AC 2011-2468: WIRELESS COMMUNICATION SYSTEMS: A NEW COURSE ON THE WIRELESS PHYSICAL LAYER WITH LABORATORY COMPONENT

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Wireless Communication Systems: A New Course on the Wireless Physical Layer with Laboratory Component

Abstract

The wireless transmission of data has emerged as one of the most important technologies currently in use, with its importance expected to increase in the future. The industries developing these technologies are looking for students with competence in the wireless field. Not only is this technology achieving broader application, but efforts to improve performance are ongoing and critical as higher and higher data rates under more adverse operating conditions are desired. The need is increasing for students to be prepared in this field in order to be competitive in the marketplace. Furthermore, currently enrolled ECE students are engaging in projects which often include wireless communication subsystems.

To meet this need, the course Wireless Communications Systems was developed and delivered. This course is intended to help ensure our students' competency in the emerging wireless communications field for now and into the future. The course concentrates on wireless physical layer communication and builds off of a traditional course in communications. Laboratories and projects are a fundamental component of the course.

In this paper, we present an overview of the course topics and describe the areas covered. We also discuss what was left out due to time and complexity considerations. We further describe the laboratory experiments and how they integrate with the lecture material. We then offer our assessment of the experience and give suggestions for further improvement in the next offering. Lastly, we include the results of a student assessment that offers insight into the applicability and interest in the course.

Introduction

In a traditional ECE curriculum, a typical senior elective is Analog and Digital Communications. Increasingly, this long-established approach to communications instruction has included units on wireless systems, with some including laboratory exercises[1,2]. Since these areas have much in common, our approach has been to favor the offering of the wireless course over the traditional communications course. It has been found that the losses incurred by scaling back the traditional communications topics (less depth and breadth in modulation formats) have been more than compensated for by greater understanding in other areas covered in the wireless course (antennas, propagation and system considerations).

The new course concentrates on the study of the physical layer of typical wireless communications systems, as opposed to a course concentrating on wireless data communication protocols[3]. The primary focus is on the enabling technologies that perform the communication of data through the air interface from one point to another. Of particular challenge is offering this course to undergraduate students for whom it cannot be guaranteed that they had had a first course in communications[4].

Topics include the block-diagram level study of the air interface, antenna design, modulation theory, coding theory and an introduction to the supporting protocols. Performance under conditions of interference and techniques to minimize the impact of interference are also considered. The laboratory component of the course utilizes a mixture of hardware-based experiments using higher-end instrumentation along with MATLAB/Simulink block-level simulation. Experiments include analog and digital modulation, antenna design and build, cellular topology, media access control and spread spectrum techniques.

Course Objectives and Topic Coverage

Course Objectives

The course objectives are given below. These objectives were generated through consultation with other faculty, a survey of textbooks in the field (some examples[5,6,7,8,9]) and an informal survey of similar courses in other institutions.

In completing this course, students will demonstrate:

1. a knowledge of wireless communication systems technology and evolution;
2. an understanding of the principles applied in the design of cellular telephony networks;
3. a knowledge of the theory and performance of the modulation schemes used in wireless communications;
4. a knowledge of the theory and implementation of antenna systems used in wireless communications;
5. a knowledge of the theory of the radio propagation model;
6. an understanding of the application of coding theory to wireless communications for both compression and error correction;
7. a knowledge of the system parameters and performance for standard wireless applications including cellular telephony, wireless LANs/PANs and RFID.

As this was a pilot-run of a new course, it was understood that the optimistic list of objectives may not be entirely satisfied. However, it was decided to “set the bar high” and attempt to deliver a course that would best serve our students. The intent was to better scale these objectives in further offerings of the course.

Topics

A schedule of topics covered in the course is given below in Table 1. Approximate time spent in each area is indicated. As can be seen from the table, significant overlap exists between this wireless class and what would be typically covered in a first senior-level elective in communications, including analog and digital modulation as well as some aspects of coding theory. New to the wireless course is significant coverage in antenna theory, cellular system design, radio propagation and fading models and spread spectrum. Following the table is an expansion of the discussion of several key topics.

