Turkish Journal of Electrical Engineering and Computer Sciences

Volume 14 | Number 1 Article 6

1-1-2006

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Recommended Citation

CONRAD, JAMES M. and HOWITT, IVAN (2006) "Introducing Students to Communications Concepts Using Optical and Low-Power Wireless Devices," *Turkish Journal of Electrical Engineering and Computer Sciences*: Vol. 14: No. 1, Article 6. Available at: https://journals.tubitak.gov.tr/elektrik/vol14/iss1/6

Turk J Elec Engin, VOL.14, NO.1 2006, © TÜBİTAK

Introducing Students to Communications Concepts Using Optical and Low-Power Wireless Devices

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Abstract

Wireless communication has become an important feature for commercial products and a popular research topic within the last ten years. There are now more mobile phone subscriptions than wired-line subscriptions. Lately, one area of commercial interest has been low-cost, low-power, and short-distance wireless communication used for "personal wireless networks." Technology advancements are providing smaller and more cost effective devices for integrating computational processing, wireless communication, and a host of other functionalities. These embedded communications devices will be integrated into applications ranging from homeland security to industry automation and monitoring. They will also enable custom tailored engineering solutions, creating a revolutionary way of disseminating and processing information. With new technologies and devices come new business activities, and the need for employees in these technological areas. Engineers who have knowledge of embedded systems and wireless communications will be in high demand. Unfortunately, there are few affordable environments available for development and classroom use, so students often do not learn about these technologies during hands-on lab exercises. The goal of a development and teaching effort was to create a low-power embedded system that could be used to teach wireless communication hardware and protocols. This paper presents the experiences of introducing board-to-board communication concepts and hardware into the classroom. The communication mediums were twisted pair, optical fiber, infrared, and finally wireless radio. Also addressed are specific assessments of student skills that were needed as a prerequisite and successes based on prerequisites. A design of additional hardware is presented. Also, a future class that builds on these tools is suggested.

Key Words: *Embedded systems, wireless communications, hands-on learning, IEEE 802.15.4, Bluetooth, optical, infrared.*

1. Introduction

Experts say that embedded systems are everywhere around us. Embedded Systems Development is the field of putting small computers in everyday items such as microwave ovens and wireless phones. Wireless communication has become an important feature for commercial products and popular research topic within the last ten years. There are now more mobile phone subscriptions than wired-line subscriptions. One area of commercial interest lately has been low-cost, low-power, and short distance wireless communications used for "personal wireless networks." Specifically, Bluetooth components have been included in mobile phones, headsets, Personal Digital Assistants (PDA), PCs, printers, and other devices. A new communications standard, IEEE 802.15.4, has been created to further reduce the power requirements and cost of devices.

Technology advancements are providing smaller and more cost effective devices for integrating computational processing, wireless communications, and a host of other functions. These embedded devices will be integrated into applications ranging from homeland security to industry automation and monitoring, and will also enable custom tailored engineering solutions, creating a revolutionary way of information dissemination and processing. The wireless embedded network is context aware, taking into account the power restrictions, the application's information flow rates, the network's location, as well as reliability and survivability. The development of wireless embedded networks requires a detailed understanding of the radio frequency (RF) environment, low power circuit design and an understanding of advancements in energy-efficient network design.

With new technologies and devices come new business activity, and the need for employees in these technological areas. Engineers who have knowledge of embedded systems and wireless communications will be in high demand. Unfortunately, there are few affordable development environments available for classroom use, so students often do not learn about these technologies during hands-on lab exercises.

The goal of a development and teaching effort was to create a low-power embedded system that could be used to teach wireless communications hardware and protocols. The specifications of these new teaching tools were that:

- The base embedded microcontroller environment should be a very low cost off-the-shelf development board. Two were selected: the Renesas M30262 SKP board (US $ 50) and the Atmel STK500 board (US $ 50). These two boards have development software and compilers included in these evaluation board kits.
- The communications electronics should be low cost Bluetooth and IEEE 802.14.5 devices that are attached to the development board via removable daughter boards.
- Basic communication protocols should be implemented to allow the boards to work and communicate, as identified by the standards specification. The use of these basic protocol software libraries should be documented so that students, with the correct development board and communications daughter board, can use this software.
- The basic protocols and daughter boards should be used by students in an embedded systems or computer interfacing course.

