Session 3420

The Incredible Hulk and Other Techniques for Teaching Waveform Demodulation

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Abstract

The University of Wyoming has introduced a 2 contact hour undergraduate/graduate course entitled, "Communications Measurement Laboratory." This new course was designed to reinforce student knowledge of their course work in signals and systems, digital and analog communication systems, and digital signal processing. The primary course objectives were to familiarize students with vector signal analysis and develop a thorough understanding of I and Q-based demodulation techniques. This paper provides an overview of this course and describes student projects that utilize a vector signal analyzer (VSA) to detect, localize, and record decimated I and Q data as would be available at the output of an intermediate frequency (IF) analog-to-digital converter (ADC) stage of a software defined radio (SDR).

1 Introduction

The University of Wyoming has introduced a 2 contact hour undergraduate/graduate course entitled, "Communications Measurement Laboratory." Creating and offering this course was part of the sabbatical leave responsibilities of the first author while visiting the University of Wyoming, Laramie campus, during the fall semester of the 2004 – 2005 academic year.

This new course was designed to reinforce student knowledge of their previous course work in signals and systems, digital and analog communication systems, and digital signal processing.

The primary course objectives were to,

- Familiarize students with vector signal analysis.
- Develop a thorough understanding of I and Q-based demodulation techniques.

Additionally, a great deal of familiarity with the operation of both baseband and passband vector signal analyzers (VSA's), radio frequency (RF) signal generators, and computer assisted test and measurement were gained.

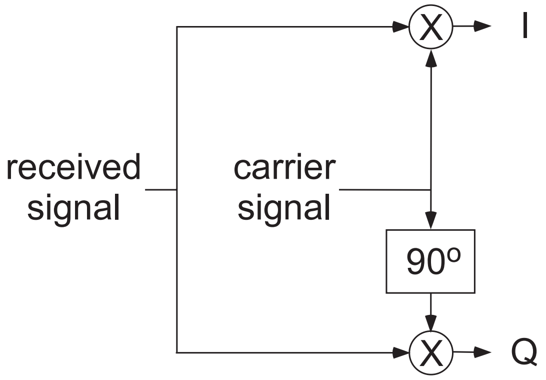

Figure 1: Block diagram of a complex mixer.

2 Course Overview

Specifically, this course consisted of:

- **week 1** Course introduction
- **week 2** Vector signal analyzers
- **week 3** Vector signal analysis
- **week 4** Amplitude modulation
- **week 5** Amplitude modulation project
- **week 6** Frequency modulation and project
- **week 7** Complex signals, complex filters, and a project
- **week 8** Frequency modulation project
- **weeks 9–10** Digital modulation and final project definition
- **weeks 11–15** Final project and presentation time

Due to hardware constraints, this first offering of the communications measurements lab was limited to 10 students.

3 In-phase and Quadrature Signals

This section is intended to provide a very brief review of in-phase (I) and quadrature (Q) signal recovery and their display [1–3].

At the heart of most traditional radio receivers is a complex mixer. This mixer is designed to translate the received signal to an intermediate frequency where additional signal processing or demodulation can be more easily achieved. A very basic block diagram of a complex mixer is shown in Figure 1 [4]. In Figure 1, the **carrier signal** label is used to represent *either* the output of the receiver's phase-locked loop (PLL) or a free running local oscillator. In either case, the received signal's center frequency is translated to accommodate the subsequent receiver stages.

Routinely, post translation filtering is performed, at a minimum, to isolate the desired signal and maximize the recovered signal's signal-to-noise ratio (SNR). The block diagram of this improved system is shown in Figure 2 [4]. Since we are dealing with sampled systems, the post translation

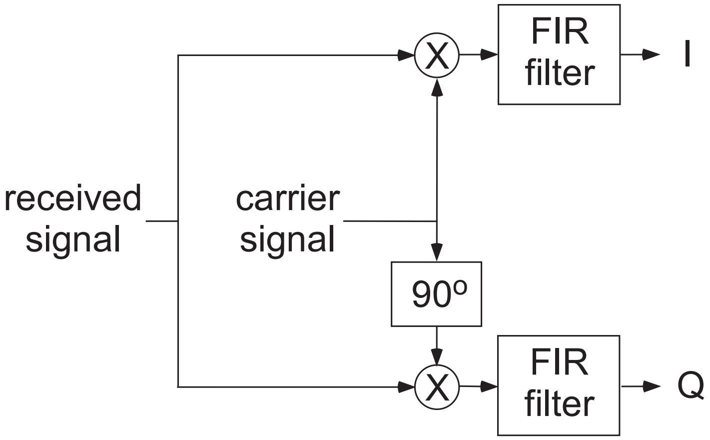

Figure 2: Block diagram of a complex mixer with filtering.