As can be seen in the table, the amount of material to cover in the given timeframe is ambitious. One strategy to assist with this problem is to limit the amount of time spent on drawn out derivations. While it is important for students to see the mathematical connections, feedback indicates that most students miss the intricate details and are better served with a clear, but brief, overview. Advanced students are directed towards references that give step-by-step detail, if so inclined. The second strategy is to take advantage of the laboratory. If a concept is not fully developed in lecture, it is possible to incorporate further theoretical explanation in the laboratory handout. Furthermore, the lab itself is designed to explore the topic conceptually. Feedback has indicated that students learn better in this two-pronged approach as opposed to simple passive note taking.

The overlap with traditional communications topics is necessary since it cannot be guaranteed that our students have taken a course in communication theory. While beneficial to expose the students to this area, there were two related concerns:

1. The need to progress to wireless-specific topics necessitated the abbreviation of the typical coverage in traditional communications instruction;

2. The class time devoted to classical communication theory restricted the amount of wireless material that could be covered.

As briefly stated earlier, our approach to mitigate concern 1 was to condense derivations to essential steps. Furthermore, we limited the variations or flavors of the modulation schemes to those most widely used. Finally, we could use laboratory exercises to actively reinforce loosely covered lecture topics. Using this approach, the students obtain a good understand of communication theory albeit with some arguably non-critical knowledge gaps.

Concern 2 is more substantial. Self-evaluation following delivery of the course indicated somewhat less than satisfactory results for several topic areas including depth into radio propagation, antennas, coding theory, system considerations and protocols. While the laboratory sessions can help “flesh-out” some areas, it cannot fully compensate. For example, statistical models for radio propagation were not discussed; a mathematical framework for antenna performance was glossed over; source coding such as speech compression was not developed; block diagram level studies for different wireless standards were limited; and an overview of wireless data protocols was missing.

The situation expressed above does not have an easy remedy. The field is too vast to condense into a single semester. Furthermore, finding faculty with adequate expertise over the broad range of areas is challenging (consider analog and digital communications, signal processing, RF, radio wave propagation, antenna design, coding theory, data communications, wireless protocols, etc). The suggested solution is that the study of wireless communications is best done in a two-course sequence.

Table 1. Course Topic Coverage

Topic	Description	Duration
Analog Modulation	Medium-depth coverage of traditional analog modulation methods. TDMA versus FDMA. Cover only DSB-SC and Broadcast AM with simple demodulation. Cover FM only (not PM). Study BW via sinusoidal Bessel analysis and Carson's rule. Discriminator FM demodulation only. State SNR performance relationships.	3 weeks
Antenna Basics	Qualitative treatment of topic concentrating on practical applications such as antenna gain and radiation pattern. Study of SWR on dipole antenna. Introduce polarization, ground effects, non-ideal behavior.	1 week
Smart Antennas	Antenna arrays to determine DOA and beamforming. Mathematical development of correlation analysis and overview of Least Squares.	1 week
Radio Propagation	Brief coverage of large-scale versus small-scale fading. Free-space propagation loss and two-ray model.	1 week
Cellular Layout System Design	Hexagonal cellular layout topology and frequency reuse schemes. Cell geometry and calculating co-channel interference (SIR). Cell splitting and sectorization. Trunking and GOS considerations related to cell layout.	1 week
Digital Communications	Baseband digital communications including line coding, pulse shaping/ISI (Nyquist's first method) and resultant BW. The matched filter and error probability in AWGN channel. Signal constellation diagrams. M-ary schemes of FSK, ASK and PSK; modulation and demodulation. Bandpass digital communications as extension to baseband. QAM and resulting error probability. MSK and GMSK as preferred schemes.	3 weeks

Topic	Description	Duration
Spread Spectrum	Introduce SS via FHSS using GMSK. Fast and slow hop error probabilities. The concept of DSSS and CDMA. DSSS probability of error. The generation of spreading codes (PN sequences, Walsh codes) and their properties.	2 weeks
Introduction to Coding Theory	Source coding versus channel coding. FEQ schemes; block codes versus convolutional codes. Systematic linear binary block codes and cyclic codes. Hamming distance and computing the syndrome. Overview of convolutional coding approach.	2 weeks
System Comparison	Overview of components of commercial systems. Block diagram study of IS-95 (first generation CDMA).	1 week

Below is more directed discussion on a few select topic areas.

