Modeling, Simulation, Testing, and Measurements of Wireless Communication Systems: A Laboratory Based Approach

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***Abstract*—Several challenges such as inter–operability, global seamless connectivity, and spectral crowding became more of a concern after the tremendous growth in wireless industry and the diversity in wireless systems and standards. Software defined radio (SDR) is envisioned to be a promising solution for all these challenges. From the point of education, all these challenges along with the introduction of new concepts such as SDR necessitate the establishment of new platforms where students can model, simulate and test wireless systems from various aspects. This paper gives an overview of a laboratory course incorporating the use of SDR capable devices. A brief description of all the laboratory experiments is included, whereas only one of the experiments focusing on synchronization in wireless systems is discussed in detail due to space limitations.**

***Index Terms*—Synchronization in wireless systems, testing wireless systems, wireless communications**

I. Introduction

Popularity of wireless systems and services have paved the way to the significant evolution of wireless technologies over the last couple of decades, from simple paging to real–time voice communication and recently to very high rate data communication. Software defined radio (SDR), which provides flexible radio functionality and avoids the use of application specific fixed analog circuits and components, is one of the technologies that is lately receiving significant attention from the wireless community [1].

Ever growing wireless communication technologies and standards along with the introduction of recent concepts such as SDR required the development of a flexible wireless laboratory platform where students can better understand the fundamental theories, software simulation of the systems, hardware test and modeling, system measurement and testing, software and hardware interactions and co-simulations through hands–on experiments.

Electrical Engineering department of University of South Florida (USF) has seen this necessity and developed a wireless communications systems laboratory course that is composed of benches equipped with SDR capable transmitters and receivers. Some of the research activities undertaken in the Electrical Engineering department of USF formed the basis for the laboratory course [2]–[4].

Vector signal generator (VSG), vector signal analyzer (VSA), and radio frequency (RF) hardware with computer aided design (CAD) tools including MATLAB, and signal studio are the integral parts of the laboratory benches. 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.

In this paper, one of the experiments, which is synchronization in wireless communication systems, is discussed in detail as an example to give readers a better understanding on the teaching methodology followed.

II. Model of the Laboratory Course

The laboratory course consists of three layers: theory, simulation, and experiments with real hardware. A conceptual layout of the course is given in Fig. 1. Theory which forms the core of the course is placed on the top row. Simulation world where students can simulate and test various wireless communication systems prior to implementing a real–world application is shown below the theory block. The next row is related to the use of test and measurement equipment which connect the simulation world with the realistic hardware.

Fig. 1 shows some of the important test and measurement equipment, *i.e.* VSG, VSA, and spectrum analyzer (SA). The modern versions of SAs with capabilities of providing I/Q (in-phase and quadrature) samples through wide bandwidth digitizer such as Agilent PSA (E4440A), can also be used as SA or vice versa.

Custom and standard waveforms can be generated by the VSG from various sources. MATLAB and signal studio software are two options for the realization of waveforms. It is also within VSG's capabilities to generate waveforms with various impairments such as noise, fading, and interference to test the receiver's ability to demodulate signals under more realistic conditions.

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III. Course Structure and Laboratory Experiments

The course is based on the successful completion of all the mandatory experiments, one of the three optional experiments, and a design project. A final exam at the end of the semester and a few pop–quizzes throughout the semester are also given.

A brief description of the mandatory experiments is given below:

