AC 2010-2374: EMBEDDED WIRELESS NETWORKS INSTRUCTION

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Embedded Wireless Networks Laboratory Instruction

Abstract

Wireless sensor networks are now considered commonplace in the automation and monitoring of home, industry and environmental habitats, as well as having applications in military applications, healthcare and traffic control. Before 2006 there was a lack of educational resources pertaining to the joint fields of embedded systems and wireless network theory, especially on the undergraduate level. Based on this need for education, The University of North Carolina at Charlotte created a class to focus on the theory and application of Embedded Wireless Networks including detailed understanding of RF environmental characteristics, advancements in energy efficient network designs, and design techniques for energy efficient embedded systems.

With the increased popularity of wireless capability and energy efficient embedded computing, this educational course has become essential in creating in-demand engineers. The accompanying lab portion of the class has also allowed the students to become proficient in the use of monitoring equipment including Spectrum Analyzers, Function Generator and Oscilloscopes for measuring and troubleshooting wireless activity.

One of the main focuses of this paper is the teaching method used to help graduate and undergraduate students bridge the gap between the theory of RF signals, standard wireless protocols, and hands-on applications. Theoretical studies consist of RF environments including RF signal propagation, multi-path interference, and co-existence issues in the unlicensed frequency band. Standard Protocols studied include IEEE 802.15.1 (Bluetooth), 802.15.4 (LR-WPAN including ZigBee, and IEEE 802.11. Hands-on applications consist of combining function generators with antennae and signal attenuators to study frequency components of modulated signals and effects of attenuation. While specialized courses in embedded systems and wireless networks had existed separately, layering the fields to display real-life applications gives students a deeper understanding of the components.

Previous Work at other Universities

Previous classes offered at other universities, including UC Berkeley[7] and Yale[9], covered parts of the material needed to understand the decisions needed to design and implement an embedded wireless sensor network, but not in the expanded combination of the theory and hands on lab experience.

A Northeastern University[4] course was highly focused on labs and projects involving wireless sensor networks for use in rescue-mission scenarios. The hardware platform used in the course included the TI MSP430 Processor and Chipcon ZigBee transceiver paired with off the shelf robot kits.

A University of Utah course focused on building reliable and efficient embedded systems, but was highly focused on C programming. The hardware platform utilized was an ARM-based embedded development board. Special topics studied in the course included software based issues including safety-critical embedded software architecture, digital signal processing, feedback control and verification and validation of communication.

The UC Berkeley[7] course examined in more detail the networks used in the other courses, involving topics such as compression and source-coding, time synchronization, coverage and density, ranging and localization, tracking, collaborative signal processing and emerging standards such as ZigBee.

The Yale[9] course also studied embedded network communications in depth along with radio technologies, communication protocols for ubiquitous computing systems, and some of the mathematical foundation of sensor behavior. The hardware used in the course consisted of an OKI ML64Q5002 processor and a ZigBee compliant radio from Chipcon.

University of North Carolina at Charlotte Course

While these courses all studied communication with a focus on embedded wireless networks, they did not delve into the signal properties associated with creating a robust embedded wireless network. In the University of North Carolina at Charlotte course, there was a strong emphasis on RF characteristics that are essential in designing a network.

The course was also created with the intent of disseminating the knowledge from the experience with other professionals in the educational community by way of sharing the course work and pedagogical approach with Frontiers in Education and ASEE, as well as sharing the final version of the laboratory material with the educational websites belonging to Agilent technologies and MathWorks for wide dissemination. The course material was also expected to be shared with Western Carolina University, the University of South Florida, and Johnson C. Smith University (JCSU).

The course was originally designed to cover a larger scope than courses previously offered in Embedded Wireless Networks, notably with the inclusion of the study of RF propagation characteristics and design practices for integrating RF communication. The main course objectives were:

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

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.

As a prerequisite for the course, the students were expected to have background knowledge of communication, and experience using computer aided design tools for communication analysis and design. This background knowledge was offered in a senior level introductory course in analog and digital communications.

