., outdoor versus indoor), security (e.g.,

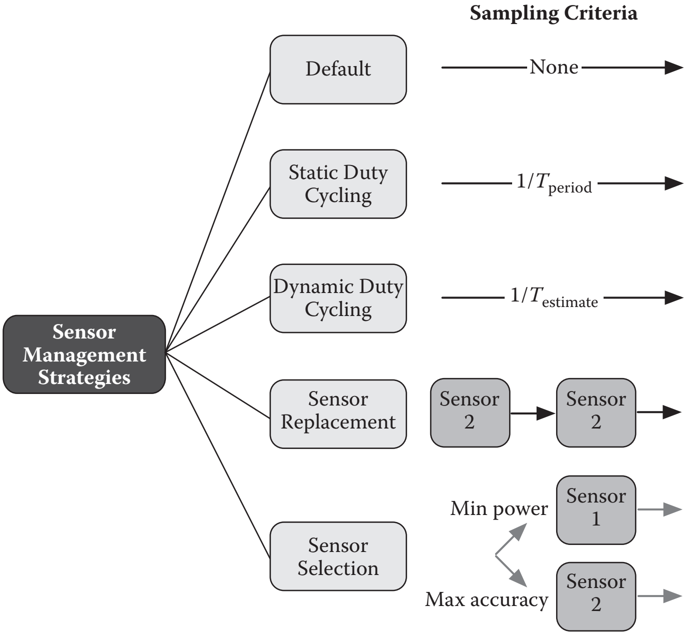

Figure 1.5 Overview of sensor management strategies.

spoofing attacks (Tippenhauer et al., 2009)), and privacy (e.g., WiFi positioning reveals a target's existence (Kjærgaard, 2007)).

In this section, we consider five types of sensor management strategies illustrated in Figure 1.5. The basic sensor management strategy is the default strategy that delivers positions as provided by a sensor. This strategy is relevant if a sensor's internal management already does a good job with regards to minimizing power consumption. The strategy of static duty cycling saves power by interleaving sampling with sleeping periods, which saves power because the sensor can be powered off during the sleeping periods. A static threshold T_{period} in seconds defines the length of the sleeping periods and, therefore, the resulting sampling frequency. This strategy is relevant for services where a lower frequency than the one supplied by a given sensor is enough to meet the requirements of the respective LBSs. The strategy of dynamic duty cycling also interleaves sampling requests with sleeping periods, but dynamically increases and decreases the sleeping periods to save power while ensuring that service requirements for the positioning accuracy are satisfied. The strategy continuously estimates a threshold $T_{estimate}$ in seconds for the sleeping period from properties, such as the speed and heading of a target. This strategy is relevant in cases where an adequate static duty-cycling threshold cannot be selected, e.g., for tracking targets with changing motion patterns.

The strategy of sensor replacement supervises the usage of high consuming sensors by events generated by a simpler and less consuming sensor. The positioning using a high consuming sensor can, for instance, be requested only when a simple motion sensor senses motion. This strategy is relevant in cases when a target has changing motion patterns that can be sensed by simpler and less consuming sensors.

The strategy of sensor selection saves power by switching between sensors with the goal to use the sensors, which use the least power to provide positions that satisfy the service requirements for positioning accuracy. This strategy is relevant in cases when services have changing requirements to positioning accuracy and several sensors are available, e.g., WiFi, GSM, or GPS with different properties with respect to power consumption and positioning accuracy.

In the following subsections, we will present concrete methods for applying the three strategies of dynamic duty cycling, sensor replacement, and sensor selection for location-based services.

1.5.1.1 Dynamic Duty Cycling

To apply dynamic duty cycling a model is needed for how to relate service requirements for positioning accuracy to sampling frequency. In the following, we present a model that relates the requested positioning accuracy to time and estimated accuracy and speed. The model consists of two steps: (1) to calculate the current accuracy and (2) to use the calculated current accuracy to calculate an estimate for the sleeping threshold $T_{estimate}$.

The first step takes into account the sensor-estimated accuracy a_{pos} as well as the time t_{pos} of the most recent position sample and the sensor estimated speed v_{pos}. The model then calculates the current accuracy $a_{current}$ with respect to the most recently delivered position as defined in the equation below:

$$a_{current} = a_{pos} + (t_{current} - t_{pos}) \times v_{pos}$$

The second step is to calculate the estimate for the sleeping period threshold $T_{estimate}$ from the service required positioning accuracy $a_{service}$, the current accuracy $a_{current}$, and the sensor estimated speed v_{pos}. The threshold $T_{estimate}$ is estimated using the equation below to calculate the time it will take a target to move beyond the service required limit, considering the current accuracy with respect to the last delivered position.

$$T_{estimate} = \begin{cases} \dfrac{a_{service} - a_{current}}{v_{pos}} & \text{if } a_{service} > a_{current} \\ 0 & \text{if } a_{service} =< a_{current} \end{cases}$$

Systems can then use this model to continuously estimate a new threshold to dynamically decrease or increase the sleeping period. Other models exist and also extensions that make the models able to handle delays, e.g., the time to first fix for GPS receivers (Kjærgaard et al., 2009).

1.5.1.2 Sensor Replacement

The different sensors in current mobile devices enable the usage of simpler sensors to supervise the usage of more consuming ones. The primary example, which we will discuss here, is to use an accelerometer as a simple sensor to sense motion. Most modern devices include a triaxial accelerometer, which provides acceleration measurements in three dimensions; the Nokia N95's accelerometer consumes only 0.05 watt compared to 0.32 watt for its GPS. Therefore, we can save power by using the accelerometer to sense motion and only use the GPS when the target is actually moving. Thus, we have to detect the two motion states, i.e., standing still and moving, relying on accelerometer readings. As the detection should not hurt the robustness of the positioning, we are interested in a detection scheme that has a low tolerance for movement, which will ensure that we detect movement very well. To implement such motion detection, the following simple scheme can be applied. First, an acceleration measurement is collected for each of the three axes, then, for each axis, the variance of the last 30 measurements is calculated and the three variance values are summed. Finally, the summed value is compared to a threshold that determines if motion is sensed or not. To optimize robustness or power consumption, the threshold can be chosen to favor either detecting motion or stillness. A drawback of this scheme is that a person walking with the device in the hand, and keeping the device steady, might lower the acceleration enough for the variance not to reach the threshold for movement detection. This poses a problem and can only be solved by using more clever movement detection schemes, such as the ones proposed by Reddy et al. (2010) or motion sensing from radio signals proposed by King and Kjærgaard (2008). Another sensor replacement strategy is to use the compass for sensing direction changes (Kjærgaard et al., 2011).

1.5.1.3 Sensor Selection

The common types of positioning both have different levels of power consumption, coverage, and positioning accuracy. Therefore, depending on the usage situation, power can be saved by selecting the optimal sensor at runtime. Recent measurements comparing GPS, WiFi, and GSM positioning for the N95 reported an average positioning accuracy of 10 m, 40 m, and 400 m, respectively, and a depletion time for a fully charged battery of 9, 40, and 60 hours, respectively (Constandache et al., 2009). Therefore, it is evident that power can be saved by switching to less accurate positioning methods when possible. The selection of which method to use can be based on parameters such as the service-requested positioning accuracy, e.g., using one of the computational frameworks proposed in Constandache et al. (2009) or Kjærgaard et al. (2009).

1.5.2 Position Update Protocols

Position update protocols control the interaction between the device and remote services, which have to consider relevant properties, such as server-side requested position accuracy, power consumption, data carrier availability, and privacy.

In terms of position update protocols, we restrict ourselves to the four device-controlled reporting protocols illustrated in Figure 1.6. Please consult Leonhardi and Rothermel (2001) for a description of other types of protocols and for an analytical analysis of the protocols in terms of their accuracy guaranties and communication efficiency. All the protocols assume that some sensor management strategy will manage the position sensors to continuously provide adequate positions to the protocols as the strategies would to any local service.

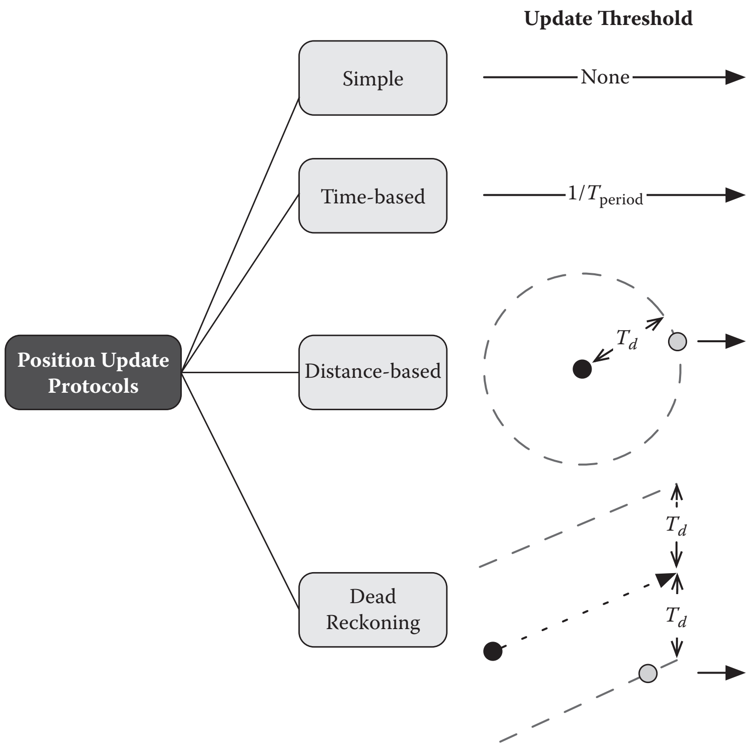

Figure 1.6 Overview of position update protocols.

The simple reporting protocol sends an update to the remote service each time a position sensor provides a new position. The advantage of this protocol is that it is simple to implement, but it results in many unnecessary position updates. Time-based reporting sends an update each time a certain time interval of T_{period} seconds has elapsed. Compared to the simple reporting protocol depending on T_{period}, this protocol can decrease the number of updates. However, because the protocol depends on a static time threshold, the protocol would produce the same number of updates regardless of whether the target is moving or not.

Distance-based reporting sends an update when the distance between the current position and the most recently reported position becomes greater than a given threshold $T_{distance}$ in meters. The advantage of this protocol is that it takes motion into account and, therefore, does not produce any updates if the device is not moving. However, during continuous movement, the protocol would still produce many updates. Dead-reckoning reporting is the most complex protocol of the four and optimizes reporting for continuous movement by not only sending the current position to the remote service, but also the current speed and heading. If the remote service at any time after the update needs the current position of the target, it should extrapolate it from the most recently sent position using the provided heading and speed. To keep the remote service's information up to date, the protocol will send an update from the device when the distance between the current position and the one extrapolated by the remote service becomes greater than a given threshold $T_{distance}$ in meters. The advantage of this protocol is that it can minimize the number of updates during both periods of continuous and no motion, but it has the disadvantage that it is more complex to implement than the other protocols. Further extensions to the dead-reckoning protocol exist, which, for instance, in the case of tracking of vehicles, make use of the road network to further reduce the number of updates (Civilis, Jensen, and Pakalnis, 2005).

1.6 Case: EnTracked

As a case, we will in this section consider the system EnTracked (Kjærgaard et al., 2009) built with the goal to dynamically track mobile devices in a both energy-efficient and robust manner. Thus, robust position updates have to be delivered to applications within service-specified accuracy limits, where accuracy refers to the distance between the known position of the application and the real position of the device. The realized system focuses on tracking pedestrian targets equipped with GPS-enabled devices. The system implements several of the presented sensor management strategies and provides all of the presented position update protocols. The system has more recently been extended to trajectory tracking and other modes of transportation (Kjærgaard et al., 2011).

1.6.1 System Description

To use EnTracked, location-based services have to provide service requirements for positioning accuracy for target tracking. In practice, location-based services do not always require the highest possible positioning accuracy as relevant occupancy limits can be calculated for many services. For example, a map service that shows the positions of a number of mobile devices can use the zoom level to determine relevant accuracy limits (such as 25 meters for street-level view, 100 meters for a suburb, and 200 meters for a city-wide view). Another example is the many types of social networking services that focus on relationships between the positions of devices, for instance, to detect when people come into proximity or when they separate. Methods have been proposed to efficiently track devices to reveal relationships, such as the ones proposed by Küpper and Treu (2006). The methods work by dynamically assigning tracking jobs with changing accuracy limits that they calculate based on the distance between the targets. Such methods produce tracking accuracy limits ranging from 10 meters to several kilometers, depending on the distance between the devices.

When a remote location-based service requests to use EnTracked, the steps illustrated in Figure 1.7 are carried out. Firstly, a service issues a request for the tracking of a device with an accuracy limit (1). Secondly, the server side of EnTracked propagates the request to the client side part of EnTracked (2). Thirdly,

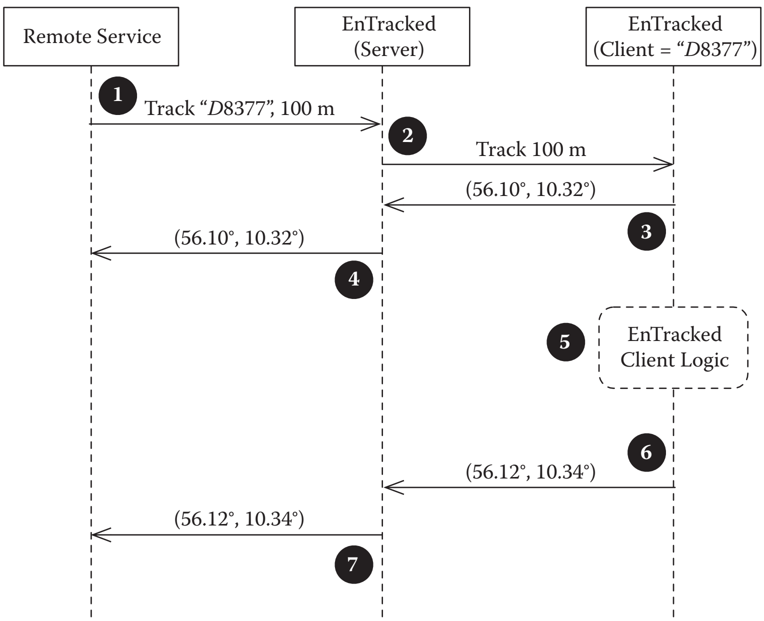

Figure 1.7 The steps of EnTracked when used by a location-based service.

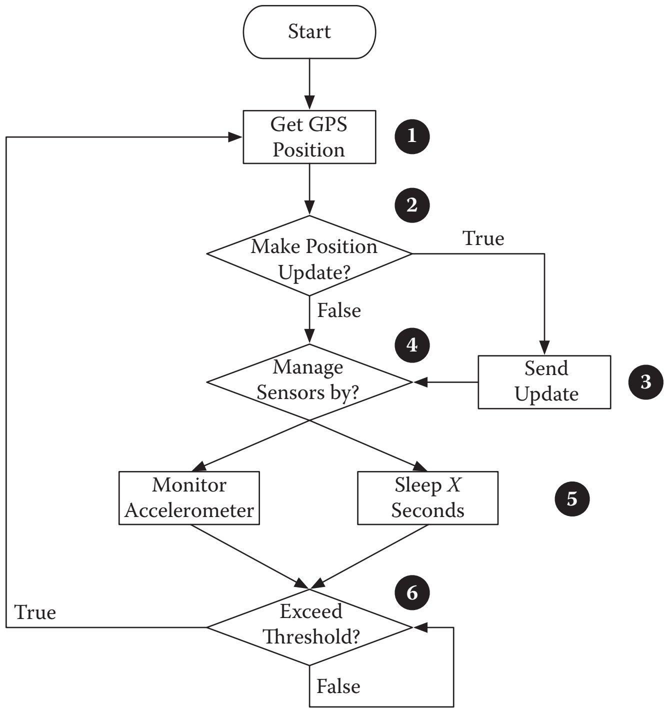

Figure 1.8 Flow chart of the EnTracked client logic.

the client finds an initial position and returns it through the server to the service (3)+(4). Fourthly, the EnTracked client logic schedules sensor management strategies and position update protocols to deliver the next position within the accuracy limit (5). Fifthly, at some point later, EnTracked determines that a new position has to be delivered to the client through the server (6)+(7). If several remote services request tracking for the same device, EnTracked configures the device for tracking with the highest requested accuracy to fulfill all of the services' limits. When a local service uses EnTracked, requests are passed directly to the client side logic.

