AC 2008-2173: A FIRST-YEAR ENGINEERING EXPERIENCE IN WIRELESS SENSOR NETWORKS FOR ELECTRICAL/COMPUTER ENGINEERING AND COMPUTER SCIENCE STUDENTS

Sanjay Raman, Virginia Polytechnic Institute and State University

Da Silva Luiz, Virginia Polytechnic Institute and State University

Masoud Agah, Virginia Polytechnic Institute and State University

Allen MacKenzie, Virginia Polytechnic Institute and State University

Christopher Maxey, Virginia Polytechnic Institute and State University

Amy Bell, Virginia Polytechnic Institute and State University

A First-Year Engineering Experience in Wireless Sensor Networks For Electrical/Computer Engineering and Computer Science Students

I. <u>Introduction</u>:

A newly restructured first-year Engineering Education course EngE 1104 "Discovering Electrical and Computer Systems" is in its first year of deployment at Virginia Tech. Currently, undergraduate engineering students at Virginia Tech generally share a common first year experience. However, in the second semester of the freshman year, students choose amongst two different tracks—one more focused on mechanical engineering and related majors, and the other more focused on electrical and computer engineering related majors. EngE 1104 is the second semester course for first-year engineering students interested in pursuing majors in Electrical Engineering, Computer Engineering, and Computer Science. Three-hundred and fifty to four hundred (350-400) students typically enroll in this course on an annual basis.

The innovative aspect of the new version of this course is its focus on *real-world problems that benefit society*; a major objective of this course revision is to increase student motivation, satisfaction, and retention in the electrical/electronics and computer related majors, including a significant impact on the underrepresentation of women and minorities in these majors at Virginia Tech. The importance of hands-on, team-based projects and societal impact has been well documented through service-learning-based programs at Colorado and Purdue [1][2].

An additional goal is to provide integrated, just-in-time teaching on a selection of fundamental topics in Electrical and Computer Engineering and Computer Science, including programming and problem solving with Matlab, signal and image processing, basic circuit analysis, and the basics of wireless communications systems. The intent is *not* to teach this material at a detailed, first-principles depth, but rather to provide introductory-level conceptual understanding of, and motivate and spark interest in, these topics in order to enhance student success in subsequent core courses.

The new 1104 course is organized into a number of short (few-week) lecture/laboratory modules delivered by *faculty subject matter experts* from the relevant field. Each module consists of an introductory lecture, including active learning opportunities, a hands-on laboratory experience, and a summary/wrap-up lecture. The lectures are delivered to the students in a single classroom, large lecture format; the labs are conducted in smaller sections of the overall course. The lab/lecture materials are carefully developed to be tractable for first-year engineering students from a wide range of backgrounds. Examples include: arrhythmia detection algorithms for implantable cardiac defibrillators (Signal Processing); blackout prevention (Electrical Power Systems); and detecting tumors using tomographic image reconstruction (Biomedical Imaging).

This paper will discuss the implementation of a particular four-part lecture/laboratory module in the area of Sensors and Wireless Sensor Networks. The development of large, distributed networks of wireless sensor nodes to gather critical information about the vast, physical world and communicate conditions back to decision makers, who may be remotely located, is an area of tremendous interest in academia, industry, and government [3]. Large sensor networks have a wide range of important applications in society, including: monitoring of environmental quality [4], detection of increased hazardous emissions [5], and assessment of civil infrastructure (e.g. bridges) [6]. While other modules in our course focus on more specific topics, this module endeavors to demonstrate to the students the *integration* of multiple areas of electrical and computer engineering/science—spanning sensor devices, electronic circuits for sensor readout and data conversion, radio frequency (RF)/wireless communications, and wireless networking (Fig. 1).