This paper presents the experiences of introducing board-to-board communications concepts and hardware into the classroom. Specific lab exercises using twisted pair wiring, optical fiber, infrared, and radio wireless communications electronics are described. Specific assessment of student skills that were needed as a prerequisite, and successes based on prerequisites are also addressed. A design of additional hardware is presented. Also, a future class that builds on these tools is suggested.

2. Electrical and Computer Engineering at UNC Charlotte

The University of North Carolina at Charlotte (UNC Charlotte), USA was established in 1946 as a short-term school for educating the hundreds of North Carolina residents who were WWII veterans. The original scope of the popular school was expanded, and Charlotte College became a two-year college, then a four-year college, and in 1964 was approved as a four-year university and part of the State of North Carolina University System. The University continues to experience growth at the rate of 4% each year, and in Fall 2005 has 20,500 students enrolled. The College of Engineering has recently experienced a sustained growth of 10% each year, and in the Fall of 2005 has 2,200 students enrolled.

The College of Engineering was established as a satellite program of North Carolina State University in 1968, and started offering a Bachelors of Science in Engineering degree in 1970. The Department of Electrical and Computer Engineering (ECE) was approved to offer its own Bachelors of Science degree in Electrical Engineering (BSEE) in 1983. Due to rapid growth and interest in the program, the department also was approved to offer additional degrees: Masters of Science in Electrical Engineering (1983), Doctor of Philosophy in Electrical Engineering (1996), and Bachelors of Science in Computer Engineering (BSCPE) (2000). The department is currently considering adding a Masters of Science in Computer Engineering degree. Table 1 shows the numbers and types of degrees offered in the last three years by the department. The BSEE and BSCPE degrees were most recently accredited in 2004 with all positive comments.

Table 1. Degrees granted by academic year from the Electrical and Computer Engineering Department, University of North Carolina at Charlotte, USA.

Academic Year	BSCPE	BSEE	MS	PhD
1999-2000	N/A	42	18	4
2000-2001	4	40	20	3
2001-2002	6	46	27	1
2002-2003	17	54	25	3
2003-2004	44	42	39	1
2004-2005	35	52	34	5

The UNC Charlotte ECE department has experienced a reduction in undergraduate enrollment over the last few years, similar to a trend seen by other ECE programs across the United States. Fortunately, the enrollment in the graduate program has recently increased in the Fall 2005 semester to levels similar to fours years before. The enrollment statistics are shown in Table 2.

Table 2. Enrollment by semester in the Electrical and Computer Engineering Department, University of North Carolina at Charlotte, USA.

Semester	Undergraduate CPE	Undergraduate EE	Masters	PhD
Fall 1999	N/A	233	63	21
Spring 2000	34	223	67	19
Fall 2000	73	203	95	18
Spring 2001	88	203	92	20
Fall 2001	122	219	91	23
Spring 2002	146	228	91	26
Fall 2002	174	210	88	27
Spring 2003	153	203	79	29
Fall 2003	171	192	79	34
Spring 2004	148	178	76	30
Fall 2004	143	188	76	35
Spring 2005	128	182	82	31
Fall 2005	140	157	95	31

The undergraduate program requires each EE and CPE student to take the same courses found in typical engineering programs, such as: calculus, differential equations, statistics, physics, chemistry, and economics. Students also take courses in programming, digital and analog electronics, and computer communications. In addition, CPE students also take courses in computer organization and, starting in 2005, embedded systems.

Graduate students are expected to have taken similar courses as undergraduate students. We often find that graduate students who have earned their BS degrees from other universities have some content missing from their background and must work on their own to quickly learn this prerequisite knowledge.

