Development and Analysis of Power Behavior for Embedded System Laboratory

Shanq-Jang Ruan
Dept. of Electronic Engineering,
National Taiwan University of Sci. & Tech.
No. 43, Sec. 4, Keelung Rd., Taipei 106, Taiwan
+886-2-27376411
sjruan@mail.ntust.edu.tw

Yi-Ruei Lai
Dept. of Electronic Engineering,
National Taiwan University of Sci. & Tech.
No.43, Sec. 4, Keelung Rd., Taipei 106, Taiwan
+886-2-27333141 ext. 7204
M9302131@mail.ntust.edu.tw

ABSTRACT
With the widespread use of portable systems, power dissipation has become a major concern of battery-driven embedded system design. This paper introduces several fundamental techniques to measure power consumption and analyze the power behavior of the embedded system. Some experiments based on the theories and concepts introduced in this class are provided to help students to build their own power measurement system for embedded systems. The target of this work is to develop an undergraduate laboratory course for teaching power analysis of embedded system to the students in electrical and computer engineering. They will find it very helpful to understand system-level low power design before they enter the field.

Keywords
Power Analysis, Power Behavior, Embedded System.

1. INTRODUCTION
In recent years, embedded systems are already used in a diverse range of products, including PDAs, cell phones, GPS, and smart cards, etc. Because of the tight energy constraints, power aware design is always a popular research topic. Therefore, energy efficiency must be considered in all phases of system design. In addition to constant improvements in battery technology, there are also rapid developments in processors and LCDs in terms of power consumption. Although [4] proposed a low power electronic design course that introduces several fundamental low power circuit design techniques, it is only for graduate students and VLSI hardware design. As the electronic low power techniques are comprehensively applied to more and more embedded system, an understanding of the power behavior is necessary for these students. Although most textbooks on embedded system include some discussions of power-aware design, there is a clear need for complete system-level low-power design skills within undergraduate education in electrical and computer engineering.

Recently, system-level power reduction has become recognized as the most efficient way to achieve low power [1], [2], [3]. Our laboratory course is devised to provide students with exploration of the effect of different system-level design decisions on energy consumption. This integrated laboratory introduces students to learn the basic knowledge and skills of low power design and system power measurement. Then the advanced concepts can help them to apply these techniques to practical electronic system design in terms of power consumption. By leading students to build their own power measurement systems and find out the power behaviors of the real embedded systems, this laboratory teaches students how to measure the power consumption accurately, store the data for analyzing, and the meaning of obtained value.

Even though high-level power aware design does not need to consider tiny power changes, we still take care in abstraction of low-level behaviors for the derivation of a power saving policy. The power behaviors can differentiate the quality and effectiveness of high-level power reduction practices for embedded systems. Furthermore, energy-efficient software design requires developers to understand the characteristics of power consumption and energy impact of software design decisions. Our course focus on software, with emphasis on the power behavior and the difference of energy cost among each kind of algorithm. In addition, the ability to efficiently analyze battery life time under different design choices of application software is an important aid in designing battery-efficient systems.

This course covers experimental techniques in the measurement of power consumption, statistical analysis, errors in measurements, and signal processing. LabVIEW enables data acquisition and control system parameters. We provide some experiments, such as power evaluation of the PDA, power analysis of computer games for handheld computer, and wireless communication on the Internet phone, to introduce students to understand the measurement flow by the computer-based data acquisition (DAQ) system. With a series of experiments, students learn basic experimental techniques to use sensor for various battery-powered embedded systems. Then students can easily build their own power module by writing LabVIEW programs.

In brief, the target of our work is to develop an undergraduate laboratory course for power analysis of embedded system. This course provides students in electrical and computer engineering with the power measurement of embedded system and the basic concepts of low power system design through several experiments including application software, various power modes of PDA and wireless Internet telephony. Students will have the basic knowledge and skills for further research topics in low power embedded system design after taking this course.

2. POWER MEASUREMENT SYSTEM
System-level power/performance optimization is a crucial element of embedded system design. To understand the energy dissipation of the embedded system, we have to build a power measurement system. A handheld data acquisition system was designed and built for use in an undergraduate engineering course [5]. [6] proposed an instrumentation and experimental methods

for mechanical engineering program at the University of the Pacific. Our work is different from that course. We focus on teaching students step by step to build their own measurement system for system level power analysis. Figure 1 shows the structure of the power measurement system that we use in this course. We can observe that Data acquisition (DAQ) system is the key component in the overall flow. In the following subsections, we will detail some LabVIEW based exercises and experiences.

