ENERGY MODELING FOR WIRELESS INTERNET ACCESS

†Debashis Panigrahi ‡Anand Raghunathan ‡Ganesh Lakshminarayana †Sujit Dey
†Dept. of Electrical and Computer Engg., University of California, San Diego, CA
‡C & C Research Labs, NEC USA, Princeton, NJ

Abstract

Wireless access to the internet is projected to be one of the driving factors behind the growth in the use of wireless handheld devices as well as wireless communication services. As improvements in wireless technologies enable applications with rich functionality and higher bandwidth requirements, battery capacity threatens to become a primary bottleneck to wireless applications. In order to address challenges imposed by the battery constraint, it is necessary to develop techniques for design of energy efficient network applications in addition to previous work on low power hardware and network protocols. As a first step towards that end, we present in this paper, a methodology for modeling the energy consumption of wireless internet access. We have applied the methodology to develop an energy model for the PalmVII handheld using the Palm.Net wireless environment. We also demonstrate, through examples, the use of the developed model in designing energy efficient applications for wireless internet access.

1 Introduction

Wireless access to the internet and web-based applications is projected to be one of the primary driving factors behind the adoption and growth in the use of wireless handheld devices and network services. Mobile internet access over 3G wireless networks is projected to become pervasive and even overtake fixed network access, while wireless data traffic is simultaneously expected to overtake wireless voice traffic, in the next four to five years [1].

The increase in communication bandwidth provided by 3G wireless networks, together with the increasingly complex protocols employed, and the rich functionality of wireless internet based applications, will elevate battery constraints to a design challenge of primary importance. Battery capacity is projected to increase at a much slower rate than the energy requirements of functionality-rich, high-performance handheld devices [2, 3]. Furthermore, the energy requirements for wireless internet access are significantly higher when compared to voice telephony (*e.g.*, based on [4], an increase of 78-1000X). The above factors make it critical to consider energy consumption and battery life during the design of radio and handset appliance architectures as well as the software that runs on them, including network protocols and networked applications.

Recognizing the energy challenges mentioned above, researchers have started working on various techniques to improve the energy efficiency of wireless computing and communications. Techniques for low-power hardware implementations of various components of wireless handhelds, including processors, memory, displays, and radio transceivers, have been proposed. While optimizing the hardware architecture and implementation does yield considerable energy savings, it is equally important to consider energy issues during the design of the network protocols and applications. Techniques for low-power protocols at the physical layer [5, 6], data link layer [7, 8], network layer [9, 10], and transport layer [11] have been recently investigated. Our work attempts to model energy consumption at the application layer in terms of the communication primitives directly used in wireless internet applications, hence it can provide insights that lead to additional energy reductions through application-level optimizations (some examples of which are presented later in this paper).

In the area of energy measurement and modeling for handheld devices, initial work focused on characterizing the power consumption of PDAs without wireless network access capabilities [12, 13]. Power measurements on network interfaces in handheld devices were presented in [14], which indicated that the network interface card can account for a large part of the total handheld power consumption. Further, the authors point out the need for modeling and optimizing energy consumption using application-level information.

Paper Overview and Contributions
The aim of our work is to study techniques for the design of energy efficient networked applications, with a focus on wireless access to the internet. As a first step towards that end, we present in this paper, techniques for energy modeling of wireless internet access. Given a handheld appliance that is capable of internet access through an available wireless data service, we use an energy measurement system based on PC data acquisition technology to study the energy consumption of the appliance and its variation with various parameters, including the amount of data sent and received, network latency, the use of caching on the handheld to locally store previously accessed web pages, and the use of compression and encryption for transmission over wireless channel. We have applied this methodology to develop an energy model for wireless web browsing us-

ing a Palm VII handheld [15] and the Palm.Net wireless network [16].

