A Systems Approach to Teaching “Introduction to Electronic Communications” for ECET Students

James Z. Zhang, Kenneth Burbank, Robert Adams
Department of Engineering Technology, Western Carolina University

Abstract

Traditional electronic communications course in ECET covers a wide range of topics in communications theory, with the focus on different modulation schemes and the respective receivers’ baseband structures and performances. However, it is often found that students do not necessarily grasp the essence of a communications system from a systematic perspective because of the wide coverage of content.

This article presents a systems approach to teaching an introductory course of electronic communications that effectively helps students consolidate their knowledge in electronic circuits, to be better prepared for later communications theory course(s) in terms of how different technologies are applied to a communications system, and to accumulate hands-on experience at a communications system’s level.

Introduction

Traditionally, an electronic communications course in ECET covers a wide range of topics in communications theory, with the focus on different modulation schemes such as AM, FM, BPSK, QPSK, FSK, QAM, DS-SS, FH-SS, and the respective receivers’ baseband structures and performances. While these topics are essential in communications theory, it is often found that students do not necessarily grasp the essence of a communications system from a systematic perspective, because of the wide coverage of content. It is more effective if the students understand the communications systems from a systematic perspective, before they apply different modulation schemes to these systems.

This article presents a system approach to teaching an introductory course in electronic communications. Instead of covering various kinds of modulation schemes, the systematic approach focuses on the functionality and analysis of each block of a communications system at the circuit level. This includes message generation (for example, QPSK signal generation), signal filtration, signal amplification, mixer/modulator/demodulator, up/down frequency conversion, and so forth. Lab experiments are being developed for each system block to provide students experiential knowledge. The system’s approach uses only two basic modulation schemes (for example, FM...
and QPSK) to cover both analog communications and digital communications. At the end of the course, the students are expected to have an overall picture of a communications system. When they learn different modulation schemes in a traditional communications theory course, they will understand how these schemes can be applied at a systems level.

The system approach to teaching "electronic communications" is expected to achieve the following goals:

1) Help students understand communications concepts from a system perspective more effectively.
2) Provide students with a better understanding of functionality, design, and related issues of communication system blocks.
3) Help consolidate students’ knowledge in electronic circuits and their applications in communication systems.
4) Provide students with a more solid foundation for higher level communications courses.
5) Provide students with a better understanding of the issues caused by inter-connection of communications blocks.

The Selected Modulation Schemes for System Approach

Selection of modulation schemes for this systems approach is imperative. Our thoughts on the modulation scheme are based on the following factors:

- The modulation schemes should cover both analog and digital communications.
- The selected modulation schemes should be representative and widely used in communications systems.
- It should be relatively straightforward to introduce important concepts in communications theory with these modulation schemes.
- It should be relatively simple to design experimental labs for students to obtain hands-on experience.

Based on the above thoughts, we decide to choose Frequency Modulation (FM) to introduce analog communications systems and Quadrature Phase Shift Keying (QPSK) to represent digital communications systems. The following is a brief review of the characteristics of these two modulation schemes.

(A) Frequency Modulation (FM)

FM is an angle modulation where the amplitude of the modulated carrier is held constant and the time derivative of the phase of the carrier is varied linearly with the message signal \( m(t) \). A general expression of FM signal is given in (1). More detailed information about FM modulation and demodulation can be found in Stremler\(^1\) Tomasi\(^2\).

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1. Stremler
2. Tomasi

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\[ x_r(t) = A_c \cos[2\pi f_c t + 2\pi f_d \int_0^t m(\tau)d\tau] \]  

(1)

where

- \( A_c \) is the carrier amplitude
- \( f_c \) is the carrier frequency
- \( f_d \) is frequency deviation of FM signal
- \( m(\tau) \) is the message signal

The ratio of frequency deviation and the modulation peak frequency \( f_m \) of the message signal \( \frac{f_d}{f_m} \) is called "modulation index" and is denoted by \( \beta \).