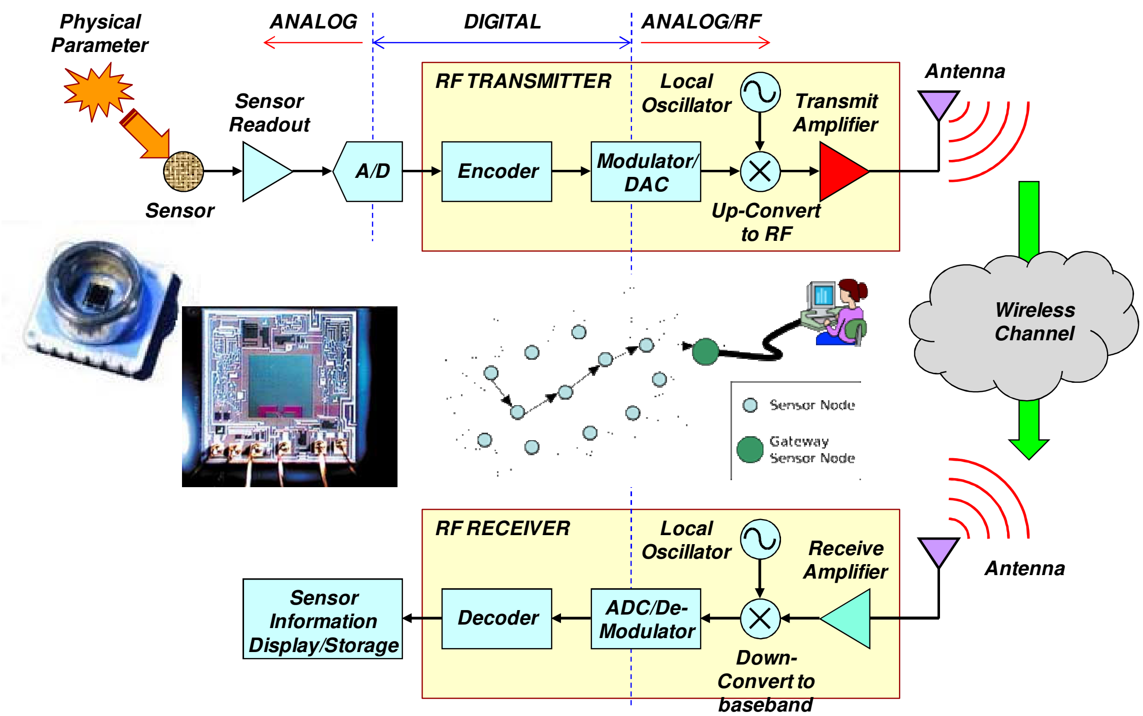

Figure 1: Students in the newly revised EngE 1104 experience first-hand the *integration* of multiple areas of electrical and computer engineering/science—sensor devices, electronic circuits for sensor readout and data conversion, RF/wireless communications, and wireless networking.

Wireless sensor systems have also been the focus of other interdisciplinary project-based undergraduate education efforts. For example, in [7], faculty at Tennessee Technological University and University of South Florida collaborated on a multi-university, distance-learning-based design course in this area. This particular effort was a *senior-level* capstone design experience, involving design and implementation of an RF proximity sensor, baseband signal processing, RF wireless transceiver, and antennas (using a combination of student-designed and COTS components). In contrast, our effort focuses on lecture and hands-on laboratory modules targeting first-year students considering ECE or CS majors.

II. Lab/Lecture Module Structure and Content:

The four-part lab/lecture module described in this paper provides first-year Electrical and Computer Engineering/Science students a unique experience in the evolution of a wireless sensor network design from the sensor/device to the network level. Students also gain an appreciation of how design decisions at lower levels impact overall system performance, and conversely how system-level specifications impact the design of individual components and sub-systems. The four lecture/laboratory modules cover the following topics over a roughly 5 week period in the semester: (1) an introduction to sensors, Microelectromechanical Systems (MEMS), and microsystems; (2) sensor readout electronics and analog-to-digital conversion; (3) wireless communications; and (4) wireless networking. The sequence concludes with a summary lecture.

Each introductory lecture is carefully designed to introduce the subject matter at a tractable level for first-year engineering students, introduce real-world applications and societal impact, and provide preparation for the related laboratory experience. The lectures are also designed to incorporate cooperative Think Pair Share (TPS) exercises to help reinforce key concepts for students. Each lab assignment consists of: pre-lab preparation, which may include simple calculations, reviewing reference material, installing software, etc.; detailed lab procedures and data collection guidelines; and post-lab analysis and discussion requirements.

