A Wireless Communications Systems Laboratory Course

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***Abstract*—A novel wireless communications systems laboratory course is introduced. The course teaches students how to design, test, and simulate wireless systems using modern instrumentation and computer-aided design (CAD) software. One of the objectives of the course is to help students understand the theoretical concepts behind wireless communication systems through hands-on experiments and to make them more confident both in system design and analysis. The course also aims at increasing the interest of students in engineering and technology. Therefore, laboratory experiments that are complementary to the materials discussed in the theoretical part of the course are designed specifically to incorporate the use of several wireless devices that students probably use extensively in their daily lives. Complementing and expanding upon the materials covered in other communication courses is another merit of this laboratory-based course. Meeting the course requirements also helps students improve their oral presentation and report preparation abilities. The evaluation of the course indicates that most of the objectives are achieved. This paper discusses the experiments designed to teach various wireless communication concepts to the students on a weekly basis, as well as the interesting projects and the other course requirements, which could be replicated by other universities.**

***Index Terms*—Electrical engineering education, hands-on experience, testing and measurement, wireless communications.**

I. Introduction

Wireless technologies and services have evolved significantly, from simple paging to real-time voice communication and recently to very high-rate data communications. Lately, software-defined radio (SDR) [1] and cognitive radio (CR) [2] concepts have gained significant interest among wireless communications communities. With this remarkable development in wireless communication technologies and standards, along with the introduction of new concepts like CR and SDR, a strong desire to develop a flexible laboratory platform to teach a wide variety of wireless techniques has emerged. Laboratory benches that are equipped with highly capable transmitters and receivers can address this goal. The Electrical Engineering Department at the University of South Florida (USF), Tampa, has seen this necessity and developed a laboratory-based course. In this paper, a wireless communications system laboratory that enables students to understand wireless concepts from different perspectives is introduced.

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Senior-level undergraduate and graduate electrical engineering students are mainly the target of the course. Although there is no prerequisite for the Wireless Communications Systems Laboratory course, students should be familiar with the basic theoretical concepts related to signal and linear system analysis such as sampling theorem, convolution, Fourier series and transform, and so on. Most of these concepts are taught in the earlier stages of an electrical engineering education. Familiarity with MATLAB is also desired, but not required.

A literature search reveals that some institutions offer laboratory-based courses focusing on other aspects of wireless communications as well. One of the examples focusing on wireless sensor networks can be found in [3]. An infrared communication system-based laboratory course is introduced in [4]. A wireless laboratory course focused on spread-spectrum technology is discussed in [5]. Some other techniques to teach wireless communications such as project-based courses and simulations are also available in the literature [6]–[8]. The Wireless Communications Systems Laboratory course introduced in this paper is unique in the sense that it is not focused on a particular technology or topic, but includes a broader range of subjects to do with wireless communications.

II. Pedagogical Issues

Teaching certain courses such as wireless communications or digital communications might be very challenging unless the theoretical materials covered are supported with a practical experience. This is mainly due to the fact that immediate relationship between cause and effect cannot be easily seen by the study of pure theory. The authors strongly believe that the efficacy of a course covering many theoretical topics can be increased through hands-on experiments as pointed out in [9]. Similar studies often appear in the literature emphasizing the importance of a laboratory environment for teaching [10]–[15]. In this respect, the laboratory course can be seen as divided into two parts.

The first part of the course—namely the in-class part—addresses the theoretical aspects of wireless communication systems, whereas the second part, which is the laboratory part, is aimed at helping students gain hands-on experience in the theoretical material covered during the classroom hours. In this way, students gain an in-depth understanding of the theoretical issues in wireless communication systems with hands-on laboratory experiments.

The basic theory of wireless communications, software simulation of the systems, hardware test and modeling, system measurement, testing and debugging, software and hardware interactions, and co-simulations are fundamental elements of the course. Although individual experiments do not include every aforementioned element since the emphasis changes weekly, the objective is achieved systematically by helping students gain new skills, experiment by experiment, throughout the semester. The benefits students derive from the course will differ depending upon their background since there is no prerequisite for the course. However, it is expected that the course will have a positive impact on student learning of the theoretical materials in wireless communications. In addition to strengthening their theoretical background, students also gain a lot of experience, especially in identifying the cause of problems associated with wireless communication systems, while performing experiments, as will be discussed in Section III.

The experiments are designed to maintain the motivation of the students at a high level. Therefore, many experiments incorporate the use of several wireless devices exploiting students' familiarity with cell phones, notebook computers, Bluetooth devices, and the like. For instance, a cell phone is used to teach students the effect of path loss on wireless signals by measuring the received signal power at distances over several meters on a vector signal analyzer (VSA). Similarly, WLAN and Bluetooth card integrated devices are used to study some other features of certain types of wireless signals such as frequency of operation, hopping scheme, and bandwidth. Observing and analyzing the wireless signals transmitted by frequently used devices is found by students to be very interesting and motivating.

In addition to preparing post-laboratory reports and meeting other course requirements, all students are obliged to complete a project and successfully demonstrate it in the laboratory (in front of their classmates) with the equipment provided. These requirements of the course enhance students' skills in terms of both oral presentation and report preparation.