Whenever the EnTracked client, as described above, has received a request, the client handles the request following the steps illustrated in Figure 1.8. To get an initial position, a GPS position is requested (1) that is in the remote case then provided to a position update protocol to evaluate whether a position update should be sent; in the local case, it is sent directly to the local service (2). If a position update is scheduled, the update is sent to the server (3). Then, the system applies the sensor management strategies of dynamic duty cycling, sensor selection, and sensor replacement to schedule the least power-consuming sensor task based on the current requirements (4). The scheduled sensor tasks to pick from could involve, e.g., monitoring the accelerometer or to sleep for a certain period (5). The process is restarted, once a task determines that a new GPS position is needed (6).

1.6.2 Results

This section presents evaluation results that characterize the magnitude of power savings that can be obtained by using EnTracked with different position update protocols to update a remote service. Furthermore, we also consider robustness with regards to the required positioning accuracy.

The previous presentation of EnTracked might indicate that out of the box any sensor strategy can be combined with any protocol. However, one has to take care of a number of implementation pitfalls. An example is the dead-reckoning protocol, which assumes that the server can extrapolate the position as long as it does not receive new updates from the mobile device. In the classic protocol, the threshold is tested continuously because a default sensor management strategy is implicitly assumed. The problem lies in what to do when an accelerometer-based sensor management strategy avoids providing new updates because the device is detected not to move. In this case, the server will continue to extrapolate the position, which might violate the threshold. To address this issue, we have extended the dead-reckoning protocol to test periodically if the server-predicted position is about to violate the threshold, and, in this case, send an extra position update with the last reported position and zero speed to stop erroneous extrapolation.

Another problem with the distance-based and dead-reckoning protocols is the limited robustness they provide because they might not be able to keep the maximum error below the required positioning accuracy due to delays and positioning errors. To improve protocol robustness, we use the GPS receiver's estimates of its current accuracy a_{pos} in meters and take this into account when evaluating if the protocol threshold has been passed, e.g., for distance-based reporting, the threshold equation then becomes: $d_{traveled} + a_{pos} < T_{distance}$ where $d_{traveled}$ is the distance between the last reported position and the current position.

To provide results for EnTracked with different position update protocols we will consider the following dataset collected for pedestrian movement patterns in an urban area with no stops, presented previously in Kjærgaard (2010). The dataset has been collected with Nokia N95 phones for three pedestrian targets walking a 4.85 km tour in an urban environment. The dataset consists of ground truth positions and 1 Hz GPS and 35 Hz acceleration measurements collected from the built-in sensors. The ground truth was collected at 4 Hz with a high accuracy u-blox LEA-5H receiver with a dedicated antenna placed on the top of a backpack carried by the collector. The ground truth measurements were manually inspected to make sure they followed the correct route of the target. Using an urban setting resulted in a rather high magnitude of average GPS errors of 29.1 meters on the Nokia N95 phones. That the dataset does not include any stops makes it more difficult to save

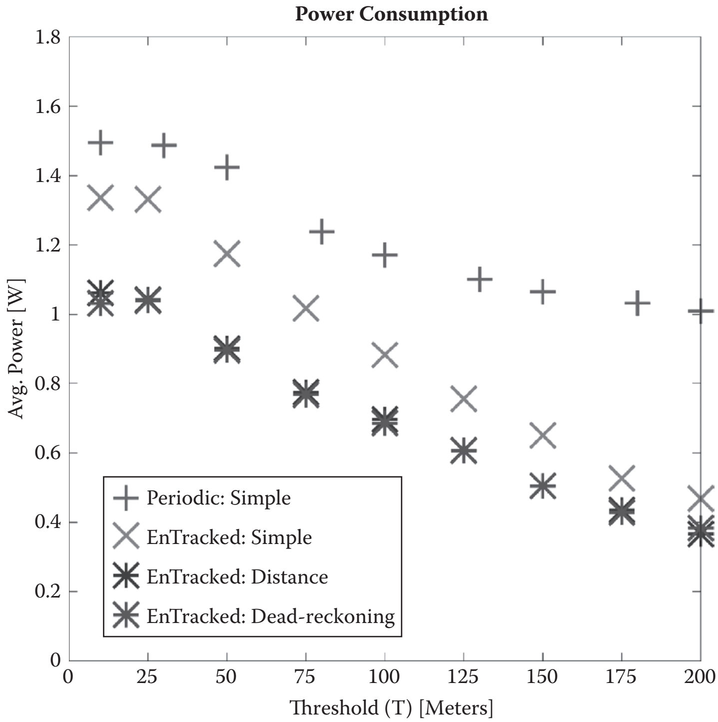

Figure 1.9 Comparison of average power consumption for Periodic: Simple (T = 10 m/s *T_{period}), EnTracked: Simple (T = $a_{service}$), EnTracked: Distance (T = $a_{service}$ = $T_{distance}$), and EnTracked: Dead-reckoning (T = $a_{service}$ = $T_{distance}$).

power since it implies that EnTracked cannot use the sensor replacement with the accelerometer, but only the dynamic duty cycling to save power.

The power consumption results from running different combinations of sensor management strategies and protocols are shown in Figure 1.9. To denote what position update protocol is used, we use the following notation EnTracked:{Protocol}. One can from the results notice how the increase of T_{period} for Periodic: Simple only provides small savings compared to the three EnTracked combinations. Of the three EnTracked combinations, the combination with the simple protocol provides the smallest savings ranging from 159 mW to 542 mW compared to Periodic: Simple depending on the threshold. The combination of EnTracked with the distance-based protocol provides a decrease in power consumption between 433 mW to 645 mW or in percentage of savings between 29 to 64 percent compared to Periodic:Simple and depending on the threshold. Comparing distance-based and dead-reckoning, there is only a small difference where the dead-reckoning version is a few mW better for the threshold of 10 meters and a few mW worse for the

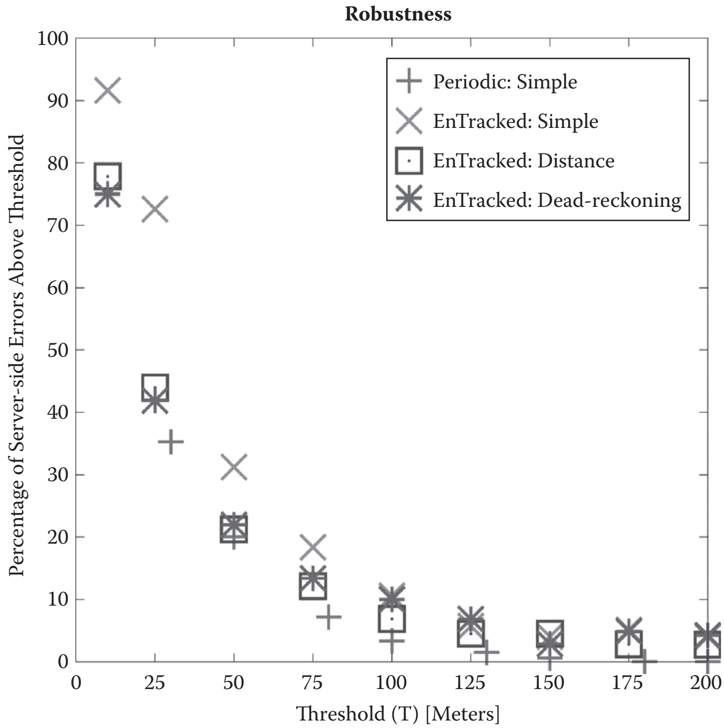

Figure 1.10 Comparison of robustness for Periodic: Simple (T = 10 m/s *T_{period}), EnTracked: Simple (T = $a_{service}$), EnTracked: Distance (T = $a_{service}$ = $T_{distance}$), and EnTracked: Dead-reckoning (T = $a_{service}$ = $T_{distance}$).

200 meters threshold. One reason for the negligible improvement of dead-reckoning over the distance-based protocol is that, if one compares with ground truth the average accuracy for the speed and the heading, estimates are low given the urban area and, therefore, the server predictions will often be extrapolated in an erroneous direction. Furthermore, it also can be linked to the movement style of an urban pedestrian, which is expected to include many and sharp turns. If the usage had included periods of still time, the savings could have dropped down to 93 percent with the help of accelerometer-based sensor replacement.

Figure 1.10 shows a robustness plot to analyze the robustness of such systems, e.g., to evaluate if the magnitude of GPS errors makes small thresholds irrelevant. The robustness is here defined as the percentage of time that the distance between the real position and the server known position is greater than the threshold. In all cases, the Periodic: Simple combination has the lowest values, in half of the cases below five percent. For the smaller thresholds, the percentage is higher because the GPS errors alone often are enough to violate the smaller thresholds, as the average

GPS error for the dataset is 29.1 meters. Comparing to the three EnTracked combinations, they all have a higher percentage of errors, but for most thresholds the difference is only a few percent points. The only major outliner is the EnTracked: Simple combination that has trouble at lower thresholds. Therefore, we can conclude that the system can save power without having a severe impact on robustness.

1.7 Summary

Location-based services have to pay careful attention to their power consumption in order not to drain the batteries of mobile devices. In this chapter, we characterized the power consumption of location-based services. Furthermore, we considered profiling and modeling the power consumption of mobile device features, which is a prerequisite for most methods for minimizing the power consumption and the evaluation thereof. Afterwards, we presented methods for minimizing power consumption where we separated the methods into sensor management strategies and position update protocols. As a case, we presented a software system named EnTracked that implements several novel sensor management strategies and position update protocols that can lower the power consumption of many types of LBSs with 64 percent for a continuous moving device and up to 93 percent for a periodically moving device.

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REFERENCES

Banerjee, N., A. Rahmati, M. D. Corner, S. Rollins, and L. Zhong. 2007. Users and batteries: Interactions and adaptive energy management in mobile systems. Proceedings of the 9th International Conference on Ubiquitous Computing. Association of Computing Machinery (ACM), Innsbruck, Austria, Sept. 16–19, 2007, pp. 217–234.

Bellavista, P., A. Küpper, and S. Helal. 2008. Location-based services: Back to the future. *IEEE Pervasive Computing* 7 (2): 85–89.

Brown, L., K. A. Karasyov, V. P. Levedev, A. Y. Starikovskiy, and R. P. Stanley. 2006. Linux laptop battery life. Proceedings of the Linux Symposium Ottawa, Canada, July 19–22, 2006.

Civilis, A., C. S. Jensen, and S. Pakalnis. 2005. Techniques for efficient road-network-based tracking of moving objects. *IEEE Transactions on Knowledge and Data Engineering* 17 (5): 698–712.

Constandache, I., S. Gaonkar, M. Sayler, R. R. Choudhury, and L. Cox. 2009. EnLoc: Energy efficient localization for mobile phones. Proceedings of the IEEE INFOCOM 2009 Mini Conference. IEEE Rio de Janiero, Brazil, April 19–25, 2009.

Hayes, B.. 2008. Cloud computing. *Communications of the ACM* 51 (7): 9–11.

King, T., and M. B. Kjærgaard. 2008. Composcan: Adaptive scanning for efficient concurrent communications and positioning with 802.11. Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM), pp. 67-80.

Kjærgaard, M. B., 2007. A taxonomy for radio location fingerprinting. Proceedings of the Third International Symposium on Location- and Context-Awareness. Berlin/Heidelberg: Springer Publishing, pp. 139–156.

Kjærgaard, M. B., 2010. On improving the energy efficiency and robustness of position tracking for mobile devices. Proceedings of the 7th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services. Berlin/Heidelberg: Springer Publishing.

Kjærgaard, M. B.. 2011. Minimizing the power consumption of location-based services on mobile phones. (Forthcoming) *IEEE Pervasive Computing*.

Kjærgaard, M. B., S. Bhattacharya, H. Blunck, and P. Nurmi. 2011. Energy-efficient trajectory tracking for mobile devices. Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM). Bethesda, MD, U.S. June 28–July 1, 2011, 307–320.

Kjærgaard, M. B., J. Langdal, T. Godsk, and T. Toftkjær. 2009. EnTracked: Energy-efficient robust position tracking for mobile devices. Proceedings of the 7th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM), Krakow, Poland, June 22–25, 2009, pp. 221–234.

Küpper, A. and G. Treu. 2006. Efficient proximity and separation detection among mobile targets for supporting location-based community services. *Mobile Computing and Communications Review* 10 (3): 1–12.

LaMarca, A., and E. de Lara. 2008. Location systems: An introduction to the technology behind location awareness. Bonita Springs, FL: Morgan and Claypool Publishers.

Leonhardi, A., and K. Rothermel. 2001. A comparison of protocols for updating location information. *Cluster Computing* 4 (4): 355–367.

Nokia. Nokia–Energy Profiler. 2011. Online at: http:/www.nokia.com (accessed January 18, 2011).

Pys60 Community. Python for S60. 2011. Online at: http://sourceforge.net/projects/pys60 (accessed January 18, 2011).

Reddy, S., M. Mun, J. Burke, D. Estrin, M. H. Hansen, and M. B. Srivastava. 2010. Using mobile phones to determine transportation modes. *ACM Transactions on Sensor Networks* (TOSN) 6 (2).

Skyhook Wireless. 2010. Online at: http://www.skyhookwireless.com/locationapps (accessed January 18, 2011).

Tippenhauer, N. O., K. B. Rasmussen, C. Pöpper, and S. Capkun. 2009. Attacks on public WLAN-based positioning systems. Proceedings of the 7th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM), Krakow, Poland, June 22–25, 2009, pp. 29–40.

References

1 Chapter 1: Energy Management for Location-Based Services on Mobile Devices

Banerjee, N., A. Rahmati, M. D. Corner, S. Rollins, and L. Zhong. 2007. Users and batteries: Interactions and adaptive energy management in mobile systems. Proceedings of the 9th International Conference on Ubiquitous Computing. Association of Computing Machinery (ACM), Innsbruck, Austria, Sept. 16–19, 2007, pp. 217–234.

Bellavista, P., A. Küpper, and S. Helal. 2008. Location-based services: Back to the future. IEEE Pervasive Computing 7 (2): 85–89.

Brown, L., K. A. Karasyov, V. P. Levedev, A. Y. Starikovskiy, and R. P. Stanley. 2006. Linux laptop battery life. Proceedings of the Linux Symposium Ottawa, Canada, July 19–22, 2006.

Civilis, A., C. S. Jensen, and S. Pakalnis. 2005. Techniques for efficient road-network-based tracking of moving objects. IEEE Transactions on Knowledge and Data Engineering 17 (5): 698–712.

Constandache, I., S. Gaonkar, M. Sayler, R. R. Choudhury, and L. Cox. 2009. EnLoc: Energy efficient localization for mobile phones. Proceedings of the IEEE INFOCOM 2009 Mini Conference. IEEE Rio de Janiero, Brazil, April 19–25, 2009.

Hayes, B.. 2008. Cloud computing. Communications of the ACM 51 (7): 9–11.

King, T., and M. B. Kjærgaard. 2008. Composcan: Adaptive scanning for efficient concurrent communications and positioning with 802.11. Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM), pp. 67-80.

Kjærgaard, M. B., 2007. A taxonomy for radio location fingerprinting. Proceedings of the Third International Symposium on Location- and Context-Awareness. Berlin/ Heidelberg: Springer Publishing, pp. 139–156.