3. Introduction and Advanced Embedded Systems Course

The IEEE Computer Society and the ACM formed a joint task force to create a model curriculum for computing. They have developed guidelines for a Computer Engineering curriculum [1], of which embedded systems and communications are core disciplines, or "knowledge areas". The task force also states that, "*Computer engineering must include appropriate and necessary design and laboratory experiences.* A computer engineering program should include "hands-on" experience in designing, building, and testing both hardware and software systems.

An embedded systems course was developed at North Carolina State University in 2002 to better prepare Computer Engineering students for the design challenges of today's marketplace. The course was brought to the University of North Carolina at Charlotte in 2003 [2]. The goal of an embedded systems course is to solidify and build upon a student's knowledge of computer organization by presenting hands-on experience with microcontrollers. Students also examine a few sensors that are used in commercial and medical products and learn how to interface them in a microcontroller system. Specifically, the course performance outcomes are that students will:

1. Recognize and identify the constraints facing embedded system designers, and determine how to assess them.
2. Program a modern microcontroller in assembly language and operate its peripheral devices.
3. Interpret how the assembly code generated by a compiler relates to the original C code.
4. Practice thread-based program design with a real-time operating system.
5. Develop programs controlling embedded systems using quick and efficient methods.
6. Predict, measure and manipulate a program's execution time.

Laboratory assignments are an integral part of the course and are intended to provide experience in applying the design techniques discussed in lecture. Because almost all of us learn by doing, the laboratory is probably the most effective method for learning the material. These assignments use the embedded systems board required for the class. Lab exercises can be performed in the Embedded Systems Teaching Lab or on a student's own home PC, but the successful implementation has to be demonstrated to a Lab teaching assistant (TA).

The laboratory setup includes networked PCs, bench power supplies, multi-meters, and 350 MHz mixed-signal oscilloscopes. The laboratory board kit is purchased by each student in the class through the university bookstore and includes the board, a ROM monitor daughter board, a USB cable, and two

Integrated Development Environment (IDE) software disks. Students keep this board after the class ends for use in other classes (e.g. Senior Design, Advanced Embedded Systems).

Students also work in pairs. The first few assignments require only one board for development and demonstration, but later lab assignments require board-to-board communications, so two boards are needed. The last assignment uses concepts from all of the previous labs, and also requires code reuse.

- An advanced course in embedded system design uses the same 16-bit microprocessor board and development environment described earlier. In this course students:
- Recognize and identify the constraints facing embedded system designers, and determine how to assess them.
- Program a modern microcontroller in assembly language and operate its peripheral devices.
- Interpret how the assembly code generated by a compiler relates to the original C code.
- Practice thread-based program design with a real-time operating system.
- Develop programs that control embedded systems using quick and efficient methods.
- Predict, measure, and manipulate a program's execution time.
- Learn software development techniques and tools used in embedded system development, including working with configuration management tools and software repositories.
- Design and build embedded systems, including architecture, schematic capture and layout, board manufacture, population, test, and system integration.

The goal of this advanced course is to solidify and build upon a student's knowledge of computer organization by providing hands-on experience with microcontrollers. Students also examine a few sensors that are used in commercial and medical products and learn how to interface them in a microcontroller system. Students in this course continue to utilize the mixed signal oscilloscopes and PCs with software development environments described earlier. They also use configuration management tools available via the campus local area network.

4. Introducing Communications in Introductory Embedded Systems Courses

Our approach to teach communications to students is bottom-up with respect to the open system interconnection (OSI) reference model. In the introductory embedded systems course students implement basic serial I/O communications using polling by transmitting data between a PC and a M30262 SKP development board. They learn the importance of setting up the physical data communications including speed, number of data bits, start and stop bits, and parity using a universal asynchronous receiver/transmitter (UART) and twisted pair wiring. Next they used interrupts to perform serial I/O between two M30262 SKP development boards, again using UARTs and twisted pair wiring. Students learned the importance of relying on the hardware and interrupt service routines to handle the physical transmission of large blocks of data.

