Session 1649

A Modular Approach to Teaching "Wireless Communications and Systems" for ECET Students

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Abstract

Recent development in wireless technologies has generated a high demand for wireless communications professionals. Rigorous math background is needed for students to fully understand wireless communications system fundamentals. However, Electrical and Computer Engineering Technology (ECET) students generally do not have such a math background to digest concepts and analyze issues associated with wireless communications. It is a better approach to focus on a point-to-point wireless system through experiential exploration, and extend the knowledge to wireless communications systems in general.

There are different educational training stations available to help achieve educational goals in wireless communications. However, these educational trainers have their obvious shortcomings, which include: (1) most of them transmit at relatively low frequencies (in one hundred MHz range), while most of contemporary communications systems transmit in GHz range; (2) most of them are built as systems and it is hard for students to test module parameters; (3) most of them are costly and it is not affordable for many schools to purchase enough units to satisfy their lab needs.

This article presents our on-going efforts of developing a modular approach to teaching a senior level "Wireless Communications and Systems" course. Mini-Circuits® RF modules are used for function block testing and system implementation. The emphasis is on the Radio Frequency (RF) modules of a communications system such as modulator, demodulator, Voltage-Controlled-Oscillator (VCO) and Frequency Mixer. The operating frequency is set at 900 MHz. Performance issues specific to wireless communications such as large and small scale fading effects are also addressed.

Introduction

The arrival of 3G cellular systems, 802.11x wireless computer networks, Bluetooth®, and other wireless technologies has made wireless communications a field of its own over the past 10 to 15 years. Rapid development of wireless technologies such as wireless sensor networks, "lastmile" solutions, and ubiquitous wireless computing environment has generated a high demand for wireless communications professionals.

The ramification of this demand is a call for marketable engineers and technologists with needed skill sets. The skill sets include a solid understanding of communications theories, wireless channel characteristics, wireless system structures, and related system standards. A firm grasp of this knowledge requires the students to possess a strong mathematical background, especially statistical properties of random variables and stochastic processes. However, most ECET students do not have the necessary math background to gain in-depth analytical skills in wireless systems. Therefore, it is a better approach to emphasize a point-to-point wireless communication system to introduce concepts and system structures, and extend the students' knowledge to the system level through guided experimentation.

This article presents our on-going efforts of developing a modular approach to teaching a senior level "Wireless Communications and Systems" course. Content coverage of this one semester (15 weeks) course is divided into 5 parts and is shown in Table 1.

Table 1. Course Contents and Teaching Time-line

Part	*Content*	*Time*
Part I	Digital modulation schemes used for wireless communications	2 weeks
Part II	RF communications function blocks	4 weeks
Part III	Channel characteristics & effects on performance	4 weeks
Part IV	Wireless system performance parameters	2 weeks
Part V	Wireless system standards	3 weeks

Part I introduces/reviews predominant digital modulation schemes used for wireless communications. Since most students take a communications fundamentals course or equivalent in which basic digital modulation techniques are introduced, this first part of the course focuses on bandwidth efficient schemes such as M-*ary* Amplitude Shift Keying (ASK), M-*ary* Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM). Part V addresses wireless systems standards such as cellular systems, 802.11x networks, and Bluetooth®. Along with these standards, wireless transmission methods such as Code Division Multiple Access (CDMA), Spread Spectrum, Orthogonal Frequency Division Multiplexing (OFDM) are covered.

The modular approach focuses on Parts II through IV, which is the core of the course. This on-going project generates lab experiments designed to emphasize the course contents described above. Details of our modular design are discussed in the subsequent sections.

The modular approach to teaching "Wireless Communications and Systems" is expected to achieve the following goals:

1) Provide students knowledge of functionality and testing parameters of wireless communications function blocks, especially modulator, demodulator, VCO, and mixer blocks.

2) Provide students knowledge of wireless channel characteristics such as large-scale and small-scale fading environments and the effects on system performance.
3) Help students understand a point-to-point wireless system and its performance parameters.
4) Extend students' knowledge to wireless voice and data networks.