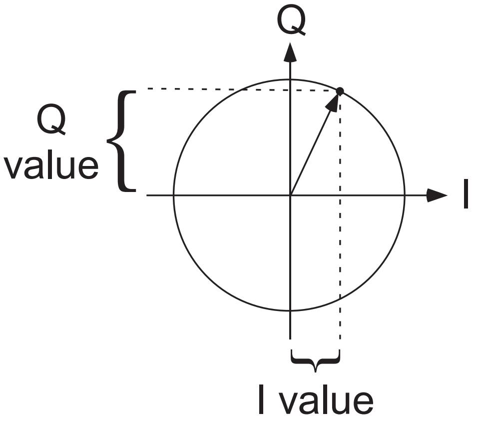

Figure 3: The I and Q plot.

filtering operations are shown as finite impulse response (FIR) filter. In practice, any filter type can be used.

At the output of both the block diagrams associated with these complex mixers is an in-phase (I) and quadrature (Q) label. Traditionally, the "I" term is associated with the output of the cosine mixer while the "Q" term is associated with the output of the sine mixer. The sine mixer has the 90 degree phase shifter connected to it while the cosine mixer is connected *directly* to the **carrier signal**.

The I and Q terms are now plotted on a traditional 2-D plot as shown in Figure 3. A variation in the signal's magnitude (amplitude) or phase can be seen in Figure 4 while variation in *both* the signal's magnitude (amplitude) and phase or frequency can be seen in Figure 5 [1–3].

It should now be clear that a great deal of information concerning the signal's modulation can be gleaned from the I and Q plot. In fact, the I and Q plot is the definitive test for what type of modulation (e.g., amplitude modulation (AM), frequency modulation (FM), phase modulation (PM), or any number of complex/higher order modulation schemes) is being used.

As an example, the I and Q plot of a commercial AM radio signal is shown in Figure 6. This plot represents approximately 140 ms of the signal and there are 3 characteristics to observe in this plot.

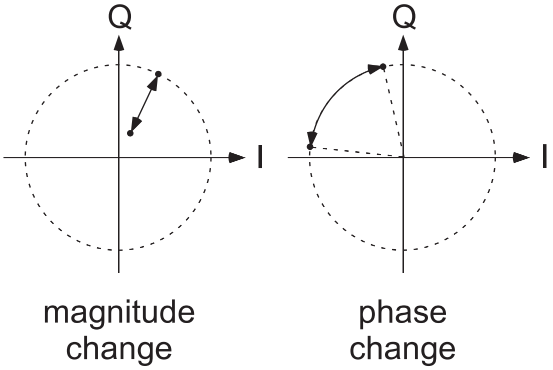

Figure 4: Magnitude and phase changes in the I and Q plot.

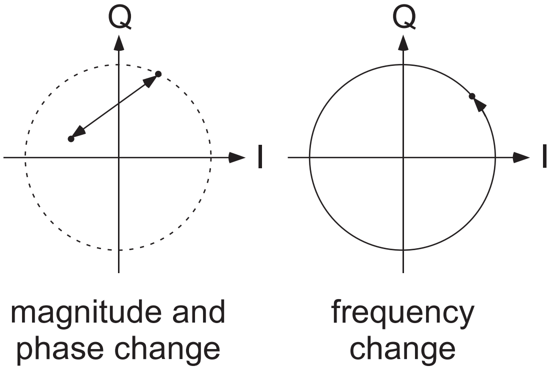

Figure 5: Magnitude and phase changes and frequency changes in the I and Q plot.