1) *An introduction to basic digital baseband communication through MATLAB simulation:* The objective of this experiment is to familiarize students with the following performance metrics by evaluating the quality of a basic digital communication system in additive white Gaussian noise (AWGN) channel : Bit error rate (BER) and signal-to-noise ratio (SNR) relationship, power spectrum, time domain representation (power versus time), constellation, polar, and eye diagrams. As an optional step, carrier frequency offset is also introduced through a simple MATLAB simulation. Designing a quadrature phase shift keying (QPSK) detector and measuring true SNR of the system is a part of the experiment as well.
2) *Understanding test equipment:* The objective of this experiment is to teach students how to use VSG and VSA in order to generate and analyze digital waveforms and emphasize their relation to SDR.
3) *Introduction to wireless RF front–end:* The objective of this experiment is to teach students the functionality and characteristics of several hardware components such as voltage controlled oscillator (VCO), bandpass filters, mixer, and low noise amplifier (LNA). A receiver is built through the use of these components and its performance is evaluated by observing several performance metrics such as error vector magnitude (EVM), power spectrum, eye, polar, and constellation diagrams.
4) *Modulation domain analysis:* The objective of this experiment is to study modulation domain analysis by examining various modulation schemes. Several issues such as their envelope characteristics through the observation of complementary cumulative distribution function (CCDF) plots, tradeoff between modulation type and order, and noise vulnerability, and distinguishing features of their EVM, eye, polar, constellation diagrams are addressed in the experiment.
5) *Filter effect in wireless communication systems:* This experiment studies the impact of different pulse shaping filters on wireless communication systems. Effect of pulse shaping filter on spectrum and power statistics of the signal, introducing roll–off factor and bandwidth–time (BT) product, relation between inter-symbol interference (ISI), Nyquist criterion and the type of the filter are some of issues that are studied in the experiment.
6) *Multi–dimensional signal analysis:* The purpose of this experiment is to teach students the necessary tools to analyze various waveforms such as code division multiple access (CDMA), Bluetooth, and wireless local area network (WLAN). Time–frequency analysis (TFA), code domain analysis, and modulation domain analysis are some of the analysis domains emphasized in the experiment.
7) *Synchronization in wireless systems:* The objective of this experiment is to understand synchronization process at the receiver side. Details of this experiment will be given in the subsequent sections.
8) *Impact of propagation channel in wireless communication:* The objective of this experiment is to study some of the effects introduced by the wireless propagation medium on the transmitted waveforms. Path loss, frequency selectivity, line-of-sight (LOS) and non-line-of-sight (NLOS) transmission, estimation of multipath delay profile through channel sounding, and effect of wireless propagation channel on transmitter and receiver design are some of points discussed.

In addition to the eight mandatory experiments, three optional experiments are offered as follows:

- A more detailed study of distortions in RF front–end
- Analysis of interference
- Introduction to orthogonal frequency division multiplexing (OFDM) signals

Students are required to select one of these optional experiments regarding their field of interest. All mandatory and optional experiments should be completed before the design project. Students are required to successfully demonstrate their project at the laboratory with the provided equipment, hardware and software tools in front of their classmates.

"Experiment 7" addresses one of the core issues in wireless communication systems. "Experiment 7" is designed to teach students how the receivers process the captured waveforms in order to extract their useful information content. Rest of the paper is dedicated only to the discussion this experiment due to space limitations followed by a brief introduction to synchronization techniques available in the literature.

IV. Synchronization in Wireless Systems

Synchronization is one of the most extensively studied fields in wireless communications [5], [6]. Although no unique view on the synchronization exists in the literature, carrier frequency recovery, carrier phase recovery, and timing recovery are the most fundamental considerations in the synchronization process. Carrier frequency recovery is based on the estimation of the frequency offset between transmitter and receiver oscillators and compensation of this offset by taking the necessary steps. Carrier phase recovery is the process of estimating and correcting the constant phase rotation on the received waveforms. Finally, timing recovery makes sure that the receiver samples the received signal at the optimum sampling instant with minimum inter-symbol interference (ISI).

In the literature, various methods are proposed to maintain synchronization. These methods can be classified as data–aided, decision–directed, semi–blind, and blind. Data–aided methods are based on the use of known training sequences which are transmitted along with the unknown data sequences. In decision–directed methods, decisions on the previous symbols are used under the assumption that the previous decisions are sufficiently accurate. Semi–blind techniques can be considered as non–data–aided methods where partial information on the received waveform (like cyclostationary features) can efficiently be used to achieve synchronization. If synchronization is achieved without requiring any known parameter on the received signal it is considered as a blind synchronization technique. Such techniques depend heavily on the statistics of the received signal.

In “Experiment 7” of the laboratory course, data–aided synchronization is discussed by the help of laboratory equipment and MATLAB simulations. Students investigate data–aided synchronization by capturing a specially formatted signal that is transmitted via one of the VSGs available in the laboratory.