In the laboratory sections, students are organized into teams of 3-4 students, which are maintained for all the lab assignments of the course. Teamwork is heavily emphasized throughout the course. In the case of our four-part sequence, a final lab report covering the entire sequence is required; lab report grades are team based. In addition, exam questions, both short answer type and more detailed design/calculation type, are derived from each of the four labs in the sequence for incorporation into subsequent course exams.

A. Sensors, MEMS and Microsystems

In the lecture portion of this first component, students are exposed at a high level to the wide range of sensor applications, and their importance in areas such as environmental monitoring and public safety, biomedical diagnostics, civil infrastructure monitoring, homeland security and defense. This is followed by an exploration of the basic physical principles behind various sensing modalities, and implementation and function of related sensor devices. Finally, the students are exposed at a high level to the state-of-the-art in microelectromechanical (MEMS) and nanoscale sensors, and the promise of low-power integrated sensing microsystems for massively deployed wireless sensor networks [8]. In particular, two different microsystems were presented in more detail—a miniaturized gas chromatography (GC) system and an implantable cochlear prosthesis. Students engaged in a cooperative learning TPS exercise to determine advantages of a micro GC over a bench-top GC. The example showed students how MEMS technology can be utilized to develop gas analyzers with faster separation and detection times, lower power consumption, and greater portability.

The laboratory component of this part included (1) demonstrations in the Virginia Tech MEMS lab, (2) a tour of the Microelectronics, Optoelectronics and Nanotechnology (MicrON) cleanroom facility, and (3) a discussion about real-world, contemporary MEMS applications and challenges. In the VT MEMS lab, students were able to inspect several microdevices including a microfluidic mixer, a microchip cooler, a microfabricated cell culture substrate, and a micro GC separation column under a high resolution microscope. They also observed the operation of a microfluidic mixer and the laminar flow of liquids in microchannels. During the cleanroom tour, students were briefly indoctrinated on the safety protocols and policies required in a cleanroom environment. In addition, they gained a first-hand exposure to the state-of-the-art facilities used in the fabrication of microsystems. In the discussion part, we reviewed the societal impacts of some of the microsystems students observed in the lab. As an example, they learned how MEMS can be used to develop microinstruments to separate breast cancer cells from normal cells found in a biopsy sample used for early breast cancer diagnosis. Through this example, students gained further appreciation for the importance of cross-cutting, interdisciplinary research.

B. Sensor Readout and Analog/Digital Conversion

The second lecture/laboratory component focuses on the electronic readout of sensor measurement data and subsequent conversion into the digital domain. In the lecture, students are first exposed to the concepts of analog and digital electrical signals, and why digital signals are used for information transfer, storage and communication. The analog-to-digital conversion process is then presented at a basic level, and key concepts such as ADC resolution and quantization error are discussed. The students engage in a cooperative learning TPS exercise on calculation of quantization error. We then briefly discuss various types of resistive sensors, which motivate the need for a basic resistance measuring circuit, the Wheatstone bridge. Ohm's Law is introduced in conceptual, just-in-time fashion and the basic operation of the bridge circuit is explained.

In the corresponding laboratory component the students build up the bridge circuit on a protoboard to measure the output from a simple resistive sensor, specifically a photosensor; however, the same basic approach could be applied to other resistive sensor types such as thermistors, piezoresistors, or chemoresistors. The majority of the bridge design is provided, but the students do calculate the bridge balance condition and select one resistance value in their prelab exercise. Since the photosensor selected has a reasonably wide resistance range, amplification of the bridge output is not needed; however a packaged instrumentation amplifier is incorporated in the circuit to provide buffering and differential to single-ended conversion. The internals of the instrumentation amp are not discussed in any detail; it is treated as a unity-gain buffer block.