Selection of RF Components

Because many of the existing wireless systems operate in the 900 MHz Industrial, Scientific, and Medical(ISM) band, we have decided to use a 900 MHz point-to-point wireless system in our modular approach. The example system uses QPSK, at a bit rate of 512 kbps. Considering that most students do not have any experience in building RF boards, we chose to use the components from Mini-Circuits® as our system building modules. Key Mini-Circuits modules incorporated in our design are listed in Table 2. In addition, Mini-Circuits amplifiers and filters are also used to complete our design. Block diagrams of transmitter and receiver RF portions are shown in Figures 1 and 2, respectively.

Table 2. Components Used from Mini-Circuits®

Part	*Description*	*Frequency Range (MHz)*
ZFMIQ - 10M	I & Q Modulator	9 - 11
ZFMIQ - 10D	I & Q Demodulator	9 - 11
ZOS - 1025	Voltage Controlled Oscillator	685 - 1025
ZFM - 4	Level 7 Frequency Mixer	IF: 0.01 - 500; LO/RF: 0.1 - 1000

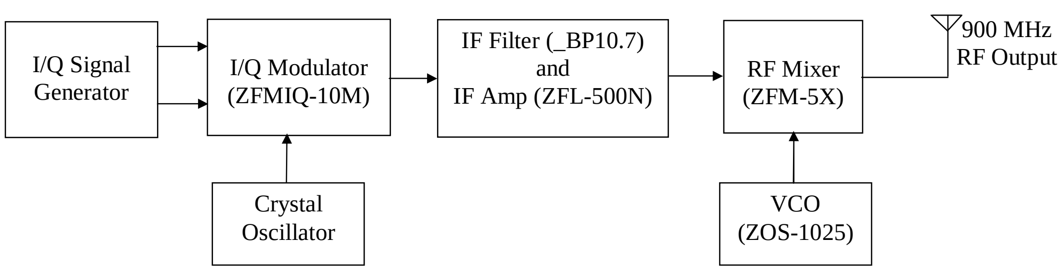

Fig. 1. Transmitter block diagram - RF portion

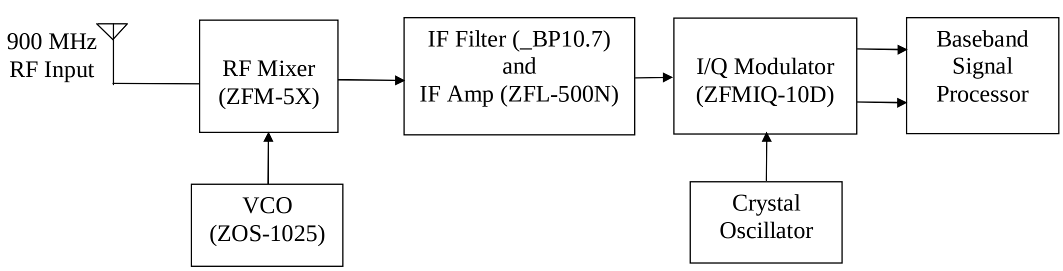

Fig. 2. Receiver block diagram - RF portion

Labs Designed for Modular Approach

The labs focus on two aspects of wireless communications. The first aspect is the functionality and parameters of the building modules of a wireless communication system. Labs associated with this part concentrate on the performance parameters of the modulator, demodulator, VCO, and frequency mixer. The second focus is on wireless communication system performance parameters and effects of wireless communications channel characteristics on system performance.

There are three labs aimed at testing module parameters. Two labs concentrate on system performance, and one lab emphasizes the effects of wireless channel characteristics on system performance. A listing of lab topics and Mini-Circuits modules used is provided in Table 3.

Table 3. Labs Designed for Modular Approach

Lab	*Description*	*Mini-Circuits parts used*
1	I/Q Modulator	ZFMIQ - 10M
2	IF System characteristics	ZFMIQ - 10M & ZFMIQ - 10D
3	Voltage Controlled Oscillator	ZOS -1025
4	Frequency Mixer	ZFM - 4
5	RF system performance	All parts used in labs 1 through 4
6	Large scale fading - path loss	All parts used in labs 1 through 4

As listed in Table 3, module-parameters are tested on three key components in RF communications - modulator, VCO, and frequency mixer. Note that the I/Q demodulator is essentially the same as the modulator when operating at the same frequency, therefore, demodulator tests are omitted. Despite the fact that Mini-Circuits® has its turn-key solutions for RF/IF signal processing components measurements, our goal is to ensure that students understand the functionality and test procedures of component parameters. Consequently, we use different lab set-ups for the students to test individual modules.

