

A Coherent Theory/Hardware Course in Communication System Design

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I. Introduction

In typical Electrical Engineering programs, various related topics are studied independently, obscuring the underlying connections between them. In addition, theory is generally taught separately from practical implementation issues. Only during a senior-level capstone design course do students attempt to combine materials treated in diverse courses in a coherent manner to solve a significant design problem. This paper describes a two-semester senior-level Electrical Engineering course in communication electronics that combines a systems-level treatment of communications theory with practical electronic circuit implementations of these systems. While most Electrical Engineering programs have courses in electronics as well as a course in communications theory, seldom are the two subjects jointly treated. The electronics courses typically describe the construction and behavior of amplifiers, filters, and oscillators but little attention is given to realistic applications of these devices. Similarly, a typical communications theory course covers basic modulation techniques along with block-level descriptions of their construction. However, deviations of these “black boxes” from theoretically ideal performance is rarely considered.

The course considered in this paper combines the electronic building blocks studied in electronics courses to construct practical communication systems. The first semester of the course treats the theoretical basis of traditional analog communication systems topics such as amplitude modulation (and demodulation), superheterodyne reception, and frequency modulation (and demodulation). Practical electronic design of building block circuits (filters, oscillators, mixers, tunable filters, discriminators, phase-locked loops) are developed. They are then combined to implement the system level topics mentioned above. The second semester treats contemporary digital communication systems topics such as digital baseband transmission, intersymbol interference caused by bandlimited channels, digital carrier modulation, and spread spectrum techniques. Practical electronic circuit designs for analog-to-digital and digital-to-analog converters, equalizers for bandlimited channels, frequency synthesizers, and modems are developed. The students investigate systems-level concepts with software (Matlab) and with systems simulation hardware (primarily using the Texas Instruments TMS320C30 digital signal processing evaluation module). Practical electronic circuit implementations are considered primarily using simulation software (Electronics Workbench). Each student is assigned a series of electronic circuit design projects that are solved via either simulation (in Electronics Workbench) or with actual electronic hardware. A typical design project treating a gated amplitude modulator is covered in detail in this paper. This

two-semester course is unique in that the theoretical and practical circuit topics are integrated in sequence and are team-taught by the co-authors (one with a systems-level perspective and the other with a practical circuit design perspective).

II. Course Description

Loyola College in Maryland is a regional liberal arts university with a small engineering program. Typical upper-level classes have ten students or less. The Electrical Engineering Program has two tracks from which seniors select two elective courses: a two-semester digital signal processing track and the newly created electronics in communications track described in this paper. The communication electronics track was intended to provide an alternate path for the student with interest in electronics hardware and with perhaps less interest in the occasionally mathematically intensive signal processing track. The prerequisites for the course are common to any senior-level Electrical Engineering student: two courses in electronics, two courses in digital design, and courses in both continuous-time and discrete-time signals and systems.

The electronics in communications course is structured so that each topic is typically treated twice: first, from a systems-level viewpoint using typical systems analysis tools (such as Fourier transforms and ideal filters), and augmented with software simulations using Matlab; secondly, the same topic is studied from a practical implementation viewpoint using physically-realizable components (typically simulated using Electronics Workbench). The selection of topics is considered below.

Semester 1: Analog Communications

- 1.0 Signal and Systems Analysis
 - 1.1 Fourier Series and Fourier Transforms
 - 1.2 Linear Systems and Convolution
 - 1.3 System Transfer Function
 - 1.4 Ideal Filters and Causality
 - 1.5 Practical Filters
 - 1.5.1 Simple RLC filters
 - 1.5.2 Active filters
 - 1.5.3 Multistage filters
 - 1.5.4 Automatic Gain Control
- 2.0 Amplitude Modulation (AM)
 - 2.1 Double-Sideband Modulation (DSBSC and DSBTC)
 - 2.1.1 Oscillators
 - 2.1.2 Mixers
 - 2.1.3 Modulators
 - 2.2 Coherent and Incoherent demodulation
 - 2.2.1 Square law detectors
 - 2.2.2 Envelope detectors
 - 2.3 Broadcast AM and Superheterodyne receiver

- 2.4 Single Sideband and Vestigial Sideband Modulation
 - 2.4.1 Hilbert Transformers
 - 2.4.2 Symmetric filters
- 3.0 Angle Modulation
 - 3.1 Instantaneous frequency and spectrograms
 - 3.2 Frequency modulation (FM)
 - 3.2.1 Narrowband FM modulators
 - 3.2.2 Voltage Controlled Oscillators
 - 3.3 Bandwidth of angle modulated signals – Carson’s Rule
 - 3.3.1 Sinusoidal message
 - 3.3.2 Arbitrary message
 - 3.4 FM demodulators
 - 3.4.1 Discriminators
 - 3.4.2 Phase-Locked Loops
 - 3.5 Broadcast FM and stereo
 - 3.5.1 Frequency Doublers
 - 3.5.2 Gain Bandwidth Issues