In addition to the classroom lectures, the lab exercises served as an application based learning experience. Agilent spectrum analyzers, signal generators and oscilloscopes were purchased for laboratory experiments (Figure 1). The equipment provided an excellent environment in which to study many types of modulated signals, as well as measure important characteristics of the varied RF signals. In addition to the main equipment, highly accurate attenuators, signal splitters and couplers were used to study effects of attenuation and interference on signals.

Fig. 1: Agilent 6000 series Mixed Signal Oscilloscope and Agilent N1996A Spectrum Analyzer[1]

The labs were organized into five segments in order to build up the knowledge needed to grasp a firm understanding of the course objectives. The main focuses of the labs were understanding equipment, recognizing characteristics of modulated signals, studying indoor RF propagation, finding the effects of noise on communication efficiency, and how to maintain communication in noisy environments.

The first lab introduced the students to the laboratory equipment by using the equipment to generate and view signals. This allowed the students to understand how to properly view a signal by utilizing such measurement choices as resolution bandwidth, averaging, minimum hold, and maximum hold, and power measurement (Figure 2). The students were also able to determine the error of the signal generator by resolving 2 signals to find the minimum frequency difference needed to find separation (Figure 3).

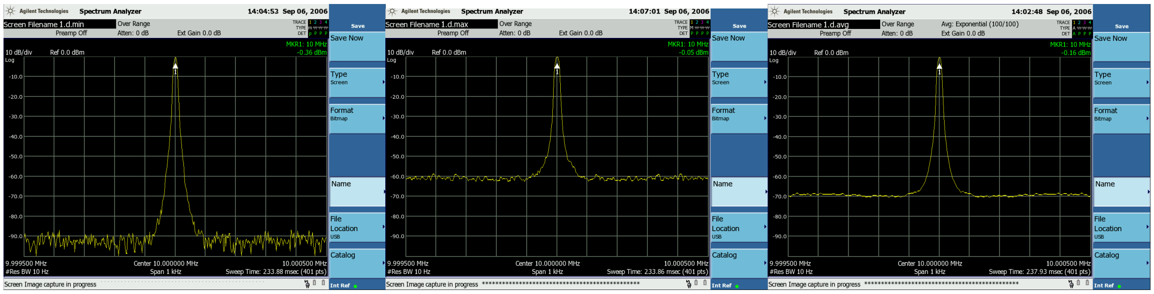

Fig. 2: Reference signal captured using (from left to right) min hold, max hold, average.