Kjærgaard, M. B., 2010. On improving the energy efficiency and robustness of position tracking for mobile devices. Proceedings of the 7th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services.

Berlin/Heidelberg: Springer Publishing.

Kjærgaard, M. B.. 2011. Minimizing the power consumption of location-based services on mobile phones. (Forthcoming) IEEE Pervasive Computing.

Kjærgaard, M. B., S. Bhattacharya, H. Blunck, and P. Nurmi. 2011. Energy-efficient trajectory tracking for mobile devices. Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM). Bethesda, MD, U.S. June 28–July 1, 2011, 307–320.

Kjærgaard, M. B., J. Langdal, T. Godsk, and T. Toftkjær. 2009. EnTracked: Energy-efficient robust position tracking for mobile devices. Proceedings of the 7th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM), Krakow, Poland, June 22–25, 2009, pp. 221–234.

Küpper, A. and G. Treu. 2006. Efficient proximity and separation detection among mobile targets for supporting location-based community services. Mobile Computing and Communications Review 10 (3): 1–12.

LaMarca, A., and E. de Lara. 2008. Location systems: An introduction to the technology behind location awareness. Bonita Springs, FL: Morgan and Claypool Publishers.

Leonhardi, A., and K. Rothermel. 2001. A comparison of protocols for updating location information. Cluster Computing 4 (4): 355–367.

Nokia. Nokia–Energy Profiler. 2011. Online at: http:/www.nokia.com (accessed January 18, 2011).

Pys60 Community. Python for S60. 2011. Online at: http://sourceforge.net/projects/pys60 (accessed January 18, 2011).

Reddy, S., M. Mun, J. Burke, D. Estrin, M. H. Hansen, and M. B. Srivastava. 2010. Using mobile phones to determine transportation modes. ACM Transactions on Sensor Networks (TOSN) 6 (2).

Skyhook Wireless. 2010. Online at: http://www.skyhookwireless.com/locationapps (accessed January 18, 2011).

Tippenhauer, N. O., K. B. Rasmussen, C. Pöpper, and S.

Capkun. 2009. Attacks on public WLAN-based positioning systems. Proceedings of the 7th International Conference on Mobile Systems, Applications, and Services. Association for Computing Machinery (ACM), Krakow, Poland, June 22-25, 2009, pp. 29-40.

2 Chapter 2: Energy Efficient Supply of Mobile Devices

[1]. Min, R., M. Bhardwaj, S.-H. Cho, N. Ickes, E. Shih, A. Sinha, A. Wang, and A. Chandrakasan. 2002. Energy-centric enabling technologies for wireless sensor networks. Wireless Communications, IEEE 9 (4): 28–39.

[2]. Rahimi, M., H. Shah, G. Sukhatme, J. Heideman, and D. Estrin. 2003. Studying the feasibility of energy harvesting in a mobile sensor network. Proceedings of the 2003 IEEE International Conference on Robotics and Automation (ICRA),Taiwan, May 12–17, Vol. 1, pp. 19–24.

[3]. Raghunathan, V., A. Kansal, J. Hsu, J. Friedman, and M. Srivastava. 2005. Design considerations for solar energy harvesting wireless embedded systems. Proceedings of the 4th International Symposium on Information Processing in Sensor Networks. Washington, D.C.: IEEE Press, p. 64.

[4]. Janek, A., C. Trummer, C. Steger, R. Weiss, J. Preishuber-Pfluegl, and M. Pistauer. 2008. Simulation based verification of energy storage architectures for higher class tags supported by energy harvesting devices. Microprocessors and Microsystems 32 (5-6): 330–339. Dependability and Testing of Modern Digital Systems.

[5]. Kansal, A., D. Potter, and M. B. Srivastava. 2004. Performance aware tasking for environmentally powered sensor networks. In SIGMETRICS ’04/Performance ’04: Proceedings of the Joint International Conference on Measurement and Modeling of Computer Systems. New York: ACM, pp. 223–234.

[6]. Hörmann, L. B., P. M. Glatz, C. Steger, and R. Weiss. 2011. Designing of efficient energy harvesting systems for autonomous WSNs using a tier model. IEEE 18th International Conference on Telecommunications (ICT), May 8–11, pp. 185–190.

[7]. Maxwell Technologies. Bcap0310 p270 t10-datasheet-bc power series radial d cell 310f ultracapacitor. Online at: http://www.maxwell.com/docs/DATASHEET_ DCELL_POWER 1014625.PDF (accessed February 2011).

[8]. Linden, D., and T. B. Reddy. 2002. Handbook of batteries, 3rd ed. New York: McGraw-Hill.

[9]. Kompis, C. and S. Aliwell. 2008. Energy harvesting

technologies to enable remote and wireless sensing. Online at: http://host.quid5.net/ koumpis/pubs/pdf/energyharvesting08.pdf (accessed June 2008).

[10]. Pouwelse, J., K. Langendoen, and H. Sips 2001. Dynamic voltage scaling on a lowpower microprocessor. Proceedings of the 7th Annual International Conference on Mobile Computing and Networking, ser. MobiCom ’01. New York: ACM, pp. 251–259.

[11]. Burd, T. D., and R. W. Brodersen. 2000. Design issues for dynamic voltage scaling. Proceedings of the 2000 International Symposium on Low Power Electronics and Design, ser. ISLPED ’00. New York: ACM, pp. 9–14.

[12]. Simunic, T., L. Benini, A. Acquaviva, P. Glynn, and G. De Micheli. 2001. Dynamic voltage scaling and power management for portable systems. Proceedings of the 38th Annual Design Automation Conference, ser. DAC ’01. New York: ACM, pp. 524–529.

[13]. Pouwelse, J., K. Langendoen, and H. Sips. 2001. Dynamic voltage scaling on a low-power microprocessor. Proceedings of the 7 th Annual International Conference on Mobile Computing and Networking, ser. MobiCom ’01. New York: ACM, pp. 251–259.

[14]. Sinha, A., and A. Chandrakasan. 2001. Dynamic power management in wireless sensor networks. Design Test of Computers, IEEE 18 (2): 62–74.

[15]. Powell, H. C., A. T. Barth, and J. Lach. 2009. Dynamic voltage-frequency scaling in body area sensor networks using cots components. Proceedings of the Fourth International Conference on Body Area Networks, ser. BodyNets ’09. Brussels: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), pp. 15:1–15:8.

[16]. Hörmann, L. B., P. M. Glatz, C. Steger, and R. Weiss. 2010. A wireless sensor node for river monitoring using MSP430 and energy harvesting. Proceedings of the European DSP in Education and Research Conference. Dallas: Texas Instruments, pp. 140–144.

[17]. Hörmann, L. B., P. M. Glatz, C. Steger, and R. Weiss. 2011. Energy efficient supply of WSN nodes using component-aware dynamic voltage scaling. In 17th European Wireless Conference (EW), Vienna, Austria, April 27–29, pp.

147–154.

[18]. Bergonzini, C., D. Brunelli, and L. Benini. 2009. Algorithms for harvested energy prediction in batteryless wireless sensor networks. Proceedings of the 3rd IEEE International Workshop on Advances in Sensors and Interfaces, Bari, Italy, June 25–26, pp. 144–149.

[19]. Dunkels, A., F. Osterlind, N. Tsiftes, and Z. He. 2007. Software-based on-line energy estimation for sensor nodes. EmNets ’07: Proceedings of the 4th Workshop on Embedded Networked Sensors. New York: ACM, pp. 28–32.

[20]. Glatz, P. M., C. Steger, and R. Weiss. 2010. Tospie2: Tiny operating system plug-in for energy estimation. IPSN ’10: Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks. New York: ACM, pp. 410–411.

[21]. Jiang, X., J. Polastre, and D. Culler. 2005. Perpetual environmentally powered sensor networks. Proceedings of the Fourth International Symposium on Information Processing in Sensor Networks, Los Angeles, April 25–27, pp. 463–468.

[22]. Langendoen, K., A. Baggio, and O. Visser. 2006. Murphy loves potatoes: Experiences from a pilot sensor network deployment in precision agriculture. Proceedings of the 20th International Symposium on Parallel and Distributed Processing (IPDPS), Rhodes Island, Greece, April 25–29, p. 8.

[23]. Watthanawisuth, N., A. Tuantranont, and T. Kerdcharoen. 2009. Microclimate real-time monitoring based on zigbee sensor network. Sensors, IEEE, October: pp. 1814–1818.

[24]. Juang, P., H. Oki, Y. Wang, M. Martonosi, L. S. Peh, and D. Rubenstein. 2002. Energyefficient computing for wildlife tracking: design tradeoffs and early experiences with zebranet. Proceedings of the 10th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS-X). New York: ACM, pp. 96–107.

[25]. Lindgren, A., C. Mascolo, M. Lonergan, and B. McConnell. 2008. Seal-2-seal: A delay-tolerant protocol for contact logging in wildlife monitoring sensor networks. Proceedings of the 5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems, Atlanta, GA, Sept.

29-Oct. 2, pp. 321-327.

[26]. Lorincz, K., B.-R. Chen, G. W. Challen, A. R. Chowdhury, S. Patel, P. Bonato, and M. Welsh. 2009. Mercury: A wearable sensor network platform for high-fidelity motion analysis. Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys 2009). New York: ACM, pp. 183-196.

[27]. Xu, N., S. Rangwala, K. K. Chintalapudi, D. Ganesan, A. Broad, R. Govindan, and D. Estrin. 2004. A wireless sensor network for structural monitoring. Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems. New York: ACM, pp. 13-24.

[28]. Texas Instruments. 2009. Msp430f15x, msp430f16x, msp430f161x mixed signal microcontroller. Online at: www.focus-ti.com, SLAS368F

[29]. Analog Devices. 2006. ±0.5˚C accurate PWM temperature sensor in 5-lead sc-70. Online at: www.analog.com, D03340 Rev.B

[30]. Microchip. Mrf24j40mb data sheet-2.4 ghz ieee std. 802.15.4 20 dbm rf transceiver module. Online at: www.microchip.com, DS70599B

[31]. Puccinelli, D., and M. Haenggi. 2005. Wireless sensor networks: Applications and challenges of ubiquitous sensing. Circuits and Systems Magazine, IEEE 5 (3): 19-31.

[32]. Texas Instruments. 2004. Tlv1117-Adjustable and fixed low dropout voltage regulator. Online at: www.focus-ti.com, SLVS561J

[33]. Glatz, P. M., L. B. Hörmann, C. Steger, and R. Weiss. 2010. A system for accurate characterization of wireless sensor networks with power states and energy harvesting system efficiency. Proceedings of the 8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM), March 29-April 2, pp. 468-473.

3 Chapter 3: Energy Cost of Software Applications on Portable Wireless Devices

Banerjee05 Kutty S. Banerjee and Emmanual Agu. Powerspy: Fine-grained software energy profiling for mobile devices. In Proceedings of the International Conference on Wireless Networks, Communications and Mobile Computing, vol. 2, pp. 1136–1141, June 2005.

Benini00 Luca Benini, Giuliano Castelli, Alberto Macii, Enrico Macii, and Riccardo Scarsi. Battery-driven dynamic power management of portable systems. In ISSS ’00: Proceedings of the 13th International Symposium on System Synthesis, pp. 25–30, Washington, D.C.: IEEE Computer Society, 2000.

Brakmo04 L. S. Brakmo, D. A. Wallach, and M. A. Viredaz. µsleep: A technique for reducing energy consumption in handheld devices. In Proceedings of MobiSys 2004, Boston, MA, June 6–9, pp. 48–56. Software Application (A) Virtual Machine/ Simulator Device (D) Cost Mapping Functions Cost Profile for ‘A’ Cost of ‘A’ on Device, D

Figure 3.12 An alternative approach for evaluating energy consumption.

Casas05 Roberto Casas and Oscar Casas. Battery sensing for energy-aware system design. IEEE Computer 38 (11): 48–54, November 2005.

Chow96 S.-H. Chow, Y.-C. Ho, and T. Hwang. Battery modeling for energy aware system design. ACM Transactions on Design Automation of Electronic Systems 1 (3): 315–340, 1996.

Creus07 G. B. i Creus and P. Niska. System-level power management for mobile devices. In 7th IEEE International Conference on Computer and Information Technology, pp. 799–804, Fukushima, Japan, October 16–19, 2007.

Desai03 M. P. Desai, H. Narayanan, and S. B. Patkar. The realization of finite state machines by decomposition and the principal lattice of partitions of a submodular function. Discrete Applied Mathematics 131 (2): 299–310, September 2003.

Dick00 Robert P. Dick, Ganesh Lakshminarayana, and Niraj K. Jha. Power analysis of embedded operating systems. In Proceedings of ACM/IEEE Design Automation Conference, pp. 312–315, Los Angeles, CA, June 5–9, 2000.

Flinn99 Jason Flinn and M. Satyanarayanan. Powerscope: A tool for profiling the energy usage of mobile applications. In WMCSA '99: Proceedings of the Second IEEE Workshop on Mobile Computer Systems and Applications, p. 2, Washington, D.C. IEEE Computer Society, 1999.

Lahiri02 Kanishka Lahiri, Sujit Dey, Debashis Panigrahi, and Anand Raghunathan. Batterydriven system design: A new frontier in low power design. In ASP-DAC '02: Proceedings of the 2002 Conference on Asia South Pacific Design Automation/ VLSI Design, p. 261, Washington, D.C.: IEEE Computer Society, 2002.

Lee06 Jeongjoon Lee, Catherine Rosenberg, and Edwin K. P. Chong. Energy efficient schedulers in wireless networks: Design and optimization. Mobile Networks and Applications 11 (3): 377–389, 2006.

Ling07 Yibei Ling and Chung-Ming Chen. Energy saving via power-aware buffering in wireless sensor networks. In Proceedings of the IEEE INFOCOM 26th International Conference, pp. 2411–2415, Anchorage, AK, May 6–12, 2007.

Lorch98 Jacob R. Lorch and Alan J. Smith. Software strategies for portable computer energy management. IEEE Personal Communications Magazine, 5(3), 60–73, June 1998.

Lu02 Yung Hsiang Lu, Luca Benini, and Giovanni De Micheli. Power-aware operating systems for interactive systems. IEEE Transactions on VLSI 10: 119–134, 2002.

Marek02 S. Marek. Battling the battery drain. Wireless Internet Magazine, January, 2002.

Musa93 J. D. Musa. Operational profiles in software reliability engineering. IEEE Software 10 (2): 14–32, 1993.

Naik01 K. Naik and D. S. L. Wei. Software implementation strategies for power-conscious systems. Mobile Networks and Applications 6 (3): 291–305, 2001.

Palit08a Rajesh Palit, Kshirasagar Naik, and Ajit Singh. Estimating the energy cost of communication on portable wireless devices. In 1st IFIP Wireless Days, pp. 346- 353, November 2008.

Palit08b Rajesh Palit, Ajit Singh, and Kshirasagar Naik. Modeling the energy cost of applications on portable wireless devices. In Proceedings of the 11th International

Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), pp. 346-353, Vancouver, Canada, October 2008.

Panigrahi01 Debashis Panigrahi, Sujit Dey, Ramesh Rao, Kanishka Lahiri, Carla Chiasserini, and Anand Raghunathan. Battery life estimation of mobile embedded systems. 14th International Conference on VLSI Design, 0: 57, Bangalore, India, January 3-7, 2001.

Powers95 R. Powers. Batteries of low electronics. Proceedings of IEEE, 83 (4), April 1995.

Rao03 R. Rao, S. Vrudhula, and D. Rakhmatov. Battery modeling for energy aware system design. Computer 36 (12): 77-87, 2003.

Shih02 E. Shih, P. Bahl, and M. Sinclair. Wake on wireless: An event driven energy saving strategy for battery operated devices. In Proceedings of the 8th Annual International Conference on Mobile computing and Networking (ACM MobiCom), Atlanta, GA, September 23-28, 2002.