The bridge output voltage data is converted to digital bits by a Freescale MC9S12C32 16-bit microcontroller unit (MCU) with on-board analog-to-digital converter (ADC) and transferred to students' laptops via USB cable. The project board DC supply rails are powered via the USB cable from a student's laptop so no external power supplies are needed, which enables us to deploy the lab in standard classrooms (with appropriately-sized table surfaces). A wired-up project board is shown in Fig. 2. The components provided to each lab group are listed in Table 1. Note that we are not emphasizing best wiring practices at this stage; the students will be introduced to these practices in later core circuits/electronics and computer engineering lab courses; the main focus here is to give the students an introductory hands-on experience with sensors, circuits and electronics.

Once the groups have built up their circuit and established data communications with their laptop, they perform a simple experiment measuring the digital output from the on-board ADC for a range of light and dark conditions presented to the photosensor. In their post-lab analysis, the groups are required to convert this digital information back to an analog resistance value for each of the recorded data points. Accurate sensor calibration was not introduced in the current version of this lab, but is planned to be introduced in future iteration of the course.

Table 1: Parts list for Wireless Sensor Networks lab.

1 Potentiometer
1 Resistive Photosensor
Resistors
1 Analog Devices AN623 Instrumentation Amplifier
1 Set of connection wires
1 USB cable
1 Freescale MC9S12C32 MCU board
1 Freescale PBS12C32SLK Project board
1 Freescale AP13192USLK Zigbee Transceiver board
1 Screwdriver
1 Flashlight

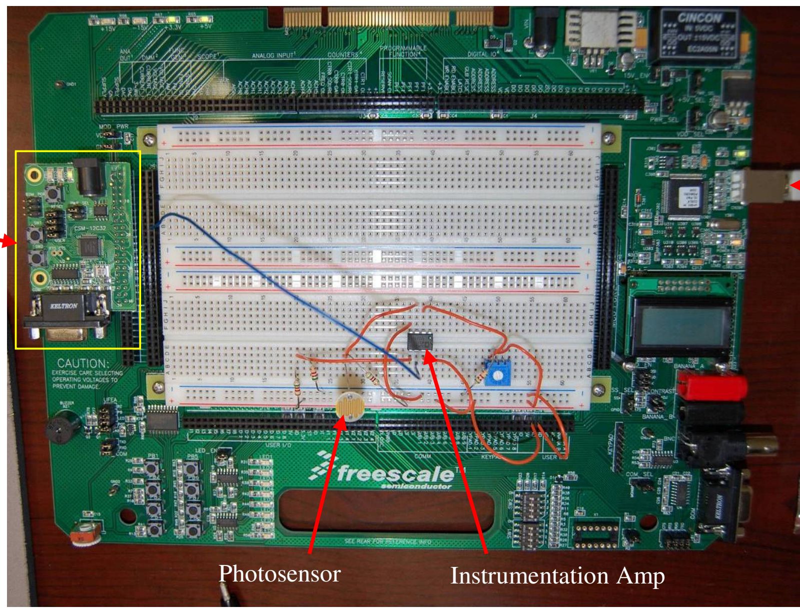

Figure 2: Project board with photosensor, resistance bridge readout circuit, and connection to A/D converter on microcontroller board. Data is read out to the student's laptop via USB connection, which also provides DC power to the board. Note that best wiring practices are not emphasized at this point; these practices will be covered in detail in later ECE core courses.

C. RF Wireless Communications

The third component introduces students to the use of wireless communications to move data between sensor nodes in a network. The lecture portion introduces students to the frequency domain through the more concrete notion of the electromagnetic spectrum, which many have studied in high school physics. The many and varied uses of the spectrum are discussed as well as the public policy issues of how spectrum is allocated to different uses and how these allocations impact our lives and our future. Through this discussion, students consider the many ways in which they use wireless communications daily: cellular telephony, wireless internet access, wireless headsets, broadcast radio, etc. In addition, students are given the opportunity to list other critical ways that wireless communications impact the functioning of our society, including public safety, transportation, and healthcare applications. From this broad discussion of the radio spectrum and its applications, we move to a discussion of *standards* and the role that they play in the development of technology, including the reasons that standards are needed and how they are developed. This leads to a discussion of the IEEE 802 family of standards that impact students lives daily. In addition to providing standards for wireless and wired Ethernet, IEEE 802 also includes a low-data-rate standard for use by sensor networks, IEEE 802.15.4, one well-known implementation of which is ZigBee [9]. For many students, this may be the first time that they have had the opportunity to decipher the "alphabet soup" of terminology and acronyms in the wireless communications arena.