The success of each student exercise was measured by grading each lab based on the functionality demonstration, code content, code structure, and lab report. A score of 85% of possible lab exercise points was considered a successful implementation of the lab. The two efforts described above had the following success rates: serial I/O-Polling = 100% and serial I/O-Interrupts = 95%.

The purpose of another educational effort was to teach students the basics and benefits of optical communication and high-speed computer control. The optical link allows very high-speed (~100kbps) data transfer between two SKP-30262 microcontroller development boards. The overall objective of this lab was to test the programmer's ability to create the most efficient code.

The hardware for the optical communication consists of a transmitter and receiver module created by Agilent (Figure 1). The HFBR-1412 standard transmitter is capable of speeds in excess of 10Mbps [3]. The HFBR-2412 TTL receiver is capable of speeds up to 5Mbps [4]. This speed far exceeds what is possible by the development board. This is important because the efficiency of the programmer's code determines the highest attainable transfer rate.

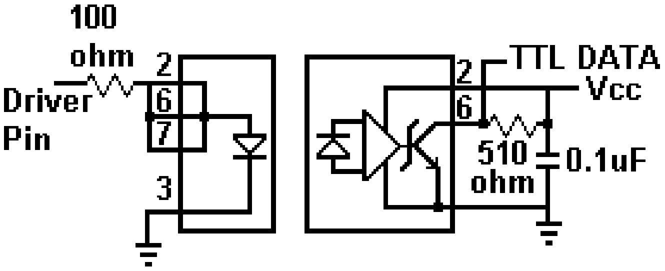

Figure 1. Agilent HFBR-1412 Optical Transmitter and HFBR-2412 Optical Receiver Schematics (respectively).

The transmitter output is controlled by one output port of the microcontroller. The communication protocol consists of 8-bit ASCII characters with a start and stop bit. The bit duration for both the transmitting and receiving microcontroller are controlled by an overflowing timer interrupt. The value for the timer is kept the same on both microcontrollers in order to maximize the synchronicity of the communication. This value is made as low as possible until the processing between bits becomes longer than the bit period. Eighteen students in nine groups were given a lab exercise to perform data communication between two Renesas microcontroller boards.

The students performed two independent tasks. The first task was to send characters through the optical fiber from one board to the other using the board UARTs at a baud rate of 19,200 baud, effectively using the previously learned skills with optical links rather than twisted pair wiring. This task had to be completed with minimum errors. This simple task was assigned to ensure the students built their hardware circuit correctly.

The second task was to perform a high-speed data transfer between two boards using the optical circuits at the greatest speed possible. The second task was more challenging because of the fact that the speed at which the communication needed to be performed was not specified, and the students could experiment and optimize their code in order to achieve the fastest speed possible.

Nearly all groups achieved the first task and all working implementation had zero errors. The results of the second task however, where disappointing. While the fastest speed achieved was a blazing 401,000 bps with few errors (using a 20 MHz processor), only 40% of the groups were able to transmit faster than using the 19,200-baud UART. The most common pitfall was that the groups had difficulty writing their own "software UART" to accurately clock their data through the board's I/O ports. However, the main objective, student learning, was achieved. A summary of student results is shown in Table 3.

Table 3. Student performance on the Optical Communications Laboratory assignment.

Student Group	Optical Comm using UART		Optical Comm using I/O pins	
	Speed (kbps)	Errors	Speed (kbps)	Errors
1	19.92	0	401.00	0
2	17.54	0	227.30	3
3	19.43	0	85.07	2
4	19.43	0	85.07	2
5	19.24	0	5.27	0
6	13.02	0	0.50	0
7	19.27	0	Did not work	Did not work
8	18.70	0	Did not work	Did not work
9	Did not work	Did not work	Did not work	Did not work

5. Infrared and Radio Wireless Communications in Advanced Embedded Systems Courses

Wireless infrared (IR) transmission has many applications such as remote control, telemetry and health care. For those applications, infrared transmission has many advantages over RF (Radio Frequency) transmission techniques [5,6]. Since intensity, modulation, and direct detection receivers are used, the multipath-fading problem can be avoided. In addition, building walls block infrared waves, so that interference rarely occurs. Furthermore, there are no regulations over the used bandwidth. Infrared transmission has some drawbacks as well: path loss could be high, it is limited to short range applications, and it has transmission power restrictions so as to not affect human eyes or skin.