Smart Antennas

Following an overview of basic antenna theory[10], an overview of the emerging area of smart antennas was given. The topic dealt first with determining the DOA of an incoming wavefront using an array of two half-wave dipoles spaced $\lambda/2$ apart with outputs summed. The DOA method was analytically derived and demonstrated for sinusoidal signals using three approaches: cross-correlation (looking for peaks in the correlation), Fourier transform (looking for phase shift) and Least Squares (optimal delay filter). The DOA was then used to adjust a delay prior to the summing junction so as to constructively add the desired signal. The idea of beamforming was then introduced as a way to shape the antenna pattern by adding gains in the individual antenna branches in addition to the delays. An example was described to achieve this result without analytical development.

Spread Spectrum

The topic of spread spectrum was introduced as a military solution to avoid radio jamming using FHSS. The probability of error calculations was then amended to include the effects of FHSS. DSSS was introduced as a method to spread and hence suppress noise interference at the receiver. Following this treatment, the concept of CDMA was discussed. The probability of error for DSSS was then arrived at along with the concept of Processing Gain. The generation of chip sequences using a LFSR (for PN sequences) and Walsh Code matrices was discussed. The auto- and cross-correlation properties of these two forms of chip sequences were derived and compared along with the respective system considerations.

Laboratory

The laboratory portion of the course is essential to student learning. As mentioned above, the laboratory course component allows for reinforcement of the lecture coverage, potentially filling knowledge gaps along the way. Furthermore, student feedback indicates that the laboratory was where "they really got it".

The laboratory for wireless communications was split into hardware-based labs and software-based labs using MATLAB Simulink[11]. The hardware based labs utilized an array of standard RF equipment[12] as listed below in Table 2.

Table 2. Laboratory Equipment

Device	Description/Features	Make/Model
Arbitrary Function Generator	100 MHz or higher; dual channel; internal/external AM/FM modulation	Tektronix AFG 3252
Spectrum Analyzer	Low kHz – 500 MHz operating range; FM demodulation	Rhode & Schwarz FSL3
Oscilloscope	100 MHz or better, dual channel	Tektronix 3012C
VSWR Meter	Measure VSWR and impedance; frequency tunable up to 500 MHz	MFJ-269[13]
Mixer; power splitter	RF passive mixers and splitter/combiner, 50Ω	Mini-Circuits[14] ZSC-2-1+ Mini-Circuits ZAD-1H+
Audio equipment	Various audio sources (music player) and audio amplifier, audio speaker	Custom audio amplifier
Miscellaneous	Various active and passive electronic components; HAM Radio; RF field-strength meter; Hand-wrapped baluns (1:1, 2:1, 4:1)	Custom-built meter based on AARL design[15]

A typical laboratory workbench setup is shown below in Figure 1. Along with a student-constructed FM-range folded dipole antenna, much of the equipment listed above in Table 2 is depicted.

A description of the labs is given below in Table 3. Labs include HW-based experiments intended to introduce students to RF signal processing and equipment, analog modulation and antenna performance. SW-based labs employing MATLAB Simulink introduce students to concepts in digital modulation, cellular system design, spread spectrum and wireless access methods.

