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# Using *MATLAB* to Improve Learning Effectiveness and Quality in an Undergraduate Course on Wireless Communications and Systems

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There are two essential elements for an undergraduate engineering student to successfully master knowledge in a course on wireless communications and systems: mathematical background including random signals and stochastic processes, and hands-on experience that allows the student to perceive a wireless information transfer process. In the authors' three-year research in teaching communications courses, a systems approach was employed for teaching and a modular approach used for implementing wireless communications laboratory experiments. However, while significant improvements in teaching and learning quality have been witnessed, disconnects between theory and practice among student learners have also been observed. During the past two years, this issue was approached by using *MATLAB* simulation tools. It has been demonstrated that this approach is an excellent solution to the problem. In this article, the authors report on the details of the design and implementation methods, how simulation is used to bridge the gap between theoretical lectures and laboratory experiences, and improvements of students' learning outcomes.

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## INTRODUCTION

Due to the nature of Radio Frequency (RF) signals and their transmission channel characteristics, there are two essential elements for undergraduate students in mastering knowledge in wireless communications: a strong mathematical background and hands-on exposure to RF experiments. Mathematical skills include the complex representation of signals, random variables and stochastic processes, spectral representation and estimation techniques, and so forth. A strong mathematical background helps students better understand RF signal properties and transmission channels characteristics using abstract thinking that are hard to perceive otherwise. Unfortunately, most undergraduate students do not necessarily possess sufficient mathematics to thoroughly understand wireless communication systems. In this case, practical experiences greatly enhance students' understanding of wireless communication theories. Typically, experiential exploration for students is in the form of laboratory experiments.

In an effort to improve teaching and learning effectiveness, and quality of communications courses,

the authors conducted a three-year research on teaching methods to help students understand concepts of electronic communications. The authors proposed and implemented a *system approach* to teaching communications fundamentals [1]. A *modular approach* was utilised for teaching wireless communications [2]. A set of RF experiments using mini-circuit modules was also designed and developed to accompany a senior-level wireless communications and systems course [3]. The goal of these efforts was to enhance students' learning experiences by enabling students to obtain a balanced knowledge of the desired skill sets.

The implementation of these methods has shown significant improvements in students' theoretical understanding of wireless communications, as well as their capabilities of hands-on skills. However, despite this success, disconnects between theories and interpretations of practical results were observed among the student learners. This article reports the authors' findings to use *MATLAB* as a vehicle to further bridge the gap between theoretical and experiential knowledge in the students' learning processes.

## COURSE DESIGN RATIONALE AND BENEFITS

As a powerful tool for mathematical analysis and computational simulation, *MATLAB* has been a predominant software package that is widely used by educators, researchers and practicing engineers. Its mathematical model-based inputs require users to understand the general concepts and theories of operation of the system to be simulated, and its excellent graphical display capability provide users with visual simulation results that are similar to experimental results. Its compatibility with most Digital Signal Processing (DSP) Integrated Circuits (ICs) offers relatively simple implementation and the realisation of systems for feasibility studies. Because of these advantages offered by *MATLAB*, it is the best tool to be utilised for bridging the gap between theoretical and practical understandings of a wireless communication system.

As part of the authors' research, *MATLAB* has been used in conjunction with course instructions for the past three years. The focus was on illustrating technical concepts and problem-solving skills. Some research results can be found in refs [4] and [5]. These results have been systematically applied and expanded in a course on wireless communications and systems by guiding students to design and implement a wireless system in *MATLAB*, and comparing the simulation results to the theoretical results from the lectures, and practical results from laboratory experiments. Details of the course design and a design example are given below.

Using a combination of lectures, laboratory experiments and *MATLAB* simulations, improvements in teaching and learning quality have been observed. In particular, the following results can be achieved when *MATLAB* is used as a vehicle to enhance students' understanding between theoretical and practical knowledge:

- Improve mathematical understanding – because students are required to write mathematical model-based scripts for simulation, they need to understand mathematical representations of each communications block and its functionality. This practice would greatly enhance and consolidate students' theoretical knowledge obtained from the lectures;
- Better understand practical results – because the designed laboratory experiments correspond to simulation blocks, students can visually compare the simulated results and those obtained from hardware in the laboratories. Students can improve

their understanding by comparing and contrasting the results from simulations and the laboratory experiments. Because the simulation results are mathematical model-based, students can better grasp the mathematics behind each functional block for a communication system;

- Bridge the gap between theory and practice – as described above, students are expected to make better connections between theory and knowledge from experiential exploration;
- Augment system understanding – because the semester-long project is geared with lectures and laboratories, students would have completed a functional hardware system and a simulated counterpart, so it is expected that students would better understand communications concepts from a systems perspective;
- Boost simulation design capability – as a bonus of this practice, students are expected to improve their fluency of using *MATLAB* as a simulation tool. This will greatly help students with subsequent courses, such as the *Digital Signal Processing* course (offered one semester after the wireless communications course).

In the following sections, the authors report on the design details, a design example, observed improvements in learning outcomes and future work for further improvements.