Semester 2: Digital Communications

- 1.0 Sampling and Quantization
 - 1.1 Ideal sampling and the Sampling Theorem
 - 1.2 Practical sampling methods and recovery
 - 1.3 Pulse modulation (amplitude, width, and position modulation)
 - 1.4 Uniform Quantization
 - 1.5 Practical A/D and D/A circuits
 - 1.6 Nonuniform quantization and companding
- 2.0 Digital Baseband Communication
 - 2.1 Pulse Code Modulation (PCM)
 - 2.2 Binary signaling formats (NRZ, Manchester, etc.)
 - 2.3 Time Division Multiplexing (T1, T3, etc.)
 - 2.4 Delta Modulation and practical implementations
 - 2.5 Matched filter detection in additive white Gaussian noise
 - 2.6 Calculation of bit error rates
 - 2.7 M-ary signaling
- 3.0 Digital Baseband Communication Through Bandlimited Channels
 - 3.1 Characterization of bandlimited channels and channel distortion
 - 3.2 Intersymbol interference and eye patterns
 - 3.3 Nyquist Criterion, signal design and synchronization
 - 3.4 Equalizers
- 4.0 Digital Carrier Modulation
 - 4.1 Amplitude Shift Keying
 - 4.2 Phase Shift Keying
 - 4.3 Quadrature Amplitude Modulation
 - 4.4 Frequency Shift Keying
 - 4.5 Spread spectrum communications

- 5.0 Source Coding
 - 5.1 Morse code
 - 5.2 Entropy and source coding theorem
 - 5.3 Huffman coding
 - 5.4 Lempel-Ziv compression
 - 5.5 Linear Predictive Coding
- 6.0 Channel Capacity and Coding
 - 6.1 Information and channel capacity: Shannon's Theorem
 - 6.2 Error correcting codes (Hamming codes)
 - 6.3 Error detecting codes (CRC methods)

III. Case Study of Gated Amplitude Modulator Project

The following project illustrates the combined theory/hardware structure for the course. This project considers the design and implementation of a simple circuit that generates an amplitude modulated (AM) waveform. Given a message waveform $m(t)$, an AM signal is given by

$$s_{am}(t) = m(t) \cos(2\pi f_c t)$$

where f_c is the carrier frequency to which the message spectrum is to be shifted.

While the above operation is straightforward mathematically, the multiplication between message and carrier wave is difficult to implement in practice. Consequently, the students are given a block diagram description of a technique that can be used to generate an AM waveform. The block diagram is shown below:

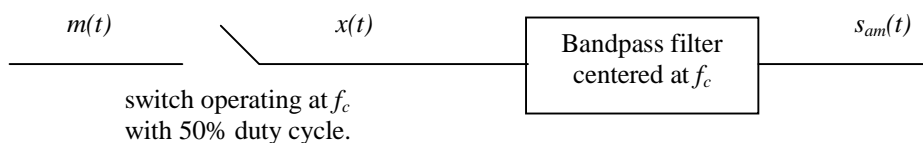


Figure 1. Block diagram of gated amplitude modulator

A "systems-level" description of this block diagram is provided to the students. In particular, note that $x(t)$ can be expressed as the product of the message $m(t)$ and a periodic square pulse $p(t)$ with frequency f_c . Representing $p(t)$ in a Fourier series expansion yields

$$x(t) = m(t) \sum_{n=-\infty}^{\infty} c_n e^{j2\pi n f_c t}$$

Taking the Fourier transform reveals that $X(f)$ contains replicated message spectra $M(f)$ at harmonics of the carrier frequency f_c with each spectral replication scaled by the Fourier series coefficients c_n of the periodic square pulse $p(t)$. Hence, the bandpass filter centered at f_c acts to extract the desired spectral replication of the message shifted to the carrier frequency resulting in an AM signal.

The students are then asked to design a circuit that implements the gated amplitude modulator. The message waveform is specified to be a simple sinusoid. The students are free to pick the message frequency as well as the carrier frequency f_c . The students are encouraged to “modularize” the design project into smaller, simpler pieces. Once the functionality of each “box” is defined, the electronic implementation of each piece is considered. Any loading between boxes must be investigated. Finally, the design is simulated (here, in Electronics Workbench) to verify its performance before construction of the actual circuit. The circuit designed by one of our students (Richard Kitay) is shown as a block diagram in Fig. 2.

