Using Software Defined Radio (SDR) To Demonstrate Concepts In Communications and Signal Processing Courses

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Abstract - The fundamental course in communications included in most electrical engineering programs introduces the challenging concepts of analog and/or digital modulation techniques, filters and other signal processing systems. Inherently mathematical in nature, communications theory is a completely abstract concept for students. This is particularly true now since most of our students lack practical, hands-on experience with communications systems. Classroom demonstrations illustrating the theoretical concepts as they are introduced can be vital in motivating students and helping their understanding.

This paper describes a set of innovative classroom demonstrations developed with software defined radio to illustrate the complex concepts presented in a communications course.

Software defined radio offers a multitude of unique and effective tools to teach signals and communications. In simplest terms, SDR is the direct implementation of the mathematics of signal processing on real world signals. Instructors can go directly from theoretical equations to a program applying the theory to sampled data from a live or recorded real signal in software defined radio. With their own laptop computers, students can experiment with communications concepts, benefiting from the immediate and tangible experience in applying the complex theories and principles they are trying to master.

IndexTerms - Classroom demonstration, Communications education, Signal processing, Software defined radio

INTRODUCTION

This paper presents a set of highly motivating classroom demonstrations developed for the senior level analog communications course common to most electrical engineering programs. By using software defined radio (SDR), communication systems are demonstrated with signals familiar to students who have little or no practical experience with communications systems.

The next section of this paper provides background on some of the issues that faculty currently face when teaching analog communications theory and explains the need for demonstrations in the course. This is followed by an overview of SDR and the features that make it an ideal platform for classroom demonstrations in communications and signal processing. The Implementation of SDR Section describes the particular SDR platform (hardware and software) that was used by the authors. The Demonstration Section presents the demonstrations created. The Results Section describes the results of using these demonstrations in a classroom and the final section presents conclusions and plans for future work in this area.

BACKGROUND

Courses on communications theory rely heavily on mathematical models. The abstract mathematical treatment of modulation and demodulation, as traditionally taught in lecture, can be difficult for students to understand. Lacking hobby or work experience, our typical students have more of a need to see that the material they are learning in class is useful in the “real world”. In addition, practical applications provide an overall structure in which to place what could be seen as unconnected equations and concepts. Unfortunately, classroom access to commercial communications systems is impractical. Classroom demonstrations illustrating the theoretical concepts as they are introduced can be vital in motivating students and helping their understanding [1],[2], particularly if they use signals that are familiar to the students (i.e. AM/FM radio, TV).

Communications laboratory experiments typically deal with simple circuits and rarely provide an opportunity for students to observe actual communications signals [3]-[7]. It would be desirable to construct an entire communications system and follow an RF signal from the antenna until it is output as an audible signal from a speaker.

In addition to affecting their performance in class, the abstract nature of the material taught in communications courses often deters undergraduate students from pursuing a course of study in the communications area. At California State University, Northridge, three communications courses are available to undergraduate students. The first is a course in analog communications and has an average of 20 undergraduate students enrolled each semester (40 per year). Students can follow this course with a course on digital communications and/or a course on communications networks. These higher level courses are usually taken by graduate students with undergraduate enrollment on the
order of only 5 per year in the digital communications course.

Therefore, the authors have created a set of communications systems demonstrations that process real world signals for the senior level analog communications course. These demonstrations use SDR to implement receivers and/or transmitters for various modulation schemes.

**WHAT IS SOFTWARE DEFINED RADIO(SDR)?**

Software Defined Radio (SDR) [8]-[11] is an emerging technology built on one of the great developments of the 20th Century: fast and cheap microcomputers. It represents a new method in processing radio signals that is a quantum leap over the older, original method of analog processing.

SDR moves the mathematical realm of communications theory into the real world. SDR offers a multitude of unique and effective tools to teach signals and communications. Put in simplest terms, SDR is the direct implementation of the mathematics of signal processing on real world signals.

