Teaching SDR through a laboratory based course with modern measurement and test instruments[1]

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ABSTRACT

In this article, a state of the art wireless communication systems laboratory that will provide students with the experience to design, test, and simulate SDR based wireless systems (along with wireless circuits) using modern instrumentation and computer aided design software is introduced. The proposed lab will enhance the current wireless and microwave curriculum significantly, and it will build a bridge between the courses on RF circuits /devices, wireless systems/networks, and digital signal processing (DSP) and DSP/FPGA Labs.

1. INTRODUCTION

The high demand for communications anywhere and anytime has been the driving force for the development of wireless services and technologies. Wireless technologies and services have evolved significantly over the last couple of decades, from simple paging to real-time voice communication and recently to very high rate data communications. Recently, cognitive radio (CR) and software define radio (SDR) concepts gained significant interest among wireless communication community. One of the main characteristics of cognitive radio is the adaptability where the radio parameters (including frequency, power, modulation, and bandwidth) can be changed depending on the radio environment, user's situation, network condition, geolocation, and so on. SDR can provide very flexible radio functionality by avoiding the use of application specific fixed analog circuits and components. Therefore, SDR can be considered as the core enabling technology for cognitive radio.

With this ever growing 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 wide variety of wireless techniques has emerged. Lab benches that are equipped with SDR capable transmitters and receivers can address this goal. Modern test and measurement instruments like advanced vector signal generators and vector signal analyzers provide such capabilities as well as providing excellent measurement options and user interfaces.

In this paper, we introduce a state of the art wireless communication systems lab that will enable students to understand the SDR concepts with hands-on experiments. In this lab, students will understand the basic theory, software simulation of the systems, hardware test and modeling, system measurement and testing, software and hardware interactions and co-simulations. This lab course is the outcome of some of the research activities developed at the electrical engineering department of University of South Florida (USF) [1-4]. Over the past several years, various communication test-beds (for example, OFDM based wireless local area network communication test-bed and impulse radio based ultra wideband communications test-bed) were developed in our research labs with the support of the industry partners including Honeywell, Conexant, Agilent, Logus broadband solutions, Anritsu Company, and Custom Manufacturing and Engineering. These test-beds integrate Vector Signal Generator (VSG), Vector Signal Analyzer (VSA), and RF hardware with CAD tools including Matlab, Advanced Design System (ADS), and Signal Studio. The test-bed 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.

2. MODEL OF THE LAB COURSE

Figure 1 shows the lab bench set-up along with the integration of various components and instruments. The

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three important elements of the model (computer simulations and software, test & measurement instruments, and hardware) are shown in different rows. The top row shows the simulation world where the students can simulate and test various wireless communication systems (or sub-systems). The simulation can help students to get intuitive feeling of how theoretical knowledge is related to the real world; how to model and implement a realistic real-world wireless communication system using computer simulations; how various parameters affect the performance of the system etc.

The next row is related to the use of test and measurement equipments to connect the simulation world with the realistic hardware. Test and measurement instruments are important elements of the wireless communication systems lab. The figure shows some of the important test and measurement equipment, i.e. Vector Signal Generator (VSG), Vector Signal Analyzer (VSA), and Spectrum Analyzer (SA). The modern versions of spectrum analyzers (with capabilities of providing I/Q samples through wide bandwidth digitizer such as Agilent PSA (E4440A), http://content.tm.agilent.com/psa/PSA_Demo.html) can also be used as signal analyzer or the other way around. Therefore, a signal analyzer will be sufficient to study temporal, spectral, and waveform characteristics of the received signal.

The VSG can generate custom waveforms from various sources. Similarly, standard based communication waveforms can also be generated using the VSG. These waveforms can either be integrated into the VSG, or they can be externally generated (using an external computer) and fed to the VSG. The simulation world in the first row can easily be connected to the VSG, as these devices are developed with such capabilities, such as the one shown in the figure, Agilent ESG (E4438C), (http://cp.literature.agilent.com/litweb/pdf/5988-4039EN.pdf). For example, a baseband signal can be developed using Matlab (or Agilent's Signal Studio software or Advanced Design System (ADS) simulator), and then downloaded to the VSG to create the physical signal. Physical signal generation is important in order to be able to feed the signal to the real hardware. Signal generators can also generate signals with noise and other impairments to test the receiver's ability to demodulate the signal in noise and impairments. Similarly, signals with fading and signals with interference can be generated very easily. A simplified block diagram of a signal generator is shown in Figure 2.

The baseband (or IF or RF) signal is then passed through the device-under-test (DUT) for study and characterization of the influence of different components, including intermediate frequency (IF) and radio frequency (RF) up-converters, filters, power amplifiers, antennas, etc. The signal can also be passed through real radio channel to learn and understand the characteristics of realistic wireless channel. Alternatively, the signal can be transmitted through a multi-path channel emulator. The channel emulator provides a controllable RF multi-path channel model.