Also listed in Table 3 are three system parameter tests. These tests focus on the Intermediate Frequency (IF) system performance at 10.7 MHz, RF system performance at 900 MHz, and part of the RF communications channel characteristics, namely, large scale fading.

Basic theory of operation, parameters to be tested, and test methods are described in the following sections.

(1) <u>I/Q Modulator Test</u>

Denote the In-phase(I) and Quadrature(Q) components of a signal by $d_I(t)$ and $d_Q(t)$, respectively. The I and Q components are used to modulate a carrier $cos 2\pi f_c t$. An I/Q modulator output can be mathematically represented as follows[1,2]:

$$x(t) = d_I(t)\cos(2\pi f_c t) + d_Q(t)\sin(2\pi f_c t) \quad (1)$$

In practice, an I/Q modulator mixes I and Q components of a baseband signal with a carrier and a 90^0 phase-shifted version, respectively. The outputs of the mixers are combined to generate an RF signal. Figure 3 shows the basic structure of an I/Q modulator.

Some important specifications of an I/Q modulator include carrier and sideband rejection, conversion loss, port-to-port isolation, amplitude and phase imbalance, and 3^{rd} and 5^{th} order products. Among these specifications, carrier and sideband rejection are the most important. Because the carrier is an unwanted signal in the modulated output and sideband rejection is an indication of the orthogonality and amplitude balance, increased rejection of the carrier and sideband is a desired quality in any modulator.

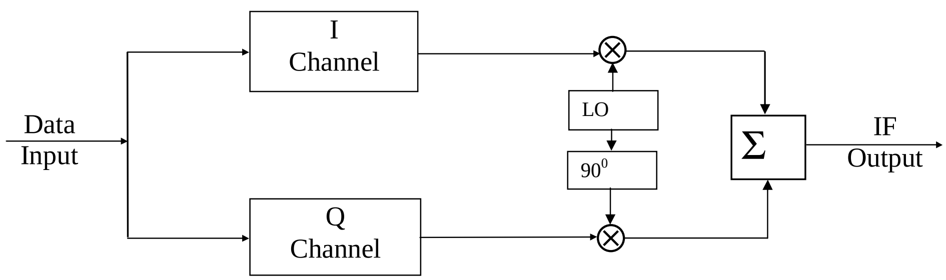

Fig. 3. An I/Q Modulator Structure

In this lab, students are required to test the functionality, carrier and sideband rejection, conversion loss, and port-to-port isolation of the modulator. Even though amplitude and phase imbalance are also important, especially for measuring the quality of the signal for the demodulator, these quantities are not tested yet because of the lack of a network analyzer. The test setup can be found in the Mini-Circuits application notes[3].

It is worth noting that demodulator characteristics are not tested in a specific lab. This is because the difference of a demodulator and a modulator is insignificant when they are operated at the same frequency. The functionality of a demodulator is examined in the next lab design.

(2) IF System Performance

This lab focuses on the performance of an IF system operated at 10.7 MHz. The purpose of this lab is to enhance the students' understanding of the functionality and performance of the I/Q modulator/demodulator and the importance of synchronization. In addition, students are asked to test the system's sensitivity to better understand the relation between Signal-to-Noise Ratio (SNR) and quality of reception in a communication system. The system setup is shown in Figure 4.

Notice that the modulator and the demodulator share the same LO in Figure 4. However, the students are required to use separate LOs for the modulator and the demodulator. This allows them to observe that the demodulated signal cannot be synchronized with the original signal. By using the same LO for both the modulator and the demodulator, students can better understand the importance of synchronization.