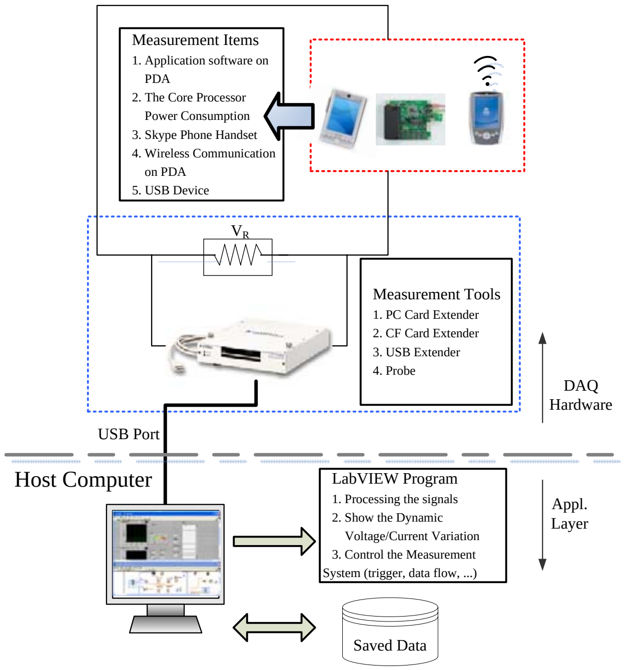

Figure 1. The power measurement flow in our course

2.1 DAQ Hardware Device

With respect to the power consumption measurement of the target system, we used a data acquisition device - National Instruments USB Series DAQ Pad 6016 - in our laboratory. A resistance is placed in series with the current source and then the DAQ device samples the voltage drop across the resistance at a custom defined rate. The acquisition data can be further processed by means of LabVIEW [20]. We will detail the treatment in the next section. It should be noted that the selection of the appropriate resistance is very important for the experiment. If a large resistance is used, it will lead to much voltage drop and crash the target device. On the contrary, if a small resistance is used, the measured value may not be accurate because of the noise. As a result, how to choose the proper resistance plays a significant role in this experiment. The instantaneous power consumption (P_{Inst}) corresponding to each sample and the average power can be determined by the following equations:

$$P_{Inst} = \frac{V_R}{R} \times V_{PowerSupply} \tag{1}$$

$$P_{avg.} = \sum_{\Delta t} P_{Inst} / T_{total} \text{ ,} \tag{2}$$

where the average power consumption ($P_{avg.}$) in this experiment is the time-weighted mean of all the time periods.

The total power consumption (P_{total}) of the device is acquired from the main battery power rail. However, in order to obtain the power composition of the whole system, we need to get the power consumption of each module in the target device by the power breakdown measurements [14]. For example, we measure the current of each power rail of a Dell AXIM X50 PDA to explore the power consumption in different modes. The PDA used in the experiment contains an Intel® PXA27x Processor Family (PXA27x processor). It is a highly integrated system-on-chip and provides several low-power operating modes that can temporarily suspend or power down the core and peripherals to reduce the power consumption. As shown in Fig. 2, the six main power rails of AXIM X50 are CPU_Core (P_{CPU}), 2.5V ($P_{2.5V}$), 3.3V ($P_{3.3V}$), Audio ($P_{Aud\_3.3}$), LCD back light (P_{LCD}) and the rest of power consumption (P_{rest}). We acquire the total power consumption under three conditions: play a WMV file, idle, and system off by measuring the power consumption of each module individually. The total power of the PDA can be determined by:

$$P_{total} = P_{CPU} + P_{2.5V} + P_{3.3V} + P_{Aud\_3.3} + P_{LCD} + P_{rest} \tag{3}$$

With Equation (3), we can illustrate the average power consumption breakdown of each mode such as the idle condition shown in Figure 3. From the experiment, students can investigate the effects of battery lifetime by placing CPU into different modes.