Shnayder04 V. Shnayder, M. Hempstead, B. Rong Chen, G. W. Allen, and M. Welsh. Simulating the power consumption of large-scale sensor network applications. In Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys), Baltimore, MD, November 2004.

Unsal03 Osman S. Unsal and Israel Koren. System-level power-aware design techniques in real-time systems. In Proceedings of the IEEE, pp. 1055-1069, 2003.

Vallerio06 K. S. Vallerio, L. Zhong, and N. K. Jha. Energy-efficient graphical user interface design. IEEE Transactions on Mobile Computing 5 (7): 846-859, 2006.

Xu03 Rong Xu, Zhiyuan Li, Cheng Wang, and Peifeng Ni. Impact of data compression on energy consumption of wireless-networked handheld devices. In Proceedings of the 23rd International Conference on Distributed Computing Systems (ICDCS), pp. 302-311, Washington, D.C.: IEEE Computer Society, 2003.

4 Chapter 4: Striking a Balance between Energy Conservation and QoS Provision for VoIP in WiMAX Systems

[1] Yang Xiao, “Energy Saving Mechanism in the IEEE 802.16e Wireless MAN,” IEEE Communication Letter, vol. 9, no. 7, pp. 595–597, July 2005.

[2] Yan Zhang and Masayuki Fujise, “Energy Management in the IEEE 802.16e MAC,” IEEE Communication Letter, vol. 10, no. 4, pp. 311–313, Apr. 2006.

[3] Junfeng Xiao, Shihong Zou, and Shiduan Cheng, “An Enhanced Energy Saving Mechanism in IEEE 802.16e,” Proceedings of GLOBECOM 2006, pp. 463–467, San Francisco, November 2006.

[4] Jaehyuk Jang and Sunghyun Choi, “Adaptive Power Saving Strategies for IEEE 802.16e Mobile Broadband Wireless Access,” Proceedings of Asia-Pacific Conference on Communications, pp. 1–5, Aug. 2006.

[5] Min-Gon Kim and Minho Kang, “Enhanced Power-Saving Mechanism to Maximize Operational Efficiency in IEEE 802.16e Systems,” IEEE Transactions on Wireless Communications, vol. 8, no. 9, pp. 4710–4719, Sept. 2009.

[6] Mugen Peng and Wenbo Wang, “An Adaptive Energy Saving Mechanism in the Wireless Packet Access Network,” Proceedings of Wireless Communications and Networking Conference (WCNC) 2008, pp. 1536–1540, Las Vegas, NV, Mar. 2008.

[7] Hyun-Ho and Dong-Ho Cho, “Hybrid Power Saving Mechanism for VoIP Services with Silence Suppression in IEEE 802.16e Systems,” IEEE Communication Letter, vol. 11, no. 5, pp. 455–457, May 2005.

[8] International Telecommunication Union–Telecommunication Standardization Sector (ITU-T) Recommendation P.59 (1993), Artificial Conversational Speech, Geneva, Switzerland.

[9] H.-H. Lee and C.-K. Un, “A Study of On-Off Characteristics of Conversational Speech,” IEEE Transactions on Communications, vol. 34, no. 6, pp. 630–637, June 1986.

[10] International Telecommunication Union–Telecommunication Standardization Sector (ITU-T) Recommendation G.114 (2003), International Telephone

Connections and Circuits—General Recommendations on the Transmission Quality for an Entire International Telephone Connection, Geneva, Switzerland.

[11] A. Bacioccola, C. Cicconetti, and E. Mingozzi, "IEEE 802.16: History, Status and Future Trends," Computer Communications, vol. 33, no. 2. pp. 113–123, Feb. 2010.

[12] Yu-Kwong Kwok and Vincent Kin Nang Lau, Wireless Internet and Mobile Computing: Interoperability and Performance. New York: John Wiley & Sons, September 2007.

[13] Yang Yang, Honglin Hu, Jing Xu, and Guoqlang Mao, "Relay Technologies for WiMAX and LTE-advanced Mobile Systems," IEEE Communication Magazine, vol. 47, no. 10, pp. 100–105, Oct. 2009.

[14] Sassan Ahmadi, "An Overview of Next Generation Mobile WiMAX Technology," IEEE Communication Magazine, vol. 47, no. 6, pp. 84–98, June 2009.

[15] Woonsub Kim, "Mobile WiMAX, the Leader of the Mobile Internet Era," IEEE Communication Magazine, vol. 47, no. 6, pp. 10–12, June 2009.

[16] K. Etemad, "Overview of Mobile WiMAX Technology and Evolution," IEEE Communication Magazine, vol. 46, no. 16, pp. 31–40, June 2008.

[17] IEEE 802.16e-2005, ''Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands," New York: IEEE, Feb. 2006.

[18] C. Cicconetti, L. Lenzini, E. Mingozzi, and C. Eklund, ''Quality of Service Support in IEEE 802.16 Networks, " IEEE Networks, vol. 20, no. 2, pp. 50–55, Mar. 2006.

[19] A. Esmailpour and N. Nasser, ''Packet Scheduling Scheme with Quality of Service Support for Mobile WiMAX Networks," Proceedings of Local Computer Networks (LCN) Conference 2009, pp. 1040–1045, Zürich, Switzerland, Oct. 2009.

[20] IEEE 802.16, ''IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems," May 2009.

[21] Chia-Chuan Chuang and Shang-Juh Kao, ''Discrete-Time Modeling for Performance Analysis of Real-Time Services in IEEE 802.16 Networks," vol. 33, no. 16, pp. 1928– 1936,

Oct. 2010.

[22] F. Hou, P.-H. Ho, and X. S. Shen, ‘‘An Efficient Delay Constrained Scheduling Scheme for IEEE 802.16 Networks,” ACM/Wireless Networks, vol. 15, no. 7, pp. 831–844, May 2009.

5 Chapter 5: QoE-Based Energy Conservation for VoIP Applications in WLAN

[1] Apple iPhone Technical Specifications. Online at http://www.apple.com/iphone/specs. html

[2] G. Miao, N. Himayat, and G. Y. Li. Energy-efficient link adaptation in frequencyselective channels. IEEE Transactions on Communications, vol. 58, no. 2, pp. 545–554, (February 2010).

[3] S. Basterrech, G. Rubino, and M. Varela. Single-Sided Real-Time PESQ Score Estimation. In Proceedings of Measurement of Speech, Audio and Video Quality In Networks (MESAQIN 2009), Prague, Czech Republic, December 7–8, 2009.

[4] http://www.itu.int/ITU-T/

[5] International Telecommunication Union–Telecommunication Standardization Sector (ITU-T) P.862. Perceptual Evaluation of Speech Quality (PESQ): An objective method for end-to-end speech quality assessment of narrow-band telephone networks and speech codecs. Geneva, Switzerland: ITU-T (February 2001).

[6] IEEE 802.11 WG: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. 1999 standard (1999).

[7] IEEE 802.11e: IEEE 802.11e Wireless LAN Medium Access Control (MAC) Enhancement for Quality of Service (QoS). IEEE 802.11e standard (2009).

[8] S-L. Zhao and Ch-H. Huang. A survey of energy efficient MAC protocols for IEEE 802.11 WLAN. Amsterdam: Elsevier Computer Communications (2010).

[9] B. Gleeson, D. Picovici, R. Skehill, and J. Nelson. Exploring Power Saving in 802.11 VoIP Wireless Links. ACM International Wireless Communications and Mobile Computer Conference (IWCMC 2006), Vancouver, Canada, January, 2006.

[10] C. Zhu, H. Yu, X. Wang, and H-H. Chen. Improvement of Capacity and Energy Saving of VoIP over IEEE 802.11 WLANs by a Dynamic Sleep Strategy. Proceedings of the IEEE GLOBECOM (2009), Honolulu, Hawaii, November 30–December 4.

[11] Internet Low Bit Rate. Online at http://www.Ilbcfreeware.org

[12] V. Namboodiri and L. Gao. Energy-Efficient VoIP over Wireless LANs. IEEE Trans. on Mobile Computing, vol. 9, no. 4, pp. 566–581, (April 2010).

[13] International Telecommunication Union–Telecommunication Standardization Sector (ITU-T) SG12: Definition of Quality of Experience. COM12 LS 62 E, TD 109rev2 (PLEN/12), Geneva, Switzerland, 16–25 (January 2007).

[14] In proceedings of 4th International Workshop on Power-Save Computer Systems, PACS 2004, Portland, Oregon. December, 2004.

[15] NS-2: The Network Simulator 2. Online at http://www.isi.edu/nsnam/ns/

[16] NS-2 ext.: WLAN power management extension. Online at http://nspme.sourceforge. net/index.html

6 Chapter 6: Minimum Energy Multicriteria Relay Selection in Mobile Ad Hoc Networks

[1] B. Karp and H. T. Kung, “GPSR: Greedy perimeter stateless routing for wireless networks,” in Proceedings of the ACM MOBICOM, Boston, MA, Aug. 2000, pp. 243–254.

[2] R. Zheng, “On routing in lossy wireless networks with realistic channel models,” in Proceedings of the ACM International Workshop on Foundations of Wireless Ad Hoc and Sensor Networking and Computing, New York, May 2008, pp. 1–6.

[3] K. Seada, M. Zuniga, A. Helmy, and B. Krishnamachari, “Energy-efficient forwarding strategies for geographic routing in lossy wireless sensor networks,” in Proceedings of the ACM SENSYS, Baltimore, MD, Nov. 2004, pp. 108–121.

[4] M. Zuniga and B. Krishnamachari, “Analyzing the transitional region in low power wireless links,” in IEEE International Conference on Sensor and Ad Hoc Communications and Networks (SECON), 2004, pp. 517–526.

[5] S. Lee, B. Bhattacharjee, and S. Banerjee, “Efficient geographic routing in multihop wireless networks,” in Proceedings of the ACM MobiHoc, Urbana-Champaign, IL, May 2005, pp. 230–241.

[6] M. Zorzi and R. R. Rao, “Geographic random forwarding (GeRaF) for ad hoc and sensor networks: Multihop performance,” IEEE Trans. Mobile Comput., vol. 2, no. 4, pp. 337–348, Oct.-Dec. 2003.

[7] H. Fubler, J. Widmer, and M. Kasemann, “Contention-based forwarding for mobile ad hoc networks,” Elsevier Ad Hoc Networks, vol. 1, no. 4, pp. 351–369, Nov. 2003.

[8] K. Egoh and S. De, “Priority-based receiver-side relay election in wireless ad hoc sensor networks,” in Proceedings of the IEEE IWCMC’06, Vancouver, British Columbia, Canada, July 2006.

[9] K. Egoh and S. De, “A Multi-Criteria Receiver-Side Relay Election Approach in Wireless Ad Hoc Networks,” in Proceedings of the Military Communications Conference, 2006. MILCOM 2006, Washington, D.C., Oct. 2006.

[10] T.-C. Hou and V. O. K. Li, “Transmission range control in multihop packet radio networks,” IEEE Trans. Commun.,

vol. 34, no. 1, pp. 38–44, Mar. 1986.

[11] H. Takagi and L. Kleinrock, “Optimal transmission ranges for randomly distributed packet radio terminals,” IEEE Trans. Commun., vol. COM-32, no. 3, pp. 246–257, Mar. 1984.

[12] M. Mauve, J. Widmer, and H. Hartenstein, “A survey on position-based routing in mobile ad hoc sensor networks,” IEEE Network Mag., vol. 15, pp. 30–39, June 2001.

[13] S. De, “On hop count and Euclidean distance in greedy forwarding in wireless ad hoc networks,” IEEE Commun. Letters, vol. 9, no. 11, pp. 1000–1002, Nov. 2005.

[14] P. -J. Wan, “A survey on position-based routing in mobile ad hoc networks,” in Network, IEEE, Nov/Dec 2001, vol. 15, no. 6, pp. 30–39.

[15] R. Tanbourgi, H. Jakel, and F. K. Jondral, “Increasing the One-Hop Progress of Nearest Neighbor Forwarding,” in IEEE Communications Letters, Jan. 2011, vol. 15, no. 1 pp. 64–66.

[16] C. Yi, P. Wan, X. Li, and O. Frieder, “Fault tolerant sensor networks with Bernoulli nodes,” in Proceedings of the IEEE WCNC, New Orleans, LA, Mar. 2003.

[17] S. C. Zhang, F. I. Koprulu, R. Koetter, and D. L. Jones, “Feasibility analysis of stochastic sensor networks,” in Proceedings of the Conference on Sensor and Ad Hoc Communications and Networks, Santa Clara, CA., October 2004.

[18] A. Rao, C. Papadimitrou, S. Ratnasamy, S. Shenker, and I. Stoica, “Geographic routing without location information,” in Proceedings of the ACM MOBICOM, San Diego, CA, Sept. 2003, pp. 96–108.

[19] M. R. Souryal and N. Moayeri, “Channel-adaptive relaying in mobile ad hoc networks with fading” in Proceedings of the IEEE SECON Santa Clara, CA, Sept. 2005.

7 Chapter 7: Energy Optimization Techniques for Wireless Sensor Networks

[1] J. Yick, B. Mukherjee, and D. Ghosal, “Wireless sensor network survey,” Comput. Netw., vol. 52, no. 12, pp. 2292–2330, Aug. 2008.

[2] M. Vemula, M. F. Bugallo, and P. M. Djuric, “Target tracking in a two-tiered hierarchical sensor network,” in Proceedings of International Conference on Acoustics, Speech and Signal Processing, vol. 4, 2006, pp. IV-969–IV-972.

[3] Z. Jin and S. Papavassiliou, “On the energy-efficient organization and the lifetime of multihop sensor networks,” IEEE Commun. Lett., vol. 7, no. 11, pp. 537–539, Nov. 2003.

[4] K. Martinez, P. Padhy, A. Riddoch, H. Ong, and J. K. Hart, “Glacial environment monitoring using sensor networks,” in Real-World Wireless Sensor Networks Workshop, 2005, pp. 10–14.

[5] G. Werner-Allen, K. Lorincz, M. Welsh, O. Marcillo, J. Johnson, M. Ruiz, and J. Lees, “Deploying a wireless sensor network on an active volcano,” IEEE Internet Comput., vol. 10, no. 2, pp. 18–25, Mar. 2006.

[6] S. Chouhan, R. Bose, and M. Balakrishnan, “A framework for energy consumption based design space exploration for wireless sensor nodes,” IEEE Trans. Computer-Aided Design Integr. Circuits Syst., vol. 28, no. 7, pp. 1017–1024, July 2009.

[7] B. L. Titzer, D. K. Lee, and J. Palsberg, “Avrora: Scalable sensor network simulation with precise timing,” in Proceedings of the International Conference on Information Processing in Sensor Networks, 2005, pp. 477–482.

[8] I. Downard, Simulating Sensor Networks in NS-2. Online at: http://nrlsensorsim. pf.itd.nrl.navy.mil

[9] S. Chouhan, R. Bose, and M. Balakrishnan, “Integrated energy analysis of error correcting codes and modulation for energy efficient wireless sensor nodes,” IEEE Trans. Wireless Commun., vol. 8, no. 10, pp. 5348–5355, Oct. 2009.

[10] T. H. Lee, ¦e Design of CMOS Radio-Frequency Integrated Circuits. Cambridge, U.K.: Cambridge University Press, 1998.

[11] Q. Wang, M. Hempstead, and W. Yang, “A realistic power consumption model for wireless sensor network devices,” in Proceedings of Conference on Sensor, Mesh and Ad Hoc Communications and Networks, Reston, VA, 2006, pp. 286–295.

[12] J. G. Proakis, Digital Communications, 4th ed. New York: McGraw-Hill, 2001.

[13] F. N. Najm, R. Burch, P. Yang, and I. N. Hajj, “Probabilistic simulation for reliability analysis of CMOS VLSI circuits,” IEEE Trans. Computer-Aided Design Integr. Circuits Syst., vol. 9, no. 4, pp. 439–450, Apr. 1990.