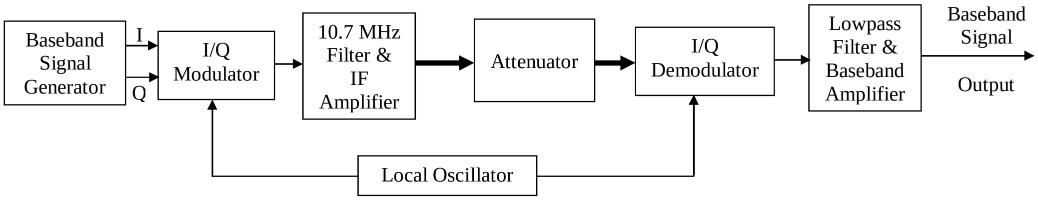

Fig. 4. A 10.7 MHz IF System

Another important aspect of the demodulator functionality is the fact that its outputs contain higher ordered frequency terms. Indeed, when a received signal is mixed with the demodulator LO, simple mathematical manipulation shows the demodulator outputs can be expressed as[1]:

$$I - Channel : x_I(t) = \frac{1}{2}d_I(t) + \frac{1}{2}d_I(t)\cos(4\pi f_c t) + \frac{1}{2}d_Q(t)\sin(4\pi f_c t) \tag{2}$$

$$Q - Channel : x_Q(t) = \frac{1}{2}d_Q(t) - \frac{1}{2}d_Q(t)\cos(4\pi f_c t) + \frac{1}{2}d_I(t)\sin(4\pi f_c t) \tag{3}$$

Higher ordered terms need to be filtered out by a lowpass filter before the baseband signal can be obtained.

The experiment procedures and benefits to the students are listed as follows:

(i) Connect baseband I/Q signal generator, local oscillator, and I/Q modulator – for the students to observe the modulated signal output using a spectrum analyzer.

(ii) Connect IF filter and amplifier – for the students to observe unwanted sideband rejection and transmitted signal amplification.

(iii) Connect I/Q demodulator and a separate LO for the demodulator – for the students to experience the functionality of the demodulator, to observe the un-synchronized waveforms, and to realize that the demodulator output contains higher ordered frequency terms that need to be filtered out.

(iv) Connect the same LO to both modulator and demodulator and lowpass filter – for the students to observe synchronized, pure baseband waveforms.

(v) Attenuate the signal input to the demodulator – for the students to understand the importance of maintaining SNR level and to find out receiver sensitivity.

(3) Voltage Controlled Oscillator (VCO)

As an important component in RF communication systems, the quality of a VCO used in the system directly affects the overall system performance. Parameters that are essential to a VCO's quality include its output power and frequency, tuning sensitivity, tuning linearity, harmonics and spurious levels, frequency pushing and pulling, modulation bandwidth, and phase noise. All of these parameters are tested in this lab except for phase noise, due to the equipment limitation.

Typical measurement setups are shown in Figures 5 to 7. The setup shown in Figure 4 can be used to measure output power and frequency, tuning characteristics, harmonics and spurious levels as well as frequency pushing parameters. The test setups shown in Figures 6 and 7 are used to measure frequency pulling and wide modulation bandwidth, respectively. More detailed information about test setup and measurement methods can be found in the Mini-Circuits application notes[4,5].