## COURSE DESIGN DETAILS

*Wireless Communications and Systems* (TEL 444) is a senior-level course offered at Western Carolina University, Cullowhee, USA. Students taking this course should have had junior-level *Electronic Communications Fundamentals* (TEL 312) as a prerequisite. Most students also take *Digital Signal Processing* (ECET 461) after taking TEL 444.

TEL 444 is a one-semester (15 weeks on average) course. It is comprised of three major activities: lectures, laboratories and recitation. There are four sessions per week: two lectures, one laboratory and one recitation. The lectures focus on the theories of operations, mathematical representations and derivations, as well as system architectures and performances. Laboratory experiments focus on the functionalities of each system block and measurements of system performance parameters. *MATLAB* simulation designs are closely geared with the lectures and laboratories, and are conducted during the recitation session. The lecture content coverage and instruction timeline are listed in Table 1, with the corresponding laboratories and simulation

designs listed in Tables 2 and 3, respectively.

Part I is a review of digital modulation schemes with an emphasis on those for wireless communications. Part V addresses wireless standards associated with wireless networks, such as cellular systems, Bluetooth technology and 802.11x networks. Part II through IV is the core of this course, with the laboratories and *MATLAB* simulations designed to strengthen students' knowledge in these parts.

The laboratories start in the third week and end in the twelfth week of the semester. All laboratory experiments are designed with mini-circuits modules. Each module can be tested individually and a 900 MHz point-to-point wireless communication system can be constructed by interconnecting the modules as described in ref. [3]. Signal time domain and frequency domain characteristics are measured using Agilent oscilloscopes and spectrum analysers, respectively. A comparison between Tables 1 and 2 reveals that the designed laboratories follow the timeline of the lectures.

Table 1: The course contents and teaching timeline.

Part	Content	Time
I	Modulation schemes for wireless communication	2 weeks
II	RF communications function blocks	4 weeks
III	Channel characteristics and performance	4 weeks
IV	Wireless system performance parameters	2 weeks
V	Wireless system standards	3 weeks

Table 2: The designed RF laboratory modules.

Lab	Description
1	I/Q Modulator and Modulated Signal Characteristics
2	IF Filter (10.7 MHz) and Bandwidth Control
3	I/Q Demodulator and Its Applications
4	Low Pass Filtering and Signal Reconstruction
5	IF System Performance in an AWGN Channel
6	Voltage Controlled Oscillator
7	RF Frequency Mixer and Frequency Up-conversion
8	RF (915 MHz) Low Noise Amplifier and Filter Characteristics
9	RF System Performance Measurements
10	Propagation and Path Loss

It can be observed that the simulation projects do not exactly follow the laboratory experiments. This is because frequency conversion only involves a simple multiplication of the carrier that is represented by a cosine (or sine) waveform, and the Finite Impulse Response (FIR) filter design techniques are similar for centre frequencies at 10.7 MHz and 900 MHz. Designs at the IF frequency of 10.7 MHz are sufficient for students to grasp theories and design concepts.

One of the significant benefits of using *MATLAB* simulation is to complement those aspects that are difficult to cover with laboratory experiments. Two major *MATLAB* modules are introduced to help remove these deficiencies. The first module introduces error correction techniques using DSP. It is not feasible to implement error correction hardware to work with mini-circuits modules and error correction is not part of this course. Furthermore, the limited time for the course does not allow students to experiment with the hardware even if it is available. On the other hand, an error correction mechanism can be implemented in *MATLAB* with relative ease and students can gain a better understanding of how a wireless system's overall performance can be improved in terms of Signal to Noise Ratio (SNR) versus Bit Error Rate (BER).

The second module introduced is system performance in a Rayleigh or Rician fading channel. Traditionally, Rayleigh and Rician models are difficult for students to understand because both involve the statistical modelling of received signals. In practice or a laboratory setting, it is almost impossible to separate a Line-of-Sight (LOS) wave from reflected waves, thus leaving the demonstration of Rayleigh and Rician fading effects on a wireless channel without a solution. To the contrary, one can easily model both fading environments utilising *MATLAB* to show the impact of either fading channel on the overall performance of a wireless communication system.

The following section illustrates a design example that has been used in TEL 444. The same concept can be applied to various design projects at different levels of complexity.

## A DESIGN EXAMPLE AND LEARNING OBJECTIVES

A typical wireless communication transmitter block diagram and its corresponding receiver block diagram are shown in Figures 1 and 2, respectively. The designed laboratory experiments also follow these block diagrams. Each block corresponds to a certain mini-circuits hardware module. In the actual laboratory