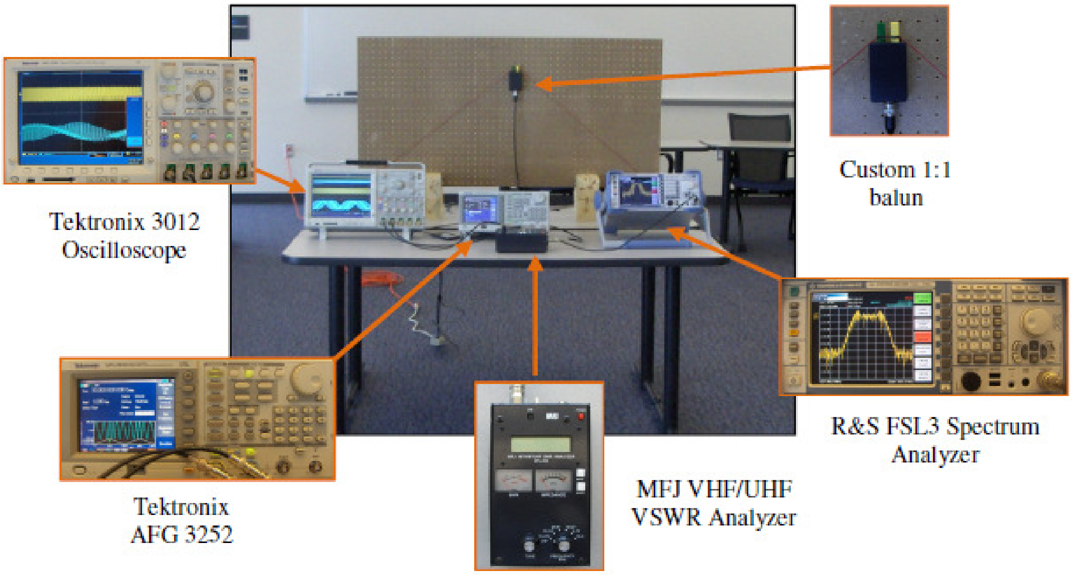

Figure 1: Laboratory Bench Setup

Table 3. Laboratory Experiments

Experiment	**Description**	**Equipment**
Mixers and AM	Serves as an introduction to the spectrum analyzer and modulation theory. Students mix tones and attempt to resolve on the spectrum analyzer. Using two mixers, DSB-SC AM is generated and demodulated. The effect of carrier phase error is studied using the variable phase of the AFG. Broadcast AM is generated via the AFG and demodulated using simple envelope detector.	▪ Spectrum Analyzer ▪ Oscilloscope ▪ AFG ▪ RF Mixer ▪ RF Summer ▪ Breadboard, passive components ▪ Audio source/sink
Frequency Modulation	Part 1: Use the AFG to generate FM with sinusoidal information signal. Adjust β to create Bessel null at various spectral lines. Part 2: Demodulate FM using BPF-based discriminator followed by envelope detector. Test with audio.	▪ Spectrum Analyzer ▪ Oscilloscope ▪ AFG ▪ Breadboard, passive components ▪ LM356 OP-AMP ▪ Audio source/sink

Experiment	Description	Equipment
Antenna Basics	Using wooden pegs on pegboard and masking tape along with 24ga wire, students construct antennas designed to work in the FM band. Students are assigned a center frequency and a design including half-wave dipole, folded dipole, inverted-V dipole, 2 or 3 element Yagi and square quad. Different baluns are used depending on design. Antennas are tuned using the VSWR meter. Using a large open area, the antennas broadcast low-power FM to a monopole receiving antenna connected to the spectrum analyzer. Students attempt to measure the effective radiation pattern of their antenna by rotating the transmitting antenna and recording the received power level. The typical experimental indoor setup is shown below in Figure 2.	▪ Spectrum Analyzer ▪ AFG ▪ VSWR meter ▪ Antenna construction materials ▪ Audio source/sink ▪ 1:1, 2:1, 4:1 baluns
Antenna Foxhunt	Students scale their FM antenna to operate at HAM frequency of 445 MHz. HAM transmits from hidden location; students use their antennas and associated directionality while connected to the RF meter to attempt to locate the hidden transmitter. First discovery "wins". A student-built Yagi antenna connected to the RF field strength meter is shown below in Figure 3.	▪ HAM Radio ▪ RF Field Strength meter ▪ Antenna construction materials ▪ VSWR meter
Cellular Systems: SIR	Students construct conceptual model of cellular hexagonal layout for different frequency reuse patterns. Students empirically determine worst case SIR and compare to theoretical predictions.	▪ MATLAB/Simulink
BFSK	Straightforward lab exercise to modulate and demodulate BFSK under conditions of AWGN. Probability of error empirical results are compared to theoretical for several transmission rates.	▪ MATLAB/Simulink
QAM and Performance Visualization	QAM modulation and demodulation are studied for an AWGN channel. Pulse shaping effect using Nyquist and Gaussian filters are compared. The BW of each scheme is measured. Eye diagrams and signal constellations are generated for each scheme while the SNR is varied. BER is measured for each pulse and the constellation and eye diagrams are studied as the SNR is varied.	▪ MATLAB/Simulink