Based on the energy models developed and the insights they provide, we illustrate techniques for energy efficient (battery friendly) web access through examples, including profile-based partitioning of information into web pages, and energy driven pre-fetching of web pages. Our experiments demonstrate that optimizations based on other criteria such as minimizing latency or minimizing the total amount of data sent/received over the wireless channel do not necessarily lead to minimum energy consumption. We believe that the proposed energy modeling techniques will be useful in the design of energy efficient network applications and architectures for mobile wireless internet access.

2 Energy Model for Wireless Web Application

In this section, we present our energy model, which is built using data accumulated by measuring the energy consumed by a Palm VII handheld for various internet access patterns. First, we describe the experimental setup used to measure the energy consumed, and then we present our energy model, which is based on the above experiments.

2.1 Experimental Setup

We describe the wireless access architecture of Palm.Net, the wireless Internet Service Provider (ISP) used by the Palm VII handheld, before presenting the data acquisition framework used for energy measurements.

Palm.Net Wireless Access Architecture: The wireless environment used for PalmVII wireless internet access is shown in Figure 1. A key component of the wireless environment is the wireless gateway server that resides at the 3Com data centers. The handhelds communicate with the wireless gateway servers using the BellSouth Wireless Data network [16]. The wireless gateway servers use standard internet and security protocols (TCP, HTTP, and SSL) to communicate with web servers over the wired network, where as on the wireless channel, protocols designed to tolerate channel errors, low bandwidth, and high latency are employed, such as reliable UDP [16].

Data Acquisition: The energy consumption of the Palm VII handheld is measured by integrating the product of the supply voltage and the current drawn over time. The Palm VII handheld has two sources of power supply: (i) a NiCd re-chargeable battery, operating at voltage 5V, is used to supply power to the radio transceiver, and (ii) two AAA alkaline batteries, operating at voltage 3V, are used to supply power to the rest of the handheld. Hereafter, the NiCd battery is termed

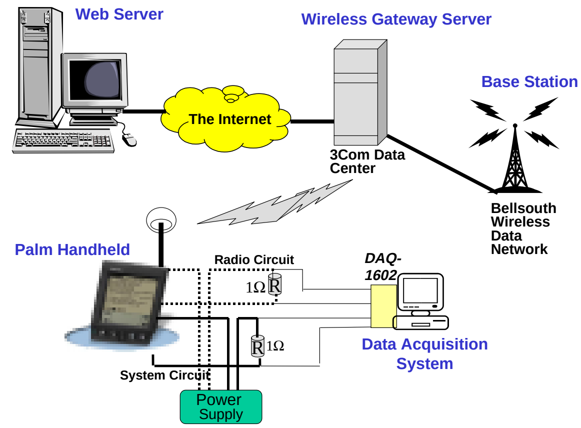


Figure 1: Palm.Net Wireless Environment and Experimental Setup for Energy Measurements

as the *radio battery*, and the AAA alkaline batteries are collectively referred to as the *system battery*.

Figure 1 shows the setup used for energy measurements. For the purpose of energy measurements, the radio and system batteries were removed from the handheld and replaced by laboratory DC power sources of the same voltage. Hence, the supply voltages were assumed to be constant over the duration of measurement. The currents drawn from the radio and system batteries were measured by sampling the voltage drop across resistances connected in series to the power supplies, as shown in Figure 1. The voltage drops were sampled using the DAQ-1602/PCI data acquisition card [17], operating at 1K samples/sec. The sampled data can be analyzed and displayed using the DaqEZ software [17]. A current profile displayed using the DaqEZ software is shown in Figure 2. In the figure, the top waveform corresponds to the current drawn from the radio battery, while the bottom waveform corresponds to the current drawn from the system battery.