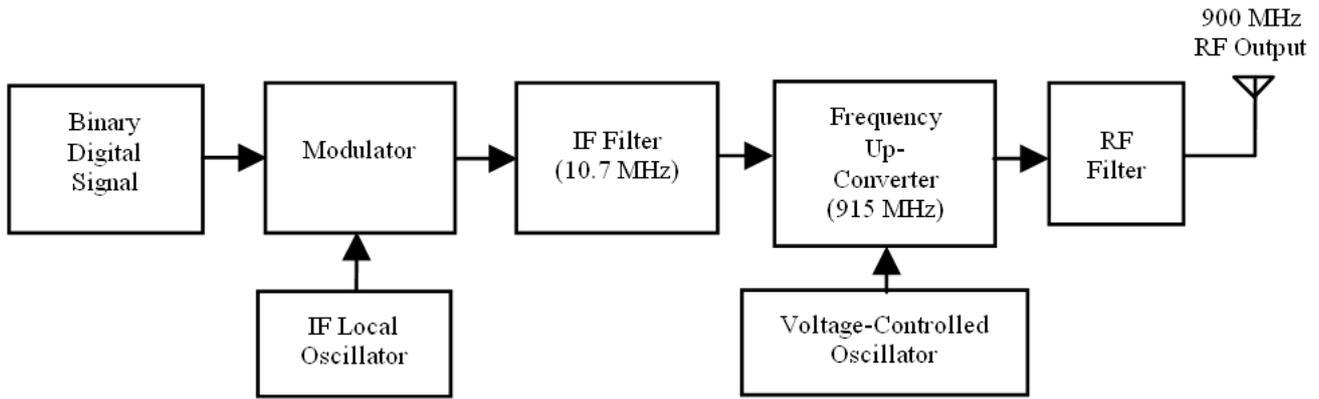


Figure 1: RF transmitter block diagram.

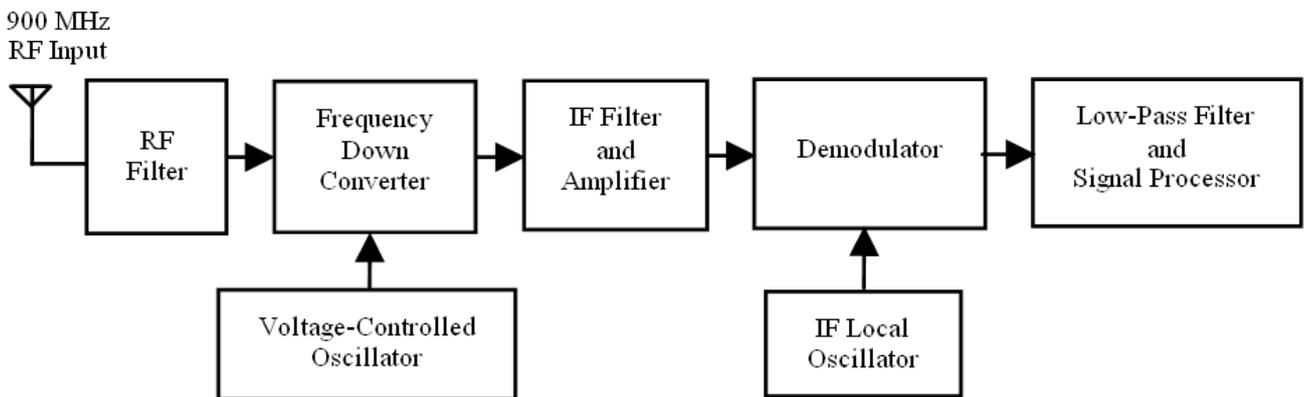


Figure 2: RF receiver block diagram.

designs in the course, the I/Q modulator and demodulator are used for a Quadrature Phase Keying (QPSK) signal, hence, information signal is split into In-phase (I) and Quadrature (Q) components before they are used to modulate the carrier.

For the sake of simplicity, the Binary Phase Shift Keying (BPSK) modulation scheme is used to illustrate *MATLAB* module design concepts. Considering that the main goal is to strengthen students' understanding of wireless communication concepts, as well as the time limitations of the course, a BPSK system serves the purpose well. A BPSK system greatly simplifies the design of other blocks, such as filters and demodulators.

The remainder of this section includes the design details and results of the designed modules.

The main task of module 1 is to ask students to generate a BPSK signal. A BPSK signal can be mathematically expressed as follows:

$$s(t) = Ad(t) \cos(2\pi f_c t) = A \cos(2\pi f_c t + \varphi) \quad (1)$$

In (1),  $A$  is the carrier amplitude,  $d(t)$  is the information data stream in Non-Return-to-Zero (NRZ) format assuming values  $\{-1, 1\}$ , and  $\varphi$  is the phase taking values  $\{0, \pi\}$ .

Upon completion of this module, students are expected to learn the following techniques:

- *MATLAB* commands to generate a random information data at a given data rate, including random signal generation, signal to NRZ data conversion and data bits generation at a predefined sampling frequency;
- Using equation (1) to create a BPSK signal at 10.7 MHz;
- Investigation of the time and frequency domain characteristics of the signal, and observation of the signal bandwidth.

In our example, the data rate is set at 128 kbps, the sampling rate is set at eight samples per bit and the carrier frequency is such that a 10.7 MHz IF BPSK signal is produced. The simulated result of this module is shown in Figure 3. The top figure shows the original message signal and the bottom figure shows the BPSK modulated signal. For a clearer illustration, the plot shown has a data rate at 1024 bps and the carrier frequency is lowered to the same frequency.