[14] F. N. Najm, I. N. Hajj, and P. Yang, “An extension of probabilistic simulation for reliability analysis of CMOS VLSI circuits,” IEEE Trans. Computer-Aided Design Integr. Circuits Syst., vol. 10, no. 11, pp. 1372–1381, Nov. 1991.

[15] R. Tjarnstrom, “Power dissipation estimate by switch level simulation,” in International Symposium on Circuits and Systems, Portland, OR, 1989, pp. 881–884, vol. 2.

[16] A. Salz and M. Horowitz, “IRSIM: An incremental MOS switch-level simulator,” in Proceedings of Design Automation Conference, 1989, pp. 173–178.

[17] S. M. Kang, “Accurate simulation of power dissipation in VLSI circuits,” IEEE J. SolidState Circuits, vol. 21, no. 5, pp. 889–891, Oct. 1986.

[18] L. W. Nagel, “SPICE2: A computer program to simulate semiconductor circuits,” Memorandum ERL-M520, Electronics Research Laboratory, College of Engineering, University of California at Berkeley, Berkeley, Tech. Rep., 1975.

[19] F. N. Najm, “Transition density, a stochastic measure of activity in digital circuits,” in Proceedings of Design Automation Conference, San Francisco, CA, 1991, pp. 644–649.

[20] A. Ghosh, S. Devadas, K. Keutzer, and J. White, “Estimation of average switching activity in combinational and sequential circuits,” in Proceedings of Design Automation Conference, Anaheim, CA, 1992, pp. 253–259.

[21] C. Y. Tsui, M. Pedram, and A. M. Despain, “Efficient estimation of dynamic power consumption under a real delay model,” in International Conference on Computer-Aided Design, Santa Clara, CA, 1993, pp. 224-228.

[22] F. N. Najm, “A survey of power estimation techniques in VLSI circuits,” IEEE Trans. Very Large Scale Integr. VLSI Syst., vol. 2, no. 4, pp. 446–455, Dec. 1994.

[23] T. Sato, M. Nagamatsu, and H. Tago, “Power and performance simulator: ESP and its application for 100 MIPS/W class RISC design,” in Proceedings of Symposium on Low Power Electronics, San Diego, CA, 1994, pp. 46–47.

[24] T. Sato, Y. Ootaguro, M. Nagamatsu, and H. Tago, “Evaluation of architecture-level power estimation for CMOS RISC processors,” in Proceedings of Symposium on Low Power Electronics, San Jose, CA, 1995, pp. 44–45.

[25] P. E. Landman and J. M. Rabaey, “Architectural power analysis: �e dual bit type method,” IEEE Trans. Very Large Scale Integr. VLSI Syst., vol. 3, no. 2, pp. 173–187, June 1995.

[26] V. Tiwari, S. Malik, and A. Wolfe, “Power analysis of embedded software: A first step towards software power minimization,” IEEE Trans. Very Large Scale Integr. VLSI Syst., vol. 2, no. 4, pp. 437–445, Dec. 1994.

[27] V. Tiwari, S. Malik, A. Wolfe, and M. T.-C. Lee, “Instruction level power analysis and optimization of software,” J. VLSI Sig. Proc., vol. 13, no. 2-3, pp. 223–238, Aug. 1996.

[28] A. Sama, M. Balakrishnan, and J. F. M. �eeuwen, “Speeding up power estimation of embedded software,” in International Symposium on Low Power Electronics and Design, Rapallo, Italy, July 2000, pp. 191–196.

[29] A. Sinha and A. P. Chandrakasan, “Jouletrack: A Web-based tool for software energy profiling,” in Proceedings of Design Automation Conference, Las Vegas, NV, 2001, pp. 340–345.

[30] D. Brooks, P. Bose, S. E. Schuster, H. Jacobson, P. N. Kudva, A. Buyuktosunoglu, J. Wellman, V. Zyuban, M. Gupta, and P. W. Cook, “Power-aware microarchitecture: Design and modeling challenges for next-generation microprocessors,” IEEE Micro, vol. 20, no. 6, pp. 26–44, 2000.

[31] D. Brooks, V. Tiwari, and M. Martonosi, “Wattch: A framework for architecturallevel power analysis and optimizations,” in Proceedings of International Symposium on Computer Architecture, Vancouver, Canada, 2000, pp.

83–94.

[32] W. Yeand, N. Vijaykrishnan, M. Kandemir, and M. J. Irwin, "The design and use of simplepower: A cycle-accurate energy estimation tool," in Proceedings of Design Automation Conference, Los Angeles, CA, 2000, pp. 340–345.

[33] MICA2. Online at: http://www.xbow.com/Products/productdetails.aspx?sid=174

[34] MICAz. Online at: http://www.xbow.com/Products/productdetails.aspx?sid=164

[35] J. Polastre, R. Szewczyk, and D. Culler, "Telos: Enabling ultra-low power wireless research," in Proceedings of the International Symposium on Information Processing in Sensor Networks, 2005, pp. 364–369.

[36] imote2. Online at: http://www.xbow.com/Products/productdetails.aspx?sid=253

[37] E. Shih, S. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan, "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in Proceedings of the International Conference on Mobile Computing and Networking, Rome, Italy, 2001, pp. 272–287.

[38] J. Rabaey and M. Pedram, Low Power Design Methodologies. Kluwer Academic Publishers, 1995.

[39] J. Mermet and W. Nebel, Low Power Design in Deep Submicron Electronics. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1997.

[40] A. Chandrakasan and R. Brodersen, Low-Power CMOS Design. Piscataway, NJ: IEEE Press, 1998.

[41] S. Devadas and S. Malik, "A survey of optimization techniques targeting low power VLSI circuits," in Proceedings of the ACM/IEEE Design Automation Conference, 1995, San Francisco, CA, pp. 242–247.

[42] L. Benini, G. D. Micheli, and E. Macii, "Designing low-power circuits: Practical recipes," IEEE Circuits and Systems Mag., vol. 1, no. 1, pp. 6–25, 2001.

[43] G. Hua and C. W. Chen, "Distributed source coding in wireless sensor networks," in Proceedings of the International Conference on Quality of Service in

Heterogeneous Wired/ Wireless Networks, 2005, Lake Buena Vista, FL, p. 6.

[44] M. Sartipi and F. Fekri, “Source and channel coding in wireless sensor networks using LDPC codes,” in Proceedings of Communications Society Conference on Sensor and Ad Hoc Communications and Networks, October 2004, Santa Clara, CA, pp. 309–316.

[45] D. Marco and D. L. Neuhoff, “Reliability vs. efficiency in distributed source coding for field-gathering sensor networks,” in Proceedings of International Symposium on Information Processing in Sensor Networks, April 2004, Berkeley, CA, pp. 161–168.

[46] C. H. Liu and H. H. Asada, “A source coding and modulation method for power saving and interference reduction in DS-CDMA sensor network systems,” in Proceedings of American Control Conference, vol. 4, 2002, pp. 3003–3008.

[47] J. Kim and J. G. Andrews, “An energy efficient source coding and modulation scheme for wireless sensor networks,” in IEEE 6th Workshop on Signal Processing Advances in Wireless Communications, 2005, New York, pp. 710–714.

[48] J. Chou, D. Petrovic, and K. Ramchandran, “A distributed and adaptive signal processing approach to reducing energy consumption in sensor networks,” in Proceedings of the INFOCOM, San Francisco, CA, 2003, pp. 1054–1062.

[49] D. Slepian and J. Wolf, “Noiseless coding of correlated information sources,” IEEE Trans. Inform. ¦eory, vol. 19, no. 4, pp. 471–480, 1973.

[50] T. Cover, “A proof of the data compression theorem of Slepian and Wolf for ergodic sources,” IEEE Trans. Inform. ¦eory, vol. 21, no. 2, pp. 226–228, 1975.

[51] S. S. Pradhan, J. Kusuma, and K. Ramchandran, “Distributed compression in a dense microsensor network,” IEEE Signal Processing Mag., vol. 19, no. 2, pp. 51–60, 2002.

[52] Z. Xiong and A. D. Cheng, “Distributed source coding for sensor networks,” IEEE Signal Processing Mag., vol. 21, no. 5, pp. 80–94, Sept. 2004.

[53] M. Sartipi and F. Fekri, "Distributed source coding in wireless sensor networks using LDPC coding: The entire Slepian-Wolf rate region," in Proceedings of Wireless Communications and Networking Conference, March 2005, New Orleans, LA, pp. 1939–1944.

[54] H. Wang, D. Peng, W. Wang, H. Sharif, and H. Chen, "Cross-layer routing optimization in multirate wireless sensor networks for distributed source coding based applications," IEEE Trans. Wireless Commun., vol. 7, no. 10, pp. 3999–4009, Oct 2008.

[55] A. Wyner and J. Ziv, "The rate-distortion function for source coding with side information at the decoder," IEEE Trans. Inform. Theory, vol. 22, no. 1, pp. 1–10, 1976.

[56] S. Pradhan, J. Chou, and K. Ramchandran, "Duality between source coding and channel coding and its extension to the side information case," IEEE Trans. Inform. Theory, vol. 49, no. 5, pp. 1181-1203, IEEE Trans. Inform. Theory, 2003.

[57] R. Bose, Information Theory, Coding and Cryptography. New Delhi: Tata McGraw-Hill, 2002.

[58] CC2420 Datasheet. Online at: http://www.ti.com/lit/gpn/cc2420

[59] L. Benini, A. Bogliolo, and G. D. Micheli, "A survey of design techniques for systemlevel dynamic power management," IEEE Trans. Very Large Scale Integr. Syst, vol. 8, no. 3, pp. 299–316, June 2000.

[60] Imote2 Datasheet. Online at: http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/Imote2_Datasheet.pdf

[61] T. Simunic, L. Benini, and G. D. Micheli, "Dynamic power management for portable systems," in Proceedings of the International Conference on Mobile Computing and Networking, Boston, MA, 2000, pp. 49–54.

[62] A. Sinha and A. Chandrakasan, "Dynamic power management in wireless sensor networks," IEEE Design & Test of Computers, vol. 18, no. 2, pp. 62–74, Mar/Apr. 2001.

[63] C. F. Chiasserini and R. R. Rao, "Improving energy saving in wireless systems by using dynamic power management," IEEE Transactions on Wireless Communications, vol. 2, no. 5, pp. 1090–1100, Sept. 2003.

[64] R. M. Passos, C. J. N. Coelho, Jr, A. A. F. Loureiro, and R. A. F. Mini, “Dynamic power management in wireless sensor networks: An application-driven approach,” in Proceedings of the Second Annual Conference on Wireless On-Demand Network Systems and Services, 2005, San Moritz, Switzerland, pp. 109–118.

[65] F. Salvadori, M. de Campos, P. S. Sausen, R. F. de Camargo, C. Gehrke, C. Rech, M. A. Spohn, and A. C. Oliveira, “Monitoring in industrial systems using wireless sensor network with dynamic power management,” IEEE Trans. on Instrumentation and Measurement, vol. 58, no. 9, pp. 3104–3111, Sept. 2009.

[66] J. Rabaey, Low Power Design Essentials (Integrated Circuits and Systems). Berlin: Springer, 2009.

[67] The International Technology Roadmap for Semiconductors. Online at: http://www.itrs. net/

[68] R. Min, M. Bhardwaj, S. Cho, N. Ickes, E. Shih, A. Sinha, A. Wang, and A. Chandrakasan, “Energy-centric enabling technologies for wireless sensor networks,” IEEE Wireless Communications, vol. 9, no. 4, pp. 28–39, Aug. 2002.

[69] Y. Chen and Q. Zhao, “On the lifetime of wireless sensor networks,” IEEE Communications Letters, vol. 9, no. 11, pp. 976–978, Nov. 2005.

[70] A. Salhieh, J. Weinmann, M. Kochhal, and L. Schwiebert, “Power efficient topologies for wireless sensor networks,” in Proceedings of the International Conference on Parallel Processing, Valencia, Spain, September 2001, pp. 156–163.

[71] O. Younis, M. Krunz, and S. Ramasubramanian, “Node clustering in wireless sensor networks: Recent developments and deployment challenges,” IEEE Network, vol. 20, no. 3, pp. 20–25, May-June 2006.

[72] K. Akkaya, M. Younis, and W. Youssef, “Positioning of base stations in wireless sensor networks,” IEEE Communications Mag., vol. 45, no. 4, pp. 96–102, Apr. 2007.

[73] A. A. Abbasi and M. Younis, “A survey on clustering algorithms for wireless sensor networks,” Computer Communications, vol. 30, no. 14-15, pp. 2826–2841, Oct. 2007.

[74] A. Chamam and S. Pierre, “On the planning of wireless sensor networks: Energyefficient clustering under the joint routing and coverage constraint,” IEEE Trans. Mobile Computing, vol. 8, no. 8, pp. 1077–1086, 2009.

[75] J. N. Al-Karaki and A. E. Kamal, “Routing techniques in wireless sensor networks: A survey,” IEEE Wireless Communications, vol. 11, no. 6, pp. 6–28, 2004.

[76] Y. Yang, R. S. Blum, and B. M. Sadler, “Energy-efficient routing for signal detection in wireless sensor networks,” IEEE Trans. Signal Processing, vol. 57, no. 6, pp. 2050–2063, 2009.

[77] N. Riaz and M. Ghavami, “An energy-efficient adaptive transmission protocol for ultrawideband wireless sensor networks,” IEEE Trans. Vehicular Technology, vol. 58, no. 7, pp. 3647–3660, 2009.

[78] Y. Sankarasubramaniam, I. F. Akyildiz, and S. W. McLaughlin, “Energy efficiency based packet size optimization in wireless sensor networks,” in International Workshop on Sensor Network Protocols and Applications, May 2003, Anchorage, AK, pp. 1–8.

[79] M. C. Vuran and I. F. Akyildiz, “Cross-layer packet size optimization for wireless terrestrial, underwater, and underground sensor networks,” in Proceedings of the IEEE Conference on Computer Communications, Phoenix, AZ, 2008, pp. 226–230. II SCAVENGING

TECHNIQUES

8 Chapter 8: Design Issues in EM Energy Harvesting Systems

[1] Huang H., and Oberle, M., “A 0.5 mW Passive Telemetry IC for Biomedical Applications,” IEEE Journal of Solid State Circuits, v. 33, n. 7, pp. 937–946, 1998.

[2] Marschner, C., Rehfuss, S., Peters, D., Bolte, H., and Laur, R. “Modular concept for the design of application-specific integrated telemetric systems.” in Proceedings of SPIE 4408, 246–255, Cannes-Mandelieu, France, April 2001.

[3] Schuylembergh, K., and Puers, R. “Self tuning inductive powering for implantable telemetric monitoring systems,” in Proceedings of the 8th Conference of Solid-State Sensors and Actuators, Stockholm, Sweden, June 1995.

[4] Sample, A., and Smith, J. R., “Experimental results with two wireless power transfer systems,” in Proceedings of the IEEE Wireless and Radio Symposium, San Diego, CA, 2009.

[5] Yan, H., Macias Montero, J. G., Akhnoukh, A., de Vreede, L.C.N., and Burghartz, J. N., “An integration scheme for RF power harvesting,” in Proceedings of the 8th Annual Workshop on Semiconductor Advances for Future Electronics and Sensors, Veldhoven, the Netherlands, 2005.

[6] Karthus, U., and Fischer, M., “Fully Integrated Passive UHF RFID Transponder IC with 16.7 mW Minimum RF Input Power,” IEEE Journal of Solid-State Circuits, v. 38, n. 10, pp. 1602–1608, 2003.

[7] De Vita, G., and Iannacone, G., “Design Criteria for the RF Section of UHF and Microwave Passive RFID Transponders,” IEEE Transactions on Microwave Theory and Techniques, v. 53, n. 9, pp. 2978–2990, 2005.