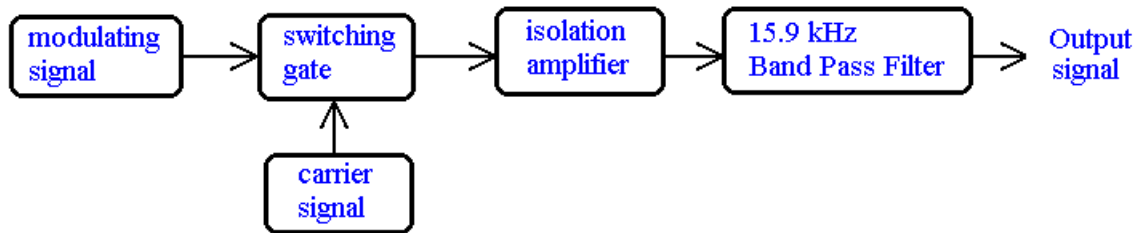


Figure 2. Block diagram for specific gated modulator design.

The completed schematic diagram is shown in Fig. 3. The circuit was evaluated by simulation in the Electronics Workbench. The two channels of the oscilloscope connect to the modulating signal (in black) and the output signal (in red). The oscilloscope display is shown in Fig. 4.

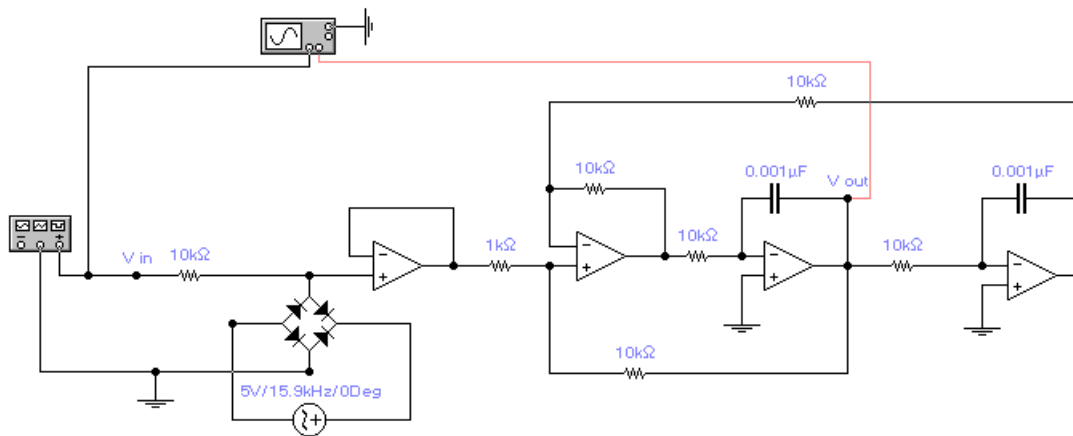


Figure 3. Circuit schematic of gated amplitude modulator.

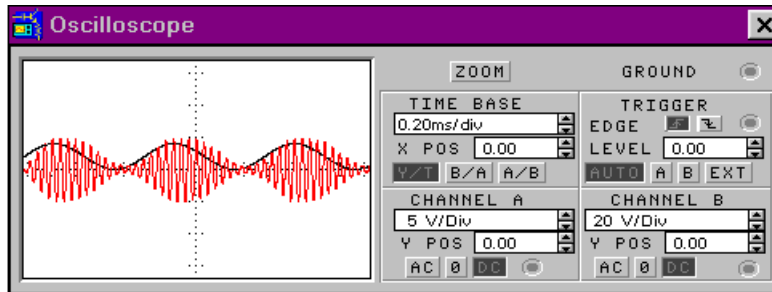


Figure 4. Sinusoidal message (black) and resulting AM signal (red).

A simple diode bridge, driven with a sinusoid at the carrier frequency (15.9 kHz), is used to implement the switching function in Fig. 1. The form of the bandpass filter selected was the HKN biquad (Kerwin-Huelsman-Newcomb). This circuit is interesting in that it realizes the three basic filtering functions: highpass, bandpass, and lowpass simultaneously. This configuration has become very popular and is also known as the *universal active filter*.

Assessment of the performance of the isolation amplifier/bandpass filter was accomplished using the Bode instrument connected as shown in Fig. 5. The frequency range displayed in Fig. 6 is 11 kHz to 22 kHz. The center frequency gain is approximately 20 dB. The vertical axis ranges from +10 dB to +20dB. The -10 dB (from peak) bandwidth is approximately 7 kHz.