Phase Lock Loop (PLL) Demodulator, Slope Detector/Discriminator, and Quadrature Detector are the three most predominant methods of demodulating FM signals. Quadrature detector is used in our lab experiment. Its theory of operation is described as follows:

The received signal \( x_{r_1}(t) \) is described in equation (2). Passing this signal through a 90° phase shifter and then a quadrature coil which introduces an additional phase shift \( \phi(t) \) that is proportional to the message signal \( m(t) \) and thus produces a signal:

\[ x_{r_2}(t) = -A_c \sin[2\pi f_c t + 2\pi f_d \int_0^t m(\tau)d\tau + \phi(t)] \]  

(2)

Mixing (multiplying) \( x_{r_1}(t) \) and \( x_{r_2}(t) \) yields:

\[ y(t) = -\frac{A^2}{2} \sin[4\pi f_c t + 4\pi f_d \int_0^t m(\tau)d\tau] - \frac{A^2}{2} \sin[\phi(t)] \]  

(3)

Since \( \phi(t) \) is proportional to the message signal \( m(t) \), original message can be reconstructed by filtering out higher ordered terms.

(B) Quadrature Phase Shift Keying (QPSK)

QPSK is a digital modulation scheme where a binary bit stream is divided into an in-phase stream, \( d_I(t) \), and a quadrature stream, \( d_Q(t) \). Each stream is composed of the odd bits or the even bits of the original message signal, respectively. Each stream assumes half of the data rate of that of the original message signal\(^{3,4,5}\). A typical QPSK waveform is achieved by amplitude modulating the in-phase and the quadrature data streams onto the cosine and sine functions of a carrier waveform, and can be mathematically expressed as follows:

\[ x(t) = \frac{1}{2} d_I(t) \cos(2\pi f_c t + \frac{\pi}{4}) + \frac{1}{2} d_Q(t) \sin(2\pi f_c t + \frac{\pi}{4}) \]  

(4)

QPSK signal can be viewed as two orthogonally transmitted Binary Phase Shift Keying (BPSK) streams. It is a bandwidth efficient modulation scheme which transmits 2bits/sec/Hz. Because of the orthogonality, a QPSK signal can be demodulated as two separate BPSK signals. The basic theory of a BPSK demodulator can be described as follows:
Suppose the received signal is \( r(t) = A \cos(2\pi f_c t + \theta_m) \), where \( A \in \{-1, 1\} \), \( \theta_m \in \{0, \pi\} \), and a local reference oscillator signal is \( f(t) = B \cos(2\pi f_c t + \theta_r) \), where \( B \) is the reference signal amplitude, and \( \theta_r \) is a constant phase component. By mixing (multiplying \( r(t) \) and \( f(t) \)), the following result is obtained:

\[
y(t) = \frac{AB}{2} \cos(\theta_m - \theta_r) + \frac{AB}{2} \cos(4\pi f_c t + \theta_m + \theta_r)
\]

Higher ordered terms can be filtered out using a low pass filter, and the resulting term \( \frac{AB}{2} \cos(\theta_m - \theta_r) \) is the desired demodulated BPSK signal, when \( \theta_r \) is sufficiently small. This can be achieved by using a PLL circuit to reduce the phase error. A low cost BPSK demodulator is presented in Benzel\(^6\).

**Transmitter Side**

The systematic approach to teaching focuses on the functionality of system blocks of a communications system, and the important concepts of communications theory associated with each block. Corresponding labs are designed for students to gain hands-on experience for each block. A typical transmitter block diagram of a communications system is shown in Figure 1. Even though the system is set to transmit a passband signal, the aim is not to introduce issues related to RF transmission. Rather, the aim is to introduce important concepts in communications such as bandwidth. The following paragraphs will elaborate on the methods used for teaching, important concepts to be introduced, and potential bonuses associated with this system approach.

![Transmitter Blocks](image)

**Fig. 1. Transmitter Blocks of a Typical Communications System**

A mathematical description of figure 1 is shown in Figure 2.