Experiment	Description	Equipment
PN Sequences and DSSS	The auto- and cross-correlation properties of PN sequences and Walsh sequences are studied and compared. A simple baseband binary communication scheme is used for CDMA access with a Walsh chip sequence. The model is extended to bandpass QPSK and BER performance is compared between CDMA QPSK and FDMA QPSK.	▪ MATLAB/Simulink
Aloha and Slotted Aloha	Students construct models of Aloha and Slotted Aloha medium access protocols. Throughput efficiency is studied using a Poisson model. Empirical throughput rates are compared to theoretical models.	▪ MATLAB/Simulink

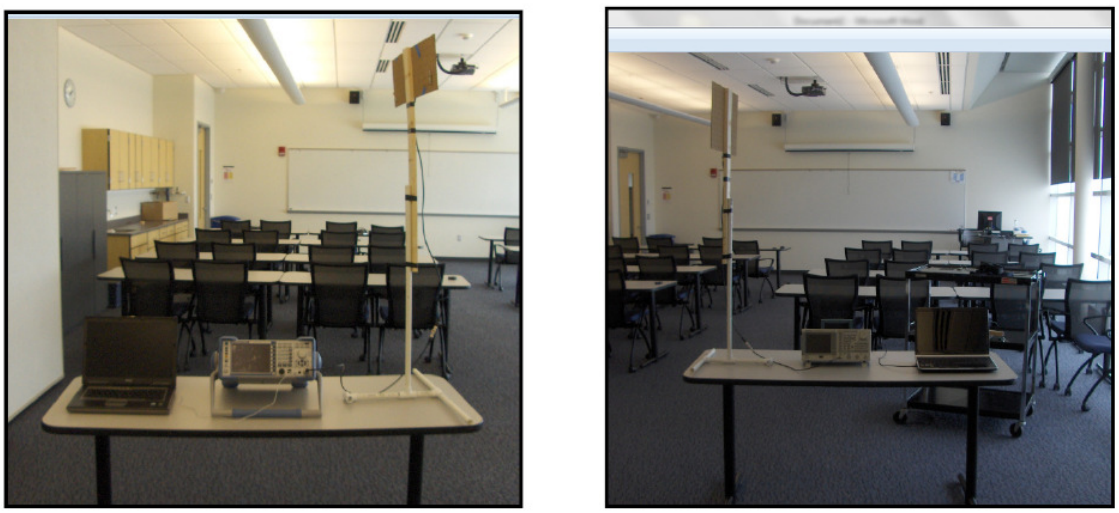

Figure 2: Antenna Radiation Pattern Measurement (left: receiver; right: transmitter)

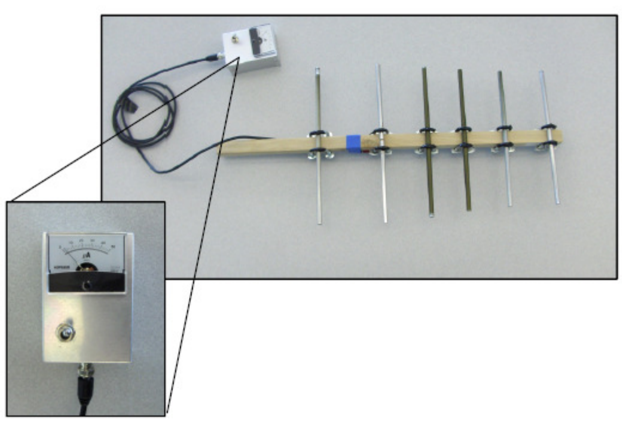

Figure 3: Example Antenna and RF Meter for Foxhunt Laboratory

Projects

In addition to the laboratory component, students proposed, developed and demonstrated a wireless-related project. Several unique projects of interest are briefly discussed below.