[8] Curty, J.-P., Joehl, N., Dehollain, C., and Declercq, M. J., “Remotely Powered Addressable UHF RFID System,” IEEE Journal of Solid-State Circuits, v. 40, n. 11, pp. 2193–2202, 2005.

[9] Umeda, T., Yoshida, H., Sekine, S., Fujita, Y., Suzuki, T., and Otaka, S., “A 950-MHz Rectifier Circuit for Sensor Network Tags with 10-m Distance,” IEEE Journal of SolidState Circuits, v. 41, n. 1, pp. 35–41, 2006.

[10] Bode, H. W., Network Analysis and Feedback Amplifier

Design, 1st ed., Princeton, NJ: D. Van Nostrand Company, 1945.

[11] Fano, R. M., "Theoretical Limitations on the Broadband Matching of Arbitrary Impedances," DSc disser., Massachusetts Institute of Technology, Department of Electrical Engineering, May 1947.

[12] Yan, H., Popadic, M., Macías-Montero, J. G., de Vreede, L. C. N., Aknoukh, A., and Nanver, L. K., "Design of an RF power harvester in a silicon-on-glass technology," in Proceedings of IEEE-STW PRORISC 2008, Veldhoven, The Netherlands, pp. 287- 290, 2008.

[13] Mandal, S., "Far Field RF Power Extraction Circuits and Systems," master's thesis, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, June 2004.

[14] Mandal, S., and Sarpeshkar, R., "Low Power CMOS Rectifier Design for RFID Applications," IEEE Transactions on Circuits and Systems I, v. 54, n. 6, pp. 1177–1188, 2007.

[15] Balanis, C. A., Antenna Theory: Analysis and Design, 3rd ed. New York: John Wiley & Sons, 2005.

[16] Johnson, R. C., and Jasik, H., Antenna Engineering Handbook, 3rd ed. New York: McGraw-Hill, 1993.

[17] Wheeler, H. A., "The radiansphere around a small antenna," Proceedings of the IRE, v. 47, n. 8, pp. 1325–1331, 1959.

[18] Friis, H. "A note on a simple transmission formula," Proceedings of the IRE, v. 34, pp. 254–256, May 1946.

[19] European Telecommunications Standards Institute (ETSI). Available online: http:// www. etsi.org/WebSite/homepage.aspx

[20] Texas Instruments. UHF Gen2 STRAP. Available online: http://www.ti.com/rfid/ docs/manuals/pdfSpecs/RI-UHF-STRAP DataSheet.pdf

[21] Lee, T. H., The Design of CMOS Radio-Frequency Integrated Circuits, 2nd ed., Cambridge, U.K.: Cambridge University Press, 2004.

[22] Neudeck, G., and Pierret, R., The PN Junction Diode,

Vol. 2, Reading, MA: AddisonWesley, 1989.

[23] Li, Q., Han, Y., Min, H., and Zhou, F., "Fabrication and Modeling of Schottky Diode Integrated in Standard CMOS Process," Auto ID Labs White Paper WP-HARDWARE-011, Massachusetts Institute of Technology, 2005.

[24] Milanovic, V., Gaitan. M., Marshall, J. C., and Zaghloul, M. E., "CMOS foundry implementation of Schottky diodes for RF detection," IEEE Transactions on Electron Devices, v. 43, n. 12, pp. 2210–2214, 1996.

[25] Cha, S. I., Cho, Y. H., Choi, Y. I., and Chung, S. K., "Novel schottky diode with selfaligned Guard Ring," IET Electronics Letters, v. 28, n. 13, p. 1221–1223, 1992.

[26] Mazzilli, F., �oppay, P. E., Jöhl, N., and Dehollain, C., "Design methodology and comparison of rectifiers for UHF-band RFIDs," in Proceedings of IEEE Radio Frequency Integrated Circuits Symposium, pp. 505–508, Anaheim, CA, May 2010.

[27] Chatzandroulis, S., Tsoukalas, D., and Neukomm, P., "A Miniature Pressure System with a Capacitive Sensor and a Passive Telemetry Link for Use in Implantable Applications," Journal of Microelectromechanical Systems, v. 9, pp. 18–23, March 2000.

[28] Zhu, Z., Jamali, B., and Cole, P. H., "An HF/UHF RFID Analogue Front-End Design and Analysis," White Paper Series Edition 1. CD. Auto-ID Labs, Massachusetts Institute of Technology, September 2005.

[29] Zhang, L., Jiang, H., Sun, X., Zhang, C., and Wang, Z., "A passive RF receiving and power switch ASIC for remote power control with zero stand-by power," in Proceedings of IEEE Asian Solid-State Circuits Conference, Fukuoka, Japan, pp. 109–112, 2008.

[30] Che, W., Yan, N., Yang, Y., and Min, H., "A Low Voltage Low Power RF Analog FrontEnd Circuit for Passive UHF RFID Tag," Journal of Semiconductors, v. 29, n. 3, 2008.

[31] De Vita, G., and Iannaccone, G., "Ultra-low power series voltage regulator for passive microwave RFID transponders," in Proceedings of NORCHIP Conference, Oulu, Finland, 2005.

[32] Morales-Ramos, R., Vaz, A., Pardo, D., and Berenguer,

R., "Ultra-low power passive UHF RFID for wireless sensor networks," in Proceedings of EUROMICRO Conference on Digital System Design, Architecture, Methods, and Tools, Parma, Italy, pp. 671–675, 2008.

[33] Yao, Y., Wu, J., Shi, Y., and Foster Dai, F. "A Fully Integrated 900-MHz Passive RFID Transponder Front End with Novel Zero-Threshold RF–DC Rectifier," IEEE Transactions on Industrial Electronics, v. 56, n. 7, pp. 2317–2325, 2009.

[34] Baker, R. J., CMOS Circuit Design, Layout, and Simulation, 3rd ed. New York: John Wiley & Sons, 2010.

[35] Curty, J.-P., Declerq, M., Dehollain, C., and Johel, N., Design and Optimization of Passive UHF RFID Systems, New York: Springer, 2007.

[36] De Vita, G., Battaglia, F., and Iannaccone, G., "Ultra-Low Power PSK Backscatter Modulator for UHF and Microwave RFID Transponders," Microelectronic Journal, v. 37, n. 7, pp. 627–629, 2006.

9 Chapter 9: Energy Scavenging for Magnetically Coupled Communication Devices

[1] H. Pei, et al., “Efficient solar power scavenging and utilization in mobile electronics system,” in International Conference on 2010 Green Circuits and Systems (ICGCS), 2010, pp. 641–645.

[2] O. Bertoldi and S. Berger, “Abservatory NANO, report on energy,” ed, 2009. http://

[3] J. Bing, et al., “Energy Scavenging for Inductively Coupled Passive RFID Systems,” in Proceedings of the IEEE Instrumentation and Measurement Technology Conference, 2005. (IMTC) 2005, pp. 984–989.

[4] R. Bansal, “Near-field magnetic communication,” Antennas and Propagation Magazine, IEEE, vol. 46, pp. 114–115, 2004.

[5] C. Bunszel. (2001). Magnetic induction: A low-power wireless alternative. Available online at:

[6] C. Evans-Pughe, “Close encounters of the magnetic kind [near field communications],” IEE Review, vol. 51, pp. 38–42, 2005.

[7] N. Jack and K. Shenai, “Magnetic Induction IC for Wireless Communication in RF-Impenetrable Media,” in IEEE Workshop on Microelectronics and Electron Devices, 2007. (WMED) 2007, pp. 47–48.

[8] V. Palermo. (2003) Near Field Magnetic comms emerges. Available online at: http://

[9] J. J. Sojdehei, et al., “Magneto-inductive (MI) communications,” in OCEANS, 2001. MTS/IEEE Conference and Exhibition, 2001, pp. 513–519, vol. 1.

[10] R. R. A. Syms, et al., “Low-loss magneto-inductive waveguides,” Journal of Physics D: Applied Physics, vol. 36, pp. 3945–3951, 2006. L 1 L 2 L 2 L 1

Figure 9.25 Schematic of diagonal connected coils in a multicoil structure.

(From W. Lihsien, et al., in Biomedical Circuits and Systems Conference, 2008.

BioCAS 2008. IEEE, 2008, pp. 101–104. With permission.).

[11] R. R. A. Syms, et al., “Magneto-Inductive Waveguide Devices,” IEE Proceedings Microwaves, Antennas and Propagation, vol. 153, pp. 111–121, 2006.

[12] S. Zhi and I. F. Akyildiz, “Underground Wireless Communication Using Magnetic Induction,” in IEEE International Conference on Communications, 2009. (ICC ‘09) 2009, pp. 1–5.

[13] S. Zhi and I. F. Akyildiz, “Magnetic induction communications for wireless underground sensor networks,” IEEE Transactions on Antennas and Propagation, vol. 58, pp. 2426–2435, 2010.

[14] S. Zhi and I. F. Akyildiz, “Deployment Algorithms for Wireless Underground Sensor Networks Using Magnetic Induction,” in 2010 IEEE Global Telecommunications Conference (GLOBECOM), 2010, pp. 1–5.

[15] J. I. Agbinya, et al., “Size and characteristics of the ‘cone of silence’ in near-field magnetic induction communications,” Battlefield Technology, vol. 13, 2010.

[16] H.-B. Li and R. Kohno, “Body area network and its standardization at IEEE 802.15. BAN,” in Advances in Mobile and Wireless Communications. vol. 16, F. István, et al., eds., Berlin/Heidelberg: Springer Publishing, 2008, pp. 223–238.

[17] S. F. Heaney, et al., “Fading Characterization for Context Aware Body Area Networks (CABAN) in Interactive Smart Environments,” in Antennas and Propagation Conference (LAPC), 2010 Loughborough, 2010, pp. 501–504.

[18] K. Y. Yazdandoost and R. Kohno, “UWB Antenna for Wireless Body Area Network,” in Asia-Pacific Microwave Conference, 2006. (APMC) 2006, pp. 1647–1652.

[19] H. Kulah and K. Najafi, “Energy scavenging from low-frequency vibrations by using frequency up-conversion for wireless sensor applications,” Sensors Journal, IEEE, vol. 8, pp. 261–268, 2008.

[20] W. Peihong, et al., “A Microelectroplated Magnetic Vibration Energy Scavenger for Wireless Sensor Microsystems,” in 5th IEEE International Conference on Nano/Micro Engineered and Molecular Systems (NEMS), 2010, pp. 383–386.

[21] J. Agbinya and M. Masihpour, “Power equations and capacity performance of magnetic induction communication systems,” Wireless Personal Communications, pp. 1-15, 2011.

[22] W. C. Chye, et al., “Electromagnetic Micro Power Generator: A Comprehensive Survey,” in IEEE Symposium on Industrial Electronics & Applications (ISIEA), 2010, pp. 376-382.

[23] C. B. Williams and R. B. Yates, “Analysis of a Micro-electric Generator for Microsystems,” in ¦e 8th International Conference on Solid-State Sensors and Actuators, 1995 and Eurosensors IX. Transducers, 1995, pp. 369-372.

[24] C. Shearwood and R. B. Yates, “Development of an electromagnetic microgenerator,” Electronics Letters, vol. 33, pp. 1883-1884, 1997.

[25] S. Turkyilmaz, et al., “Design and Prototyping of Second Generation METU MEMS Electromagnetic Micro-Power Generators,” in International Conference on Energy Aware Computing (ICEAC), 2010, pp. 1-4.

[26] W. J. Li, et al., “Infrared Signal Transmission by a Laser-Micromachined, VibrationInduced Power Generator,” in Proceedings of the 43rd IEEE Midwest Symposium on Circuits and Systems, 2000, pp. 236-239, vol. 1.

[27] J. M. H. Lee, et al., “Vibration-to-Electrical Power Conversion Using High-AspectRatio Mems Resonators,” presented at the Power MEMS, 2003.

[28] P.-H. Wang, et al., “Design, fabrication and performance of a new vibration-based electromagnetic micro power generator,” Microelectronics Journal, vol. 38, pp. 1175-1180, 2007.

[29] C. Xinping and L. Yi-Kuen, “Design and Fabrication of Mini Vibration Power Generator System for Micro Sensor Networks,” in 2006 IEEE International Conference on Information Acquisition, 2006, pp. 91-95.

[30] W. Ko Ko, et al., “Efficient Solar Energy Harvester for Wireless Sensor Nodes,” in 2010 IEEE International Conference on Communication Systems (ICCS), 2010, pp. 289-294.

[31] L. Xin and Y. Shuang-Hua, “�ermal Energy Harvesting

for WSNs," in 2010 IEEE International Conference on Systems Man and Cybernetics (SMC), 2010, pp. 3045-3052.

[32] Y. K. Tan and S. K. Panda, "Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless sensor nodes," IEEE Transactions on Industrial Electronics, vol. PP, pp. 1-1, 2010.

[33] A. J. Minnich, et al., "Bulk nanostructured thermoelectric materials: Current research and future prospects," Energy and Environmental Science, 2009.

[34] J. Tervo, et al., "State-of-the-art of thermoelectric materials processing," presented at the VTT Technical Research Centre of Finland, Oulu, Finland, 2009, vol. 2, No. 5, pp. 446-479.

[35] T. Isobe, et al., "A Soft-Switching Boost DC to AC Converter without Smoothing Capacitor Using a MERS Pulse Link Concept," in 2010 International Power Electronics Conference (IPEC), 2010, pp. 2815-2821.

[36] J. Bing, et al., "Energy scavenging for inductively coupled passive rfid systems," IEEE Transactions on Instrumentation and Measurement, vol. 56, pp. 118-125, 2007.

[37] S. Cichos, et al., "Performance Analysis of Polymer-Based Antenna Coils for RFID," in 2nd International IEEE Conference on Polymers and Adhesives in Microelectronics and Photonics, 2002. (POLYTRONIC), 2002, pp. 120-124.

[38] G. D. Horler, et al., "Inductively coupled telemetry and actuation," in ¦e IEE Seminar on (Refl No. 2005/11009) Telemetry and Telematics, 2005, pp. 5/1-5/6.

[39] M. Sawan, et al., "Multicoils-based inductive links dedicated to power up implantable medical devices: Modeling, design and experimental results," Biomedical Microdevices, vol. 11, pp. 1059-1070, 2009.

[40] W. Lihsien, et al., "An Efficient Wireless Power Link for High Voltage Retinal Implant," in IEEE Biomedical Circuits and Systems Conference, 2008. (BioCAS), 2008, pp. 101-104.

[41] O. M. O. Gatous and J. Pissolato, "Frequency-Dependent Skin-Effect Formulation for Resistance and Internal

Inductance of a Solid Cylindrical Conductor," IEE Proceedings of Microwaves, Antennas and Propagation, vol. 151, pp. 212-216, 2004.

10 Chapter 10: Mixed-Signal, Low-Power Techniques in Energy Harvesting Systems

[1] J. Kahn, R. Katz, and K. Pister, “Next century challenges: Mobile networking for smart dust,” in Proc. of the ACM International Conference on Mobile Computing and Networking (MobiCom), August 1999, pp. 271–278.

[2] M. Hempstead, N. Tripathi, P. Mauro, G. Wei, and D. Brooks, “An ultra-low power system architecture for sensor network applications,” in Proc. of the International Symposium on Computer Architecture (ISCA), June 2005, pp. 208–219.

[3] S. Priya, and D. J. Inman (Eds.), Energy Harvesting Technologies, New York: Springer, 2009.

[4] L. Schwiebert, S. Gupta, and J. Weinmann, “Research challenges in wireless networks of biomedical sensors,” in Proc. of the ACM International Conference on Mobile Computing and Networking (MobiCom), July 2001, pp. 151–165.

[5] R. Weinstein, “RFID: A technical overview and its application to the enterprise,” IEEE IT Professional, vol. 7, no. 3, pp. 27–33, May–June 2005.