In spite of having no prerequisite or co-requisite to the Wireless Communications Systems Laboratory course, the theoretical content of the course and the laboratory experiments and projects are designed in such a way to take advantage of other theoretical courses offered by the Electrical Engineering Department of the USF, such as Personal and Mobile Communications, Advanced Topics for Wireless Communication Systems, Cognitive and Software Defined Radio, Digital Communication Systems, and RF Circuits I and II. Many of the experiments are directly related to the concepts introduced in the Personal and Mobile Communications and Advanced Topics for Wireless Communication Systems courses in which the wireless propagation channel, wireless receiver and transmitter architecture, and wireless systems and technologies are discussed in detail. Considering the trend in wireless communications, students are encouraged to undertake projects related to SDR and CR in line with the Cognitive and Software Defined Radio course. The Digital Communication Systems course and the laboratory course also have many concepts in common, with topics such as digital modulation types, pulse-shaping filters, and synchronization in wireless systems being discussed in both courses. In addition, some of the experiments require the use, testing, and understanding of various RF hardware components widely used in wireless systems, which helps students better understand the concepts introduced in the RF I and II courses.

III. Description of the Course and Experiments

The Wireless Communications Systems Laboratory course is a three-credit course designed for graduate and senior-level undergraduate students. The theoretical aspects of the course are discussed in a weekly in-class session, which lasts approximately 2 h. Principles of wireless communications, popularly used wireless communication technologies, standards and waveforms, wireless communication receiver and transmitter hardware components, digital modulation, pulse-shaping filters, synchronization, and wireless propagation channel are among the theoretical issues discussed. Experiments are designed in order to strengthen the student perspective on theoretical materials and last approximately 3.5 h weekly.

The laboratory course is based on the successful completion of eight mandatory experiments, one optional experiment, and a project. Considering the requirements, teamwork and cooperation with the other students are strongly encouraged throughout the course. Table I shows a summary of the mandatory experiments. Post-laboratory reports, which are supposed to outline conclusions and outcomes derived from the experiments, are an essential part of the course. Students are also required to submit a report detailing the outcomes of their project and share their experiences with their classmates through a 30–min demonstration at the end of the semester. Several pop quizzes and a final exam are also given to test students' understanding of the materials studied.

The course is the outcome of some of the research activities developed at the Electrical Engineering Department of USF. The laboratory benches provided integrate a vector signal generator (VSG), VSA with enhanced capabilities, RF hardware, and a computer with software including MATLAB as a simulation tool and Signal Studio. Fig. 1 shows one of the typical benches. The bench setups are very flexible and allow generation of various signal waveforms, measurements and modeling of the RF and baseband circuitry under different stimulus conditions, modeling of wireless radio channel effects and RF impairments, and optimization of the transceiver structures and baseband algorithms.

A. Experiment I—An Introduction to Basic Digital Baseband Communication Through MATLAB Simulation

In this experiment, various fundamental concepts in wireless communications are introduced to students in a MATLAB simulation environment through the observation of several diagrams that are widely used for assessing the performance of wireless systems. A system in additive white Gaussian noise (AWGN) channel with QPSK modulation scheme is simulated using MATLAB. The students investigate the performance of the communication system with various SNR values by considering various types of performance diagram, such as constellation, polar, eye, and spectrum. The experiment is based on observation of the aforementioned diagrams; students are also required to develop a simple QPSK detector to detect transmitted bits and to compute BER performance with varying SNR values.

In the second stage of the experiment, which is left as an optional step, the effect of the frequency offset that is intentionally introduced on the received waveform through simulation

TABLE I
SUMMARY OF MANDATORY EXPERIMENTS

Experiment No	Experiment Title	Objectives
Experiment I	An introduction to basic digital baseband communication through MATLAB simulation	• Familiarize with MATLAB and its functions widely used in wireless communication simulations • Understand the plots to quantify a wireless system through MATLAB simulation • Develop an QPSK detector and understand the relation between BER and SNR • Understand frequency offset and its effect
Experiment II	Understanding Waveforms and Their Properties	• Teach certain waveforms and their properties • Lean how to capture transmitted waveforms and use MATLAB to further process them
Experiment III	Introduction to wireless front–end	• Understand the functionality of hardware components such as mixers, VCOs, amplifiers, and filters
Experiment IV	Modulation domain analysis	• Study popular modulation types and their features • Understand CCDF and its relation to the envelope of the carrier
Experiment V	Effects of filters in wireless communication systems	• Study various pulse–shaping filters widely used in wireless communication systems • Learn about matched filtering
Experiment VI	Multi–Dimensional signal analysis	• Study tools to find out several unknown parameters of wireless communication systems through multi–dimensional signal analysis • Introduce joint TFA
Experiment VII	Synchronization in wireless systems	• Study and implement coarse and fine synchronization, • Learn about the effect of frequency offset and its correction • Understand and correct phase / amplitude impairments due to the wireless channel on waveforms
Experiment VIII	Channel impact in wireless communication	• Observe path loss and frequency selectivity • Understand the LOS and NLOS • Learn about channel sounding techniques

is studied. Frequency offset, which stems from the difference between carrier frequencies generated by the local oscillators of transmitter and receiver, poses a significant problem for coherent receivers. Although frequency offset and its effect are to be studied in the forthcoming experiments in a very detailed way, this optional part can be considered an introduction to the impairments in wireless communication systems.

The benefit of using a MATLAB environment to teach students the fundamental concepts is twofold. First, students understand the interpretation of diagrams that are popularly used in the wireless community in order to evaluate the performance of wireless communication systems. Second, students become familiar with the MATLAB functions and simulation environment upon performing simple tasks, such as the development of a QPSK detector.