The wide frequency range of VSG can allow the study of RF signals up to tens of gigahertz range. Also, the wide bandwidth of the VSG can generate waveforms with high data rates. These flexibilities allow students to generate a wide variety of custom and standard based waveforms which can help them study and analyze current and possible future wireless communications systems and understand the related problems. Some of the important performance parameters of signal generators include: Level Accuracy (measure of how precisely the signal generator is able to output the desired signal level); Level Repeatability (measure of how much the level output of the signal generator drifts); Phase Noise (random noise within the source that causes the power of a CW signal to be spread over a small range of frequencies); Broadband Noise (measure of noise over a wide frequency range); Output power; etc.

The signal is received through the receiver antenna (or can be through direct cable) along with the interference sources that can be generated realistically in the test-bed by another signal generator (or the interference model can be generated in the baseband signal that was transmitted along with the desired signal). Then, the received signal is passed through the receiver hardware and it is digitized with the VSA. The VSA has the ability to demodulate the standard signals. However, it can also capture any arbitrary digital IQ samples and these samples can be processed with software components described in the first row. The simulation software (either Matlab or ADS or any other possible software) can process the received data with the baseband receiver algorithms. The interaction between simulations and VSA is an excellent mechanism for teaching and research to study and analyze the current and possible future generation wireless systems. It allows a detailed study of the received waveform and development of advanced receiver algorithms considering realistic scenarios. Figure 3 shows a simplified block diagram of VSA. Input to VSA can be a RF, IF, or baseband signal. Some of the important performance parameters of signal analyzers include: Demodulation bandwidth (analysis bandwidth determines the maximum bandwidth that can be analyzed by the VSA); Dynamic Range (measure of how well a small signal can be analyzed in the presence of a big signal); IQ memory (indication of how many samples can be captured and stored into memory, especially critical for wideband system measurements); Residual EVM (measure of how much the VSA contributes to the measured EVM); Speed (measure of how fast the data can be processed); etc.

3. SOME POSSIBLE LAB EXPERIMENTS

Using the model described above, the complete transceiver components can be studied step-by-step throughout the semester. Students can observe the transmitted and received signals at several levels of the transceiver circuitry using the bench set-up. Also, students can change noise, interference, and other impairment sources to see their effect on the component, sub-system, and overall system performance. In addition to these experiments, some project assignments for groups of students can be given to provide them with the opportunity to discover new ideas using the test-bed. Some of the possible experiments are given below:

- PA nonlinearities: Modeling the PA nonlinearities and understanding their effect on the system (see next section for details).
- Channel sounding and measurements: Understanding multipath and fading channel as well as the effect of the channel on the system and transceiver design.
- I/Q modulation and I/Q impairments: Modeling I/Q impairments (I/Q imbalance, I/Q offset, I/Q quadrature error), and studying the effect of I/Q impairments on the system.
- Digital modulation and measurements: Understanding various digital modulation/demodulation (PSK, ASK, QAM, etc), testing and measuring digital modulations. Understanding power versus spectral efficiency (data rate) trade-offs. Understanding various digital modulation quality measurements.
- Time/Frequency/Space/Waveform characteristics of wireless signals: Understanding spectral measurements (power spectrum, spectral masks, spectral flatness, frequency selectivity), temporal measurements (power versus time, transient behaviors, temporal selectivity of signals), spatial measurements (angular spread, space selectivity), etc. Relating the multi-dimensional characteristics of the signals and exploring the dualities among various dimensions.
- Test and measurements methodologies: Understanding various generic system measurements (EVM, CCDF, PAPR, Constellation, Eye diagram, spectral flatness, power vs. time, ACPR, spectral mask, etc.) and specific waveform dependent measurements (like OFDM measurements, CDMA measurements) and relating them with possible impairments, trouble shooting etc.
- Filters: Study of various filters (Nyquist, Gaussian, etc.) and their effect on the system, like spectrum shaping, PAPR effects, EVM and BER effects, inter-symbol interference and eye diagram effects, vector (polar) diagram, etc.
- Measurement instruments: Understanding the operation and internal structure of generic measurement instruments and relating them with the instruments used in the lab. Also, relating these instruments with SDR and cognitive radio concepts.
- Transient analysis of non-stationary signals (understanding and measuring transient behaviors of signals)
- Interference analysis and measurements
- Cyclostationarity analysis

7. CONCLUSIONS

There has been a strong interest to develop a flexible lab platform to teach wide variety of wireless systems and components that constitute the system. In this paper, a wireless communication system lab is developed and described to address this demand. The wireless lab will enhance the wireless communications and signal processing curriculum greatly. This lab course will complement the traditional theoretical courses such as Introduction to Communication Systems, Mobile and Personal Communications, Wireless Network Architectures, RF Microwave measurements, Digital Signal Processing that are being offered in our curriculum. Also, this lab can be utilized for other wireless courses at all levels. In addition, the lab can serve as a resource for several research projects for both undergraduate and graduate students.