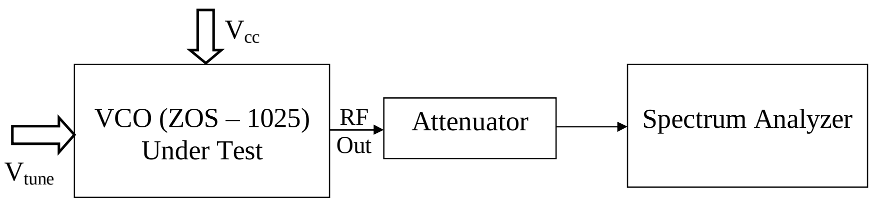

Fig. 5. General VCO Test Setup

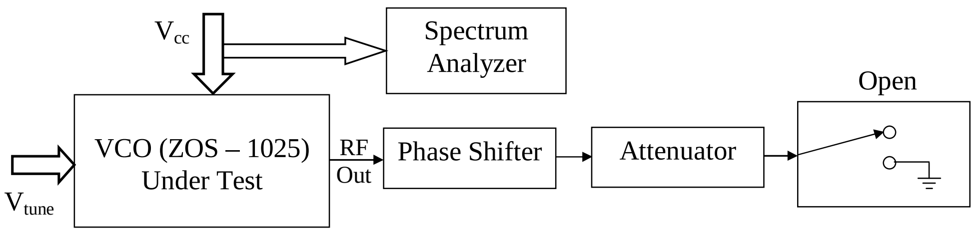

Fig. 6. VCO Pulling Test Setup

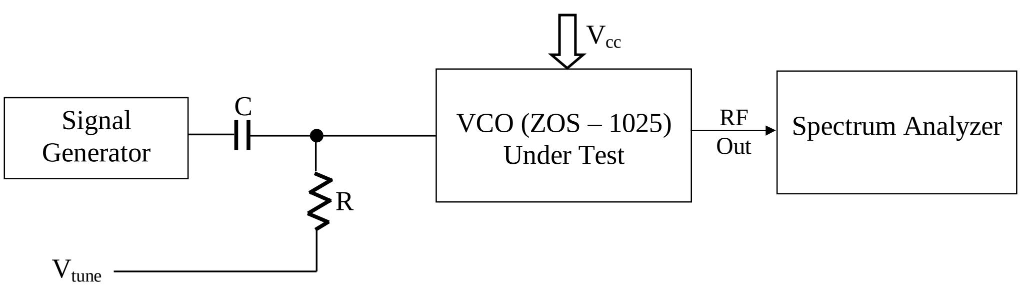

Fig. 7. VCO Wide Modulation Bandwidth Test Setup

(4) Frequency Mixer Characteristics

Selection of the right mixer is imperative to the performance of an RF communications system. Under-specifying a mixer will result in the degradation of system performance, while overspecifying a mixer will significantly increase the cost. Therefore, a thorough understanding of a mixer's performance parameters is crucial to the selection of the right mixer for a specific application.

This lab is designed to enable students to further their understanding of mixer performance parameters through experimentation. Originally, a Mini-Circuits level 23 mixer was selected simply for the desired operating frequency range. It turns out that this mixer requires a minimum LO input power of 23 dBm, while the Mini-Circuits ZOS-1025 VCO only provides a maximum output of 8 dBm. Even though an RF amplifier can be used to raise the LO level to the desired 23 dBm, unwanted intermodulation products at this level were shown to be detrimental to the system's performance. As a result, we decided to use the Mini-Circuits ZFM-4 level 7 mixer that only requires 7 dBm LO input and operates in the same desired 900 MHz frequency range.

Even though the right mixer is selected and proper up- or down-conversion can be achieved, the mixer performance parameters should still be carefully considered to guarantee the system's performance. Among these parameters, conversion loss, RF-IF or RF-LO isolation, VSWR, and two-tone 3^{rd} order distortion (IP3) are some critical factors that need to be taken into consideration.

It is worth mentioning that the two-tone, 3^{rd} intercept point determines suppression capability of a mixer and is closely related to what is known as the 1 dB compression level. 1 dB compression level refers to the RF input power level that causes 1 dB conversion loss. Once the 1 dB compression level is determined, the intercept point can be calculated by adding 15 dB to the 1 dB compression point at low frequencies and 10 dB at higher frequencies. This provides us with an alternative measuring method for determining the intercept point. Using this method also provides an estimate of the mixer's dynamic range and maximum power capabilities[6].

Mini-Circuits has proposed more sophisticated methods to measure these parameters. Considering this is a lab for ECET students, we decide to use simplified measurement methods to convey concepts to the students. Test setups for the above parameters are shown in Figures 8 and 9.