B. Experiment II—Understanding Waveforms and Their Properties

The main objective of this experiment is to familiarize students with typical waveforms and their properties. Students learn how to generate various waveforms, ranging from very basic signal types such as a sine wave to popular standard waveforms such as NADC and GSM using VSG. VSA is used to analyze the generated waveforms. Power, central frequency, and modulation type of the waveforms are manipulated, and their effects on the received signal are observed.

The analysis of the waveforms is first performed by a cable connection between VSG and VSA and then by a pair of antennas so that students can spot the effect of the wireless propagation channel on the transmitted signals. In addition to the gen-

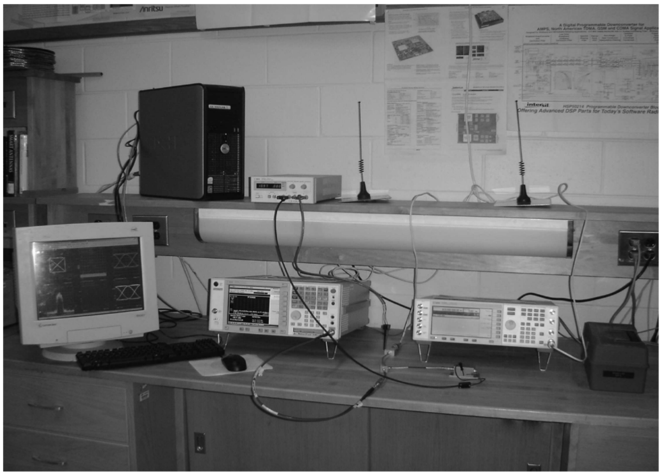

Fig. 1. A typical laboratory bench.

erated waveforms, signals transmitted by a mobile phone operating in the PCS band and by the WLAN card of a notebook computer are analyzed by tuning the VSA to the corresponding frequency bands. Students compute the bandwidth and power of these signals by using the tools provided by the VSA.

In the experiment, the relation between the VSA and MATLAB is also emphasized. An NADC waveform with a particular symbol rate and modulation type is generated through the VSG. The VSA is used to capture and download the waveform on computer so that it can be analyzed on MATLAB. MATLAB is used to plot the frequency and time-domain representation of the signal. These plots are compared with the ones seen on the VSA screen. This part is especially important for students who may need an extensive use of MATLAB in line with the laboratory equipment in their projects.

C. Experiment III—Introduction to Wireless Front-End

Mixers, LNA, band-pass filters, and voltage-controlled oscillator (VCO) are some of the hardware components that are widely used in wireless communication systems. Teaching their functionalities and characteristics is the core objective of this experiment. Students construct several scenarios to understand the behavior of each of these components.

Mixers and LNA are nonlinear devices and generate undesired signals at various harmonic frequencies. In this experiment, students are able to see the effect of nonlinear behavior of these devices on the frequency spectrum. Proper band-pass filters are provided to suppress undesired harmonics so that students understand both the inconveniences that nonlinear devices cause in the wireless communications systems and the techniques to cope with them. Moreover, an LNA operating in the saturation mode causes distortion in the received signal. Observing the distortion in the waveforms by forcing the LNA into saturation mode is one of the scenarios that are implemented in the experiment.

A VCO is one of the indispensable components of any wireless system. They are very sensitive devices in that environmental conditions such as temperature and humidity have a great impact on their performance. Due to this highly dependent nature of VCO on environmental conditions, a stabilizer circuit is

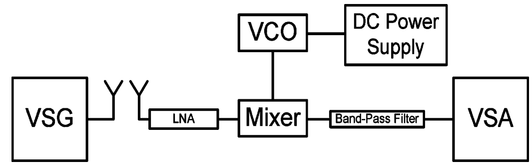

Fig. 2. Final setup for experiment III.

generally used along with the VCO so that it exhibits the desired performance under various circumstances. In this experiment, students come to understand its sensitive nature and the need for a stabilizer circuit, by using the VCO to generate a tone that is to be used in the next step of the experiment to downconvert an RF signal to IF.

In the final section of the experiment as depicted in Fig. 2, a scenario in which all the above-mentioned components are used is implemented. An NADC signal with a particular power and central frequency value is downconverted to 70 MHz and demodulated at this frequency. The quality of the demodulation process is evaluated by observing several quality measures such as polar, eye, error vector magnitude (EVM), and constellation diagrams.

D. Experiment IV—Modulation Domain Analysis

The performance of a wireless communication system is strongly dependent on the different modulation formats and demodulation techniques used. This experiment will expose these popular formats and techniques by characterizing them in terms of BER performance, bandwidth efficiency, out-of-band radiation, easiness of implementation, carrier envelope, and so on.

The modulation types studied in the experiment are QPSK, OQPSK, GMSK, 8–PSK, $\pi/4$–DQPSK, and 16–QAM. QPSK is a type of phase shift keying modulation where each modulation symbol represents two bits; it is used in many wireless communications standards such as IEEE 802.11b and IEEE 802.16. It is worth mentioning that although QPSK is a phase modulation, its envelope is not constant due to abrupt phase changes, especially for a possible 180° phase transition. This drawback leads to the development of modulation types that exhibit better peak-to-average-power ratio (PAPR) characteristics such as OQPSK, GMSK, and DQPSK. OQPSK is a slight variation of QPSK. It is used in several wireless communication standards such as IEEE 802.15.4. OQPSK avoids the 180° phase transition caused by a possible simultaneous change of the I and Q components of the signal by delaying the even pulse stream by a half symbol-period with respect to the odd pulse stream. GMSK is commonly used in various wireless communication systems such as GSM and DECT. It is very similar to MSK; however, the pulses are shaped with a Gaussian filter to enhance the bandwidth efficiency of the transmission. The constant envelope is one of the most favorable features of GMSK. 8–PSK is a type of phase shift keying modulation. There are eight constellation points corresponding to three bits per symbol. EDGE and Bluetooth 2.0 are among the technologies employing this modulation type. $\pi/4$–DQPSK is a variation of QPSK modulation that is used in many wireless communication standards such as Bluetooth 2.0 and NADC. It uses two identical QPSK