In SDR, the signal is still picked up by an antenna. However, almost immediately, the signal is converted digitally to a sequence of numbers representing the value of the signal at regular time intervals. These digital values are then processed in software, using the very formulas that student engineers have studied for the last century. The resulting output can then be converted back into audio, video or remain data. In a sense, the SDR is given a signal and it “solves for” or “calculates” the intelligence riding on it.

The next section describes the SDR platform (hardware and software) that the authors have used for this project along with references to some of the other systems.

**IMPLEMENTATION OF SDR**

The Ettus Research Universal Software Radio Peripheral (USRP) [12] was chosen by the authors because of its performance and price. The basic architecture allows sampling or generation of signals from 0 to 32 MHz, the entire HF band. Daughter boards expand the range of frequencies to VHF, UHF, and microwave up to 5.9 GHz at present. Almost all USRP specifications are programmable, offering maximum flexibility and experimental possibilities. A number of other platforms are available for implementing SDR systems. These include Soft Rock [13], Flex Radio Systems [14], High Powered Software Defined Radio [15], and others [16]-[19].

SDR developers can write their own code to process signals and control the USRP. However, there is an enormous body of pre-written, free software in GNU Radio [20]. GNU Radio is a community of programmers who have written blocks of code in C++ to handle a wide range of signal processing functions. These blocks can be combined and compiled using scripts written in PYTHON and GNU Radio blocks all run under a LINUX based system such as Ubuntu. The beauty of GNU Radio is in the “connect” function which allows programmers to string together the prewritten processing blocks, much the same as a radio design engineer connects subsystems to make a transmitter and/or receiver.

The available blocks perform as low-, high- and band pass filters. Modulation and demodulation blocks are provided for FM and the digital modes, including PSK, QPSK and m-QAM. Modulation and demodulation in other modes, such as AM and SSB are accomplished using more basic blocks such as multipliers and adders.

A variety of interface blocks is also included. These control the USRP and interface with the audio card on the PC or with files. This last feature is a distinct advantage over simulations in the authors’ application. Signals can be pre-recorded off air and saved, unprocessed. In addition, there are signal databases available [21]-[23]. Various processing schemes can then be applied to the same signal, even if the USRP, external antennas or the signal are not available.

GUI blocks are available that create windows with buttons and controls. Also FFT, oscilloscope and constellation displays can be “wired in” to any point in the signal stream, providing built-in test equipment for development or displays for the end user. This feature is vital in the demonstrations created by the authors, allowing students to experience first-hand the principles of filtering and other signal processing concepts.

Programming in C++ and PYTHON can be daunting and cumbersome. Josh Bloom of GNU Radio has created a program, GNU Radio Companion (GRC) [24], which allows someone with almost no experience in programming to create and manipulate complex routines using every standard block available in GNU Radio.

Using GRC (see figure 1), the authors were able to create working programs, complete with GUIs, for such complex systems as an AM receiver, wideband FM receiver and an HF SSB receiver – all within the space of an hour. The capture of signals for demonstration, such as chunks of the AM broadcast band, HF bands and various baseband signals was equally straightforward.

**DEMONSTRATION DESCRIPTIONS**

The authors developed six classroom demonstrations for a senior analog communications course, ECE 460, at California State University, Northridge. The goal was to give students a tangible, in-class experience with such concepts as the relationship between time varying signals and bandwidth, common baseband signals, linear systems and filters, amplitude modulation and angle modulation. The demonstrations simultaneously illustrated signals and processing in both the time and frequency domain, constantly reinforcing the connection between these important views of signals in the communications world.
I. Demonstration 1: Relation of Time and Frequency Domains

It is vital that students understand the fundamental relationship between the time and frequency domains before proceeding deeper into any communications course. This demonstration allowed the students to see and hear this relationship.

A simple program was created in GRC connecting a white noise source to a low pass filter. The output of the low pass filter was routed to the computer’s speaker to give students an audible impression, an oscilloscope sink to show the signal in the time domain and an FFT sink to give the frequency domain. The GNU Radio oscilloscope and FFT displays are shown in figure 2. The bandwidth of the low pass filter was then varied (see figure 3). The students could hear the change in the sound of the signal as the bandwidth was reduced. They could also observe that the signal varied more slowly as the spectrum shrunk.