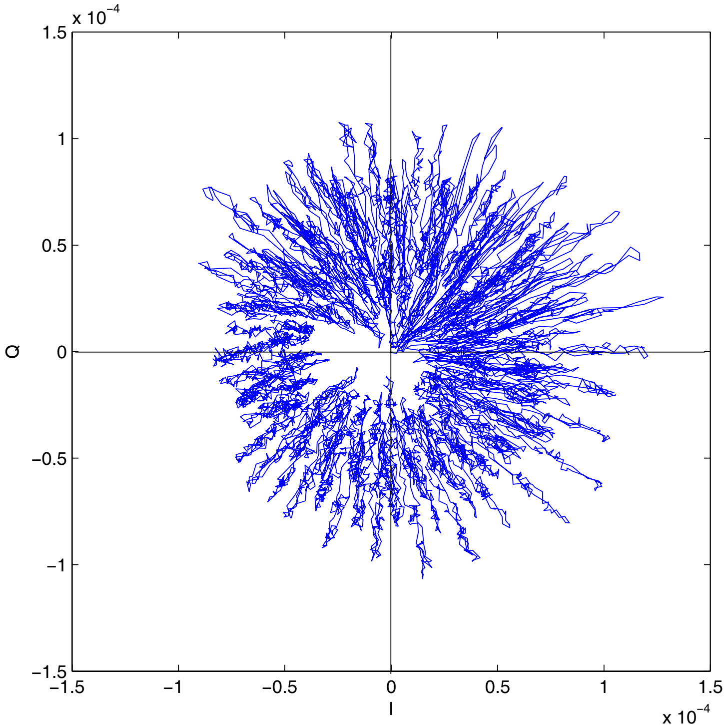

Figure 6: I and Q plot associated with 140 ms of an AM radio signal.

Figure 7: The "Incredible Hulk" handheld, 2-way radio (walkie talkie).

- The radial variation of the signal is due to the amplitude modulation.
- The rotation of the signal about the origin indicates that the received signal's carrier frequency and the center frequency of the VSA are not frequency locked.
- The jagged nature of the plot is an indication that the signal contains noise. A closer look at the scale of Figure 6 shows that the maximum value of the received signal is about 0.1 millivolts (mV).

Even though the carrier frequency of this radio station was 1290 kHz, the I and Q data was recorded at only 64,000 sample per second. This drastically reduced sampling rate is possible because of the decimation and filtering operations [5] required to extract *only* the signals message (information) *prior* to the signal being buffered and recorded. All of these operations are performed by the VSA in real-time.

4 The Incredible Hulk and Other RF Signal Sources

To allow for a more graduated transition from perfect, distortion and noise free signals to real-world signals, we routinely added the extra step of using an RF signal generator to provide extremely high quality test waveforms for the students to analyze and demodulate. Then, after mastering these "test equipment generated waveforms," real-world signal sources are investigated such as commercial AM and FM radio station signals.

Additionally, the "Incredible Hulk" shown in Figure 7 is actually a handheld, 2-way radio (walkie talkie) and was used as one of the laboratory demodulation exercises. The Hulk's raised right arm is actually the radio's antenna.

In-class exercises routinely required the students to utilize the VSA to detect, localize, and record decimated I and Q data. The students then wrote MATLAB [6] based demodulation routines to recover the transmitted message. While this exercise may seem somewhat contrived, it contains every stage necessary to build a software defined radio (SDR). Working with real-world signals was incredibly motivating to our students.

5 Student Projects

Student projects were conducted in teams of 2. Where possible, a graduate and an undergraduate student comprised a team. Possible topics were introduced and discussed through out the semester, but eventually, each team selected their own project. Student projects included,

- Nintendo WaveBird wireless controller for GameCube
- Automotive keyless entry and wireless keyboard
- M-ary frequency shift keying (FSK) pager
- Remote control transmitter decoding and signal generation
- MATLAB TV

5.1 Nintendo WaveBird wireless controller for GameCube

This system generates binary data at 96 kilobits per second (kbps). This data is then spread using direct-sequence spread-spectrum (DSSS) techniques. The DSSS system uses a repeating 15 state pseudo-random noise (PN) sequence to achieve a chip rate of 1.44 megachips per second (Mcps). These chips are modulated using Gaussian frequency shift keying (GFSK), using a frequency deviation of 580 kHz. Finally, the game controller's signal is transmitted on one of 16 channels contained in the 2400 MHz to 2483.5 MHz industrial, scientific, and medical (ISM) band.

The students first utilized the VSA to detect, localize, and record decimated I and Q data. Using a number of references for additional information, the students then wrote MATLAB routines that despread and demodulated the I and Q data and determined the control signals being sent to the GameCube. Prior to this project neither student *claimed* to know *anything* about spread-spectrum communication systems or the underlying theory.

5.2 Automotive keyless entry and wireless keyboard

This system generated a packet of 183 bits (6 start bits and 177 data bits) then transmitted the packet using amplitude modulation at a carrier frequency of 315 MHz. The students first utilized the VSA to detect, localize, and record decimated I and Q data. The students then wrote MATLAB routines to demodulate the signal. The students rapidly determined that the same "command", for example, "unlock the car door," resulted in a different bit pattern each time the key fob was activated. Additional research revealed that the system was encrypted!

This team then shifted their efforts to a wireless keyboard project. The wireless keyboard sends 3 blocks of data for every keystroke. These data blocks are transmitted using frequency shift keying (FSK) at a carrier frequency of 27 MHz. The students first utilized the VSA to detect, localize, and record decimated I and Q data. The students then wrote MATLAB routines to demodulate the signal and recover the transmitted keystrokes.