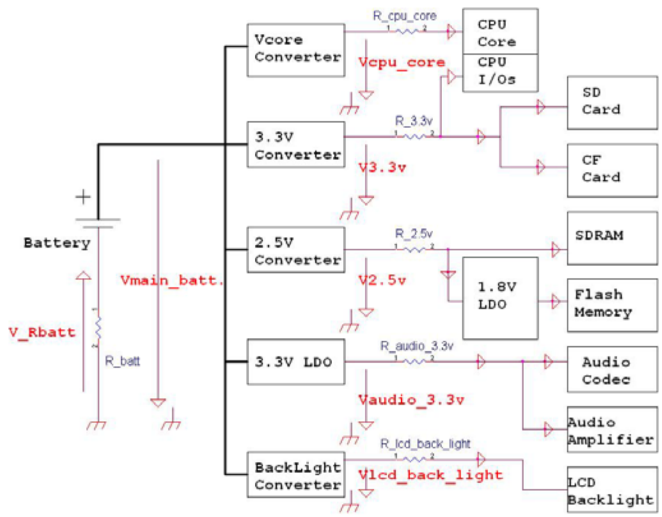

Figure 2. Power rails of Dell AXIM X50 PDA system

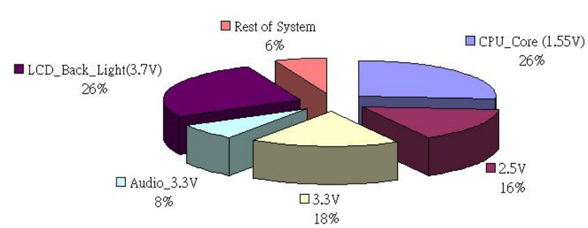

Figure 3. Average power consumption breakdown in Idle mode.

The findings of this study suggest that improvement of power consumption can be achieved by switching CPU into deep sleep mode instead of sleep mode while system is off. With the discussion students can understand how to estimate the power consumption of the embedded system by power-breakdown experiment and extend the battery lifetime by improving the power management algorithms of CPU.

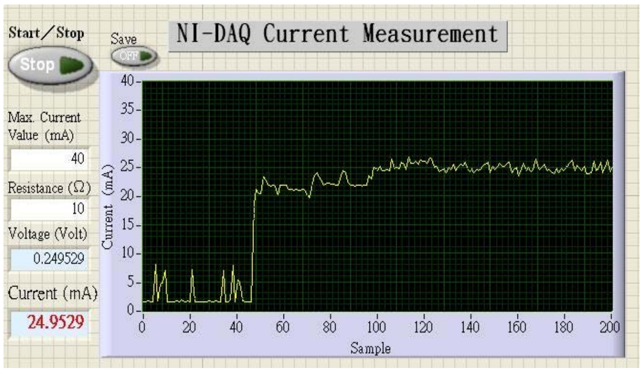

Figure 4. An example of the front panel

2.2 Using DAQ Software

One of the targets in this paper is to incorporate fundamental experiment techniques with modern computer-based data acquisition using LabVIEW. LabVIEW is a GUI-based data acquisition, measurement analysis, and presentation software which is developed from National Instruments Inc. The data acquisition software runs on a personal computer as a power measurement system and directly connects to the PDA through the USB port. Virtual Instruments (VIs) are the program of LabVIEW and which are made up of two parts: the front panel and the block diagram.

In the beginning, students should learn how to write VI's source code in the block diagram and then add needed instruments and indicators in the front panel. The front panel is the user interface of the VI. It looks similar to Figure 4. With the strong library functions in LabVIEW, students are encouraged to further exploit advanced function such as combining C/C++ language with LabVIEW, event structure, signal processing, and data acquisition. The power measurement system can be well established by the following steps:

(1) Setup the DAQ Device and use the test panel in DAQ-mx driver to check whether the device is ready.

(2) Connect the device to the DAQ system with probe and check whether the channel is correct or not.

(3) Issue commands to control DAQ. With the recent versions of LabVIEW, we can easily control and communicate with the DAQ device by using the DAQ Assistant. Otherwise we could use the functions in block diagram with older version.

(4) Write the LabVIEW programs to process and analyze the signals. LabVIEW supports various loop, mathematical, and conditional functions to make a complex program which is similar to a C program.

(5) Store the data and then analyze the record. Make sure the measurement time is long enough to obtain the reasonable average result.