Acoustic Beamforming Array

The smart antenna idea was applied to an acoustical array of microphones. Following signal conditioning and amplification, four microphones sources are sampled and input to a DSP board for further processing. The delays and gains on each channel are varied in order to create an acoustical beam that favors a particular direction. The device has a manual tune mode, where a knob is turned and the DSP adjusts its gain/delay to follow the direction indicated by the knob. There is also an automatic mode that attempts to measure the signal strength and adjust to maximize the signal in the perceived direction. The system block diagram is given below in Figure 4.

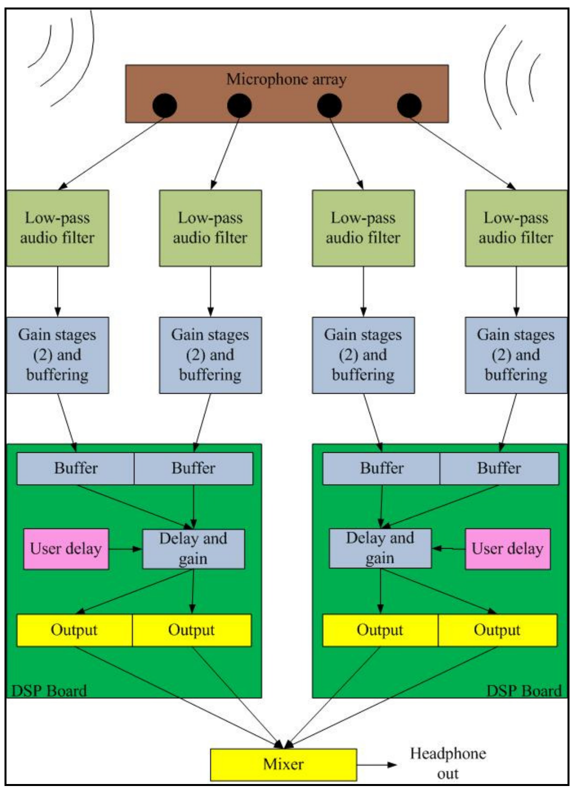

Figure 4: Acoustic Beamforming Array Block Diagram

Wireless Home Environmental Monitor

The Wireless Home Environmental Monitoring and Reporting System uses off-the-shelf remote temperature sensors to monitor the temperature in different areas. The temperature and humidity data is received from the sensors using a 434 MHz receiver and decoded using the Texas-Instruments evaluation board. Once the data is extracted, it is repackaged and sent to the data logging station over a UART. The logging software records each reading with a timestamp and displays the information for the user for remote monitoring. The system block diagram is given below in Figure 5.

Serial Communication over FM Radio

This project utilizes MFSK modulation that is further FM modulated in order to transmit digital data serially over a short range FM channel. Both text and image protocols were developed. MATLAB Simulink was used for the MFSK modulation and non-coherent demodulation. The computer sound card was used as the DAC/ADC interface between the computer and FM modulation/demodulation equipment. A custom GUI was developed in MATLAB that allowed a user to enter text, choose image files and adjust transmission rates. The system block diagram is given below in Figure 6.