5.3 M-ary frequency shift keying (FSK) pager

This system uses multi-level (M-ary) FSK to transmit data at 1600 bps. The students first utilized the VSA to detect, localize, and record decimated I and Q data. The students then wrote MATLAB routines to demodulate the signal. No attempt was made to convert the recovered bits into ASCII text using the Post Office Code Standardization Advisory Group (POCSAG) air interface standard.

5.4 Remote control (RC) transmitter decoding and signal generation

This system uses pulse width modulation (PWM) within 22 millisecond (ms) slots to encode the position commands for the remotely controlled (RC) model airplane's control surfaces. These commands were modulated using FM with a frequency deviation of 75 kHz. The carrier frequency depended on the channel that the RC airplane was selected to. The students first utilized the VSA to detect, localize, and record decimated I and Q data. The students then wrote MATLAB routines to demodulate the signal.

This team then programmed an Agilent 33120A arbitrary waveform generator to re-create the baseband signals recovered by their MATLAB routines. These baseband signals were then used to excite the FM transmitter in an Agilent E4438C vector signal generator (VSG).

5.5 MATLAB TV

The students first utilized the VSA to detect, localize, and record decimated I and Q data from both a cable television (TV) system and digital versatile disk (DVD) player. The DVD player's audio and composite video signals were modulated to TV channel 3 using a commercially available (e.g., RadioShack or WAL*MART) RF modulator.

The students then wrote MATLAB routines to demodulate the black and white (BW) video, audio, and color video signals. The BW test pattern they recovered is shown in Figure 8

6 Conclusions

We have described a new course entitled "Communications Measurement Laboratory." This new course was designed to reinforce student knowledge of their prerequisite course work by familiarizing them with vector signal analyzers and vector signal analysis techniques.

Even though this course awarded only a single academic credit, students learned a phenomenal amount of information. This new information drew on a wide variety of theory and skills developed in prerequisite courses. Solving real-world communications problems was exceedingly motivational

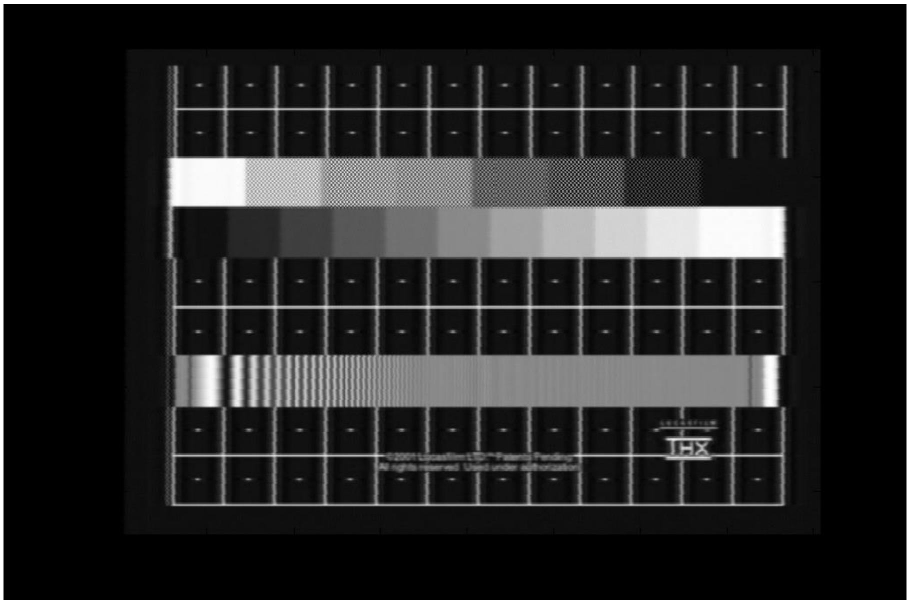

Figure 8: The BW test pattern recovered from a portable DVD player.

to our students! Selected material pertaining to vector signal analysis can be found at `www.usna.edu/EE/Research/VSA/index.htm`.

References

[1] Agilent, *Vector Signal Analysis Basics (Application Note 150-15).*

[2] Agilent, *Digital Modulation in Communications Systems - An Introduction (Application Note 1298).*

[3] Agilent, *Testing and Troubleshooting Digital Communications Receiver Design (Application Note 1314).*

[4] B. Sklar, *Digital Communications: Fundamentals and Applications.* Prentice Hall, 2nd ed., 2001.

[5] R. G. Lyons, *Understanding Digital Signal Processing.* Addison Wesley, 1997.

[6] The MathWorks, Inc., Natick, MA, *MATLAB: The Language of Technical Computing*, 2004.

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