A key component of various wireless standards, which the students also subsequently explore in the lab, is the principle of shared access to the communications medium. Students learn that in designing a protocol (or "etiquette") to govern access to a shared medium, they must consider both efficiency and fairness, two goals which often conflict. Students learn about two basic random access protocols: ALOHA, in which nodes access a channel at will, and Carrier-Sense Multiple Access (CSMA), in which nodes listen to see if the channel is busy before attempting to access it. The advantages and disadvantages of these approaches, as well as a simple analysis of performance in the two cases, are presented.

In the lab, students add the Freescale AP13192USLK ZigBee transceivers to the project boards (Fig. 3) that they have been working with in the preceding sensor interface lab. Antennas are not required due to the relatively close proximity of the groups in the lab classroom. It should be noted that the semester-long development of a simple radio platform in conjunction with a first year engineering course has been recently demonstrated in [10]. However our goal is for the students to experience the overall component to system integration and real-world applications in environmental sensing and monitoring, so we choose to exploit flexible, commercially available radio boards for this project.

Using these transceivers, which transmit digital representations of the data detected by the sensor, the students measure the performance of both ALOHA and CSMA and compare these values to predicted performance. The student teams in each lab section work together to perform the measurements. Some teams are designated to transmit packets while others are designated to receive packets. The transmitting and receiving teams each count the number of packets sent and received for various conditions. Over the course of the lab, the number of transmitters, the protocol (ALOHA or CSMA) that the transmitters are using, and the rate at which the transmitters send packets are varied.

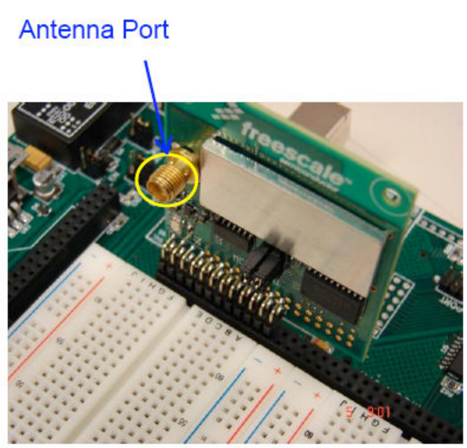

Figure 3: Freescale AP13192USLK ZigBee RF transceiver board attached to the PBS12C32SLK student project board.

D. Wireless Sensor Networks

The final lecture in the sequence discusses the applications of multiple wireless sensor nodes integrated into wireless sensor networks. The concept of ad hoc networks is explored, and students are introduced to state-of-the-art developments such as sensor motes and smart dust [11]. The lecture proceeds to describe the operation of IEEE 802.15.4 technology at a conceptual level, specifically the Zigbee wireless sensor protocol. From this lecture, students are able to identify, and discuss at a basic level, tradeoffs between infrastructure-based and ad hoc wireless networks; between size and cost considerations in sensor design versus processing and energy storage capabilities of sensors; and between single-hop versus multi-hop communications.

In sensor networks, information collected by individual sensors must eventually be delivered to a network node, usually referred to as a *sink*, responsible for interpreting the data and taking appropriate action. In the final lab for this module, an entire lab section establishes a Zigbee wireless sensor network using the previously discussed sensor/sensor readout circuitry and ZigBee RF transceiver boards. The individual groups then aggregate the sensor information from all the nodes in the network onto their laptops. They also experimentally observe the impact of various channel impairments as well as collisions and backoff produced by random medium access control methods on the ability of the network to reliably deliver sensor node information to the users.