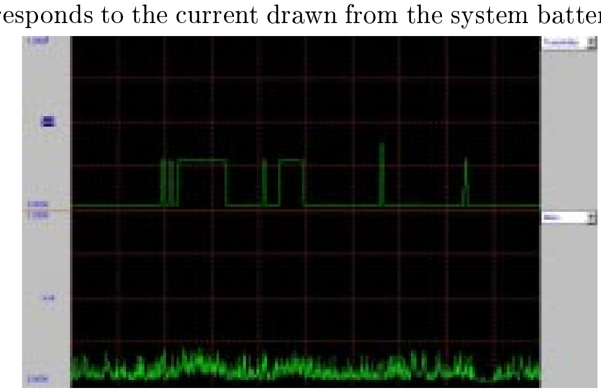


Figure 2: An Example Current Waveform

For our energy measurements, we developed a testbed that consists of a client test program running on the Palm VII handheld, and a web application that resides on a web server. The client test programs were developed using the communication primitives available in the PalmOS library [18]. We executed several client test programs by changing the application level parameters of interest, and measured the energy consumption for each execution.

2.2 Energy Measurements and Analysis

In this section, we present our energy model for wireless web applications. First, we discuss various parameters which impact the energy consumption. We then present a mathematical model for energy consumption, based on these parameters. We use the data gathered by the experimental setup presented earlier and perform regression fitting in order to derive the values of the constants/coefficients used in our energy model.

The factors that affect the energy consumption for wireless internet access can be classified into two categories : (i) application level parameters, and (ii) network related parameters. Application level parameters correspond to the parameters that are determined by the application level communication primitives used in wireless web based applications. Figure 3 shows a flow of PalmOS system calls (communication primitives) used in a wireless web based application along with the parameters. The application level parameters considered in this model include volume of data transmitted/received, the compression and encryption schemes employed, and the use of caching. Network-related parameters include the wireless channel conditions (signal strength), noise level, and latency. We now present the results of experiments designed to analyze the effect of these parameters on the energy consumption.

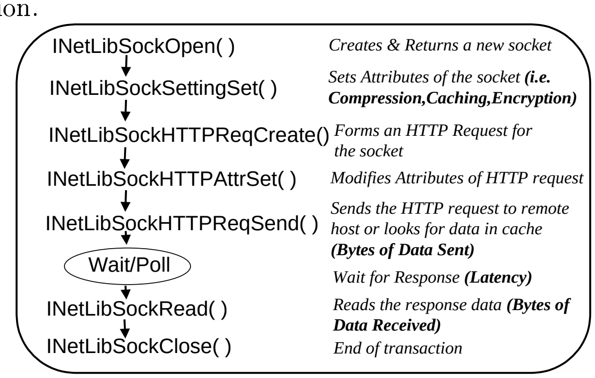
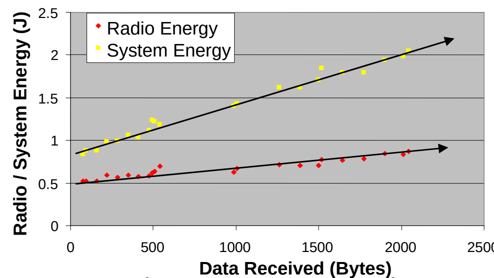
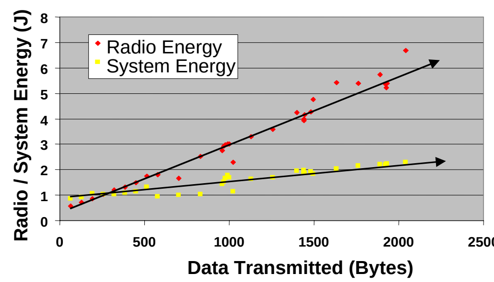


Figure 3: Application level communication primitives and parameters for PalmOS web based applications

Volume of transmitted/received data: We performed several experiments to study the dependency of energy on the volume of data transferred by accessing web pages of different sizes (varying the bytes of data received), and by filling forms with varying amounts of information (varying the bytes of data to be transmitted). In order to minimize measurement errors, each experiment was iterated multiple times, and the results were averaged. Figure 4(a) and 4(b) show the dependency of the radio energy (drawn from the radio battery) and the system energy (drawn from the system battery) consumption on the amount of data transmitted or received. It is important to note that, for receiving data, the radio energy is always less than the system energy, where as in case of transmitting data the radio energy is significant compared to the system energy. In general, the energy varies linearly with the amount of data sent or received, with a constant overhead for establishing the HTTP connection.