Infrared emitters and detectors capable of high-speed transitions are available at a low cost, so it was a simple task to create labs to introduce students to the basics of IR communications systems [7]. The desired outcomes of the lab exercises were an understanding of modulation, transmission, and demodulation techniques through establishing a board-to-board communication using two SKP-30262 microcontroller evaluation boards, LEDs, photo detectors and some transistor level devices. In this lab students used onboard timers, serial UARTs, and I/O ports of the board to create the IR communications device. Two boards were programmed with the same code and had the same IR hardware. Two serial cables and one PC with two serial ports were needed. The first effort simply sent a single byte, and waited for an acknowledgement (ACK) or non-acknowledgement (NAK) byte to be returned. Students also implemented a time-out function to allow resending the byte if an ACK or NAK was not received in sufficient time after transmission. An example of the lab set-up for the infrared communications experiment is shown in Figure 2.

The next effort involved creating packets of data and transmitting these between boards. The packets had a sync byte, source and destination bytes, a packet size byte, the data payload, and a checksum byte. In this exercise, the students learned the value of building packets, then buffering data and decoding packets.

The last effort in this series of exercises was to involve a packet store-and-forward exercise, where any received packet that was not intended for the device would be forwarded to the next device, but the success rate of the packet exercise was too low to allow groups to easily reuse their code.

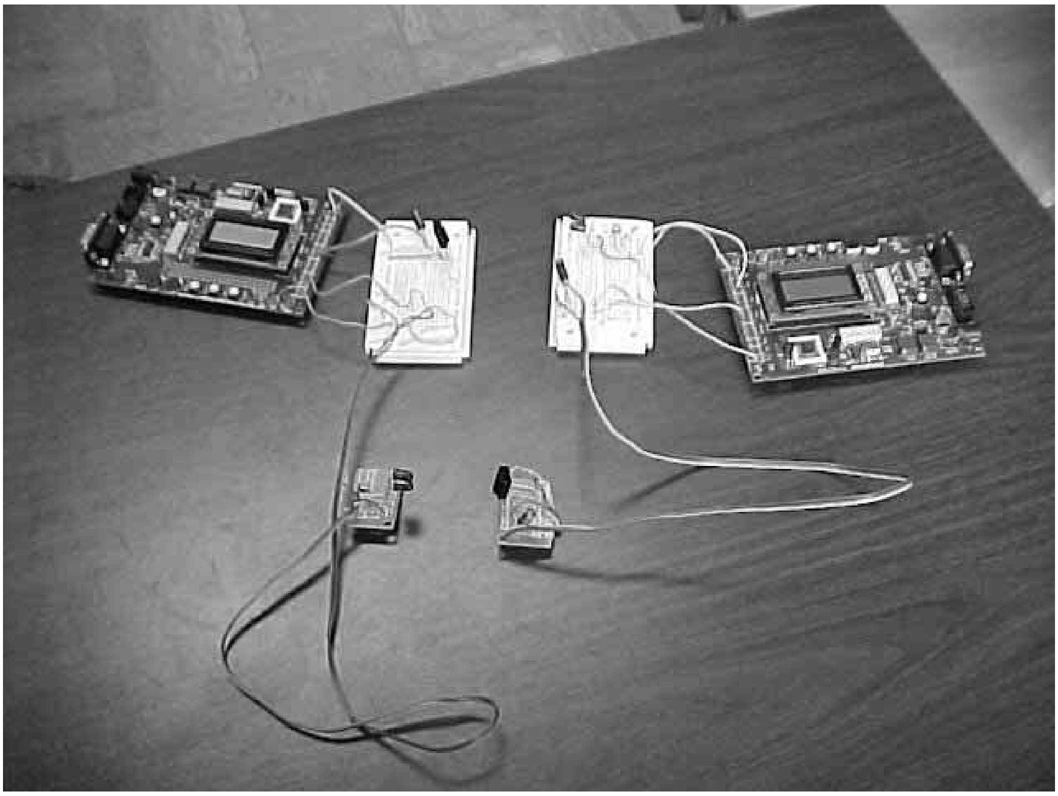

Figure 2. A lab setup for the infrared communications exercise.