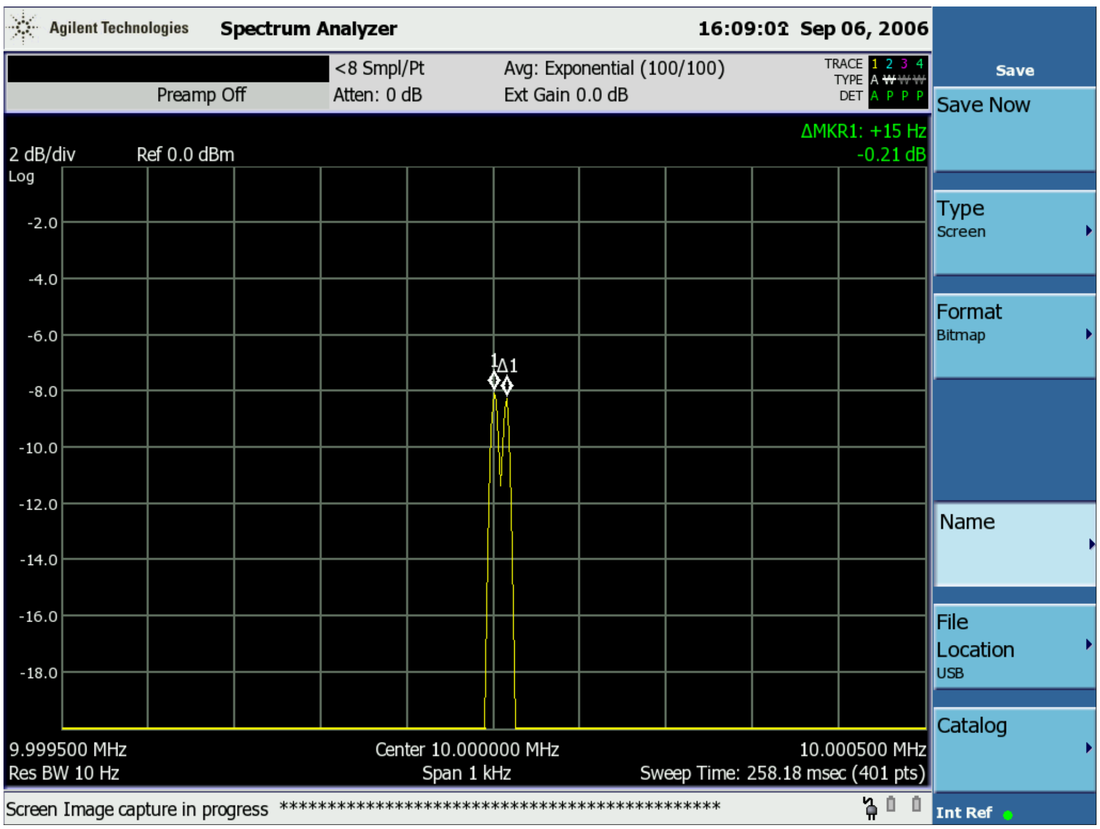

Fig. 3: Discovering the minimum separation of two separate frequencies

The second lab introduced the students to modulated signals in a way that could not be taught in a classroom. By creating and measuring amplitude modulated and frequency modulated in the time and frequency domain, the students were able to understand characteristics such as amplitude modulated depth, rate and waveform (Figure 4). Also pulsed signals were introduced to understand the effects of pulse width and duty cycle. As a precursor to Bluetooth, the students created and recorded frequency hopped signals.

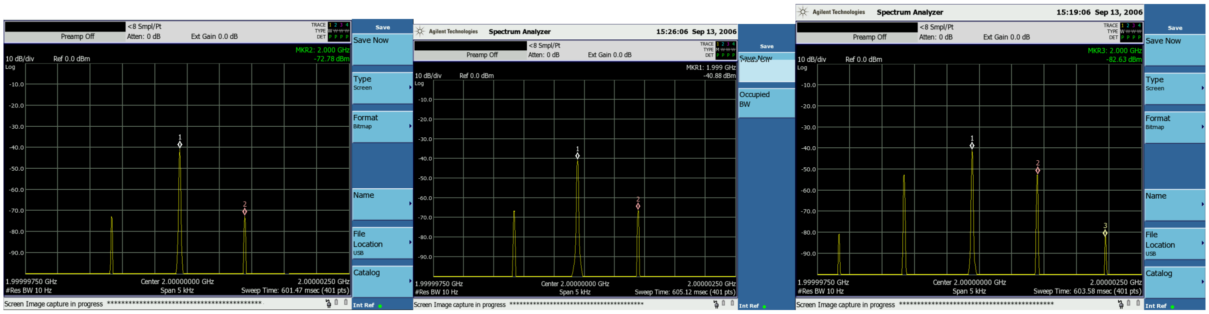

Fig 4: AM signals with (from left to right) 5% depth, 10% depth, 50% depth

Effects of physical environment were studied in the third lab, which started with a survey of the signals present in the engineering lab wing (Figure 5). The students then used the knowledge learned in the survey to determine the relationship between empirical measurements and RF propagation models using the MATLAB RF propagation tool (Figure 6). Path loss equations and attenuation factors taught in the classroom were applied in determining this relationship. The groups also created a model of the lab by applying these lab lessons.