[6] L. Bisdounis and O. Koufopavlou, “Short-circuit energy dissipation modeling for submicrometer CMOS gates,” IEEE Trans. Circuits & Systems I: Fundamental ¦eory and Applications, vol. 47, no. 9, pp. 1350–1361, September 2000.

[7] J. D. Carothers and R. Radjassamy, “Low-power VLSI design techniques—the current state,” Integrated Computer-Aided Engineering, IOS Press, vol. 5, no. 2, pp. 153–175, April 1998.

[8] J. Rabaey and M. Pedram (eds.), Low Power Design Methodologies, Boston: Kluwer Academic Publishers, 1996.

[9] D. Liu and C. Svensson, “Trading speed for low power by choice of supply and threshold voltages,” IEEE Journal of Solid State Circuits, vol. 28, no. 1, pp. 10–18, January 1993.

[10] A. P. Chandrakasan and R. W. Brodersen, Low Power Digital CMOS Design, Boston: Kluwer Academic Publishers, 1995.

[11] A. P. Chandrakasan and R. W. Brodersen, “Minimizing

power consumption in digital CMOS circuits," Proceedings of the IEEE, vol. 83, no. 4, pp. 498–523, April 1995.

[12] S. Wolf, ¦e Submicron MOSFET, Sunset Beach, CA: Lattice Press, 1995.

[13] M. B. Srivastava, A. P. Chandrakasan, and R. W. Brodersen, "Predictive system shutdown and other architectural techniques," IEEE Trans. Very Large Scale Integration (VLSI) Systems, vol. 4, no. 1, pp. 42–55, March 1996.

[14] E. A. Vittoz, "Low-power design: Ways to approach the limits," in Proc. of the IEEE International Symposium on Circuits and Systems (ISCAS), June 1994, pp. 14–18.

[15] C. C. Enz and E. A. Vittoz, "CMOS low-power analog circuit design," in Designing Low Power Digital Systems, Emerging Technologies Tutorial, Proc. of the IEEE International Symposium on Circuits and Systems (ISCAS), May 1996, pp. 79–133.

[16] M. Declercq and M. Degrauwe, "Low-power/low-voltage IC design: An overview," Advanced Engineering Course on Low-Power/Low-Voltage IC Design, Lausanne, Switzerland: École Polytechnique Fédérale de Lausanne (EPFL), June 1994.

[17] A. P. Chandrakasan, S. Sheng, and R. W. Brodersen, "Low-power CMOS digital design," IEEE Journal of Solid-State Circuits, vol. 27, no. 4, pp. 473–484, April 1992.

[18] T. G. Noll and E. de Man, "Pushing the performance limits due to power dissipation of future ULSI chips," in International Solid-State Circuits Conference (ISSCC) Digest of Technical Papers, February 1992, pp. 1652–1655.

[19] R. Castello, and P. R. Gray, "Performance limitation in switched-capacitor filters," IEEE Trans. Circuits Systems, vol. CAS-32, no. 9, pp. 865–876, September 1985.

[20] C. Toumazou, G. Moschytz, and B. Gilbert (eds.), Tradeoffs in Analog Circuits Design, A Designer's Companion, Boston: Kluwer Academic Publishers, 2003.

[21] Y. Tsividis, "Companding in signal processing," IEE Electronics Letters, vol. 26, no. 17, pp. 1331-1332, August 1990.

[22] Y. Tsividis, "Externally linear, time-invariant

systems and their application to companding signal processors," IEEE Trans. on Circuits & Systems II: Analog and Digital Signal Processing, vol. 44, no. 2, pp. 65–85, February 1997.

[23] E. Seevinck, "Companding current-mode integrator: A new circuit principle for continuous-time monolithic filters," IEE Electronics Letters, vol. 26, no. 24, pp. 2046–2047, November 1990.

[24] R. L. Geiger, P. E. Allen, and N. R. Strader, VLSI Design Techniques for Analog and Digital Circuits, New York: McGraw-Hill, 1990.

[25] A. Wang, B. H. Calhoun, and A. P. Chandrakasan, Sub-threshold Design for Ultra LowPower Systems, New York: Springer, 2006.

[26] A. Tajalli and Y. Leblebici, Extreme Low-Power Mixed Signal IC Design, New York: Springer, 2010.

[27] J. Rabaey, Low Power Design Essentials, New York: Springer, 2009.

[28] D. Soudris, C. Piguet, and C. Goutis (eds.), Designing CMOS Circuits for Low Power, Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002.

[29] M. Santarini, "Taking a bite out of power: Techniques for low-power ASIC design," Electronic Design, Strategy & News (EDN) Magazine, vol. 10, no. 11, May 2007.

[30] L. Benini, and G. De Micheli, "System-level power optimization: Techniques and tools," ACM Trans. Design Automation of Electronic Systems, vol. 5, no. 2, pp. 115–192, April 2000.

[31] E. Macii (ed.), Ultra Low-Power Electronics and Design, Dordrecht, The Netherlands: Kluwer Academic Publishers, 2004.

[32] C. Piguet (ed.), Low-Power CMOS Circuits: Technology, Logic Design and CAD Tools, Boca Raton, FL: CRC Press, 2006.

[33] M. Pedram and J. Rabaey (eds.), Power Aware Design Methodologies, Dordrecht, The Netherlands: Kluwer Academic Publishers, 2002.

[34] D. Chinnery and K. Keutzer, Closing the Power Gap

between ASIC & Custom: Tools and Techniques for Low Power Design, New York: Springer, 2007.

[35] S. Henzler, Power Management of Digital Circuits in Deep Sub-Micron CMOS Technologies, New York: Springer, 2007.

[36] C. Toumazou, and C. A. Makris, “Analog IC design automation, Part I—Automated circuit generation: New concepts and methods,” IEEE Trans. Computer-Aided Design of Integrated Circuits and Systems, vol. 14, no. 2, pp. 218–238, February 1995.

[37] J. Lee, and Y. B. Kim, “ASLIC: A low power CMOS analog circuit design automation,” Integration, ¦e VLSI Journal, Elsevier, vol. 39, no. 3, pp. 157–181, June 2006.

[38] B. Geden, “Taking power analysis to the transistor level for a full chip,” Electronic Design, Strategy & News (EDN) Magazine (guest opinion), December 2009.

[39] Synopsys Inc., HSPICE Simulation and Analysis, User Guide, Mountain View, CA, 2007.

[40] Cadence Design Systems Inc., Cadence PSPICE A/D & PSPICE Advanced Analysis, Technical Brief, San Jose, CA, 2010.

[41] Synopsys Inc., NanoSim Datasheet, Mountain View, CA, 2001.

[42] Magma Design Automation Inc., SiliconSmart Datasheet, San Jose, CA, 2009.

[43] Synopsys Inc., AMPS Datasheet, Mountain View, CA, 1999.

[44] Synopsys Inc., RailMill Datasheet, Mountain View, CA, 2000.

[45] Synopsys Inc., PrimePower Datasheet, Mountain View, CA, 2002.

[46] Synopsys Inc., PowerCompiler Datasheet, Mountain View, CA, 2007.

[47] Cadence Design Systems Inc., Building energy efficient ICs from the ground up, White Paper, San Jose, CA, 2009.

[48] Apache Design Solutions Inc., RTL Design for Power Methodology, White Paper, San Jose, CA, 2010.

[49] Magma Design Automation Inc., Talus PowerPro Datasheet, San Jose, CA, 2008.

[50] ChipVision Design Systems Inc., PowerOpt Datasheet. Available online: http://www.chipvision.com/products/index.php

[51] F. Catthoor, Unified Low-Power Design Flow for Data-Dominated Multimedia and Telecom Applications, Boston: Kluwer Academic Publishers, 2000.

[52] J. Coburn, S. Ravi, and A. Raghunathan, “Power emulation: A new paradigm for power estimation,” in Proceedings of Design Automation Conference (DAC), June 2005, pp. 700–705.

11 Chapter 11: Toward Modeling Support for Low-Power and Harvesting Wireless Sensors for Realistic Simulation of Intelligent Energy-Aware Middleware

[1] D. Saha and A. Mukherjee, “Pervasive computing: A paradigm for the 21st century,” Computer, vol. 36, no. 3, pp. 25–31, Mar. 2003.

[2] J. M. Kahn, R. H. Katz, and K. S. J. Pister, “Next century challenges: Mobile networking for ”smart dust,” in Proceedings of the 5th annual ACM/IEEE International Conference on Mobile Computing and Networking, ser. MobiCom ’99. New York: ACM, 1999, pp. 271–278. Online at: http://doi.acm.org/10.1145/313451.313558

[3] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: A survey,” Computer Networks, vol. 38, no. 4, pp. 393–422, 2002.

[4] J. Yick, B. Mukherjee, and D. Ghosal, “Wireless sensor network survey,” Comput. Netw., vol. 52, no. 12, pp. 2292–2330, 2008.

[5] S. Giordano, Mobile Ad Hoc Networks, in Handbook of Wireless Networks and Mobile Computing. New York: John Wiley & Sons, 2002, chap. 15.

[6] W. Du, D. Navarro, F. Mieyeville, and F. Gaffiot. Towards a taxonomy of simulation tools for wireless sensor networks. In Proceedings of the 3rd International ICST Conference on Simulation Tools and Techniques (SIMUTools ‘10). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, Article 52, 2010. Online at: http://dx.doi.org/10.4108/ICST.SIMUTOOLS2010.8659

[7] R. Rao, S. Vrudhula, and D. Rakhmatov, “Battery modeling for energy aware system design,” Computer, vol. 36, no. 12, pp. 77–87, 2003.

[8] P. M. Glatz, L. B. Hörmann, C. Steger, and R. Weiss, “A system for accurate characterization of wireless sensor networks with power states and energy harvesting system efficiency,” in IEEE International Workshop on Sensor Networks and Systems for Pervasive Computing, March 2010, pp. 468–473.

[9] L. B. Hörmann, P. M. Glatz, C. Steger, and R. Weiss, “Energy efficient supply of WSN nodes using

component-aware dynamic voltage scaling," in European Wireless 2011 (EW2011), pages 147-154, Vienna, Austria, 2011.

[10] J. Polastre, R. Szewczyk, and D. Culler, "Telos: Enabling ultra-low power wireless research," in Fourth International Symposium on Information Processing in Sensor Networks (IPSN), 2005.

[11] P. Levis, N. Lee, M. Welsh, and D. Culler, "TOSSIM: Accurate and scalable simulation of entire tinyOS applications," in SenSys '03: Proceedings of the 1st International Conference on Embedded Networked Sensor Systems. New York: ACM, 2003, pp. 126–137.

[12] E. Perla, A. O. Cath´ain, R. S. Carbajo, M. Huggard, and C. McGoldrick, "PowerTOSSIM z: Realistic energy modelling for wireless sensor network environments," in PM2HW2N '08: Proceedings of the 3rd ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks. New York: ACM, 2008, pp. 35–42.

[13] B. Titzer, D. Lee, and J. Palsberg, "Avrora: Scalable sensor network simulation with precise timing," in Fourth International Symposium on Information Processing in Sensor Networks, 2005. IPSN 2005, pp. 477–482.

[14] O. Landsiedel, K. Wehrle, and S. Gotz, "Accurate prediction of power consumption in sensor networks," in EmNets '05: Proceedings of the 2nd IEEE Workshop on Embedded Networked Sensors. Washington, D.C.: IEEE Computer Society, 2005, pp. 37–44.

[15] J. Hill and D. Culler, "A wireless embedded sensor architecture for system-level optimization," in Technical report, Berkeley, CA: Computer Science Department, University of California at Berkeley, 2001.

[16] J. Polley, D. Blazakis, J. McGee, D. Rusk, and J. Baras, "ATEMU: A fine-grained sensor network simulator," in 2004 First Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004 (IEEE SECON), 2004, pp. 145–152.

[17] S. Mahlknecht, J. Glaser, and T. Herndl, "PAWiS: Towards a power aware system architecture for a soc/sip wireless sensor and actor node implementation," in Proceedings of 6th IFAC International Conference on Fieldbus Systems and ¦eir Applications, 2005, pp. 129–134.

[18] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, “Cross-level sensor network simulation with Cooja,” in Proceedings 2006 31st IEEE Conference on Local Computer Networks, 2006, pp. 641–648.

[19] P. M. Glatz, P. Meyer, A. Janek, T. Trathnigg, C. Steger, and R. Weiss, “A measurement platform for energy harvesting and software characterization in WSNs,” in IFIP/IEEE Wireless Days, Nov. 2008, pp. 1–5.

[20] P. M. Glatz, L. B. Hörmann, and R. Weiss, “Designing perpetual energy harvesting systems explained with RiverMote: A wireless sensor network platform for river monitoring,” Electronic Journal of Structural Engineering, Special Issue: Wireless Sensor Networks and Practical Applications, pp. 55–65, 2010.

[21] L. Mateu and F. Moll, “System-level simulation of a self-powered sensor with piezoelectric energy harvesting,” International Conference on Sensor Technologies and Applications, vol. 0, pp. 399–404, 2007.

[22] A. Seyedi and B. Sikdar, “Modeling and analysis of energy harvesting nodes in wireless sensor networks,” in 46th Annual Allerton Conference on Communication, Control, and Computing, 2008, pp. 67–71.

[23] G. Merrett, N. White, N. Harris, and B. Al-Hashimi, “Energy-aware simulation for wireless sensor networks,” in 6th Annual IEEE Communications Society Conference on Sensor, Mesh, and Ad Hoc Communications and Networks, 2009. (SECON), 2009, pp. 1–8.

[24] P. De Mil, B. Jooris, L. Tytgat, R. Catteeuw, I. Moerman, P. Demeester, and A. Kamerman, “Design and implementation of a generic energy-harvesting framework applied to the evaluation of a large-scale electronic shelf-labeling wireless sensor network,” EURASIP J. Wireless Commun. Netw., vol. 2010, pp. 7:1–7:14, February 2010. Online at: http://dx.doi.org/10.1155/2010/343690

[25] P. M. Glatz, C. Steger, and R. Weiss, “Tospie2: Tiny operating system plug-in for energy estimation,” in IPSN ’10: Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks. New York: ACM, 2010, pp. 410–411.

[26] Duracell, “Entire mno2 technical bulletin collection.” Online at:

http://www1.duracell.com/oem/Pdf/others/ATB-full.pdf

[27] V. Pop, H. Bergveld, P. Notten, and P. Regtien, “State-of-the-art of battery state-ofcharge determination,” Measurement Science and Technology, vol. 16, no. 12, pp. R93– R110, 2005. Online at: http://doc.utwente.nl/62192/

[28] B. Schweighofer, K. Raab, and G. Brasseur, “Modeling of high power automotive batteries by the use of an automated test system,” IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 4, pp. 1087–1091, 2003.

[29] S. Abu-Sharkh and D. Doerffel, “Rapid test and non-linear model characterisation of solid-state lithium-ion batteries,” Journal of Power Sources, vol. 130, no. 1–2, pp. 266–274, 2004. Online at: http://www.sciencedirect.com/science/article/B6TH1-4BK2FX3-1/2/4938d1b3771bb71f4989b7010f4d160a

[30] Z. Salameh, M. Casacca, and W. Lynch, “A mathematical model for lead-acid batteries,” IEEE Transactions on Energy Conversion, vol. 7, no. 1, pp. 93–98, Mar. 1992.

[31] D. Linden, Handbook of Batteries, 3rd ed. New York: McGraw-Hill, 2002.

[32] M. Pedram and Q. Wu, “Design considerations for battery-powered electronics,” in Proceedings of the 36th annual ACM/IEEE Design Automation Conference, ser. DAC ’99. New York: ACM, 1999, pp. 861–866. Online at http://doi.acm.org/10.1145/309847.310089

[33] P. Nuggehalli, V. Srinivasan, and R. Rao, “Energy efficient transmission scheduling for delay constrained wireless networks,” IEEE Transactions on Wireless Communications, vol. 5, no. 3, pp. 531–539, March 2006.