The next communications experiment involved building transmission packets for the Teleca (Ericsson-made) Bluetooth module. Students set up the Bluetooth module for data communication, then continuously transmitted the temperature value (in ASCII) of the development board's thermistor to another Bluetooth module connected to a PC. Again students needed to build packets with the destination address and payload. One aspect that they did not program was the Bluetooth discovery process - they had to rely on an already written PC program to do this. See Figure 3 for an example of the Bluetooth lab setup.

Again, student success of each exercise was measured by grading each lab based on the functionality, code content, code structure, and lab report. A score of 85% of possible lab exercise points was considered a successful implementation of the lab. The three efforts described above had the following success rates: IR communications - basic = 100%, IR communications - packets = 50%, Bluetooth communications = 100%. The reason the packet communications lab exhibited a low success rate was due primarily to the difficulty of synchronizing the bits of the entire packet between the two boards. Students learned that the timers and system clocks of individual boards were often too far apart to allow synchronization based on only the synchronization byte. Nonetheless, this is an important concept and in future labs we may incorporate this concept through discovery-based learning.

6. Future Work – A Wireless Enabled Embedded Systems Course

One effort that was started but not completed was the creation of an IEEE 802.15.4 “daughter board,” that could plug into the class development board. This daughter board would contain only the radio transceiver chip and supporting circuitry for IEEE 802.15.4 communications, and rely on the development board for the software stack needed to communicate between boards. We would provide the students with the necessary libraries needed to build messages for transmission, and decode received messages. We are currently completing this work and hope to have it available for the last lab exercise of the Fall 2005 semester.