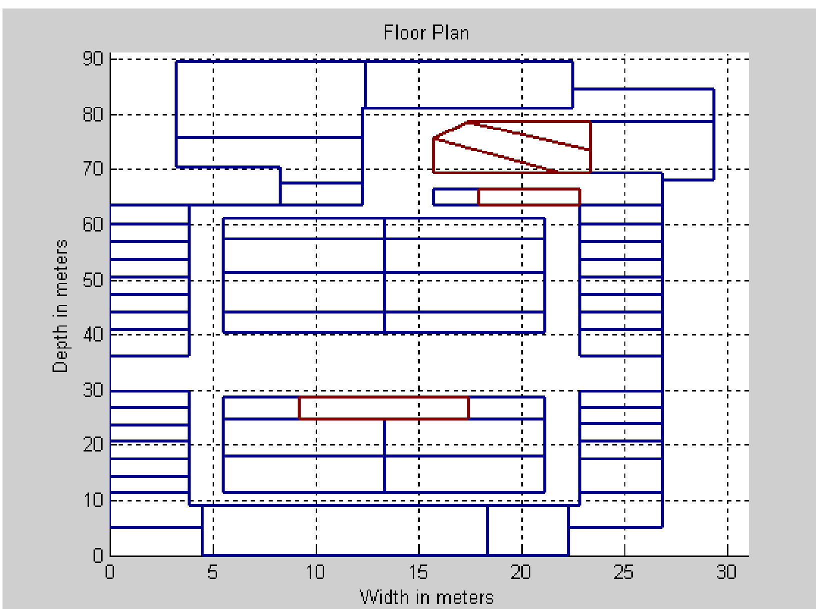

Fig. 5: Model of the Engineering lab wing

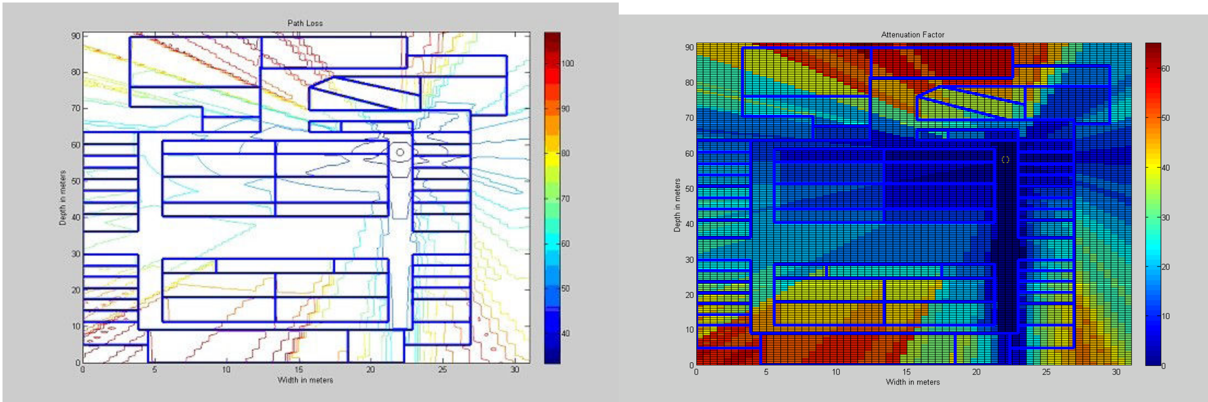

Fig. 6: Models showing path loss (left) and attenuation factors (right)

The fourth lab brought the Freescale ZigBee development kits into the lab for studying the effects on noise and interference with actual packet transmission. First, the LR-WPAN signals generated by the embedded hardware were recorded and described (Figure 7). The signals were then coupled with noise and interference to view the effects on the packet error rate (Figure 8).