![Mathematical Description](image)

**Fig. 2. Mathematical Description of Transmitter Blocks**

(A) Baseband Signal Generator
This block introduces students the concept of analog and digital communications at the message level. An analog audio signal source is to be used for FM scheme, and a QPSK modulator is to be built using Altera UP2 development kit and Max++Plus II software.

- For the FM system, we are going to use a CD player with analog audio output as the signal source.
- A Pseudo-Noise (PN) sequence generator is implemented in ALTERA’s Complex Programmable Logic Device (CPLD) UP2 prototyping board. Using this PN sequence, a QPSK modulator is designed and implemented with the same Altera UP2 Development kit and Max+Plus II software to generate a QPSK baseband signal. Our lab implementation is shown in figure 3.

The following important concepts are introduced at the message level:

- Transmission of analog signals vs. digital signals.
- Signal Bandwidth - For example, Half-power bandwidth, null-to-null bandwidth of QPSK signal and so on.
- Relationship between Data Rate and Bandwidth.

One of the goals of this system approach to teaching is to encourage students to apply their knowledge in circuit theory to communications circuits design. At the message level, students refresh their skills in VHDL design through this QPSK modulator design application.

(B) Baseband Signal Filter

In this block, the message signal is filtered by a low-pass analog filter. An active, Op-Amp based linear phase filter is used for this application. Figure 4 shows our lab implementation of the filter circuit.

Associated with this block, the following important concepts in communications theory are introduced:
• Fractional Power Containment Bandwidth. This criterion has been adopted by the Federal Communications Commission (FCC) and is used as a yardstick for measuring the bandwidth occupancy of communications products.
• Bounded Power Spectral Density. In general, the attenuation levels might be 35 dB or 50 dB. Through this block, students learn the effects of a filter on the spectral shape.
• Effects of phase linearity on the signals. Butterworth filter provides linear phase characteristics to signal filtration which is important to QPSK signal reconstruction.

The bonus of having this block in the system is to provide students the opportunity to review filter design techniques and to understand the importance of the effects of filters in communications systems.

(C) Local Oscillator (LO)

This block is a carrier generator, which will be used for frequency up-conversion. The baseband signal is used to modulate the carrier through a mixer circuit to produce a modulated signal output. Because of its simplicity, the carrier generator used here is a Colpitts crystal oscillator. The oscillating frequency is set so that the modulated signal output is at an Intermediate Frequency (IF) of 10.7 MHz. Our lab implementation of this oscillator is shown in Figure 5.

Some critical factors that can affect the performance are introduced in this block:

• Carrier stability - students are to learn the importance of carrier stability and the effects of carrier drift on the transmission and reconstruction of the signals. Students are also to learn how to measure the carrier drift in their lab experiment.
• Phase noise - Phase noise is a major contributing factor to the performance of a communications system. Through this block, students will learn the detrimental effects of phase noise on the phase of the transmitted signal, and hence the performance of the system. Amount phase distortion can be measured, and degradation on the QPSK system performance can thus be quantified.

The bonus of introducing this block is self-evident. Not only will the students have an opportunity to refresh their knowledge in oscillator design, but they will learn the importance of having a stable and clean carrier for a communications system.
(D) Modulator / Mixer

Different types of modulators are used for different modulation schemes. Indirect FM is generated using a Gilbert-cell based, double-balanced modulator/mixer (for example, NE602 from Philips) \(^8,^9\). For QPSK, an I/Q modulator module is used (for example, Mini-Circuits’ ZFMIQ-10M). The modulated signal center frequency is at 10.7MHz. Students will learn different aspects of modulation:

- RF bandwidth - in the case of FM transmission, students are able to measure the bandwidth and verify Carson’s rule as stated in section II.
- Relationship between carrier frequency and data rate - in the case of QPSK signaling, students can measure the RF bandwidth of the modulated signal, and relate the required bandwidth to data rate of the transmitted baseband signal.
- Different means of transmission - for example, Double-Side-Band (DSB) transmission, Single-Side-Band (SSB) transmission, Double-Side-Band-Suppressed-Carrier (DSBSC) will be introduced both in lectures and through lab experiments.

Through this block, students are exposed to modulator/mixer components used in the industry which allow them to accumulate some "real-world" design experience.