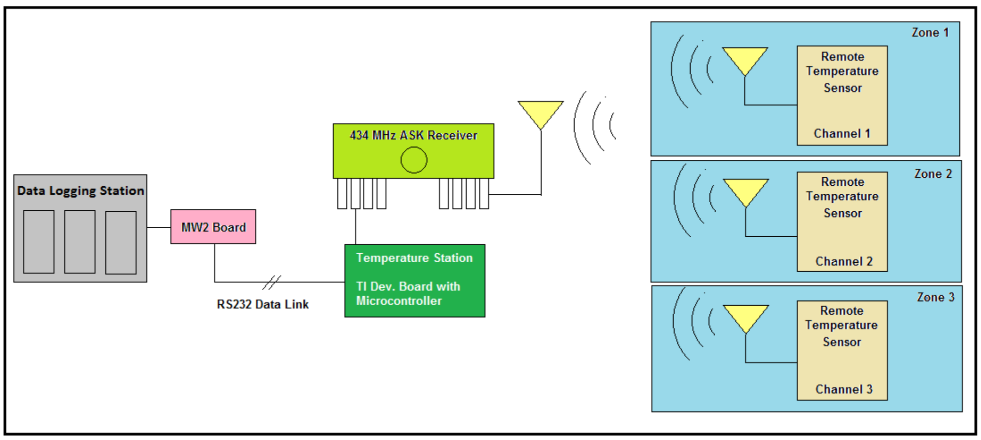

Figure 5: Wireless Home Environmental Monitor Block Diagram

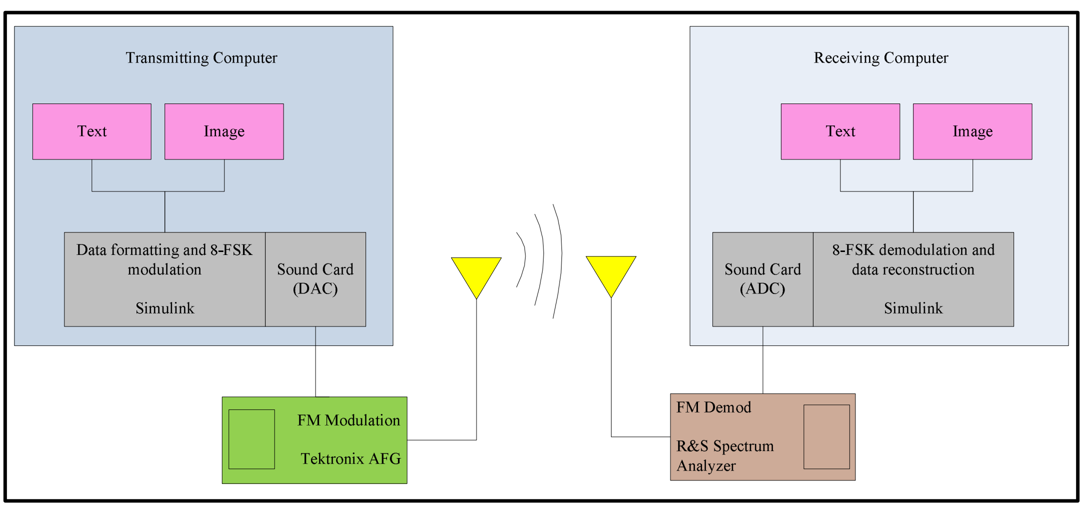

Figure 6: Serial Communication over FM Radio Block Diagram

Assessment

Course Objectives

Course objectives were assessed through homework assignments, laboratory assignments and examination. As indicated throughout this paper, the objectives were optimistic, and the results somewhat support this opinion. Results for specific objectives are given below:

1. Wireless evolution: assessed through homework essay questions. Students had a good understanding of the evolution of wireless access methods and a fair understanding of wireless generation evolution.
2. Cellular network design: assessed through homework, laboratory and examination. Students obtained a good understanding of cellular topology considerations and a fair understanding of traffic-load system design.
3. Modulation schemes: assessed through homework, laboratory and examination. Students had a good, thorough review of wireless modulation methods.
4. Antenna system design: assessed through laboratory and examination. Students demonstrated a working knowledge of the principles of antenna design including an introductory knowledge of smart antennas.
5. Radio propagation: assessed through homework. Students demonstrated a poor to fair understanding of the theory of radio propagation as this area received limited coverage in the course.
6. Coding theory for compression and error correction: assessed through homework and examination. Students were able to demonstrate a fair understanding of the basic methods for FEQ but were unable to meet the objective of demonstrating understanding of the topic of coding for compression as this was not substantially covered.
7. Standards for wireless systems including cellular, LANs/PANs and RFID: not assessed. This topic was discussed at the end of course for a limited number of systems.