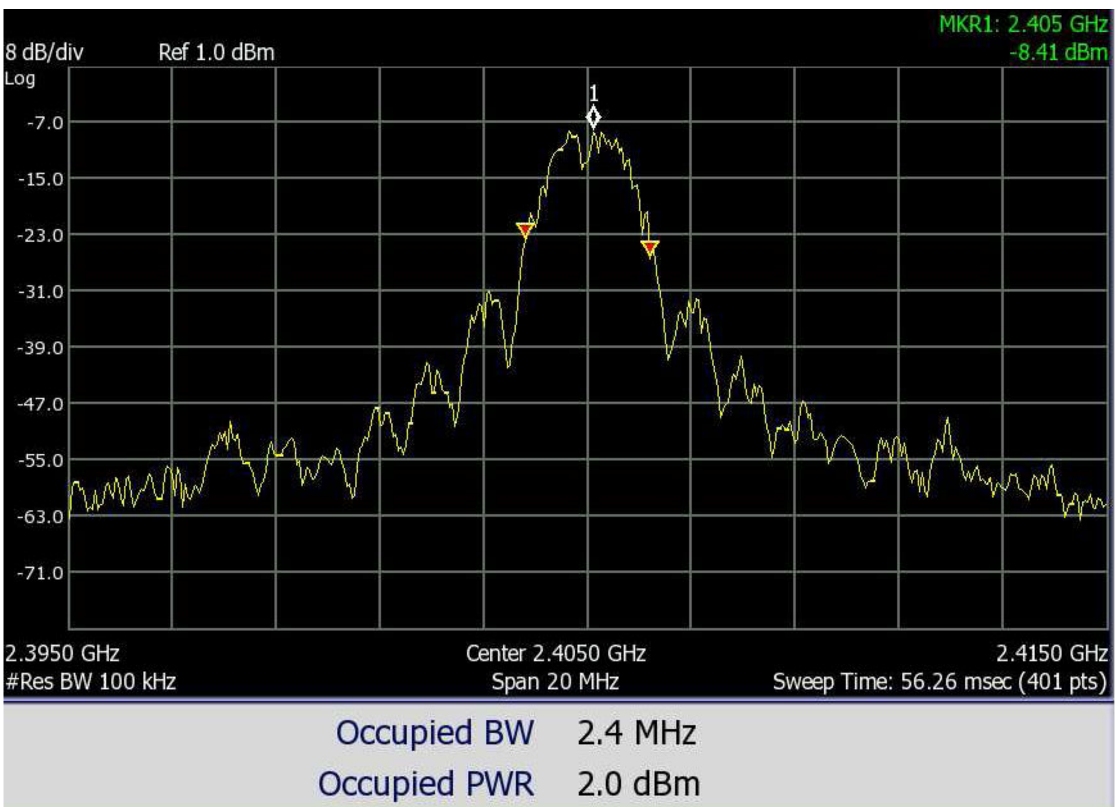

Fig. 7: Observation of a LR-WPAN signal

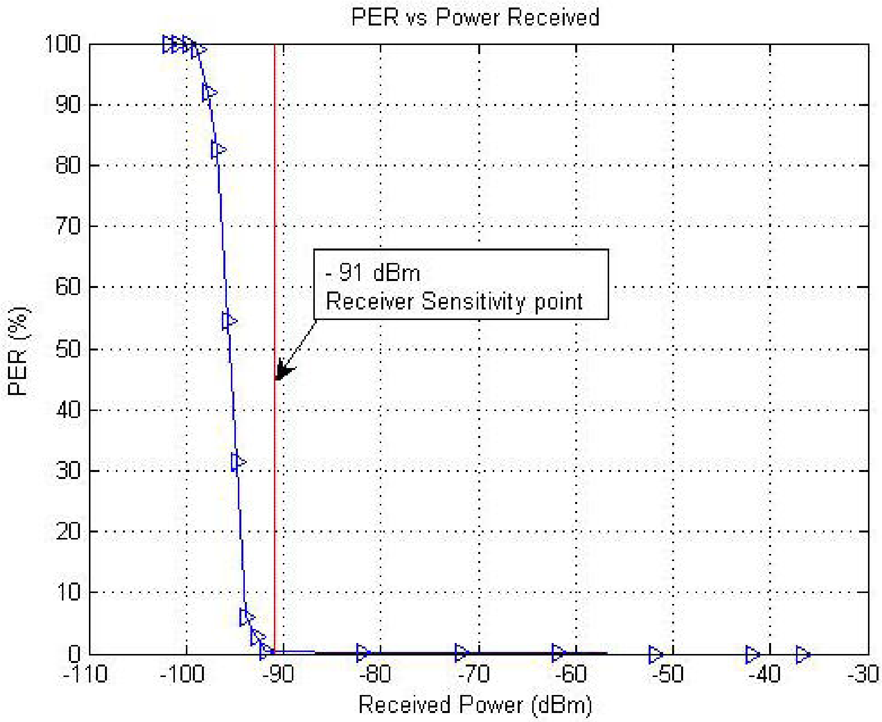

Fig. 8: Packet Error Rate vs. Signal Power Received

In Lab 5, the included antenna was connected to the board to measure the antenna gain. Packet error rates were also measured using co-channel interference. The students also determined the distance necessary between packet routing boards to overcome a given interference source (Figure 10).

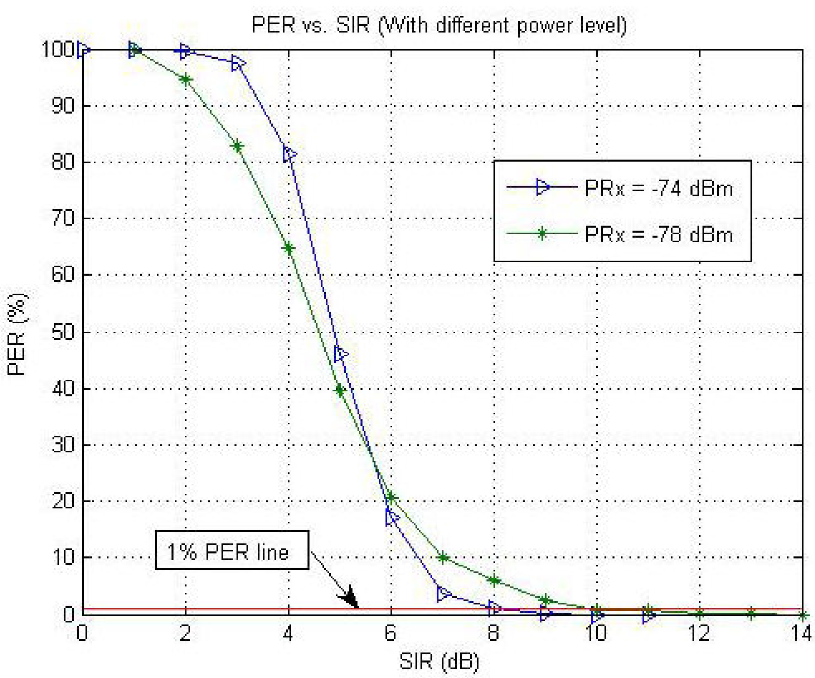

Fig. 9: Packet Error Rate vs. Signal to Interference Ratio with different power of Interference

The embedded hardware used in the labs consisted of Freescale Development boards[3] (Figure 10a) based on the MC-1322x package, including sensor reference boards and a network coordinator board. The software with the devices included a ZigBee stack with example programs that were adjusted to be used in the lab. Due to the nature of the first year course, the hands on programming that was expected to be done by the students was minimized in efforts to complete the lab assignments. The labs for the second two course offerings used the Texas Instruments eZ430-RF2500 development kit[6] (Figure 10b), again with limited communications stack programming.

Fig. 10a: Freescale 1322x development kit[3]; Fig. 10b: TI eZ430-RF2500 development kit[6]

Student Assessment of Performance

The first effort of the course left the students with an extensive knowledge of FP propagation and a great understanding of modulated signals, including the makeup of signals, as well as understanding how to capture the signals, and identify their unique properties using advanced laboratory instruments. The students also walked away with a strong understanding of the effects of interference and physical environmental impacts when designing embedded wireless networks.