(E) Passband Filter

In this block, a center frequency of 10.7MHz bandpass filter is introduced (for example, Mini-Circuits’ BP-10.7). Associated with this block, students are to learn the following important concepts:

- Spectral Shaping - students will learn the techniques of suppressing higher order components and the concepts of rejecting out-of-band interference.
- FCC spectral mask for transmission - FCC spectral requirements for transmission are introduced. Students are to learn the importance of design communications systems meeting FCC requirements, and to learn the techniques of measuring communications system parameters per FCC specifications.
- Insertion loss and matching circuits - by using a passive filter, students will learn the loss effects of filtration on the signal and the importance of design good matching circuits to reduce loss.

In addition to the above items, filter characteristics (linearity, group delay and so on) will further be emphasized.

(F) Power Amplifier

A power amplifier module will be used in this block (for example, Mini-Circuits’ ZFL-500LN low noise power amplifier). In this block, the following important concepts are introduced:

- Transmitted power - students will learn how to measure transmitted power per FCC specifications.
- Power efficiency of amplifiers -
- Linearity of amplifiers - students will learn the effects of linearity of power amplifiers on the communications systems. Specifically, in the case of FM transmission, constant envelope signal allows power efficient amplification using non-linear amplifiers. However, in the case of QPSK transmission, non-linearity of power amplifiers could affect the transmitted signal quality, and thus degrade the system performance.
- Noise figure - students will learn the importance of noise figure and its role in link budget analysis.

One added bonus to this block is that students will have the chance to review different types of amplifiers and their appropriate applications.

Receiver Side

In general, a receiver performs the reverse processes of those in a transmitter. A typical communications receiver block diagram is shown in figure 6.

Fig. 6. Receiver Blocks of a Typical Communications System

From this block diagram, one can see the major difference between the receiver and the
transmitter is the "demodulator" block. Therefore, our focus on the receiver side is on the theory of operation of the demodulator and testing of receiver performance.

(A) Demodulator

Two different demodulators are used in our lab design. For FM signaling, we use Philips’ SA605, a high performance low power FM IF system. Detailed design and application information can be found in Wong[10,11,12]. For QPSK, we use a standard I/Q demodulator (for example, Mini-Circuits’ ZFMIQ-10D) to reconstruct the baseband signal. An alternative method is to direct students to build simple BPSK demodulators using PLL concept, and use two BPSK demodulators to demodulate I-Channel and Q-Channel, respectively. The demodulated \( d_I(t) \) and \( d_Q(t) \) can then be combined together using a multiplexer.

The quality of signal reconstruction can be characterized by comparing the reconstructed signals against the transmitted signals. By capturing transmitted and reconstructed signals with an oscilloscope, students will observe the mismatch (errors) between the two signals. With this experimental observation, it is imperative to introduce the major factors that affect the quality of signal reconstruction. These factors include, but not limited to the following:

- White noise - students will learn the characteristics of additive White Gaussian Noise (AWGN) and its effect on the performance of a communications system.
- Transmitter and receiver noise figures - students will gain knowledge of the effects of noise figures on the performance of communication systems and how noise figures affect system’s link budget calculations.
- Signal attenuation through transmission medium - students will understand that this signal attenuation reduces the received Signal-to-Noise Ratio (SNR), and thus the quality of the communication system’s performance.

With a good understanding of the major factors that affect the system performance, it is natural to consolidate students’ knowledge by introducing receiver performance testing techniques.

(B) Receiver Performance Testing

Two major performance parameters, receiver sensitivity and Bit Error Rate (BER) are introduced. Receiver sensitivity is measured in absolute received signal power level (dBm) at a pre-defined BER level (10\(^{-5}\)). BER is measured against the received Signal to Noise Ratio (SNR), and BER vs. SNR curve (known as “waterfall” curve) is plotted.

Figure 7 shows a typical setup for sensitivity test.