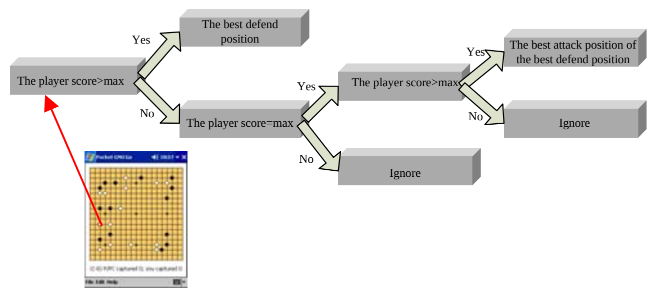

Figure 5. AI decision tree for a typical board game

A key point of the measurement system is the precision and resolution. LabVIEW provides various kinds of timer and random generator for users to perform measurement accurately. For example, if the voltage drop is 0.01V and the precision is only 0.1V. The result of this experiment is meaningless because the lack of precision. The time resolution is another factor that should be noted. The experiment will be subjected to a critical distortion if the resolution is not accurate enough to get the true value. In most cases the time resolution is closely related to the data acquisition rate. In addition, in order to eliminate the personal equation students should try to utilize triggers and conditions to start the measurement, turn on/off the program, and change the state of the device, and so on.

3. USING DAQ SYSTEM TO BUILD POWER MEASUREMENT MODULES

The DAQ hardware and software described in the previous section are used to support our laboratory for power measurement. Furthermore, we provide students the methodology for finding the characteristics of the power consumption and the power behavior of a system. The methodology together with DAQ usage taught in this laboratory course is very helpful for students to engage on future research projects related to low power system design. In this paper, two examples are given: power behavior of computer game algorithms and power analysis of wireless Internet (Skype) telephony.

3.1 Power Behavior of Software Algorithms

Communication and computation are two major sources of power consumption in a mobile computer [3] [15] [16] [19]. According to the applications running on the system, CPU power can be varied from 14% to 52% [22]. The algorithm design for developing application software will result in different computation complexities. This section covers a brief overview of the low power software design and guides students to play a part in the power analysis procedure of software algorithms by means of a laboratory project – power analysis of computer games algorithms for embedded system [18].

Algorithms for games can be classified into some parts of field, such as graphic operation, AI, memory access, and message process. It should be noted that the same algorithm used in different game types may incur opposite power behavior in the same PDA. This is due to that any particular algorithm is closely tied to how it is used within a game. So we consider the algorithms used in different types of game. For the sake of inspiring students to apply the measurement system introduced in this course, we discuss the motivation for characterizing game energy with students and propose a systematic methodology for their further study.

First of all, for analyzing the power consumption we have to select several games and some of them have been modified to conform to our test conditions. Most computer games used in our experiments are quite simple and concise. On one hand the limited resource and hardware of PDAs can not implement or execute the complex games effectively, and on the other hand simple games have purer power behavior than complex ones. Hence students can easily observe the energy effect by different algorithms running on a PDA.

By means of measuring the total power consumption of the PDA main battery, we can obtain a preliminary analysis of the power behaviors between different game types. In order to further understand the power consumption of games, we undertake the analysis of the CPU current. Depending on different game types the core processor of the PDA consumes power in specific regular behavior. Figure 5 shows the AI decision tree for a typical board game such as the game called “Go” [12]. The game is a kind of board game that expends a great deal of time in evaluating the next position. As can be seen in Figure 6, the power is much higher than wait when the game AI calculating score and comparison the game rules. In addition, the examples Blackout1 and Blackout2 that are designed in different methods are given. As listed in Table 1, the different design approaches lead to much difference in power consumption. The game library provides the designer to develop the games easily but it produces redundant code and results in more energy consumption.

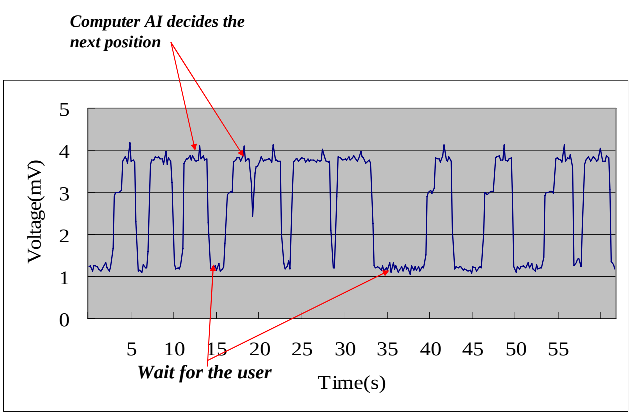

Figure 6. The power consumption behavior of the game of “Go”.