(a) Dependency of energy on the volume of data received



(b) Dependency of energy on the volume of data transmitted

Figure 4: Effect of the volume of data on energy consumption

Caching Effects: Caching can significantly reduce the energy consumed during wireless web transactions as it replaces a network transaction with a local access to the cached data. Caching can not affect the energy consumed in transmitting data (*e.g.*, data generated as result of filling out forms in web pages), but can have a significant effect in typical web sessions (dominated by receiving data). To study the effect of caching on energy consumption, we compared the energy consumed by accessing the page from the web server with the energy spent to retrieve it from local cache. Figure 5 shows

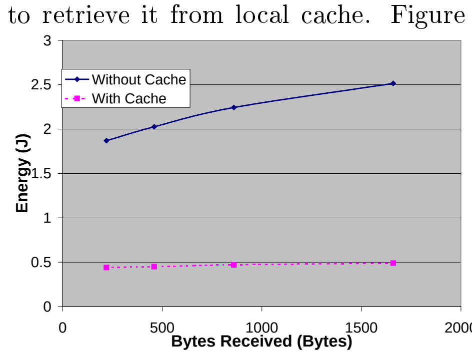


Figure 5: Effect of caching on energy consumption

the effect of caching on the energy consumption when web pages of different sizes are accessed. Note that, for receiving data, the presence of caching reduces the energy consumption drastically.

Compression and Encryption: Compression of data can potentially decrease the energy consumed in transmission by reducing the amount of data transferred. On the other hand, encryption typically increases the amount of data transfered. Additionally, for compression and encryption, energy is consumed at the handheld in compressing/decompressing and encrypting/decrypting the data. It is important to note that the energy variation due to compression or encryption strongly depends on the algorithms used.

Figure 6 shows the effect of the *ConvCML* compression algorithm, one of the compression algorithms supported by the PalmVII. In the Palm.Net environment, compression is currently used only for the communication from the wireless gateway servers to handhelds. It can be noted that for data sizes more than 500 Bytes, the energy consumption without compression is less than the energy consumed in receiving compressed data. This is due to that fact that the energy consumed in decompressing data outweighs the energy savings resulting from reduced amounts of data.

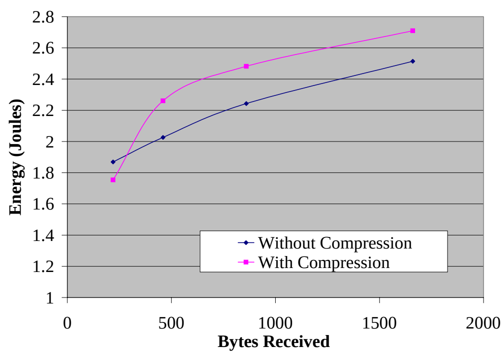


Figure 6: Effect of compression on energy consumption

Network latency and signal strength. Network latency is one of the parameters related to the wireless network environment that can significantly affect the energy consumption. In our context, the network latency is defined as the delay from the time when the HTTP request is made by the application to the time when the first packet containing the response is received. Network latency is caused by the wireless channel as well as the wired network. The handheld consumes energy during this period while it is waiting for the response. Our measurements indicated that the energy overhead due to network latency increases linearly with the duration of latency.

Signal strength is another parameter that can potentially affect the energy consumption. The main factors affecting the signal strength include the distance from the the base station, channel noise *etc.* As the signal strength decreases, the radio tries to increase the power level of the transmitted signal, thus increasing the total energy consumption. It was difficult for us to evaluate the effect of signal strength on energy consumption since the signal strength is not easily available to direct control by end users. However, analytical models for the dependency between energy and distance from the base station can be used, as in [19].