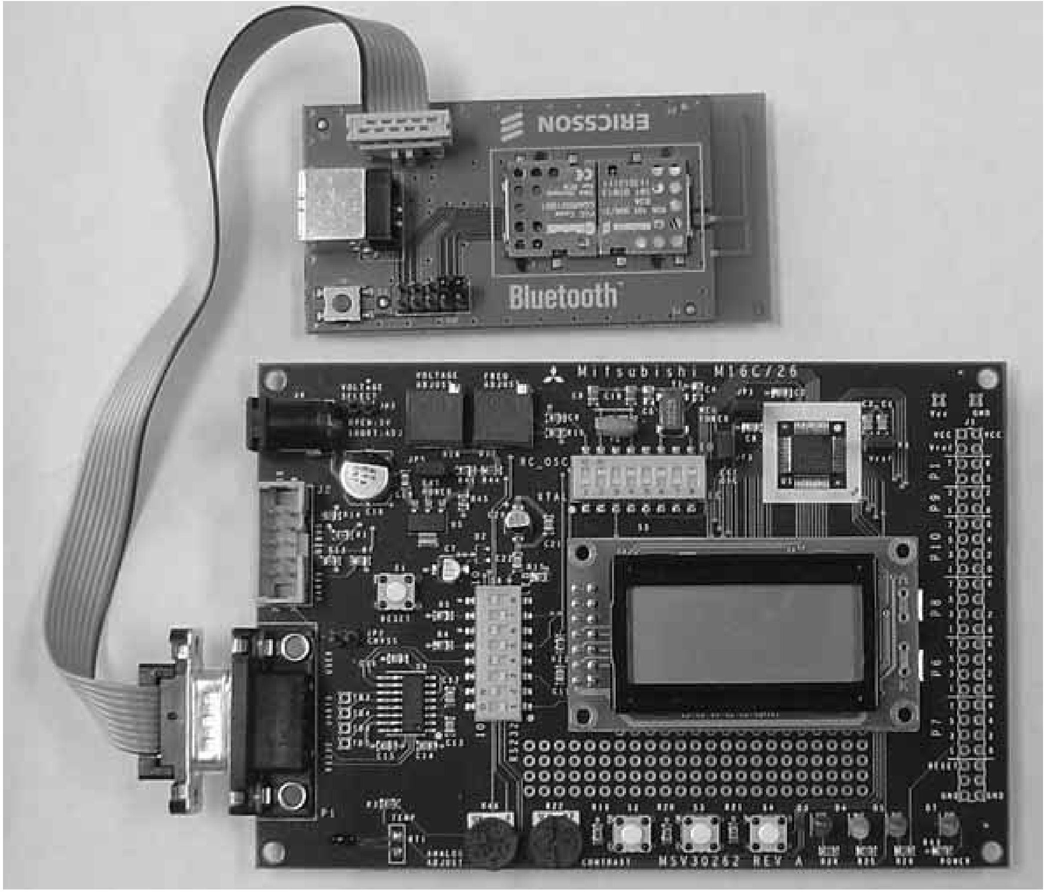

Figure 3. A lab setup for the Bluetooth communications exercise.

Figure 4. Sample embedded development board with proposed attached IEEE 802.15.4 communications daughter board.

A new senior technical elective course will be developed to address issues associated with designing and implementing wireless sensor networks. The course builds upon and is motivated by extensive educational literature which supports the integration of classroom learning with laboratory experience for educating students in communications [8-20]. The proposed course will have the following five educational objectives:

1. Issues and design practices for integrating sensor, control logic, and RF communications for low cost and low power sensor applications.

2. Introduction to low power and low cost RF communication standards. Specifically, the IEEE 802.15.1 (Bluetooth) and IEEE 802.15.4 (LR-WPAN). These two standards will be compared and contrasted to examine trade-offs in transceiver design for wireless sensor network (WSN) applications.

3. Introduction to low power network protocols for WSN. Current routing and scheduling schemes for WSN will be covered based on techniques addressed in the literature as well as methods being developed by the authors.

4. Environmental issues including RF signal propagation, multipath and interference as well as coexistence issues based on operating the WSN in an unlicensed frequency band.

5. Context aware design, i.e., understanding the WSN application and exploiting the characteristics of the problem to achieve an improved design.

6. Prerequisites for the new course will be an introductory course in analog and digital communications and an introductory course in embedded systems.

A three prong approach is to be investigated for engaging the students and facilitating learning: 1) traditional lecture, 2) computer modeling & simulation, and 3) laboratory with empirical investigation. Communication theory and analytical models are often considered dry by undergraduate students, leading to poor retention of the material. Understanding these concepts is an important part of understanding approaches required to solve real world problems. Therefore, a pedagogical goal is to develop learning modules for the topics in the course. Each module would use multiple approaches and multiple teaching approaches to engage the student to grasp difficult concepts and see underlying principles. To illustrate, radio frequency signal propagation is an essential component in designing WSNs and there are well-established analytical models that characterize signal propagation. The analytical models are involved and difficult for most undergraduates to grasp. A learning module for RF propagation could include the following: 1) Lecture introducing the concept of RF propagation at a high level with limited use of mathematical models, 2) Laboratory experiment which extends the lecture and requires the student to engage in discovery-based learning, 3) Follow up lecture, which discusses the analytical models in detail, drawing upon the students observations from the lab, 4) Additional computer simulation assignment on RF propagation, which reinforces the concepts discovered in the laboratory and presented in the classroom. Identifying the correct set of topics and the development of the learning modules is central to meeting the objectives of the project.

7. Conclusions

Engineers who have knowledge of embedded systems and wireless communications will be in high demand. Unfortunately, there are few affordable development environments available for classroom use, so students often do not learn about these technologies during hands-on lab exercises. We have provided students with hands-on lab exercises that represent some areas of communications and wireless communications used in industry. Several examples of communications lab exercises were described, including wireless communications. A future lab will investigate IEEE 802.15.4 in great detail. A follow-on Wireless Enabled Embedded Systems course is also suggested. Some of these labs were also reported in earlier papers [21,22].

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