Module 2 involves learning to design an FIR bandpass filter centred at 10.7 MHz and use this filter

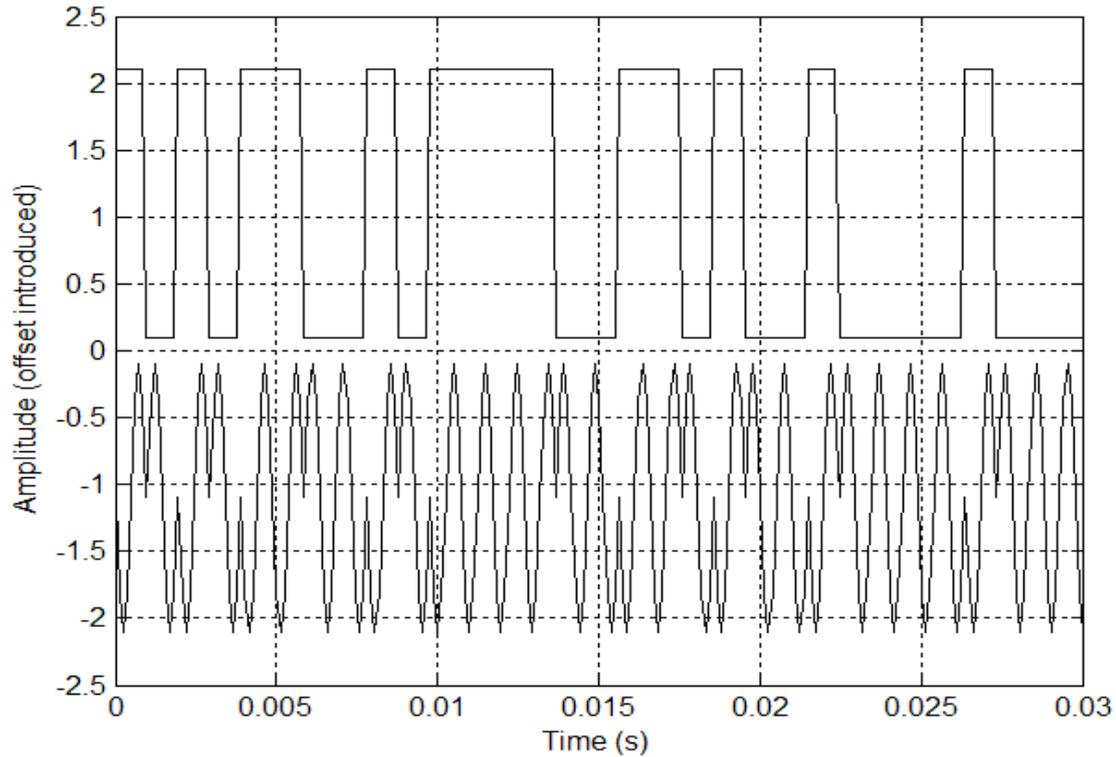


Figure 3: The data and BPSK modulated waveform.

to define the bandwidth needed for transmission. The successful completion of this module enables students to learn the following:

- Filter design technique using the Parks-McClellan algorithm;
- The bandwidth requirement for BPSK transmission;
- The difference between *filtfilt* and *filter* commands.

The results are shown in Figure 4; the top graph shows the unfiltered signal spectrum while the bottom graph illustrates the transmitted signal spectrum. It is worth noting the difference between *filtfilt* and *filter*; when using *MATLAB* commands, *filtfilt* does not introduce additional phase shift to the signal while *filter* adds extra phase shift to the transmitted signal.

Module 3 focuses on the demodulation process of the BPSK signal. Suppose the carrier signal generated by the receiver local oscillator is  $r_{sc}(t) = B\cos(2\pi f_c t + \theta)$ , where  $B$  is the carrier amplitude and  $\theta$  is the initial phase, the demodulation process is the multiplication of the received signal in equation (1) with  $r_{sc}(t)$ . Mathematical manipulation shows that the demodulated signal can be expressed as follows:

$$r_1(t) = \frac{AB}{2} \cos(\varphi - \theta) + \frac{AB}{2} \cos(4\pi f_c t + \varphi + \theta) \quad (2)$$

From this module, students are expected to consolidate their knowledge in the following aspects:

- Demodulation is a reverse process of modulation. The original data signal can be reconstructed from the modulated signal by multiplying with a local carrier at the same frequency;
- Synchronisation is important in a communication system. When the received signal is synchronised,  $\theta$  in equation (2) equals zero; therefore, the maximum reconstructed message signal amplitude is obtained (the first term in equation (2));

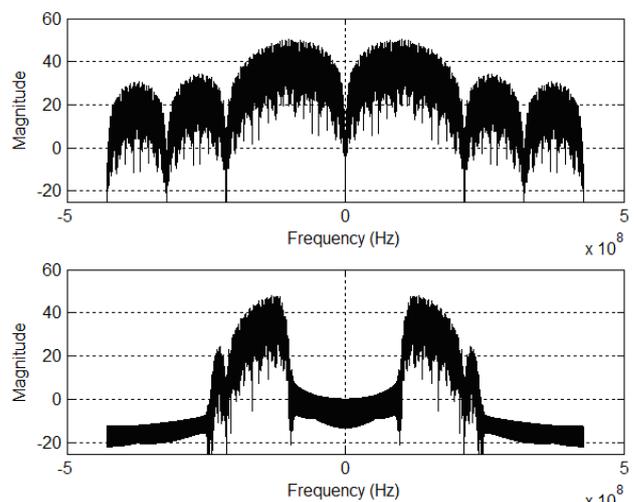


Figure 4: The unfiltered spectrum (top) and the transmitted spectrum (bottom).