[34] C. Ma and Y. Yang, “Battery-aware routing for streaming data transmissions in wireless sensor networks,” Mob. Netw. Appl., vol. 11, pp. 757–767, October 2006. Online at: http://dx.doi.org/10.1007/s11036-006-7800-2

[35] C.-F. Chiasserini and R. Rao, “Improving battery performance by using traffic shaping techniques,” IEEE Journal on Selected Areas in Communications, vol. 19, no. 7, pp. 1385–1394, July 2001.

[36] YEG Components, “HC power series ultracapacitors datasheet,” Maxwell Technologies, San Diego, CA.

[37] EPCOS, “Ultracap single cell 5 F/2.3V B49100A1503Q000 data sheet.” Online at: http://www.epcos.com/inf/20/35/ds/B49100A1503Q000.pdf

[38] N. White and S. Beeby, “Energy Harvesting for Autonomous Systems,” Boston: Artech House, June 2010.

[39] M. Belleville, E. Cantatore, H. Fanet, P. Fiorini, P. Nicole, M. Pelgrom, C. Piguet, R. Hahn, C. V. Hoof, R. Vullersand, and M. Tartagni, “Energy autonomous systems: Future trends in devices, technology, and systems,” Paris: Cluster for Application and Technology Research in Europe on Nanoelectronics (CATRENE), 2009.

[40] B. Chu, Selecting the Right Battery System for Cost-Sensitive Portable Applications While Maintaining Excellent Quality, Chandler, AZ: Microchip Technology Inc.

[41] M. D. Stoller, S. Park, Y. Zhu, J. An, and R. S. Ruoff, “Graphene-Based Ultracapacitors,” Nano Letters, vol. 8, no. 10, pp. 3498–3502, 2008.

[42] Z.-J. Fan, J. Yan, T. Wei, G.-Q. Ning, L.-J. Zhi, J.-C. Liu, D.-X. Cao, G.-L. Wang, and F. Wei, “Nanographene-Constructed Carbon Nanofibers Grown on Graphene Sheets by Chemical Vapor Deposition: High-Performance Anode Materials for Lithium Ion Batteries,” ACS Nano, vol. 5, no. 4, pp. 2787–2794, 2011.

[43] P. M. Glatz, C. Steger, and R. Weiss, “Design, simulation and measurement of an accurate wireless sensor network localization system,” in ¦e 5th ACM International Workshop on Performance Monitoring, Measurement and Evaluation of Heterogeneous Wireless and Wired Networks (PM2HW2N 2010), Bodrum, Turkey, October 2010.

[44] P. M. Glatz, L. B. Hörmann, C. Steger, and R. Weiss, “Designing sustainable wireless sensor networks with efficient energy harvesting systems,” in IEEE WCNC 2011– Service and Application (IEEE WCNC 2011), Cancun, Mexico, March 2011.

[45] P. M. Glatz, L. B. Hörmann, C. Steger, and R. Weiss, “MAMA: Multi-application middleware for efficient wireless sensor networks,” in 2011 18th International Conference on Telecommunications (ICT 2011), pp. 1–8, Ayia Napa, Cyprus, May 2011.

[46] M. Rahimi, R. Baer, O. I. Iroezi, J. C. Garcia, J.

Warrior, D. Estrin, and M. Srivastava, “Cyclops: In situ image sensing and interpretation in wireless sensor networks,” in Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems, SenSys ’05. New York: ACM, 2005, pp. 192–204. Online at: http://doi.acm. org/10.1145/1098918.1098939

12 Chapter 12: Energy Consumption Profile for Energy Harvested WSNs

[1] Crossbow IRIS motes. Online at: http://www.xbow.com/Products/productdetails. aspx?sid=264

[2] David Lindley, e Energy Should Always Work Twice. Nature, vol. 458, March 12, 2009.

[3] Nigel Jefferies, “Global vision for a wireless world,” 18th Meeting of WWRF, Helsinki, Finland, June 2007.

[4] Online at: http://www.eubusiness.com/topics/internet/ict-low-carbon/

[5] D.-A. Borca-Tasciuc, M. M. Hella, and A. Kempitiya, “Micro-power generators for ambient intelligence applications,” 4th International Workshop on Soft Computing Applications, Arad, Romania, June 15–17, 2010.

[6] Online at: http://www.news.cornell.edu/stories/May10/VibroWind.html

[7] Online at: http://web.mit.edu/newsoffice/2008/trees-0923.html

[8] T. Becker, M. Kluge, J. Schalk, T. Otterpohl, and U. Hilleringmann, “Power management for thermal energy harvesting in aircrafts,” Proceedings of IEEE Sensors, 2008.

[9] Online at: www.micropelt.com/

[10] Online at: www.mide.com/products/volture/v21bl.php

[11] EnOcean, e EnOcean GmBH, Germany. Online at: http://www.enocean.com/en/ home/

[12] Online at: www.cymbet.com/

[13] Online at: www.excellatron.com

[14] Online at:

[15] Online at: www.linear.com/

[16] Amit Sinha, Energy Aware Software, master’s thesis, Massachusetts Institute of Technology, Cambridge, MA, December 1999.

[17] Texas Instruments, MSP430. Online at: http://focus.ti.com/docs/prod/folders/print/msp430f1612.html

[18] IEEE 802.15.4-2006 Standard. Online at:

[19] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, “Power Management in Energy Harvesting Sensor Networks,” ACM Transactions on Embedded Computing Systems, vol. 6, no. 4, September 2007.

[20] Vijay Raghunathan, Aman Kansal, Jason Hsu, Jonathan Friedman, and Mani Srivastava, “Design considerations for solar energy harvesting wireless embedded systems,” Proceedings of 4th International Symposium on Information Processing in Sensor Networks (TPSN), April 15, 2005, Los Angeles, California.

[21] Konstantin Mikhaylov and Jouni Tervonen. “Energy efficient data restoring after power-downs for wireless sensor networks nodes with energy scavenging,” Proceeding of the 4 th IFIP International Conference: New Technologies, Mobility and Security (NTMS), Paris, France, February 2011.

[22] Clemens Moser, David Brunelli, Lothar Thiele, and Luca Benini, “Real time scheduling for energy harvesting sensor nodes,” ACM Real Time Systems, vol. 37, no. 3, December 2007.

13 Chapter 13: Radio Frequency Energy Harvesting and Management for Wireless Sensor Networks

[1] F. E. Little, J. O. McSpadden, K. Chang, and N. Kaya, “Toward Space Solar Power: Wireless Energy Transmission Experiments Past, Present and Future.” AIP Conference Proceedings of Space Technology and Applications International Forum, vol. 420, pp. 1225– 1233, 1998.

[2] D. Bouchouicha, F. Dupont, M. Latrach, and L. Ventura, “Ambient RF Energy Harvesting,” International Conference on Renewable Energies and Power Quality (ICREPQ’10), Granada (Spain), March, 2010.

[3] S. P. Beeby, M. J. Tudor, and N. M. White, “Energy Harvesting Vibration Sources for Microsystems Applications,” Measurements Science and Technology, vol. 17, pp. 175– 195, 2006.

[4] R. M. Dickinson, “Evaluation of a microwave high-power reception-conversion array for wireless power transmission,” Tech. Memo 33-741. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Sept. 1975.

[5] H. Hayami, M. Nakamura, and K. Yoshioka, “The Life Cycle CO_2 Emission Performance of the DOE/NASA Solar Power Satellite System: A Comparison of Alternative Power Generation Systems in Japan,” IEEE Transactions on Systems, Man, and Cybernetics Part C: Applications and Reviews, vol. 35, no. 3, August 2005.

[6] T. W. R. East, “Self-Steering, Self-Focusing Phased Array for SHARP,” Antennas and Propagation Society International Symposium, 1991, AP-S, Digest 24–28, pp. 1732– 1735, vol. 3, June 1991.

[7] RF HAMDESIGN Microwave equipments and parts. Online at:

[8] Y. Zhang, L. D. Kuhn, and M. P. J. Fromherz, “Improvements on Ant Routing for Sensor Networks,” Ant Colony, in Optimization and Swarm Intelligence, Lecture Notes Computer Science, 2004, 3172, pp. 289–313.

[9] P. X. Liu, “Data Gathering Communication in Wireless Sensor Networks Using Ant Colony Optimization,” 2004 IEEE International Conference on Robotics and Biomimetics, 2004, pp. 822–827.

[10] Y.-Feng Wen, Y.-Quan Chen, and M. Pan, “Adaptive ant-based routing in wireless sensor networks using Energy*Delay metrics,” Journal of Zhejiang University SCIENCE A, vol. 9, Mar. 2008, pp. 531–538.

[11] R. GhasemAghaei, M. A. Rahman, W. Gueaieb, and A. El Saddik, “Ant ColonyBased Reinforcement Learning Algorithm for Routing in Wireless Sensor Networks,” 2007 IEEE Instrumentation & Measurement Technology Conference (IMTC), May 2007, pp. 1–6.

[12] X. Wang, L. Qiaoliang, X. Naixue, and P. Yi, “Ant Colony Optimization-Based Location-Aware Routing for Wireless Sensor Networks,” in Proceedings of the ¦ird International Conference on Wireless Algorithms, Systems, and Applications (WASA’08), Springer-Verlag, Berlin, Heidelberg, vol. 5258, 2008, pp. 109–120.

[13] M. Paone, L. Paladina, M. Scarpa, and A. Puliafito, “A multi-sink swarm-based routing protocol for Wireless Sensor Networks,” in IEEE Symposium on Computers and Communications, July 2009, pp. 28–33.

[14] G. De-Min, Q. Huan-Yan, Y. Xiao-Yong, and W. Xiao-Nan, “Based on ant colony multicast trees of wireless sensor network routing research,” Journal of iet-wsn.org, vol. 2, 2008, pp. 1–7. Online at

[15] S. Xia and S. Wu, “Ant Colony-Based Energy-Aware Multipath Routing Algorithm for Wireless Sensor Networks,” in 2009 Second International Symposium on Knowledge Acquisition and Modeling, Nov. 2009, pp. 198–201.

[16] G. Wang, Y. Wang, and X. Tao, “An Ant Colony Clustering Routing Algorithm for Wireless Sensor Networks,” in 2009 ¦ird International Conference on Genetic and Evolutionary Computing, Oct. 2009, pp. 670–673.

[17] T. Le, K. Mayaram, and T. Fiez, “Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks,” IEE Journal of Solid-State Circuits, vol. 43, no. 5, pp. 1287–1302, May 2008.

[18] H. Jabbar, Y. S. Song, and T. D. Jeong, “RF Energy Harvesting System and Circuits for Charging of Mobile Devices,” IEEE Transaction on Consumer Electronics, Jan. 2010.

[19] C. Lu, V. Raghunathan, and K. Roy, “Micro-Scale Harvesting: A System Design Perspective,” in Proceedings

of the 2010 Asia and South Pacific Design Automation Conference (ASPDAC'10), IEEE Press: Piscataway, NJ, 2010.

[20] L. Tang and C. Guy, "Radio Frequency Energy Harvesting in Wireless Sensor Networks," in Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing (ICWCMC'09): Connecting the World Wirelessly, ACM: New York, 2009.

[21] J. A. Hagerty, T. Zhao, R. Zane, and Z. Popovic, "Efficient Broadband RF Energy Harvesting for Wireless Sensors," Colorado Power Electronics Center (COPEC), Boulder, CO, 2003.

[22] W. Seah and Y. K. Tan, "Review of Energy Harvesting Technologies for Sustainable Wireless Sensor Network," in Sustainable Wireless Sensor Networks, Y. K. Tan (ed.), pp. 15–43. Tech Publishing, Rijeka, Croatia, Dec. 2010.

[23] J. M. Gilbert and F. Balouchi, "Comparison of Energy Harvesting Systems for Wireless Sensor Networks," International Journal of Automation and Computing, vol. 5, no. 4, pp. 334–347, Oct. 2008.

[24] MICAz Datasheet. Online at: http://courses.ece.ubc.ca/494/files/MICAz_Datasheet. pdf

[25] Waspmote: Technical Guide-Libelium. Online at:

[26] Zigbee Protocol. Online at: http://wiki.kdubiq.org/kdubiqFinalSymposium/uploads/Main/04_libelium_smfkdubiq.pdf

[27] Imote2 Documents—WSN. Online at: http://www.cse.wustl.edu/wsn/images/e/e3/Imote2_Datasheet.pdf

[28] JN5139—Jennic Wireless Microcontrollers. Online at: http://www.jennic.com/products/wireless_microcontrollers/jn5139

[29] T. T. Le, "Efficient Power Conversion Interface Circuits for Energy Harvesting Applications," PhD disser., Oregon State University, Corvallis, 2008.

[30] Powercast Documentation. Online at: http://Powercastco.com/

[31] B. Dixon, "Radio Frequency Energy Harvesting." Online at: http://rfenergyharvesting. com/

[32] J. A. Shaw, "Radiometry and the Friis Transmission Equation." Online at: http://www.

[33] Wireless Power Calculator. Online at: http://Powercastco.com/wireless-power-calculator. xls

[34] Power Density. Online at:

[35] R. Struzak, "Basic Antenna Theory." Online at: http://wirelessu.org/uploads/ units/2008/08/12/39/5Anten_theor_basics.pdf

[36] N. Dusit, H. Ekram, M. R. Mohammad, and K. B. Vijay, "Wireless Sensor Networks with Energy Harvesting Technologies: A Game-Theoretic Approach to Optimal Energy Management," IEEE Wireless Communications, vol. 14, no. 4, pp. 90–96. September 2007.

[37] D. Waltenegus and P. Christian, Fundamental of Wireless Sensor Networks: Theory and Practice, New York: Wiley Series on Wireless Communication and Mobile Computing, pp. 207-213, 2010.

[38] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," in Proceedings of ACM Transactions on Embedded Computing Systems, vol. 6, September 2007, pp. 32–66.

[39] A. G. A. Elrahim, H. A. Elsayed, S. El Rahly, and M. M. Ibrahim, "An Energy Aware WSN Geographic Routing Protocol," Universal Journal of Computer Science and Engineering Technology, vol. 1, no. 2, Nov. 2010, pp. 105–111.

[40] W. Li, M. Chen, and M-M. Li, "An Enhanced AODV Route Protocol Applying in the Wireless Sensor Networks," Fuzzy Information and Engineering, vol. 2, AISC 62, pp. 1591–1600, 2009.

[41] T. C. Camilo, Carreto, J. S. Silva, and F. Boavida, "An Energy-Efficient Ant Based Routing Algorithm for Wireless Sensor Networks," In Proceedings of 5th International Workshop on Ant Colony Optimization and Swarm Intelligence, Brussels, Belgium, pp. 49–59, 2006.

[42] C. Alippi, G. Anastasi, M. D. Francesco, and M. Roveri, "Energy management in Wireless Sensor Networks with Energy-Hungry Sensors," IEEE Instrumentation and Measurements Magazine, vol. 12, April 2009, pp. 16–23.

[43] X. Jiang, J. Taneja, J. Ortiz, A. Tavakoli, P. Dutta, J. Jeong, D. Culler, P. Levis, and S. Shenker, “Architecture for Energy Management in Wireless Sensor Networks,” ACM SIGBED Review, Special issue on the workshop on wireless sensor network architecture, vol. 4, no. 3, pp. 31-36, July 2007.

[44] K. Kalpakis, K. Dasgupta, and P. Namjoshi, “Maximum Lifetime Data Gathering and Aggregation in Wireless Sensor Networks,” in Proceedings of IEEE International Conference on Networking, vol. 42, no. 6, August 2003.

[45] NS2 installation on Linux. Online at: http://paulson.in/? p=29

[46] NS-2 Module for Ant Colony Optimization (AntSense). Online at: http://eden.dei. uc.pt/~tandre/antsense/