2.3 Energy Model

Based on the above observations and experimental results, we performed regression analysis on the data collected to get an energy model for HTTP transactions. In the regression, we consider the various parameters identified above as the independent variables, and energy consumption as the dependent variable. The resulting energy model is presented in Figure 7. Each term in the energy model corresponds to a distinct operation in one web transaction, namely connection setup, waiting for the response, receiving, transmission, encryption/decryption, and compression/decompression. As discussed earlier, the option of encryption and compression affects the actual number of bytes to be received or transmitted at the low level; encryption typically increases the amount of data where as compression reduces it. In the Palm environment, compression is currently used only for data transfer from the base station to the mobile handheld, hence compression does not affect the number of bytes to be transmitted from the handheld. The co-efficients of the energy model are derived from the data gathered using the experiments discussed earlier. Next, we present results of experiments validating the energy model developed for wireless application.

2.4 Validation of the Energy Model

In order to validate the energy model, we conducted experiments to measure the energy consumption of a web session and compared it with the energy estimated using our energy model. Table 1 presents the results of the experiment for different web applications, *i.e.*, a news web-site (NEWS), a travel web-site (TRAVEL), and a personal homepage (PERSONAL). Column 2 reports the energy measured using the data acquisition framework, and column 3 presents the the energy estimated using the energy model. It can be observed that the energy model estimates the energy consumption of web based applications very accurately (maximum error of 6%).

Table 1: Validation of the energy model

Application	Measured Energy(J)	Estimated Energy(J)	% Error
NEWS	2.983	2.8	6.0
TRAVEL	2.219	2.2	5.0
PERSONAL	0.735	0.73	0.5

$$E(R,T,C,L,S,Enc,Comp) = C_0 + C_l * L + C_r * (C * R * Enc/Comp) + C_t * (T * Enc) + C_{enc} * T + C_{comp} * R$$

where

R	: data received in bytes	C_0	: co-efficient related to connection overhead (0.002)
L	: average network latency in secs	C_r	: co-efficient related to recv. (0.0008 varies with S)
S	: Signal strength	$Comp$	: Compression factor (>=1)(1 if no compression)
T	: data transmitted in bytes	Enc	: Encryption factor (>=1)(1 if no encryption)
C_l	: co-efficient of idle waiting (0.09)	C_t	: co-efficient related to tran. (0.0035 varies with S)
C	: option of caching	C_{enc}	: Encryption energy per byte (0 if encryption off)
E	:Energy Consumed in Joules	C_{comp}	: Compression energy per byte (0 if compression off)

Figure 7: Energy model for wireless internet access for Palm

3 Application of the Energy Model

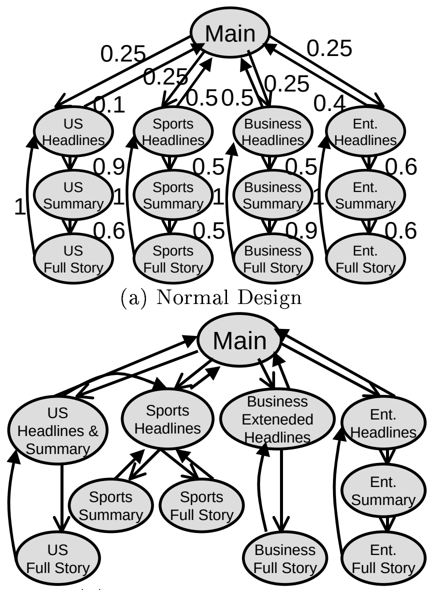
In this section, we demonstrate using two case studies how our energy model can be used to design energy efficient web based applications. The first example considers content design of a news-related web site while the second web site considers pre-fetching, a technique commonly used to improve the latency of web access.

3.1 Energy Efficient Web site Design

Consider a news website for the Palm VII handheld that is organized in a hierarchical manner as described next. The home page contains links to different news categories (*e.g.*, such as politics, sports *etc.*). For each category, headlines are presented on a separate web page. Summaries for each news article can be accessed by following links from the headlines page. The full stories constitute the last layer in the hierarchical structure. Figure 8(a) shows the above organization of content for a typical website, where each node represents one web page and each edge corresponds to a link.