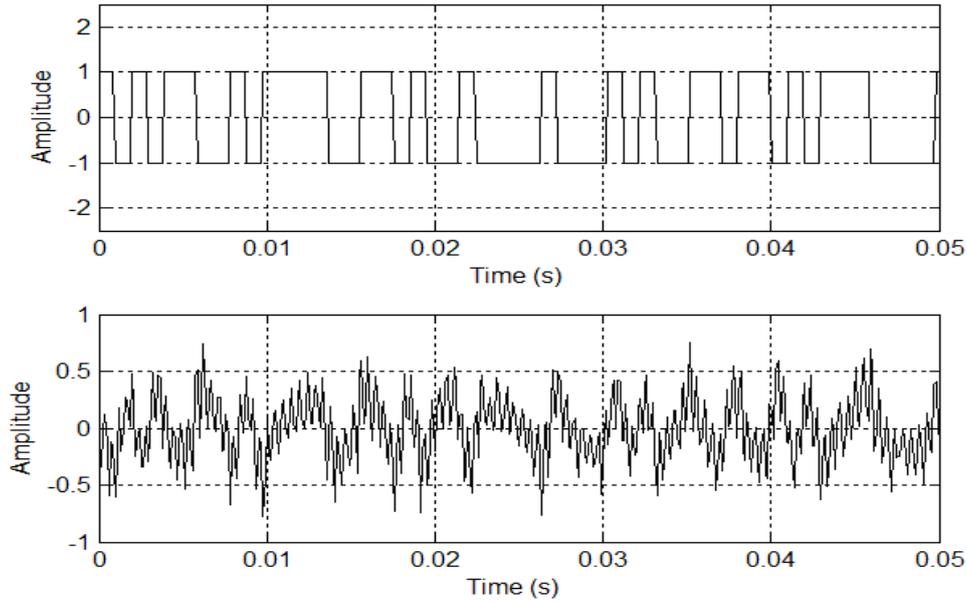


Figure 5: Original data (top) and demodulated data (bottom).

- The higher ordered term exists in the demodulated signal and needs to be filtered out before the baseband signal can be extracted (second term in equation (2)).

The third item of the above list naturally leads to the next module of a lowpass filter design and signal reconstruction. The results of module 3 are shown in Figure 5.

Module 4 aims at the design of a lowpass filter that removes the higher ordered term from the demodulated signal. Because the transmitted data rate is at 128 kbps, a filter with a minimum cut-off frequency at 128 kHz is needed to accomplish the task. The original

data signal and the reconstructed message signal are shown in Figure 6.

It can be observed from Figure 6 that the reconstructed signal does not preserve its original waveform shape due to filtering. However, zero crossings of this signal do correspond to the boundaries of the binary data stream  $d(t)$ . Consequently, a zero crossing detector and a waveform shaper need to be designed to completely reconstruct the original binary data. Results of the zero crossing detection and waveform shaper output are shown in Figure 7. Zero crossings are indicated by the stems and the waveform shaper output is shown in bold in Figure 7 (bottom).

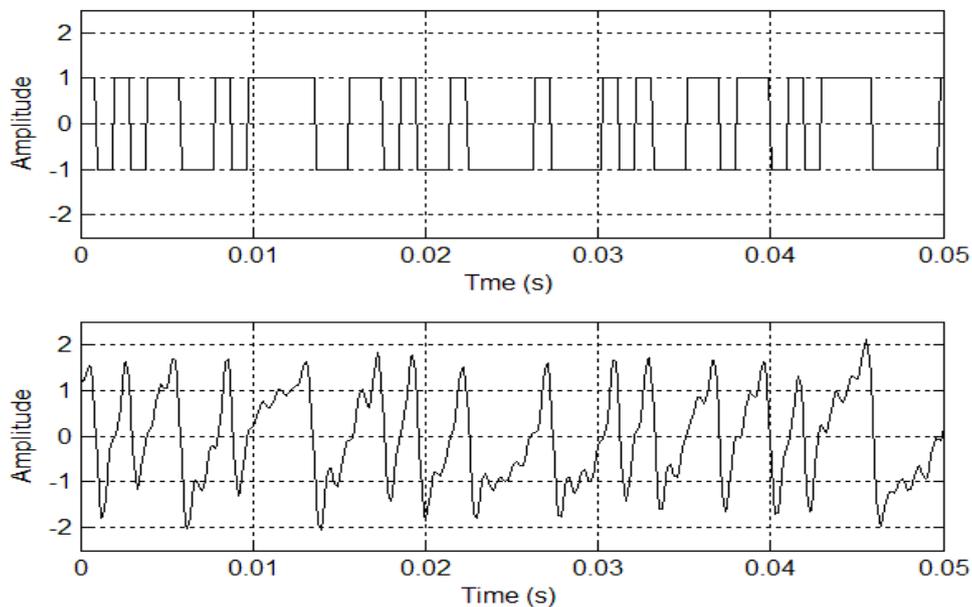


Figure 6: Original data (top) and low pass filtered data (bottom).