In the second part of the demonstration, pre-recorded files of various common baseband signals were played back in GRC, with the output connected to the speaker and an FFT sink. These included a male voice, a female voice, music and low speed data. A NTSC analog video spectrum was also displayed. It would be difficult to demonstrate these signals using simulation. Students could observe the spectra and the differences in energy content at various frequencies while gaining an understanding of the signal sources that will be applied to the communications systems that they will study in the course.

II. Demonstration 2: Linear Systems and Filters

In this demonstration students observed the effects of filtering on the baseband signals encountered in Demonstration 1. High-pass, low-pass and band-pass filters with various bandwidths and cutoff frequencies were

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applied to the recorded voice samples. For example, students could hear how the signals remained easily intelligible even when the bandwidth of the voice signals was reduced to only 2.8 KHz, the nominal bandwidth transmitted over most communications circuits. In a second example, the 1200 baud baseband data signal was bandwidth limited to the first null. Students could observe that, although the signal edges slowed considerably, the original data could be recovered by sampling at specific points.

The filters used in the demonstrations to this point were essentially near-ideal filters. In GNU Radio, it is possible to “look under the hood” of the filter process and see that the software can easily implement a 700th order filter with a 700 tap finite impulse response (FIR) filter. A line was added to the PYTHON script to print out the filter order on compilation.

SDR also illustrated the phase linearity of FIR filters when compared to infinite impulse response (IIR) filters. In this part of the demonstration, a square wave was generated and passed through an FIR filter and an IIR filter in parallel. Both filters had identical cutoff and stop frequencies. Students could readily observe the effects of non-linear phase response in the distortion of the square wave, an important concept to remember when dealing with data signals.

The demonstration concluded with the extraction of a communications signal from a band of other signals, the most common application of a filter. A pre-recorded section of the AM broadcast band containing multiple signals was played back and a band pass filter used to isolate the signal of interest for further processing (see figure 4). Students could hear the difference between the demodulated unfiltered signal and the demodulated filtered signal.

III. Demonstration 3: Amplitude Modulation

Picking up where Demonstration 2 left off, this demonstration dealt with the most basic form of modulation: amplitude variation of a carrier signal, including amplitude modulation (AM), double sideband (DSB) and single sideband (SSB). Both the generation and demodulation of these signals was covered in detail. Students could observe the relationship between the baseband bandwidth and that of the modulated signal.

This demonstration illustrates one of SDR’s greatest powers when used in education: the direct application of mathematical equations to signal processing. The basic equation of an AM signal is:

\[ s_{\text{AM}}(t) = [1 + a x_{m}(t)] \cos(2\pi f_c t) \]

where: 
- \( s_{\text{AM}}(t) \) = modulated AM signal
- \( x_m(t) \) = baseband signal
- \( f_c \) = carrier frequency

Figure 5 shows the implementation of this equation in GRC. The upper signal source is the baseband signal at 1500 Hz with amplitude 1. A constant, 1, is added to the baseband signal before it is multiplied by the other signal source, 22.5 KHz, acting as a carrier. The output of the multiplier, the amplitude modulated signal, is sent to both an FFT sink and an oscilloscope sink to display the frequency and time domains, respectively.

Students can readily follow the signal flow, with the function of each block clearly marked and relate it to the classic AM equation.

The output of the modulator (see figure 6) gives the satisfying result of the sine wave modulated carrier on the oscilloscope and, in the frequency domain, the two sidebands 6dB down, flanking the carrier 1500 Hz above and below it.

Back in the GRC window, an AM demodulator is added. Students can hear and see the output of the demodulator.
In the next part of the demonstration, the signal flow was reconfigured “live” in front of the students with the removal of the constant being added to the baseband signal. A DSAC signal was generated and the output in both the time and frequency domain was examined. Students could easily see the phase reversal of the carrier during the negative part of the baseband signal. They could also see that the AM demodulator will not produce the original signal but rather the full wave rectified cosine wave. They heard the distorted signal at twice the frequency as the original baseband.