TABLE II
HIGHLIGHTS FOR MODULATION TYPES

Modulation Type	Highlights
QPSK	Each modulated symbol represents two bits. It is used in many communication standards such as IEEE 802.11b and IEEE 802.16.
OQPSK	A slight variation of QPSK where half symbol-period timing offset between I and Q components is introduced. It is used in several wireless communication standards such as IEEE 802.15.4.
GMSK	Gaussian filtered MSK. Its generation and detection is much more convenient than MSK. It has a constant envelope which is highly desired in wireless systems. It is used in GSM.
8–PSK	More spectrally efficient compared to BPSK or QPSK; however, it is more susceptible to bit errors for the same average power. Bluetooth 2.0 and EDGE are the technologies employing this modulation type.
$\pi/4$–DQPSK	A variation of QPSK modulation where two identical QPSK constellations which are rotated by $\pi/4$ with respect to one another are used. Bluetooth 2.0 and NADC are among the technologies which use this modulation.
16–QAM	Each modulation symbol represents four bits where both amplitude and phase of the carrier are modulated. IEEE 802.16 is one the technologies employing this modulation.

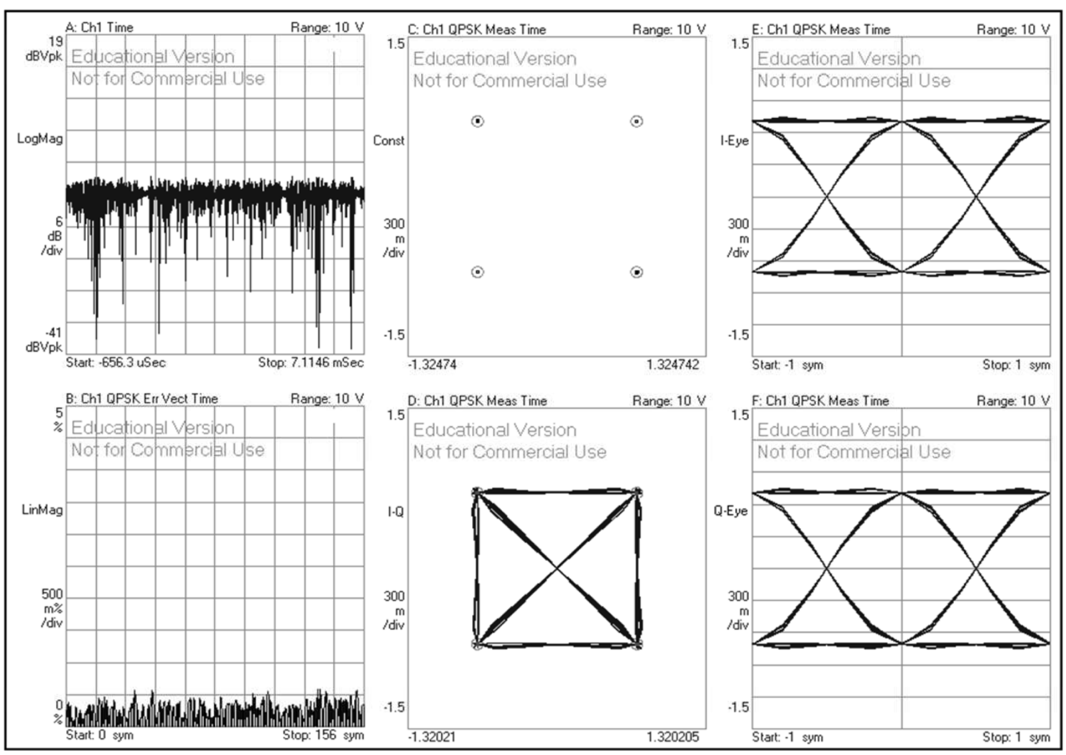

Fig. 3. A snapshot of the analysis tools: (A) waveform envelope; (B) EVM; (C) constellation diagram; (D) polar diagram; (E) eye diagram of I-component; (F) eye diagram of Q-component.

constellations that are rotated by 45° with respect to one another, resulting in eight absolute carrier phases. The symbol phases are alternately selected from one QPSK constellation and then the other, eliminating a possible 180° of phase shift from one symbol to another. This manipulation reduces the PAPR of the complex envelope. 16–QAM is a type of digital modulation where each symbol represents four bits. IEEE 802.16 is one of the standards that employs this modulation type. A more detailed study of these modulation types can be found in [16] and [17]. Table II outlines the modulation types used in the experiment along with a brief highlight.

In the experiment, several waveforms modulated with the aforementioned modulation types are generated. These waveforms are evaluated through the observation of spectrum, time domain, EVM, CCDF, I-Q polar, constellation, and eye diagram plots.