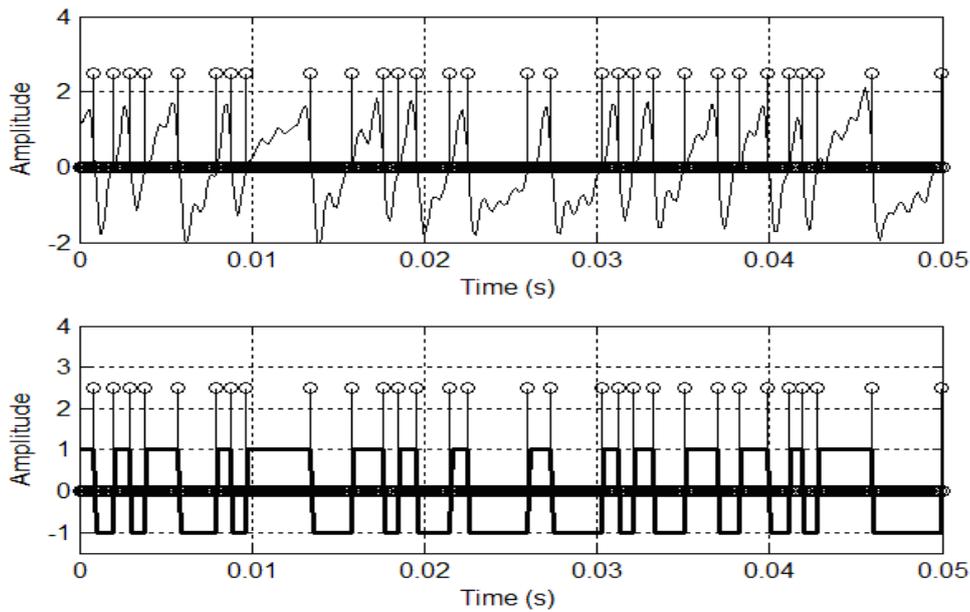


Figure 7: Detected zero-crossings (top) and reconstructed binary data (bottom).

Students are expected to learn the following:

- Design of a lowpass filter with the correct bandwidth;
- Zero-crossing detector design;
- Waveform shaper design.

Theoretically speaking, a complete wireless system design is accomplished. The rest of the modules are aimed at simulating the performances of the system. These include performances in an Additive White Gaussian Noise (AWGN) channel, a multi-path environment and path loss of the signal.

Module 5 investigates the impact of white noise on

the signal transmission. White noise is added to the received signal before demodulation. The reconstructed signal is shown in Figure 8. Compared to its non-noisy counterpart in Figure 6 (bottom), it can be observed that zero-crossings are not preserved due to noise contamination of the received signal. This means that errors occur in the received signal. Different levels of noise are added to the received signal to allow students to observe the severity of signal distortion. Students start to appreciate a clean transmission environment and realise the hostilities of a wireless transmission channel.

Module 6 is a natural extension of module 5. In this module, students are required to assess the system's

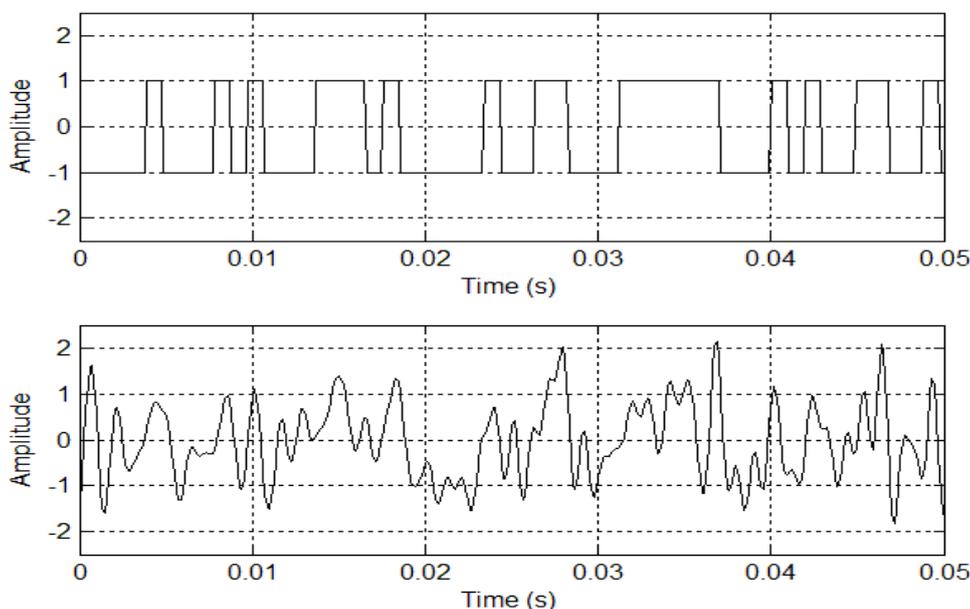


Figure 8: Original data (top) and received data through an AWGN (bottom).

performance by calculating BERs that correspond to various SNRs. Figure 9 shows the results of this simulation. Through this module, students gain a better understanding of the system performance in an AWGN channel. It is worth noting that the plot is BER versus SNR rather than traditional BER versus  $E_b/N_0$ .