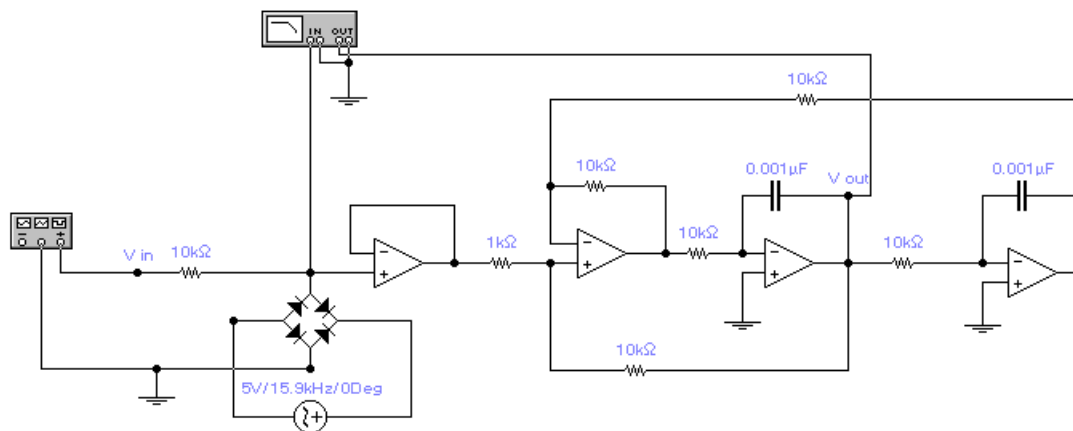


Figure 5. Circuit configuration and bandpass filter measurement.

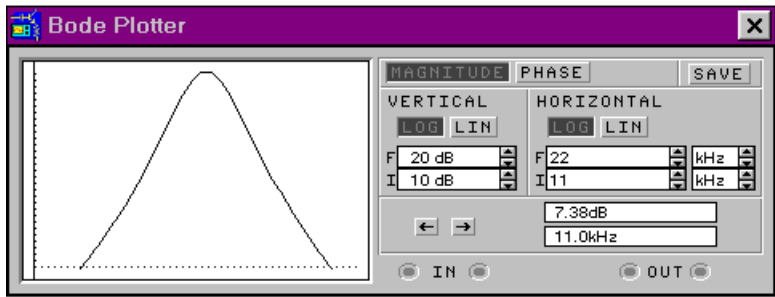


Figure 6. Frequency response of the bandpass filter.

The oscilloscope was reconnected to display the signal at the output of the gate shown as Fig. 7 and then to display the final output shown as Fig. 8.

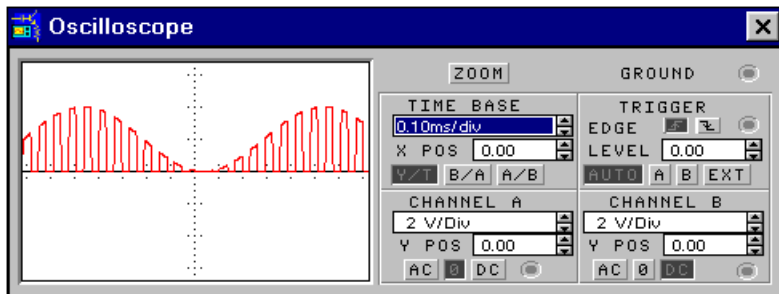


Figure 7. "Gated" message signal.

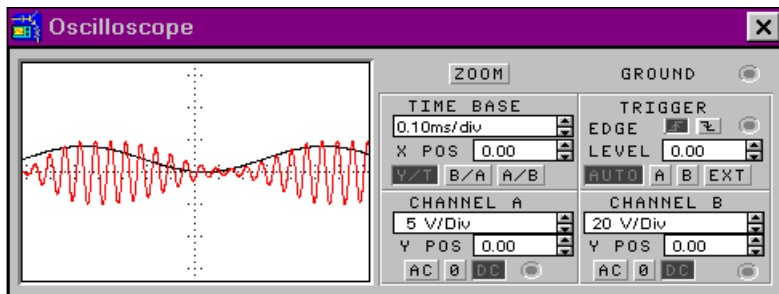


Figure 8. Message signal (black) and AM signal (red).

IV. Summary

This paper described a novel course in communication electronics that combines a study of practical hardware implementation issues along with the systems-level perspective found in typical communications courses. Each topic is treated twice: first, from a theoretical systems viewpoint; and secondly, from a practical implementation viewpoint. The co-authors have found this approach beneficial to the students as each student typically responds best to one of the above viewpoints. In addition, the students are encouraged to recognize the interconnection between earlier courses in electronics and systems analysis. Finally, the course has proven beneficial to the two instructors in understanding and appreciating the value in the other instructor's perspective on designing and implementing communications systems.

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