A. Details of “Experiment 7”: Synchronization in Wireless Systems

The objective of this experiment is to teach students one of the most basic synchronization techniques that is based on the use of known training sequences. Three different messages followed by training sequences (m–sequences) of three different lengths (seven, eight, and nine) are generated through one of the VSGs in the laboratory. Binary phase shift keying (BPSK) is used as the modulation scheme in the experiment. The structure of the transmitted waveform is depicted in Fig. 2. Training sequences are repeated twice to enable the students to exploit the simplicity of auto–correlation in the synchronization process. Students, which are divided into three groups considering the number of transmitted messages, are asked to capture the waveform through the use of VSA located on their laboratory benches and synchronize to the waveform by using their functions that are supposed to be generated through MATLAB and reveal the content of their corresponding message.

Time domain representation of the captured waveform where three different bursts can be clearly seen is shown in Fig. 3. Students are expected to perform the following steps to correctly extract the message part of their corresponding burst.

- coarse synchronization
- frequency offset estimation and correction
- fine synchronization
- phase estimation and correction
- bit–to–character conversion

Coarse synchronization is based on the use of auto–correlation by exploiting the repetition in the m–sequences. Since m–sequences are transmitted twice one after another, output of the auto–correlation process roughly indicates the start of the burst as shown in Fig. 4. Upon rough estimation on the start of the burst, frequency offset effect, which is depicted in Fig. 5, must be estimated and corrected. The effect of the wireless channel can also be seen through the examination of eye diagram as shown in Fig. 6. After frequency offset is removed from the received waveform, fine synchronization must be applied in order to find the exact position of the burst and correct symbol reference. Fine synchronization is based on cross-correlation. An m–sequence having the same length as the m–sequence in the corresponding burst is generated for this purpose. Generated and received m–sequences are cross-correlated considering the output of the auto–correlation process to avoid computational complexity. The output of the cross–correlation process indicates the exact position where the burst starts. Phase estimation and correction is the final step before revealing the message. The effect of the phase offset on the received waveform can be seen in Fig. 7. Previously generated and received m–sequences are used in this step in order to estimate and correct phase offset. After all impairments are compensated in the received waveform, Fig. 8 and Fig. 9 are obtained as eye diagram and scatter plot, respectively. These two figures clearly indicate the modulation type as BPSK. After all undesired effects are removed from the received signal, the next step is to detect the received symbols by implementing a BPSK detector and convert them into bits. Finally, these bits should be converted into characters revealing the message content of the transmitted waveform.

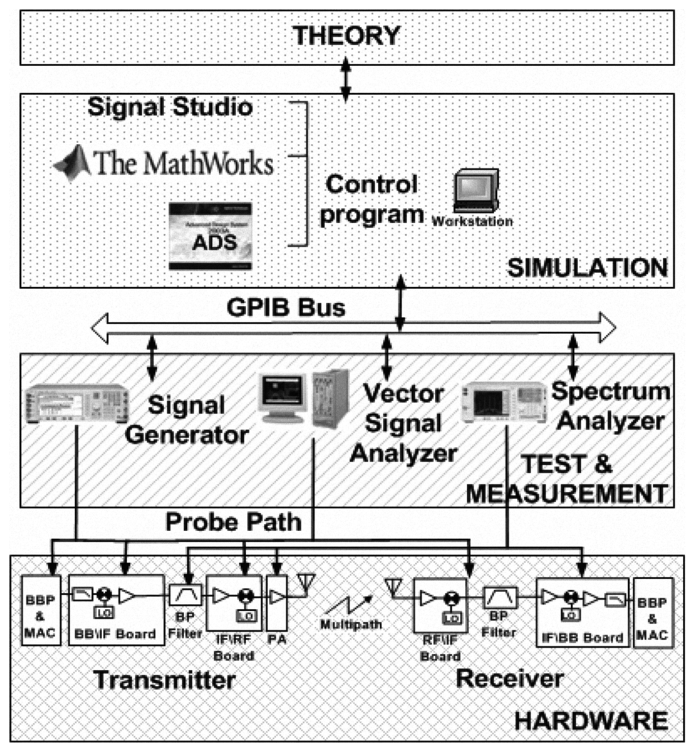

Fig. 1. Conceptual representation of the model used for the wireless communication systems laboratory. (Theory, simulation, test, measurement, and hardware comprise the core of the laboratory course.)