Yet another factor that severely decreases a wireless system's performance is multipath. Module 7 addresses this concern by requiring students to simulate Rayleigh and Rician fading channels. Rician fading contains a dominant LOS signal plus a collection of infinite number of reflected waves and can be mathematically modelled as follows:

$$r(t) = A \cos(2\pi f_c t + \varphi) + \sum_{n=1}^{\infty} A_n \cos(2\pi f_c t + \varphi + \rho_n) \quad (3)$$

In (3),  $A_n$  and  $\rho_n$  are the amplitude and phase of the  $n^{\text{th}}$  ray, respectively.  $\rho_n$  normally depicts a

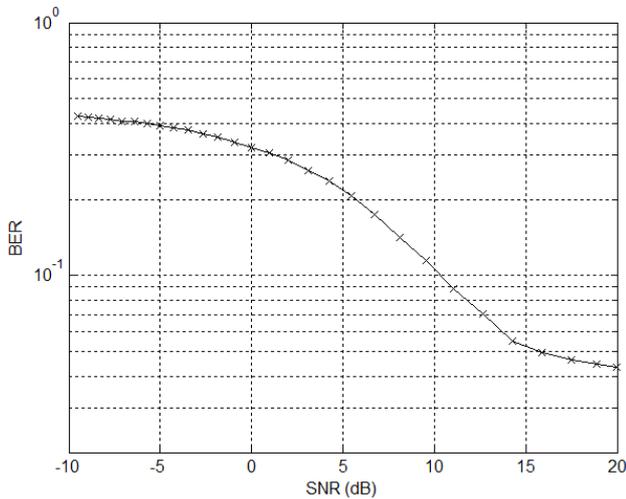


Figure 9: System performance: SNR versus BER.

delayed arrival of signals.

Rayleigh fading is a collection of infinite number of reflected waves without an LOS. Therefore, by setting  $A = 0$  in equation (3), a Rayleigh fading channel is recovered.

Even though the theory calls for an infinite number of rays, it is impossible to simulate this condition. For the purpose of enhancing students' learning, 3~5 rays are sufficient. When a 3-ray model is used, the recommended values for  $A_n$  and  $\rho_n$  are  $A/8$ ,  $A/4$  and  $A/2$ , and  $\pi$ ,  $\pi/2$  and  $\pi/4$ , respectively. Figure 10 shows the received Rayleigh and Rician signals. When compared to the original transmitted signal in Figure 3, a distortion of the signal can be observed.

Students are asked to carry out the same tasks in module 6 where the system's performance is assessed. Students will observe that, unlike that in an AWGN channel, the system's performance in a fading channel improves slowly with increased SNR.

As described in the previous section, it is not feasible to implement error detection and correction mechanisms given the current equipment available. In this case, *MATLAB* provides an excellent opportunity for students to appreciate the power of DSP techniques in detecting and correcting errors. Although the detection and correction method is very primitive, the concept is well conveyed to the students.

Module 8 guides students to carry out a task of detecting and correcting errors in the reconstructed signal. Because the message data is over-sampled at eight samples per bit, therefore, any reconstructed bit that does not contain exact eight consecutive 1s or -1s is an error bit. The majority rule for the decision is