By utilizing the state of the art equipment in their lab experience, the students were able to observe effects of attenuation and signal interference in a "closed" environment. Also, by surveying the surrounding environment for typical and atypical signals that can and may appear, most notably the stray signals generated by common 802.11 networks as well as the "jumping" frequency signals of widely used Bluetooth devices.

This course has been offered three times since its establishment: Fall 2006, Spring 2008, and Spring 2009. The course enrollment has been capped to a small number due to its extensive hands-on characteristics and limited number of measurement instruments. The course has remained virtually the same, with the exception that the development kit was changed to the TI MSP430EZ.

Student performance is based on the ability of students to correctly complete the lab exercise and effectively answer a quiz based on the laboratory activities and learning objectives. The results are that we have improved in our ability to present the laboratory exercises and emphasizing the learning objectives.

Table 1: Student Performance of Laboratory Learning Objectives

Percent understanding all objectives	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5
Fall 2006 (n=10)	100%	80%	80%	70%	70%
Spring 2008 (n=16)	100%	88%	88%	81%	81%
Spring 2009 (n=12)	100%	92%	92%	92%	92%

Additional University Offerings Since 2006

Since the creation of the course in 2006, more classes have started to bring the importance of studying RF characteristics into courses studying embedded wireless networks.

A Carnegie Mellon[2] course has been offered since the fall of 2006 that spans a variety of topics which include radio communications, network stack, systems infrastructure including QoS support and energy management, programming paradigms and distributed algorithms. Hands-on exercises were used to teach the programming of FireFly sensor nodes by using the 'nano-RK' power-aware sensor real-time operating system (RTOS) and using 802.15.4 radio communications. Then, project groups define, design, implement and test a sensor network project.

An introductory Stanford University[5] course studied system design and implementation for energy-constrained embedded devices. The main focus for this course however appears to be software systems for microcontroller-based embedded wireless devices.

A University of California at San Diego[8] course in 2008 studied wireless networked systems from a design perspective focusing on aspects related to energy efficiency. Some main focuses of this course, with respect to energy efficient wireless systems, are channel modeling and communication theory, including theoretical analysis. Also studied are common protocols and standards, and general aspects of emerging sensor network systems. Most of the projects are hands on experience with Telos Motes (running TinyOS), involving extensive coding.

The San Diego course site for the 2008 class states that “Due to the continuing and fast developments in the field of wireless embedded networks, no established textbook is available that covers all topics relevant to this course.” With the exclusion of the extensive programming, this course is by far the most similar to the course started at the University of North Carolina at Charlotte, with lesson topics that include digital modulation principles, transmit power considerations, and system level power issues. However it still seems to lack the focus of hands on and theoretical study of RF properties.

Conclusions

With the low cost and low energy use of embedded wireless networks, it is easy to see why these networks could be widely used in military applications, building automation, and for monitoring the structural safety of the countries aging buildings and bridges. While off the shelf development systems can be purchased at a decent price, the design of a network is a specialized task that involves taking into account many effects. In order for embedded systems engineers to properly understand how to develop with wireless networks, courses like this must be adopted in the future. Embedded systems engineers with the proper knowledge needed to work with a wireless network are a very valuable asset to many fields of engineering. It is also cost beneficial to companies that are creating embedded consumer devices that can use wireless communication, and it keeps the intellectual property in-house when an innovative portion of a new product design does not need to be outsourced.

With the recent trends in increasing bandwidth used by consumer wireless products as an effect of larger file sizes and increasing demands, people don't often hear about the need for energy efficient, low data rate networks. With the increasing trend of energy savings and cost-reduction, there will be many areas in which networks such as ZigBee and the engineers who design these networks will be a valuable investment for a variety of industries.

References

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