CCDF, which is a measure used to characterize the power statistics of a modulated signal, is specifically emphasized in the experiment. It indicates the probability that the instantaneous signal power exceeds the average value, and gives an idea of the PAPR. The constant envelope feature is very desirable when the operation of nonlinear RF devices is considered whose characteristics are highly dependent on the input power as observed in experiment III. From this perspective, this experiment complements experiment III and helps students understand modulation types that exhibit better PAPR characteristics. Fig. 3 shows a snapshot of the diagrams that are used to evaluate the modulation types. Please note that the modulation type in Fig. 3 is QPSK.

E. Experiment V—Effects of Filters in Wireless Communication Systems

Pulse-shaping filters are used to map symbols into waveforms. The characteristics of the pulse-shaping filter are very important, considering the bandwidth of the transmitted signal and ISI. ISI that arises from the interference of a symbol with the subsequent symbols has a distortion effect on wireless signals. Pulse-shaping filters should satisfy a condition called the Nyquist pulse-shaping criterion for ISI free transmission [16]. The objective of this experiment is to study the impact of the pulse-shaping filters on system performance through examining signals by the tools provided by the VSA. GSM and NADC signals are generated to study the effect of Gaussian and root raised cosine (RRC) filters on the system performance. Characteristics of RRC and Gaussian filters are determined by their roll-off and BT product values, respectively. These two values of the transmitted signals are changed and their effect on spectrum, CCDF, polar, constellation, eye, and time domain plots of the received signal are seen.

The Gaussian filter does not satisfy the Nyquist pulse-shaping criterion and induces ISI. Bandwidth efficiency and the extent of ISI of the Gaussian filter are determined by BT product where B is the 3-dB bandwidth and T is the symbol duration of the signal. Small values of BT lead to narrower bandwidth and more ISI, whereas large values lead to wider bandwidth and less ISI. This tradeoff between the extent of ISI and the bandwidth efficiency requires a very careful selection of the BT value. Students are able to see this tradeoff clearly by analyzing the received waveforms through the VSA.

Matched filtering is used to maximize the SNR at the receiver side and is realized by convolving the received signal with the pulse-shaping filter used at the transmitter [16]. The importance of matched filtering and its positive effect on wireless systems are the other issues covered in this experiment. An NADC signal with an RRC pulse-shaping filter is generated. On the receiver side, the quality of the received signal is evaluated through the observation of several quality measures such as polar and constellation diagrams. The observation is performed under both circumstances, with and without matched filtering, so that the student can visually see its positive effect on the received signal.

F. Experiment VI—Multidimensional Signal Analysis

Interpretation of several diagrams, such as spectrum, EVM, polar, eye, and constellation, have been discussed by this point in order to prepare students for the experiment by providing them with the tools widely used for evaluating the performance of wireless signals. This experiment tests students' ability to use these tools in order to extract unknown parameters of the transmitted signals. These tools are used to extract the unique features of signals used in very popular wireless communication standards such as NADC, GSM, CDMA, and Bluetooth. These signal types are generated with some parameters known to the students. Having a very limited knowledge of transmitted signals, students are expected to use the proper tools to examine the signals in multiple dimensions in order to obtain various unknown features such as their exact frequency of operation, modulation type, and pulse-shaping filter characteristics for NADC, time slot structure and relative burst power values for GSM, number of active codes for CDMA, and the frequency-hopping scheme for Bluetooth. Students are expected to use several tools in order to complete the experiment, including spectrum, time domain, polar, EVM, code domain analysis, and joint TFA plots. The signal types, known and unknown parameters, and the tools that students are expected to use in order to extract unknown parameters, are outlined in Table III.

TABLE III
HIGHLIGHTS FOR EXPERIMENT VI

Signal Type	**(+)Known/(-)Unknown Params.**	**Tool**
Single Carrier NADC	(+)Approximate carrier frequency (–)Exact carrier frequency (–)Bandwidth	Spectrum
Multi-Carrier NADC	(+)Approximate carrier frequency (–)Exact carrier frequency (–)Bandwidth (–)Carrier spacing	Spectrum
Single Carrier NADC	(+)Exact carrier frequency (+)Symbol rate (+)Pulse–shaping filter features (–)Modulation type	Polar diagram
Single Carrier NADC	(+)Exact carrier frequency (+)Symbol rate (+)Pulse–shaping filter (+)Modulation type (–)Roll-off factor	EVM plot
Multi-Carrier GSM	(+)Approximate Carrier Frequency (–)Number of carrier (–)Time slot configuration (–)Relative powers of each burst	Spectrum Time domain
CDMA	(+)Exact carrier frequency (–)Number of codes	Code domain
Bluetooth	(+)Operating frequency range (–)Hopping scheme	Joint TFA

The focus of the previous experiments has been to teach students the use of several tools that help them analyze waveforms in various domains. This experiment complements the previous experiments in that the students learn how to use the provided tools in order to extract the unknown features of several waveforms in a very realistic scenario.

G. Experiment VII—Synchronization in Wireless Systems

The objective of this experiment is to teach students how receivers process the captured waveforms in order to extract their useful information content. A BPSK modulated signal with the

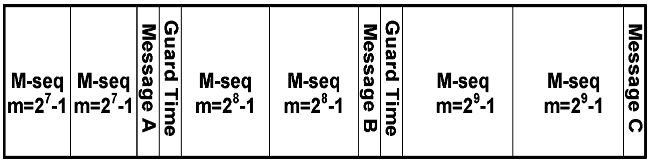

Fig. 4. Data structure used in experiment VII.

structure depicted in Fig. 4 is transmitted via one of the VSG in the laboratory. Students are asked to capture the transmitted signal via the VSA located on their bench.