We conclude and discuss various opportunities for realizing energy-efficient implementations of game algorithms. We do believe that such investigations are an important first step towards addressing the challenges of energy efficient algorithms for battery-constrained systems to students.

Table 1. Different methods to design the game

Game	Design Method	Avg. CPU power(mW)	Avg. Battery Power(mW)
Blackout1	Game Library	241.00	802.22
Blackou2	WinCE API	152.20	662.80

3.2 Power Analysis of Wireless Communication

The other major source of power consumption of a mobile computer is the wireless communication. To study the energy usage of the wireless network, we make use of a Skype phone which is designed and implemented by our research group for education. The Skype phone employed 2.4 GHz wireless network to extend the work range and avoid the radio interference by hopping technology that is similar to Bluetooth. However, unlike Bluetooth, our wireless Skype phone can also dial out by its hand-set device.

The Skype phone consists of a mixed implementation of software and hardware. It is composed of two parts: the base station and the handset. The system hardware design consists of baseband circuit, RF circuit and MCU circuit. The speech coprocessor used in our design is a low-power, small size and highly integrated (on-chip ADC, DAC and 25 MIPS peak CPU) 8051 micro-controller. We adopted Nordic nRF2401 as the RF transceiver because its output power and frequency channels are easily programmable and especially suit to this laboratory. The third party application on the host computer communicates with the device and transfers the human interface control parameters to Skype by the USB HID driver. The MCU controls the data transmission, enables the RF transceiver, ADC/DAC, and the communication with the host computer and the handset. This system is very convenient for students to understand some power aware factors in the wireless environment. Figure 7 is the prototype of the handset system.

Due to the tight power consumption of the handset, we design the power saving mode for it. When the user presses the OFF button (see Figure 7), the micro-controller switches off all the external current and then enters into sleep mode. Then the micro-controller sets the RF transceiver to receive mode in order to synchronize with the basestation. At last, the micro-controller