The demonstration continued with observation of the AM broadcast band and reception of signals in the band—something that cannot be done with simulations.

IV. Demonstration 4: Angle Modulation

The final demonstration of the series dealt with the most complex form of modulation, angle modulation. At this point in the semester, students had learned about the mathematics behind phase and frequency modulation. They had been exposed to Carson’s Rule and Bessel Functions for determining the bandwidth of an FM signal.

In GNU Radio, there are pre-written blocks to generate and demodulate phase and frequency modulated signals. Implementing either form of modulation with basic blocks was considered beyond the scope of the course and the authors decided to limit the demonstration to the bandwidth/modulation index relationship in FM.

Using the FM modulator block and a simple 1 kHz cosine signal, the spectrum of the modulated signal was observed. Students could observe that the amplitude of the FM signal did not change in the time domain, but the bandwidth of the signal increased as the modulation index increased as predicted by the Bessel function analysis. Confirmation of the Bessel functions for relating carrier amplitude to modulation index was demonstrated using a simple narrowband FM modulator and a baseband signal of 2079 Hz. The carrier null (50dB down) occurred, as predicted, at a deviation of 5 KHz (see figure 7).

The demonstration included some off-air commercial broadcast signals. A wideband FM receiver was implemented in GRC and students could hear the distortion increase in the demodulated signal as the bandwidth of the receive filter was reduced. Students were also exposed to the various subcarriers riding on the broadcast signal, including the stereo information and stereo pilot tone, subsidiary communications authorization signal (SCA) and radio data system signal (RDS) (see figure 8).

Finally, using a narrow band FM receiver implemented in GRC, the authors demonstrated the quieting and threshold effects associated with an increasing signal to noise ratio. The authors used a commercial handheld radio and a variable attenuator on antenna input to the USRP. The students could hear and observe the demodulated signal to noise ratio and compare it to the incoming carrier to noise ratio using FFT sinks placed just after the USRP and after the FM demodulator.

RESULTS

In the Fall 2008 semester, the demonstrations described above were presented in the ECE 460 course (analog communications) at California State University, Northridge.
The class was composed of 20 students, primarily undergraduates. This course covers a review of linear systems and signals followed by material on AM, DSB, SSB, FM, PM and system performance. Throughout the semester, the demonstrations were presented to the class as the appropriate topics were covered in class. It was clear after the first demonstration that they created student interest in the subject. This was demonstrated by an increase in participation during the lecture. This gave the authors encouragement to continue to develop subsequent demonstrations.

There is also evidence to support the claim that the demonstrations increased student interest in communications as a field of study among undergraduate electrical engineering students. Of the 16 undergraduate students in this course, all but two continued on to the digital communications course offered the following semester. Generally less than 5 undergraduate students continue on to this second level course.

Because of their increased interest in the field of communications, a large number of students expressed a desire to complete their senior design projects in the area. As a result, this semester the authors are supervising 12 undergraduates on senior design projects that utilize SDR to implement complete communications systems.

Using SDR to create these demonstrations provides the additional advantage of introducing students to an emerging interdisciplinary technology. Furthermore, the entire system with all its capabilities can easily migrate to the lab. Instructors can even extend the use of this demonstration platform to courses in digital communications and digital signal processing.

CONCLUSIONS AND PLANS FOR FUTURE WORK

Based on the experience with these demonstrations, we conclude that the use of demonstrations in communications courses can improve student learning, motivation, and interest in the area of communications systems. SDR is an excellent platform for creating demonstrations since it allows the creation of complex systems without the complex hardware constructions and debugging.

Due to the success of this project, the authors are continuing this work with the creation of a set of SDR demonstrations for the digital communications course. These will be developed and used in the spring 2009 semester at California State University, Northridge.

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