The frame consists of three different messages along with the m-sequences of three different lengths (127, 255, 511). Students are divided between three of the laboratory benches, and each bench is given the task of revealing the content of only one of the transmitted messages (Message A, Message B, or Message C). In order to avoid confusion over the message to be handled, the length of the m-sequence used prior to the corresponding message is given to the benches as *a priori* information so that this information can be used while searching for the desired message within the frame. By considering the correlation property of m-sequences of different lengths, students should be able to pinpoint the position of the desired message in the frame by using only the correct length of m-sequence. This experiment requires the use of MATLAB in processing the captured waveform. Steps that students should follow to extract the message can be outlined as follows:

- coarse synchronization;
- frequency offset estimation and correction;
- fine synchronization;
- channel estimation and correction;
- bit-to–character conversion.

Coarse synchronization is performed by the use of autocorrelation. Since two m-sequences are appended one after another, using autocorrelation in the captured data stream gives a rough estimate of the start of the corresponding section. Upon coarse synchronization, the frequency offset is estimated by exploiting its relation with time or index for digital data. The frequency offset must be compensated for before moving into the next step, which is fine synchronization. An m-sequence with the correct length depending upon the burst of interest is locally generated. Fine synchronization is based on cross-correlating this generated m-sequence with the signal. It must be noted that the rough estimate point that is obtained after coarse synchronization should be considered to avoid computational complexity. Channel estimation and correction is the last step before revealing the message. The m-sequence that is generated in the fine synchronization step is compared with the m-sequences obtained from the signal, in order to estimate the effect of the wireless channel on the transmitted waveform. The phases and amplitudes of the symbols are corrected upon estimation. After all impairments on the received signal are mitigated, the bits are obtained and converted into characters revealing the content of the message.

This experiment helps students understand both the impairments introduced on the transmitted waveforms in wireless communication systems and the steps that the waveforms go through in order to countereffect these impairments in a real receiver.

H. Experiment VIII—Channel Impact in Wireless Communication

The last mandatory experiment teaches students the effect of the wireless propagation channel on the transmitted signals. The wireless propagation channel is the most important factor limiting the performance of wireless communication systems, and its analysis is not an easy task due to its extremely random nature. When a wireless signal is transmitted, the signal received at the receiver consists of attenuated, delayed, and phase-shifted replicas of the transmitted signal. These replicas combine at the receiver destructively and constructively generating a composite received signal. Constructive and destructive addition of the replicas at the receiver cause random variations in the amplitude and phase of the composite signal, which lead researchers to consider the randomness in the wireless channel carefully while designing wireless systems [17].

The purpose of this laboratory experiment is to show students some of the fundamental issues of the wireless propagation channel. It must be noted that the channel imposes various effects on wireless signals such as distance- and frequency-dependent path loss, reflection, scattering, diffraction, small-scale and large-scale fading, multipath delay, and Doppler spread. However, the number of effects that can be observed within a laboratory framework is very limited. Distance-dependent path loss, frequency selectivity and the line-of-sight (LOS) and non-line-of-sight (NLOS) transmission are some of the issues that are addressed in the experiment.

Distance-dependent path loss is one of the fundamental considerations for the wireless channel; it indicates the reduction in transmitted signal power. Its effect on the received signal with varying transmitter–receiver antenna separations is seen by observing various plots such as spectrum, polar, and constellation. The power of the received signal can be calculated from its spectrum. The change in the received power value is noted by making this calculation with various transmitter and receiver antenna separations in order to observe the impact of the distance on the distant-dependent path loss. Moreover, the effect of the reduction in the received power with increasing distance can be noticed clearly by observing the constellation and polar diagrams of the signal since the noise becomes more prominent as the received power decreases. In a realistic scenario, the communication path between the transmitter and the receiver may take several forms. The effect of LOS and NLOS conditions that indicate the presence and absence of a direct path between the transmitter and receiver antennas is also investigated in this experiment through the observation of the aforementioned performance plots [17].

Frequency selectivity is another issue studied in this experiment. It is observed when the signal bandwidth exceeds the coherence bandwidth of the wireless propagation channel. It is worth mentioning that the transmission bandwidth, and the separation between transmitter and receiver antennas, must be sufficiently large in order to observe the effect of frequency selectivity in an environment of such a limited size as a laboratory.

Its effect is best seen by observing the spectrum of the signal with various transmission bandwidths and antenna separations.

Characterization of the wireless channel is very important for the reliability of wireless communication systems. There are three main sounding techniques available in the literature that are used to characterize the wireless propagation channel. These are direct pulse measurements, spread-spectrum sliding correlator measurements, and swept frequency measurements. Extracting the channel characteristics of the university corridors by employing the spread spectrum sliding correlator technique is left as an optional step of the experiment.

Recently, the use of reverberation chambers has been very popular for testing wireless systems in more realistic situations [18]. The authors strongly believe that the use of a reverberation chamber will significantly enhance the content of this experiment in many aspects. For this purpose, a reverberation chamber was being built at the time of the preparation of this paper.

I. Optional Experiments

Students are required to select one of the three optional laboratory experiments relating to their field of interest upon successful completion of the mandatory experiments. These experiments are:

1) a more detailed study of the distortions in RF front-end;
2) analysis of interference;
3) introduction to OFDM.

The first experiment focuses on the nonlinear distortions that may occur in the front-end of the wireless communication systems. Nonlinearities due to PA, LNA, and mixers are among the issues addressed in the experiment. dc offset, I-Q gain imbalance, I-Q quadrature offset, and sampling timing offset are the other points studied in detail.