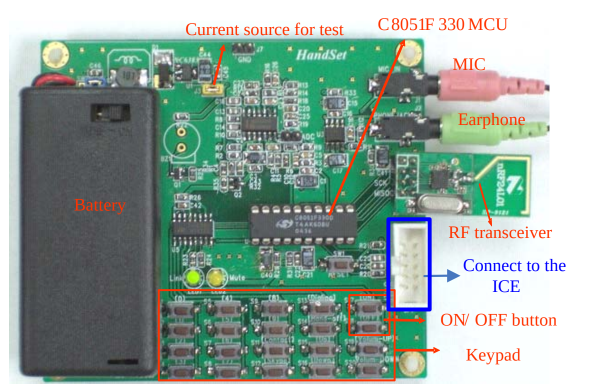

Figure 7. The system prototype of the handset

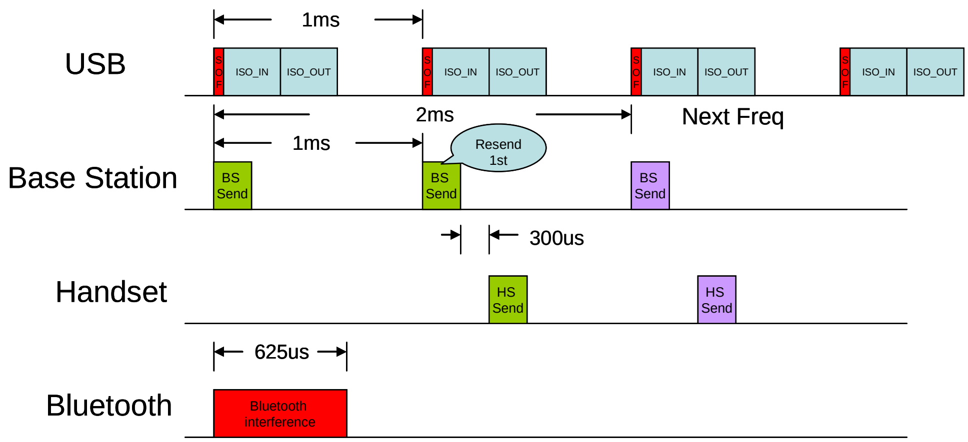

Figure 8. The communication protocols for our wireless Skype system

examines the control field of the received data and decides the next state. In this phase student can observe the micro-controller wakes up periodically by external RC charging and detects if any button has been pressed. In follow-up advanced course students can try to change the firmware of the device by writing their specific 8051 programs. The example program was written by Keil C. As shown in Figure 7, we have designed a port to connect with the 8051 ICE to download the program and a test connection for power measurement.

For energy-efficient design, one of the most important factors is to design the power saving mode. How to find the idle time and turn off the useless units is a major function for power management to switch system into power saving mode. The concept of power management is an important issue and has been employed in most battery-driven embedded system in recent years [7] [8]. Students should learn about how to improve the example program and compare with the Bluetooth products in the market. A great deal of research also discusses the power management concept and applies to various aspects [9] [10] [11]. For the first step student should have the general idea of power management in this experiment.

Wireless communication protocol is another issue worth to discuss. Many researches about wireless network have been proposed for optimizing mobile computer in system level design [3] [13] [17]. [21] presented a new energy efficient and secure communication protocol that exploits the locality of data transfer in distributed sensor network. In our example program, the core technology of the Skype phone employed 2.4GHz wireless network. There is a problem should be noted that 2.4GHz band is the same as industry, science and medicine (ISM) channel shared by a variety of other applications such as wireless network, bluetooth product and so on. Therefore, frequency hopping technology is used to avoid the radio interference in our design. Students can start with a non-hopping version to know how the protocol work, and then compare the differences of power behavior between hopping and non-hopping versions.

The detail of the protocol is shown in Figure 8. The original design of the Skype phone operates in half-duplex mode to avoid interference between transmitter and receiver. We design the hopping mode as Bluetooth with 80 different channels. Due to the switch time of RF transfer/receive is 130us, we set the hopping frequency to 500Hz. A timer is exploited to count time in both sides to synchronize between handset and basestation. Note that we also provide data retransmission mechanism to keep the speech data in certain quality. We recommend students to begin with adjusting the parameters such as the scale of data frame, time interval, and so on. When students are gradually familiar with the communication system, they can try to improve the framework of the example protocol and apply other possible techniques to reduce the power consumption. The speech compression, fault-tolerance, advanced data transmission mechanism or other functions about power reduction can be the project topics.

4. Conclusion

Power dissipation has become an important consideration in modern embedded system design. The primary objective of the laboratory is to deliver the understanding of system-level power analysis to undergraduate students in electrical and computer engineering, and eventually to make a promotion to low power system design experts. At the first, this paper conducts a number of measurements about power consumption. According to the measurement results, students can observe the power behavior of an embedded system and find out the key factors of the power consumption. Students need to pay attention to some factors, such as the precision and resolution, in the measurement procedure. Then the students have a chance to experience low power schemes in both software and hardware. We provide some experiments for example to help students with understanding the methodological approach to analyze power behavior. For the power behavior of software algorithms, we can rely on analyzing of the power behavior of the core processor to realize how the algorithms affect the energy. In addition, different algorithm designs of games lead to very different power consumptions. For the analysis of wireless communication, students can understand the effect of each power-aware factor and try to improve the battery life of the mobile handset.

We developed an undergraduate laboratory course for power analysis of embedded system. This course provides students in electrical and computer engineering with the power measurement of embedded system and the basic concepts of low power system design through several experiments

5. REFERENCES

[1] N. Chang, H. Lim, K. Lee, Y. Cho, H. G. Lee and H. Shim, "Graduate Class For System-Level Low-Power Design". *In Proceedings of the MSE*, pp. 31-32, 2005.

[2] Y. W. Bai and Y. C. Lin, "Measurement and Improvement of Power Consumption for Portable Computers," *IEEE International Symposium on Consumer Electronics – (ISCE2005)*, Macau China, pp. 122-127, June 14-16, 2005.

[3] J. Warren, T. Martin, A. Smailagic, D. P. Siewiorek, "System Design Approach To Power Aware Mobile Computers," *IEEE Computer Society Annual Symposium on VLSI (ISVLSI'03)*, p. 101-106, February 2003.