V. Conclusion

SDR allows nearly limitless number of ways of generating radio signals. Rapid penetration of these devices in the wireless market is highly dependent on the accurate testing and measurement of SDR capable devices. An SDR–based laboratory

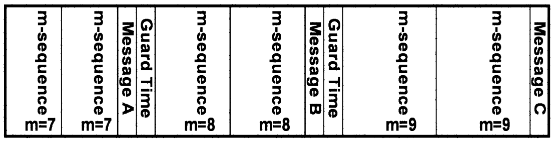

Fig. 2. Frame and slot structure used in the "Experiment 7". (A burst is composed of two m–sequences and the message. Two m–sequences are sent one after another in order to enable students to use auto–correlation while synchronizing with the burst. Each burst is separated from each other by a guard interval with a particular duration of time.)

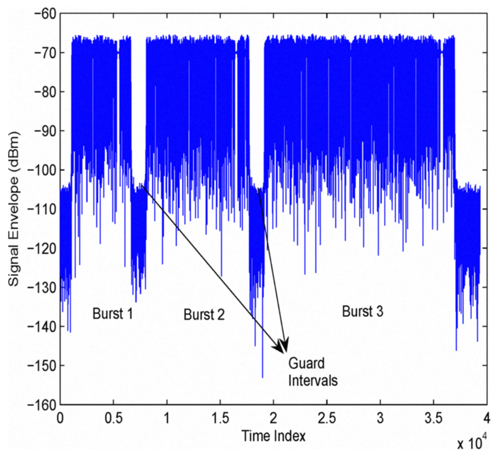

Fig. 3. Time domain representation of the captured waveform

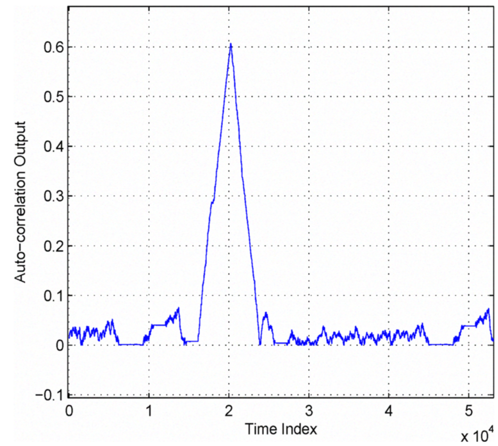

Fig. 4. Auto–correlation peaks. (Upon applying auto–correlation on the received waveform, a peak pointing the start position of the burst of interest should appear. This step is called as the coarse synchronization)

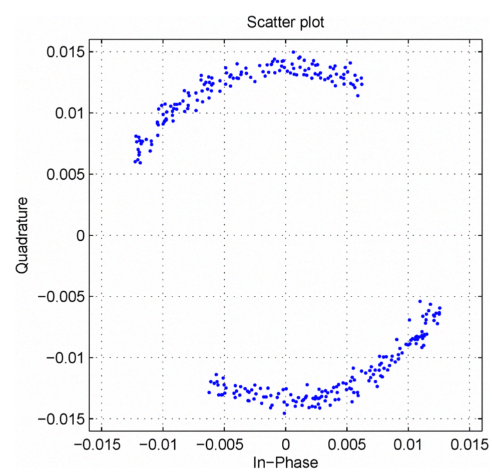

Fig. 5. Scatter plot of the waveform before frequency offset correction. (Frequency offset is introduced due to the mismatch between transmitter and receiver oscillators and causes a circular rotation in the symbol locations on the constellation diagram. The extent of this rotation depends on the frequency offset value. This effect can be clearly seen in this plot.)

course, which is developed in Electrical Engineering department of USF, is outlined in this paper. The laboratory is based on the use of SDR capable devices and structured in a way that it is composed of complementary experiments. One of the experiments performed as a part of the course is discussed in detail to reveal the principles followed in the design of the experiments.