Interference analysis forms the core of the second optional experiment. The importance of some interference avoidance and averaging techniques, such as CSMA used in WLAN signals and frequency hopping employed in most notably Bluetooth, is emphasized. An intentional interference is generated through one of the VSG and its effect on the received waveform is observed. Near–far problem and the immunity of the spread-spectrum techniques to interference are among the issues discussed in this experiment.

The main features of OFDM are studied in the third optional experiment. An IEEE 802.11g signal employing OFDM technology is generated through signal studio software. Its spectrum and time domain features are observed. The PAPR characteristics of the OFDM signals are studied with various numbers of active subcarriers through the observation of CCDF plots. Filtering and its effect on side-lobes of OFDM signals is discussed as well. The importance of the use of EVM versus a spectrum plot is emphasized by introducing an intentional interfering signal on one of the active subcarriers.

IV. Design Projects

Design projects are the most important part of the student assessment process. Students are encouraged to pick a project topic as soon as possible and to work on it throughout the semester. Each project topic must be approved by the course instructor; it is worth mentioning that SDR- and CR- related projects are encouraged, considering the recent trends in wireless communications. Upon the completion of the experiments, the laboratory and the in-class hours operate as open laboratory hours so that students can have access to the laboratory equipment for an extra amount of time in order to complete their projects on schedule. Vertical hand-off among overlapped wireless networks, signal identification for technologies operating in ISM band, blind modulation type identification, blind carrier frequency and symbol rate identification, I-Q modulation through the use of FPGA, and hand-off with sectored antennas are some examples of the projects undertaken by students. Students are required to demonstrate their project successfully in the laboratory with the equipment, hardware and software tools provided, in front of their classmates. A detailed report summarizing the outcomes of the project study is also expected from the students at the end of the semester.

V. Evaluation of the Course

The evaluation of the Wireless Communications Systems Laboratory course had two stages. In the first stage, students were asked to fill out a survey on their opinions and experiences. The second stage was based on assessing the improvement of student learning and performance.

A. Assessment by Student

In order to evaluate the course and receive feedback from the students, a survey was carried out. The survey was given to the students before the final exam and was answered by 20 students in total. It was composed of nine questions. Four of the questions were based on a statement with which students were asked to express their agreement in the range: a-strongly disagree (SD); b-disagree (D); c-neutral (N); d-agree (A); e-strongly agree (SA). Four of the questions were open-ended with a space below, in which students were asked to provide their opinions on certain course-related issues. The last question was aimed at learning students' overall satisfaction with the course materials and laboratory experiments.

Table IV outlines the student responses to the numerical questions. From responses to the first and second questions, it is obvious that the course helped most of the students understand the difficult theoretical concepts and improved their skills in both design and analysis. The third question was to evaluate the correlation between the in-class part and laboratory part of the course. As can be seen from the responses, the in-class and laboratory parts of the course were found to be highly correlated by most of the students. The last numerical question was asked in order to understand how enthusiastic students became about the technology after taking this course. Most of the students agreed that they were more interested in the technology because of the materials covered during the class hours and experiments performed in the laboratory hours.

In the open-ended questions, students were asked to comment on the best and worst part of the course as well to make suggestions to render the course more attractive. The comments collected include the following:

- "The best thing about the course is to see how communication systems work in real life."

TABLE IV
STUDENT SURVEY RESPONSES

Statement	SD	D	N	A	SA
This laboratory course helps students grasp the principles of difficult wireless communications concept.	0	0	0	8	12
I feel more confident with wireless communications concepts both in design and analysis.	1	0	0	9	10
The laboratory experiments are complementary to the materials covered in the course.	1	0	2	4	13
My interest in engineering and technology increased after I take this course.	1	0	0	8	11

- "This course is where the theory meets practicality. This is the best thing about the course."

On the worst part of the course, a few students complained about the workload and the time they needed to commit to satisfy the requirements of the course.

On the suggestion part, some of the students suggested making the in-class part of the course, where the theoretical materials are discussed, longer and the laboratory hours shorter. However, it must be noted that this is a laboratory-based course and it is normal to put more emphasis on its experimental aspects.

The last question asked the students to rate their overall experience of the course; 75% of the students rated their overall experience as excellent, whereas the remaining 25% as good.

B. Student Improvement

The effectiveness of the course was not only evaluated based upon the feedback received from students. A follow-up study was carried out in order to see the effect of the Wireless Communications Systems Laboratory course on the performance of students in other courses. The Digital Communication Systems course offered in Fall 2008 was chosen for this purpose. Digital Communication Systems is a senior undergraduate and graduate level course that presents the basic principles of digital communication system design and analysis. The number of students registered in the Digital Communication Systems course in Fall 2008 was 21 in total. Seven of these students had already taken the Wireless Communications Systems Laboratory course in the previous semester. Responses given to some of the core questions asked in the final exam of the Digital Communication Systems were used in order to see the impact of Wireless Communications Systems Laboratory course on student performance. The final exam of the Digital Communication Systems course was comprehensive on all of the materials covered over the semester. The test contained a mixture of multiple choice and open questions. Student improvement was investigated based upon some of the core questions asked in the final test. Average scores of both groups are outlined in Table V. It is worthwhile mentioning that the scores are normalized to 10 and students are divided into two groups as Group I and Group II, which correspond to those who took the Wireless Communications Systems Laboratory course earlier and who did not, respectively. It is clearly seen from the scores that the impact of the Wireless Communications Systems Laboratory course on student performance is more significant on topics such as sampling, matched filtering, pulse-shaping filters, and BER calculation. In spite of being less significant, the performance of Group I on other topics such as Gram-Schmidt orthogonalization, channel capacity, and coding also seems to be better, although there was no emphasis on these topics in the Wireless Communication Systems Laboratory course.