8. REFERENCES

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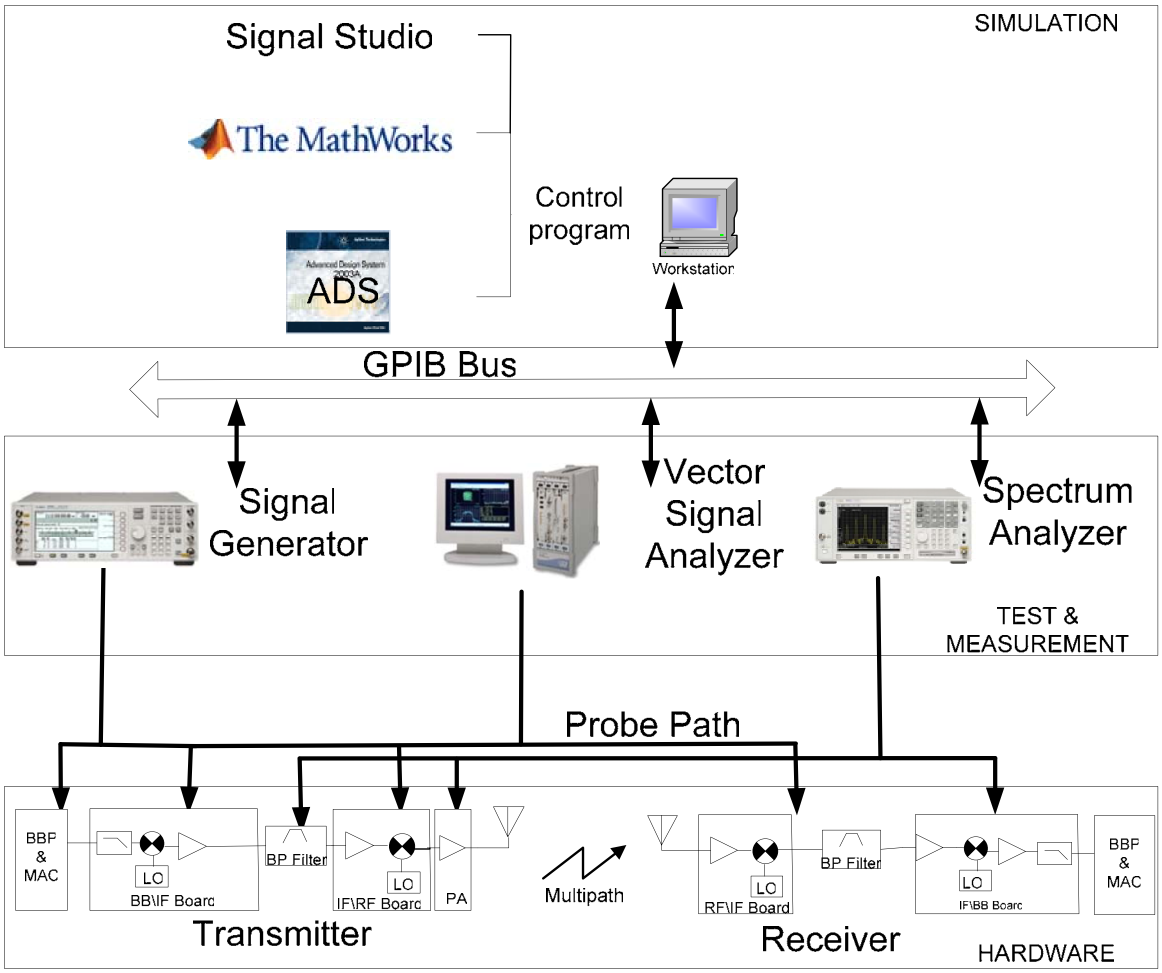

Figure 1 Pictorial representation of the model used for the wireless communication systems lab