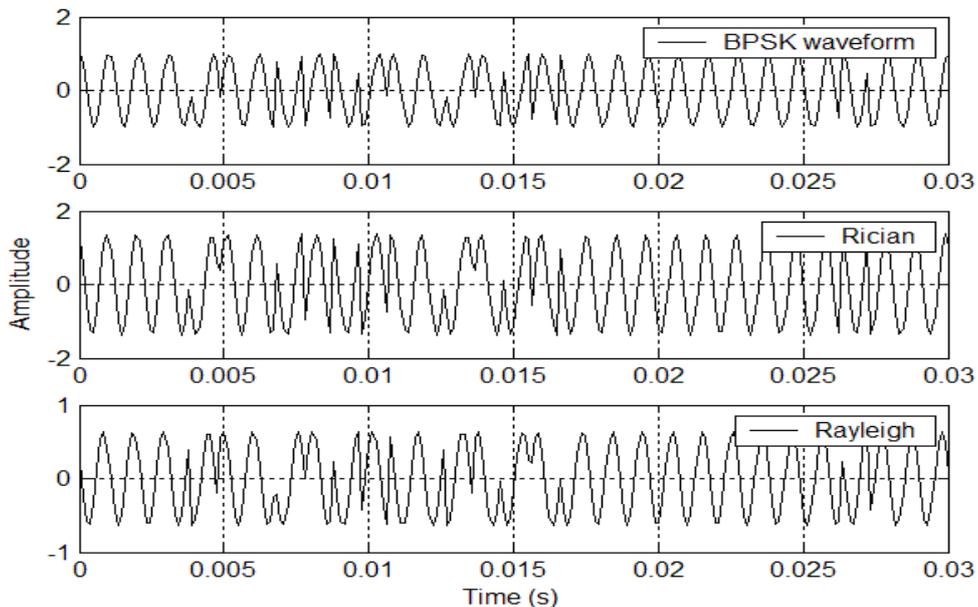


Figure 10: Received signals in Rician and Rayleigh channels.

used in this brutal force approach: the *MATLAB* program checks bit-by-bit by checking eight sampling points at a time. If the majority of these sampling points have values of  $1$ , other sample values are also forced to be  $1$ . Otherwise, a decision is made that the transmitted bit is a  $-1$ . Although somewhat time-consuming when the transmitted data stream is of a large size, nevertheless, the detection and correction job is well done. Uncorrected and corrected received data are shown in Figure 11.

The last module is designed to investigate the propagation properties of the signal and pass loss. The theoretical received signal strength is mathematically expressed as follows:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (4)$$

where  $P_r(d)$  is the received signal power at distance  $d$ ,  $P_t$  is the transmitted power,  $G_t$  and  $G_r$  are transmitter and receiver antenna gains, respectively,  $\lambda$  is the signal wavelength, and  $d$  is the distance between the transmitter and the receiver.

Because the path loss is reflected by the received signal amplitude reduction, distance cannot be directly simulated in *MATLAB*. Therefore, the strategy is changed slightly to achieve the maximum learning outcome. In the module, students are required to measure the overall received signal strength and calculate the path loss of the system. This is accomplished by laboratory module 10 listed in Table 2. The details of laboratory procedures can be found in ref. [3].

Figure 12 is a plot of the measured received signal power from the laboratory and theoretical received signal power calculated using equation (4). Path loss

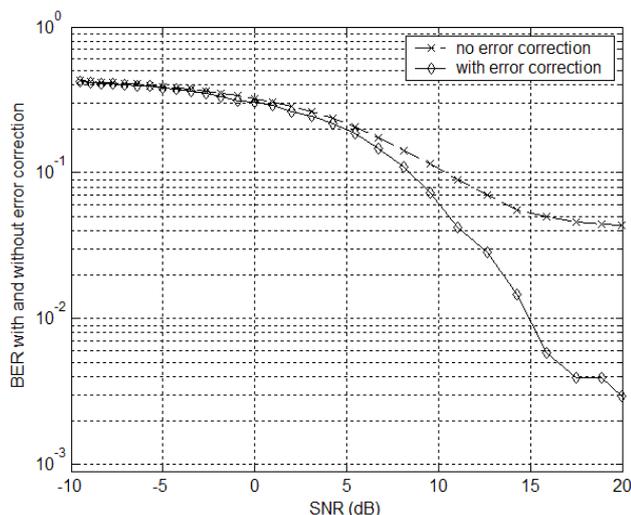


Figure 11: SNR versus BER with and without error correction.

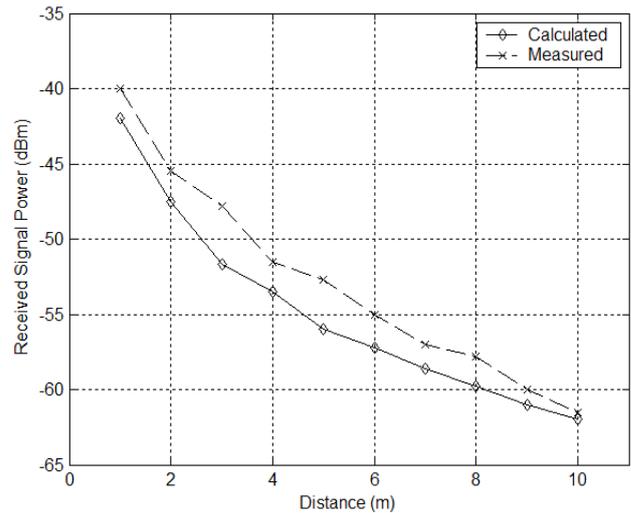


Figure 12: Measured versus theoretical path-loss comparison.

can be calculated by taking the difference between the transmitted and received powers.

## CONCLUSIONS AND FUTURE WORK

In this article, the authors report on the progress of a three-year research project aimed at improving the learning effectiveness and quality in a senior-level course on wireless communications and systems. *MATLAB* is used as a vehicle to enhance students' learning experiences by bridging students' understandings of the relevant theories and abilities of interpreting experimental results. As a result, improvements have been observed in students' problem-solving capabilities.

Further research will be focused on more complicated system designs and a systematic assessment of students' learning outcomes.

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