Through this experience, our first year students have observed first-hand the implementation of wireless sensor networks from the device level through the networking layer. The lecture and laboratory structure for this four part module is summarized in Table 2.

Table 2: Summary of lab/lecture module content

Part	Lecture Material	TPS Exercise	Lab Activity
1	Intro. to Sensors and Actuators, MEMS and Microsystems; chemical, environmental, and biomedical applications	Brainstorm advantages and applications of micro-scale chemical/gas sensing systems	Tour of cleanroom and MEMS lab, hands-on experience with microfluidic devices
2	Analog vs. Digital signals; A/D conversion and quantization error; Ohm's law and resistive sensors; Wheatstone bridge operation	Determine quantization error from A/D converter specs.	Build Wheatstone bridge sensor readout circuit; measure characteristics of resistive photosensor; relate digital read-out to measured analog values
3	Intro. to the radio spectrum and wireless standards; Intro. to Medium Access Control, ALOHA and CSMA	Brainstorm applications and impact of wireless communications on society	Set up Zigbee radio nodes; experiment with communications using ALOHA vs. CSMA; observe capacity limitations of system
4	Intro. to wireless networks, infrastructure vs. ad hoc networks; 802.15 and Zigbee	Solve puzzle related to a real-time situation, such as the impact of RF technology used in automatic toll collection	Set up Zigbee wireless network among lab groups in section; observe sensor data transmission from other nodes and perform data aggregation
	Summary Lecture	Brainstorm sources of data errors in a wireless sensor network	

III. Recent Outcomes:

This lecture/laboratory sequence in wireless sensors and sensor networks was first implemented as part of the new format of EngE 1104 during Fall semester 2007. The student population was 63 students (this is the "off" semester of the course, which provided us a more manageable class size for prototyping the new approaches in this course). The class was broken up into 17 lab groups (assigned by the instructors) in two lab sections; as mentioned above, these teams were maintained throughout the semester. Figure 4 shows 1104 students actively engaged in the sensor readout laboratory in one of the Fall 2007 sections.

One of the indicated outcomes of the new 1104 course structure is accelerated student awareness and knowledge of key concepts in electrical/computer engineering and computer science disciplines, and improved preparation for subsequent core courses. As an example of the student knowledge gained, a challenging Wheatstone bridge design problem was given on the semester final exam, representing roughly 30% of the exam grade. The students scored 66% on this particular question, which compares very favorably to the overall class average on the exam of 72%. When we recognize that these are *first-year students*, the majority of who have not had a core course in basic circuit analysis yet, the students' performance on this particular question is even more compelling. We believe that this bodes well for the success of this cadre of students in their second-year ECE and CS core courses.

Another outcome indicated is a general increase in student satisfaction from the entire course. For example, the overall student course/instructor evaluation of EngE 1104 in Fall 2007 showed a dramatic 31% increase over the previous version of this course taught in Fall 2006 (both sets of data were for "off-track" semesters). Students also report increased appreciation for the role of electrical and computer engineers and computer scientists in society. We are currently in the process of analyzing student feedback data and expect to be able to report numerical results during the conference.

Figure 4: EngE 1104 students engaged in the sensor readout electronics laboratory.

Conclusions and Future Work:

This paper has discussed the development of a four-part integrated lab/lecture sequence in wireless sensors and sensor networks as part of a newly restructured first-year course for Electrical and Computer Engineering and Computer Science students at Virginia Tech. The course and this specific four-part module were successfully deployed during Fall semester 2007; Fall is the "off semester" for EngE 1104. We are in the process of analyzing assessment data from Fall semester 2007 and anticipate reporting on some of the results of this assessment at the conference.

The new 1104 is being taught again for the current Spring semester 2008. Spring semester has the larger population of students in this course—approximately 280 students are currently enrolled in the course. This larger population will allow us to evaluate the scaling of our new approach to the much larger number of students, and gather a significant amount of additional assessment data.

We are also in the process of improving on specific aspects of the sensor and sensor networks lab/lecture modules, including introducing sensor-specific calibration procedures, and extending the wireless networking experiment to an investigation of multi-hop communications in sensor networks.

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