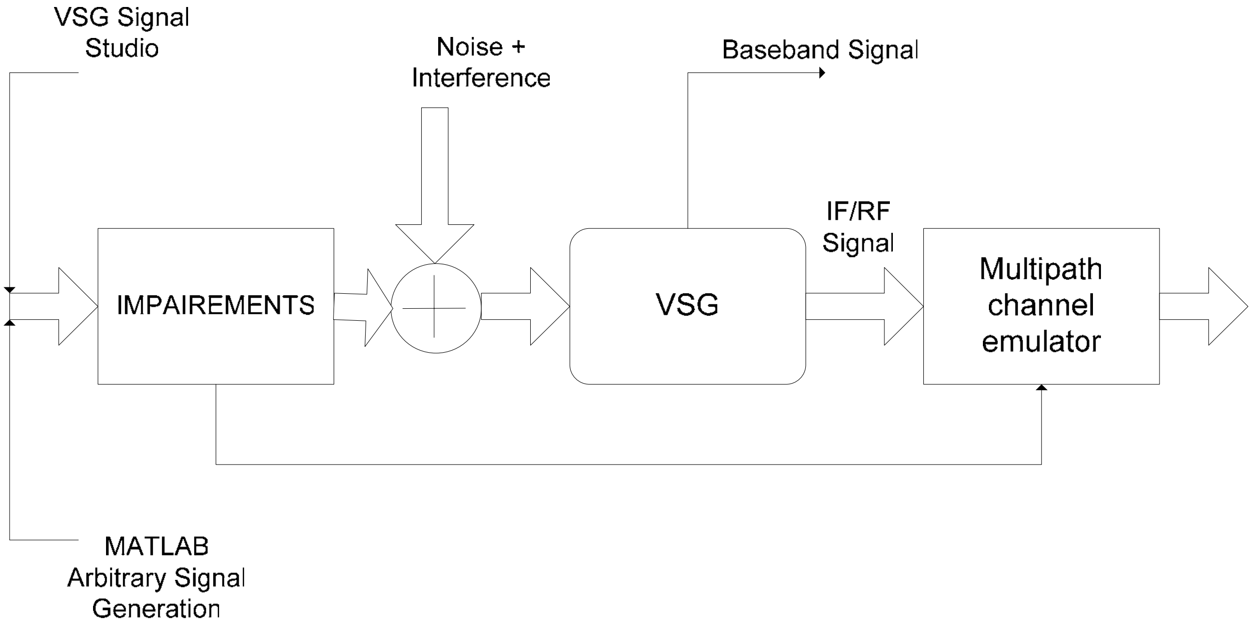

Figure 2 A simplified block diagram of vector signal generator.

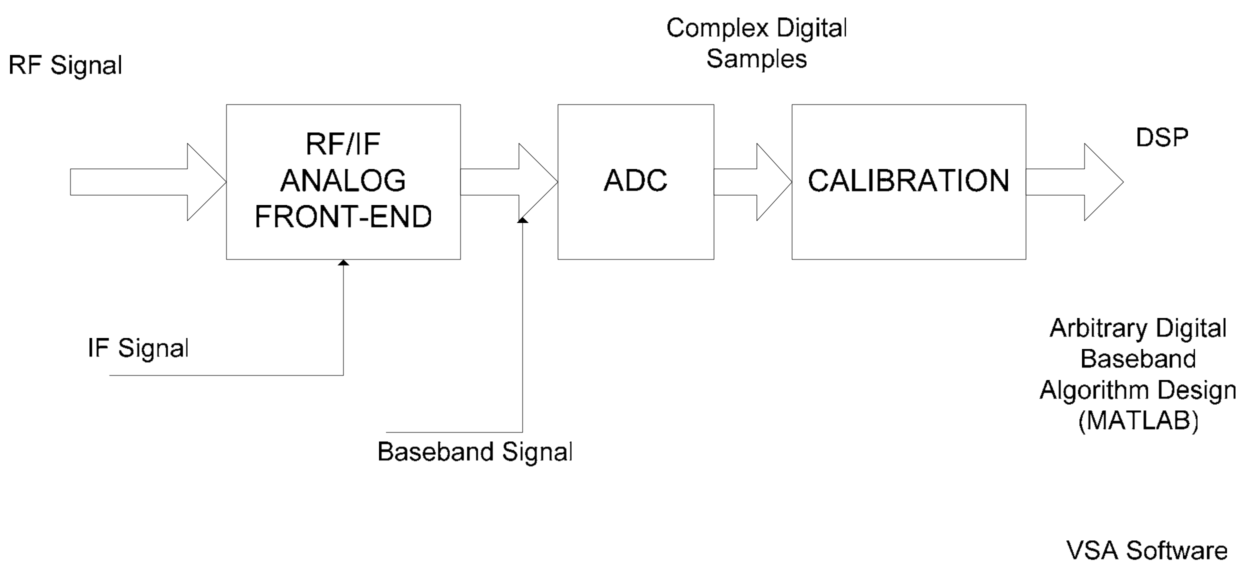

Figure 3 A simplified block diagram of vector signal analyzer. The input to VSA can be RF signal, IF signal or baseband signal. The digital IQ samples can be processed with user developed algorithms in Matlab or any other computer software or using VSA software developed by Agilent for standard based signals.