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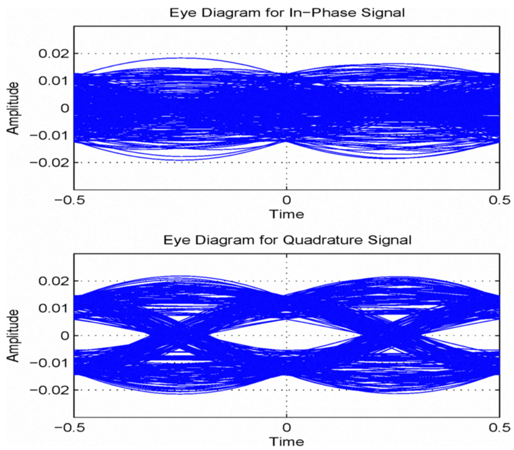

Fig. 6. Eye diagram of the received waveform before frequency offset correction. (The effect of ISI, noise, and the pulse shaping filter on the transmitted signal can be best seen through the observation of eye diagram. This eye diagram shows the total effect of the channel before frequency and phase offset correction on the BPSK modulated waveform.)

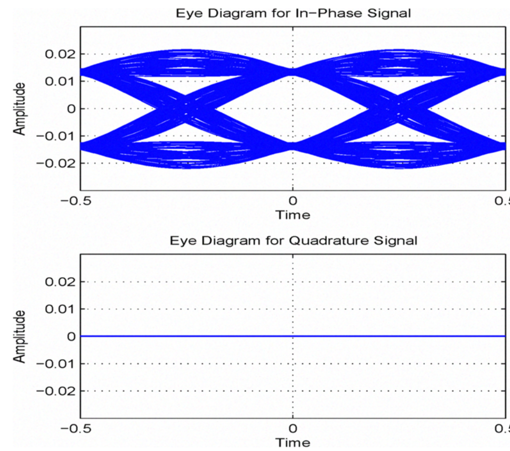

Fig. 8. Eye diagram of the received waveform after frequency and phase offset correction. (The effect of frequency and phase offset correction can be seen in the eye diagram above. Note that the quadrature component of the eye diagram does not exist in line with our expectations for a BPSK modulated signal. It is obvious that the diagram resembles a BPSK modulated signal and wide open.)

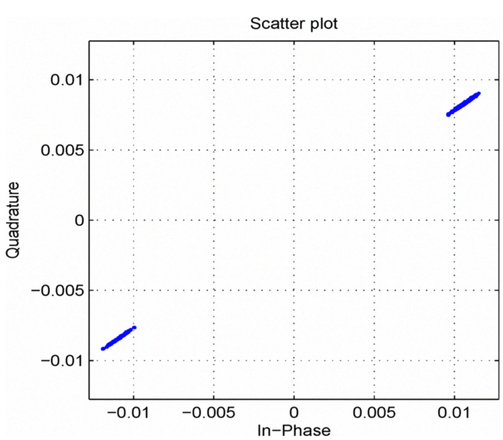

Fig. 7. Scatter plot of the waveform before phase offset correction. (It can be seen that the circular rotation that stems from the frequency offset is handled. However, it is obvious from the above constellation diagram that there is still a constant phase shift in the received symbols.)

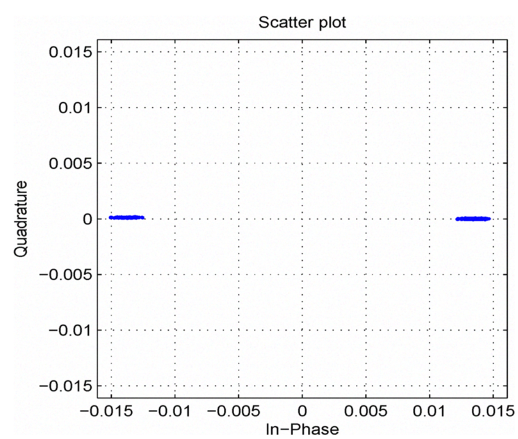

Fig. 9. Scatter plot of the waveform after frequency and phase offset correction. (The effect of frequency and phase offset correction can also be seen clearly in the constellation diagram. This is obviously the constellation diagram of a BPSK modulated signal where only in–phase component exists. Please note that spread in the constellation digram is due to the fact that no sample clock error correction algorithm is employed.)