The wireless website design can be made more energy efficient by optimally partitioning the information into different web pages, and organizing the web pages to best suite the access patterns of users. So, the first step in designing an energy efficient website would be to model the user behavior. The user access pattern can easily be modeled by collecting access information at the web server, and analyzing the accesses to build a high level access model for the website. In our experiments, we developed a probabilistic model for the user access pattern based on the user information collected at the server side by assigning a probability for each edge in the graph model, as shown in Figure 8(a).

After careful study of the above access patterns for a news website, we designed an alternate news website taking into account the user access patterns and access patterns in each categories. Figure 8(b) shows the alternate energy efficient organization of the content in the news-related website. Our experimental energy estimation indicated that, on the average, web sessions accessing the original website design of Figure 8(a) consumed 27.1J, whereas in case of the optimized website (Figure 8(b)), the energy consumption was 21.97J, an energy improvement of 27.1%.



(a) Normal Design

(b) Energy Efficient Design

Figure 8: Organization of Content in a news-related website

The above example illustrated that judicious design of a website based on access statistics can lead to significant improvements in the energy consumption of a handheld that accesses it.

3.2 Energy-Latency Tradeoffs in Pre-fetching

One of the techniques to partially overcome the bandwidth limitations of web access is web page pre-fetching. In web page pre-fetching, while the user views the current web page, a web page is automatically accessed by choosing one link from the current web page. Pre-fetching of web pages is known to have a significant impact on the latency of internet access over low bandwidth networks [20]. However, pre-fetching may increase the energy consumption by sometimes pre-fetching web pages that will never be accessed. Hence, there is a tradeoff between the energy consumed and the average latency depending on the pre-fetching algorithm. To our knowledge, such a tradeoff has not been quantitatively demonstrated or explored in the literature.

In order to study the effect of pre-fetching algorithms on the energy-latency tradeoff, we performed energy and latency estimation for a website access while varying pre-fetching algorithm used. We consider a generic class of pre-fetching algorithms that use the probabilities of accessing each link in a web page to decide which page(s) to pre-fetch. We characterize this generic class of pre-fetching algorithms by a parameter called the *pre-fetching threshold*, which can take any value between 0 and 1. A threshold value of 0 results in the background pre-fetching of all links while a user reads the information contained in a web page. Larger values of the threshold indicate more conservative policies, while a value of 1 indicates no pre-fetching at all.

Figure 9 shows the dependency of energy and latency on the *pre-fetching threshold*. As expected, the latency of communication increases with the *pre-fetching threshold*. However, the dependency of energy on the *pre-fetching threshold* follows a different trend. Pre-fetching, if done optimally, can potentially reduce the energy consumption because the energy consumed in waiting for the response (the idle energy due to network latency) can be avoided by pre-fetching while the user is reading the current web page. However, excessive pre-fetching also leads to wasted energy. It can be seen from Figure 9 that the net result of these conflicting factors is that the energy consumption is optimal in the middle region (threshold probability of around 0.6).

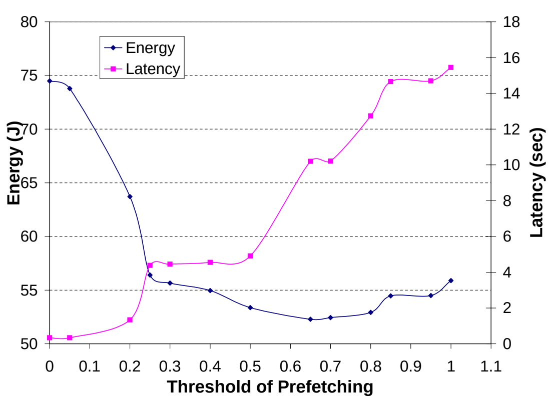


Figure 9: Effect of Pre-Fetching on Latency and Energy

The above two case studies demonstrate the utility of the energy modeling techniques proposed in this paper in the design energy efficient web-based applications.