[4] J. S. Yuan, Senior Member, IEEE, and Jia Di, "Teaching Low-Power Electronic Design in Electrical and Computer Engineering," *IEEE transactions on education*, vol. 48, no. 1, pp.169-182, February 2005.

[5] G. Mason, "A Handheld Data Acquisition System for Use in an Undergraduate Data Acquisition Course," *IEEE transactions on education*, vol. 45, no. 4, pp. 388-393, November 2002.

[6] C. Lee, "LabVIEW Based Instrumentation and Experimental Methods Course," *Proceedings of the ASEE Annual Conference*, July 2001.

[7] T. Simunic, G. D. Micheli, and L. Benini, "Event-Driven Power Management of Portable Systems," *Proceedings of the 12th international symposium on System synthesis*, p.18, November 01-04, 1999

[8] Y. Chen, N. Smavatkul and S. Emeott, "Power Management for VoIP over IEEE 802.11 WLAN," *IEEE Wireless Communications and Networking Conference*, Vol3, pp.1648-1653, March 2004.

[9] C. Schurgers, V. Raghunathan, and MB Srivastava, "Power Management for Energy Aware communication systems," *ACM Transactions on Embedded Computing Systems*, August 2003.

[10] S. Banerjee and S. Khuller, "A Clustering Scheme for Hierarchical Control in Multi-hop Wireless Networks," *Proceedings of the IEEE Conference on Computer Communications (INFOCOM)*, vol. 2, 1028-1037, April 2001.

[11] C. Chen, "Energy Efficient Routing for Clustered Wireless Sensors Network," *In Proceedings of the 29th Annual IEEE Conference on Industrial Electronics*, Vol. 2, pp. 1437–1440, November 2003.

[12] Vieka Technology Inc, Pocket GNU Go is a GNU Go player for Windows mobile devices, including Pocket PC and Smartphone. http://www.vieka.com/gnugo/

[13] Havinga PJM, Smit GJM, "Low Power System Design Techniques for Mobile Computers", internal report University. of Twente, 1997.

[14] M. A. Viredaz, D.A. Wallach, "Power evaluation of a handheld computer,**"** in *Proceeding of IEEE Computer Society*, Vol. 23, Issue 1, pp.66--74, 2003

[15] K. Farkas, J. Flinn, G. Back, D. Grunwald, and J. Anderson, "Quantifying the Energy Consumption of a Pocket Computer and a Java Virtual Machine," *In Proceedings of the ACM SIGMETRICS '00 International Conference on Measurement and Modeling of Computer Systems*, Santa Clara, CA, June 2000.

[16] G. Chen, B. T. Kang, M. Kandemir, N. Vijaykrishnan, M. J. Irwin, R. Chandramouli, "Studying Energy Trade Offs in Offloading Computation/Compilation in Java-Enabled Mobile Devices," *IEEE Transactions on Parallel and Distributed Systems*, vol. 15, no. 9, pp. 795-809, Sept., 2004.

[17] A. Smailagic, M Ettus, "System design and power optimization for mobile computers," *VLSI on Annual Symposium, IEEE Computer Society ISVLSI 2002*.

[18] Y. R. Lai and S. J. Ruan, "Power Analysis of Computer Game Algorithms for Handheld Embedded System," *In Proceeding of 1st IEEE International Conference on Industrial Electronics and Applications (ICIEA 2006)*, Singapore May 24-26 2006.

[19] D. Bertozzi, A. Raghunathan, L. Benini, and S. Ravi, "Transport Protocol Optimization for Energy Efficient Wireless Embedded Systems," *IEEE Design, Automation and Test in Europe Conference and Exhibition, 2003*, pp. 706-711.

[20] National Instruments Corp. http://www.ni.com.

[21] H. Saputra, N. Vijaykrishnan, M. Kandemir, R. Brooks, MJ Irwin, "Exploiting Value Locality for Secure-Energy Aware Communication," *In Proceedings of SiPS'03*, pp. 116-121, Aug. 2003.

[22] A. Mahesri and V. Vardhan, "Power Consumption Breakdown on a Modern Laptop," *Workshop on Power Aware Computing Systems, 37th IEEE International Symposium on Microarchitecture*, Dec. 2004.