Assessment via Student Survey

Student reaction to the course was generally positive. In an effort towards continuous improvement, the students were anonymously surveyed using a series of questions intended to get their honest opinions about various aspects of the course. Below, some of the more pertinent questions and selected, enlightening responses are given.

1. The course topics that seemed most appropriate to me were the following:

   - Digital modulation seemed the most appropriate.

   - Antennas.

   - Cellular topology.

   - Constellation diagrams.

2. The course topics that seemed least appropriate to me were the following:

   - Least Squares for DOA estimation.

   - Cellular topology.

   - Too many formulas for Probability of Error for too many schemes.

   - Too much mathematical derivation.

3. The following topics were covered in too little detail:

   - System-level applications.

   - Antennas.

   - Wireless protocols.

4. The following topics were covered in too much detail:

   - AM

   - Too many variations of Probability of Error.

   - Line coding.

The takeaway from the survey indicates that the students want to see less of traditional communications and more of the issues that occur with wireless systems. This suggests that of the many flavors of both analog and digital modulation, it is perhaps necessary to only discuss a few variations. Additionally, this will lessen the analytic burden and the seemingly repetitive process of computing error probabilities. Also noted, the time spent deriving the Least Squares approach to DOA was unfruitful. Finally, the adjustments suggested by the survey results will allow more time for wireless topics such as further development in antennas, propagation and coding.

Conclusion

The course Wireless Communication Systems was developed and delivered as a senior-elective or first graduate course for ECE students. Despite the challenges in compressing the material into a single semester, the course was successful. Of great importance is the laboratory component, necessary to reinforce the concepts in the lecture. Finally, assessment metrics have indicated that the course should adapt to place less emphasis on classical communication theory and more emphasis on topics directly related to wireless communications.

Bibliography

1. Frolik, J., "*A Comprehensive, Laboratory-Enhanced Communications Curriculum,*" Proc. of ASEE 2004 Annual Conference, Salt Lake City, Utah, June 2004.
2. Frolik, J., "*Laboratory Enhancement of Digital and Wireless Communications Courses,*" Proc. of ASEE 2005 Annual Conference, Portland, OR, June 2005.
3. Aburdene, M.F., Xiannong Meng, L. Felipe Perrone and Mododean, G.L.,"*Analysis of Wireless and Mobile Computer Networks Courses*," Proc. of ASEE 2005 Annual Conference, Portland, OR, June 2005.
4. Shankar, P.M. and Eisenstein, B.A., "*Project-Based Instruction in Wireless Communications at the Junior Level,*" IEEE Trans. on Education, Vol. 43, No. 3, August 2000.
5. Rappaport, T.S., "*Wireless Communications: Principles and Practice: 2nd Ed.*," Prentice Hall, 2002.
6. Stallings, W., "*Wireless Communications & Networks: 2nd Ed.,*" Prentice Hall, 2004.
7. Goldsmith, A., "*Wireless Communications*," Cambridge University Press, 2005.
8. Molisch, A.F., "*Wireless Communications*," Wiley – IEEE, 2005.
9. Tse, D. and Viswanath, P., "*Fundamentals of Wireless Communication*," Cambridge University Press, 2005.
10. Carr, J.J., "*Practical Antenna Handbook*," Blue Ridge Summit, PA: TAB Books, 1989.
11. *Internet URL:* http://www.mathworks.com/products/matlab/ : MATLAB Simulink software (retrieved Jan. 17, 2011).
12. Cassara, F.A., "*Wireless Communications Laboratory,*" IEEE Trans. on Education, Vol. 49, No. 1, February 2006.
13. *Internet URL*: http://www.dxzone.com/cgi-bin/dir/jump2.cgi?ID=19033 : MFJ-269HF/VHF/UHF SWR Analyzer, Counter (retrieved Jan. 17, 2011).
14. *Internet URL*: http://www.minicircuits.com/ (retrieved Jan. 17, 2011).
15. Wilson, M.J. (Auth./Ed.) and Ford, S.J. (Ed.), "*The AARL Handbook for Radio Communications,*" American Radio Relay League, 2009.