4 Conclusion

In this paper, we presented an application level energy model for wireless internet access as provided by the Palm VII handhelds based on experimental measurements. The energy model takes into account application level parameters such as the amount of data transfered, use of encryption/compression, *etc.*, as well as network parameters such as latency. Through two case studies, we also demonstrate how the energy model developed can be used for energy efficient wireless web-based application design.

References

[1] L. Ericsson, "Mobile subscribers survey," 1999.

[2] R. Powers, "Batteries for Low Power Electronics," *Proceeding of the IEEE*, vol. 83, pp. 687–93, Apr. 1995.

[3] H. A. Kiehne, *Battery Technology Handbook*. Marcel Dekker, 1989.

[4] D. Raychaudhuri, "Wireless atm networks: Technology status and future directions," *Proceedings of the IEEE*, vol. 87, Mar. 1999.

[5] P. Cherriman and L. Hanzo, "Error-rate based power-controlled multimode h.263-assisted video telephony," in *IEEE Transaction on Transactions of Vehicular Technology*, vol. 48, pp. 1726–38, Sept. 1999.

[6] G. Hanington, P. Chen, V. Radisic, T. Itoh, and P. Asbeck, "Microwave power amplifier efficiency improvement with a 10mhz hbt dc-dc converter," in *IEEE MTT-S International Microwave Symposium Digest*, vol. 2, pp. 589–92, 1998.

[7] K.M.Sivalingam, M. Srivastava, P. Agrawal, and J.-C. Chen, "Low-power access protocols based on scheduling for wireless and mobile atm networks," in *Proc. of IEEE Universal Personal Communications*, pp. 420–33, Oct. 1997.

[8] P. Lettieri, C. Schurgers, and M. Srivastava, "Adaptive link layer strategies for energy efficient wireless networking," *Wireless Networks*, vol. 5, no. 5, pp. 339–55, 1999.

[9] S. Singh, M. Woo, and C. Raghavendra, "Power-aware routing in mobile ad hoc networks," *Proceeding of MOBICOM*, pp. 181–90, Oct. 1998.

[10] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient routing protocols for wireless microsensor networks," in *Proc. of Hawaii International Conference on System Sciences*, Jan. 2000.

[11] R. Kravets and P. Krishnan, "Power management techniques for mobile communication," *Proceeding of MOBICOM*, pp. 157–68, Oct. 1998.

[12] K. Farkas, J. Flinn, G. Back, D. Grunwald, and J. Anderson, "Quantifying the energy consumption of a pocket computer and a java virtual machine," *Proceeding of ACM SIGMETRICS*, 2000.

[13] T. L. Cignetti, K. Komarov, and C. S. Ellis, "Energy estimation tools for the palm," in *Proc. ACM MSWiM 2000 : Modeling, Analysis and Simulation of Wireless and Mobile Systems*, pp. 96–103, 2000.

[14] M. Stemm, P. Gauthier, D. Harada, and R. Katz, "Reducing Power Consumption of Network Interfaces in Hand-Held Devices," *Proceeding 3rd International Workshop on Mobile Multimedia Communications*, Sept. 1996.

[15] "PalmVII white paper." http://www.palm.com/pr/palmvii/7whitepaper.pdf, accessed Dec. 2000.

[16] "Bellsouth wireless data network services." http://www.bellsouthwd.com/solutions/personal_solutions.html#palm, accessed Dec. 2000.

[17] "Daq-1602 pci data aquisition card." http://www.quatech.com/shopquatech/products/prod419.asp, accessed Feb. 2001.

[18] "Palmos 3.0 software developement kit." http://www.palmos.com/dev/tech/tools/sdk30.html, accessed Dec. 2000.

[19] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient routing protocols for wireless microsensor networks," in *Proc. Hawaii International Conference on System Sciences (HICSS '00)*, Jan. 2000.

[20] T. S. Loon and V. Bharghavan, "Alleviating the latency and bandwidth problems in www browsing," *Proceedings of USENIX Symposium for Internet Technologies and Systems*, Dec. 1997.