The two inputs of the BER tester are connected to the baseband signal generator on the transmitter side and the baseband signal output on the receiver side. Without any attenuation, BER level is maintained at 10\(^{-5}\). Measure the received signal power level \( P_{r0}(\text{dBm}) \) at the input of the receiver. Then attenuate the receiver input signal via attenuator by \( L_{\text{attenuation}}(\text{dB}) \) until the
BER becomes higher than $10^{-5}$. The receiver sensitivity can be estimated as: Receiver sensitivity  

$$P_{r_0} + L_{\text{attenuation}} \ (dBm).$$

Figure 8 shows a typical BER versus SNR test setup. The test could be conducted using the setup in figure 7, however, we decide to use the test setup in figure 8 to let students learn a different technique of BER vs. SNR measurements. In addition, students will gain a better understand of the power spectrum of Additive White Gaussian Noise (AWGN), and its effect on the performance of a communications system.

First, without adding white noise to the channel, measure the received signal power $P_{r_0} (dBm)$ at the input of the receiver. Then increase the noise power at $N_0 (dB)$ per step. Record the BER at each step. Through these measurements, a series of data $\left[SNR_i, BER_i\right]$ (where ‘i’ indicates the $i^{th}$ measurement) can be gathered. Thus, a BER vs. SNR curve can be plotted.

**Matlab Simulation Exercises**

While practical experience is of utmost importance to ECET students, we do believe that understanding theoretical aspects of a communications system is crucial. We understand the difficulty of in-depth analysis of a communications system without a background in mathematics and statistics. However, we believe that students’ theoretical knowledge can be augmented by understanding the blocks from a theoretical standpoint as presented in figure 2. Matlab simulation...
package can be used as an excellent vehicle to achieve this goal without requiring students’
strong mathematical capabilities. For example, students can use “fft” command in Matlab to
investigate spectral characteristics of a signal. They will understand the mathematical process of
transforming a time domain signal to frequency domain via Fourier Transform, without requiring
them to understand the mathematical details of performing a Fast Fourier Transform (FFT).

Matlab exercises can be given in the form of homework. Students are required to use Matlab
to obtain simulation results for a specific block before they attend the corresponding lab session.
In so doing, the students are expected to benefit from the following aspects:

- Gain a more in-depth theoretical understanding of each communications system block.
- Learn how to use Matlab as an analysis tool.
- Have the opportunity to compare simulation results to lab experimental results.

Conclusion

The systems approach described in this article is being implemented in both lectures and lab
experiments. Positive results have been observed by the authors. Assessment of this method will
be reported when more data become available.

The systems approach to teaching “Electronic Communications Fundamentals” course provides
ECET students a systematic view of a communications system. This is essential to students in
terms of communications system design, analysis, testing, and troubleshooting. Lab experiments
provide students hands-on experience and enhance their problem-solving skills. Through working
on the design and testing of communications circuits, students can consolidate their knowledge in
analog and digital circuits, gain better understanding of “real-world” applications of these circuits,
and accumulate experience in solving problems caused by inter-connection of communications
blocks. Coupled with exercises through Matlab simulations, students are expected to gain a more
thorough understanding of theoretical perspectives of a communications system.

References


**JAMES Z. ZHANG** is an Assistant Professor and Director of Telecommunications Program at Western Carolina University. Dr. Zhang’s research interests include Communications Theory, Wireless Networks, Bandwidth Efficient Modulation Schemes, Signal Design and Information Coding, and Digital Signal Processing Techniques for Communications. Dr. Zhang is a member of IEEE and ASEE.

**KEN BURBANK** is an Associate Professor and Director of Electrical and Computer Engineering Technology at Western Carolina University. Dr. Burbank is active with IEEE, SME, and TAC of ABET, and strives to bring practical engineering activities into the classroom. His current project is the development of a photonics program within the Electrical Engineering curriculum.

**ROBERT ADAMS** is currently an Assistant Professor in the Department of Engineering Technology at Western Carolina University. He teaches courses in electronics and electric circuit analysis. His research interests include electrocardiography, 3D modeling, and simulation of the adverse electrical and thermal effects of electrosurgical devices. He is a member of the IEEE and ASEE.