TABLE V
STUDENT SCORES IN THE FINAL EXAM OF DIGITAL COMMUNICATION SYSTEMS COURSE

Question	Question Type	Scores Grp. I / II
Sampling theorem	Multiple choice	8.5 / 5.7
Matched filtering	Multiple choice	10.0 / 6.4
Pulse–shaping filter	Multiple choice	7.1 / 5.0
BER calculation for various modulation types	Open question	7.3 / 4.5
Gram–Schmidt procedure	Open question	7.4 / 6.9
Channel capacity	Open question	4.6 / 4.1
Linear block codes	Open question	8.5 / 7.2
Convolutional codes and Viterbi algorithm application	Open question	6.8 / 5.9

VI. CONCLUSION

Course evaluation, based on student feedback and on the performance of students in another communication course, reveals that many objectives of the course were achieved. Several waveforms were analyzed in multiple dimensions and their features were studied. Many fundamental concepts were discussed in detail. Laboratory experiments that are carefully designed to keep students motivated toward the subject complemented the theoretical part of the course and built a bridge between other communications courses by enhancing the curriculum significantly. In addition to teaching the theoretical topics through hands-on experiments, the Wireless Communications Systems Laboratory course helped students improve their oral presentation and report preparation capabilities. Many interesting projects that specifically address SDR- and CR-related issues were developed. The authors believe that this course will also affect the professional engineering life of the graduates in a very positive way.

The course was found to be very motivating and interesting by the majority of the students. Evaluation of the course was very encouraging as well. Other institutions that wish to establish a laboratory-based course for wireless communications related concepts can benefit from the experiences discussed in this paper. The content of the experiments, the design projects, and the methodology followed in order to keep students motivated can be very inspiring and useful for other institutions. More information on the Wireless Communication Systems Laboratory course can be found in [19].

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REFERENCES

[1] J. Mitola, "The software radio architecture," *IEEE Commun. Mag.*, vol. 33, no. 5, pp. 26–38, May 1995.

[2] J. Mitola, "Cognitive radio: An integrated agent architecture for software-defined radio," Ph.D. dissertation, Royal Institute of Technology (KTH), Stockholm, Sweden, 2000.

[3] J. Frolik and M. Fortney, "A low-cost wireless platform for first-year interdisciplinary projects," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 105–112, Feb. 2006.

[4] W. Padgett, B. Black, and B. Ferguson, "Low-frequency wireless communications system-infrared laboratory experiments," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 49–57, Feb. 2006.

[5] F. Cassara, "Wireless communications laboratory," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 132–140, Feb. 2006.

[6] N. Sarkar and T. Craig, "Teaching wireless communication and networking fundamentals using Wi-Fi projects," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 98–104, Feb. 2006.

[7] P. Shankar and B. Eisenstein, "Project-based instruction in wireless communications at the junior level," *IEEE Trans. Educ.*, vol. 43, no. 3, pp. 245–249, Aug. 2000.

[8] G. Prabhu and P. Shankar, "Simulation of flat fading using Matlab for classroom instruction," *IEEE Trans. Educ.*, vol. 45, no. 1, pp. 19–25, Feb. 2002.

[9] M. F. Young, "Instructional design for situated learning," *Educ. Technol. Res. Develop.*, vol. 41, no. 1, pp. 43–58, Mar. 1993.

[10] C. Hacker and R. Sitte, "Interactive teaching of elementary digital logic design with winlogilab," *IEEE Trans. Educ.*, vol. 47, no. 2, pp. 196–203, May 2004.

[11] D. M. Etter, "Signal processing within an integrated teaching laboratory," in *Proc. Conf. Record 28th Asilomar Conf. Signals, Syst. Comput.*, Nov. 1994, pp. 1309–1313.

[12] M. Moallem, "A laboratory testbed for embedded computer control," *IEEE Trans. Educ.*, vol. 47, no. 3, pp. 340–347, Aug. 2004.

[13] R. F. Schwartz, "Laboratory: Its scope and philosophy," *IRE Trans. Educ.*, vol. 2, no. 4, pp. 120–122, Sep. 1959.

[14] A. Hofstein and V. H. Lunetta, "The laboratory in science education: Foundations for the twenty-first century," *Sci. Educ.*, vol. 88, no. 1, pp. 28–54, 2004.

[15] M. Abdulwahed and Z. Nagy, "Towards constructivist laboratory education: Case study for process control laboratory," in *Proc. 38th Annu. FIE Conf.*, Oct. 2008.

[16] J. G. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2001.

[17] T. S. Rappaport, *Wireless Communications: Principles and Practice*. Upper Saddle River, NJ: Prentice-Hall, 1996.

[18] C. L. Holloway, D. A. Hill, J. M. Ladbury, P. F. Wilson, G. Koepke, and J. Coder, "On the use of reverberation chambers to simulate a Rician radio environment for the testing of wireless devices," *IEEE Trans. Antennas Propag.*, vol. 54, no. 11, pp. 3167–3177, Nov. 2006.

[19] "Hüseyin Arslan: University of Southern Florida, Electrical Engineering Department," [Online]. Available: http://www.eng.usf.edu/~arslan/

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