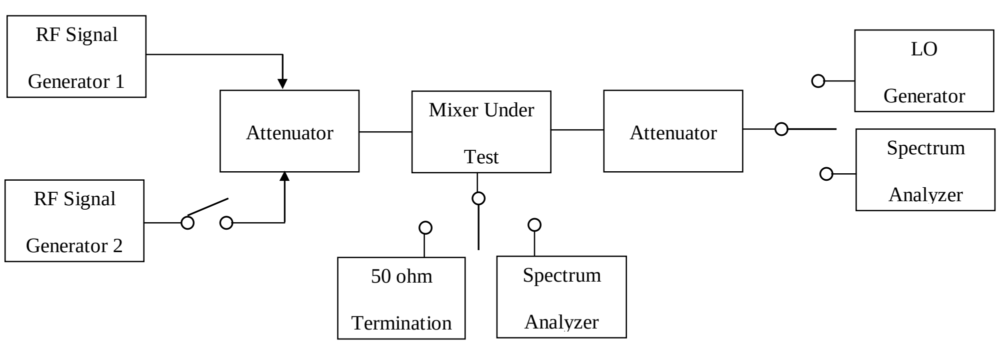

Fig. 8. Test Setup for Conversion Loss, Isolation, and IP3

Figure 8 shows the test setup for conversion loss, isolation, and IP-3 measurements. For conversion loss measurement, the IF and LO ports of the mixer should be connected to the spectrum analyzer and LO generator, respectively. Varying RF input power level to measure IF output level, the conversion loss curve can be obtained by calculating $L_{conv} = P_{RF} - P_{IF}(dB)$.

Isolation measurements involve RF-LO and RF-IF isolation parameters in our experiment. When measuring RF-LO (RF-IF) isolation, the unused IF (LO) port should be connected to the 50 Ω termination as shown in Figure 8.

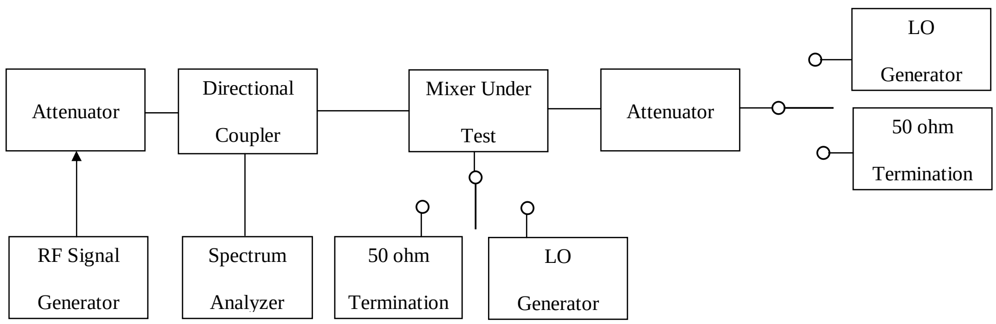

Fig. 9. VSWR Test Setup on IF and RF Ports

IP3 describes the intermodulation performance of a mixer. When two RF signals with the same amplitude are received by the mixer, nonlinearity produces intermodulation products. Assume that the power level difference between the main IF signal and the intermodulation product is X dB, and main IF power level is P_{in} dBm, then IP3 is defined as $IP3$ (dBm)= $P_{in} + \frac{X}{2}$.

Voltage Standing Wave Ratio is a parameter that measures the ratio of the amplitude of a standing wave at an antinode (maximum) to the amplitude at the adjacent node (minimum). The VSWR measurements of a mixer consist of VSWR at the RF and the IF ports. When measuring this parameter at one port, one should terminate the unused port with a 50Ω termination. The VSWR test setup is shown in Figure 9. Depending on the directional coupler used, a reference level can be established without connecting the mixer, and then RF power reflected from the mixer can be measured with the mixer connected to the directional coupler. More details about measurement procedures can be found in the Mini-Circuits application notes[7].

(5) RF System Performance

Once the students gain a solid understanding of the functionality and performance parameters of an RF communication system through the experiential exploration obtained above, they are ready to put the modules together to build a complete point-to-point RF communication system and to further investigate system performance. In our case, we use a 900 MHz point-to-point system for RF performance testing.

The main purpose of this experiment is to let the students see the operation of a complete RF system, and gain a better understanding of the operating environment of an RF communication system. We especially focus on those factors that are specific to wireless communication channels such as receiver sensitivity, Carrier-to-Interference Ratio (CIR), co-channel and adjacent channel rejection, and receiver throughput delay. Because we use VCOs in the RF transmitters, sources for CIR measurement, co-channel and adjacent interferences can be easily generated.

Receiver sensitivity is measured in absolute received signal power level (dBm) at a pre-defined Bit Error Rate (BER) level. In this test setup we have chosen to use a BER level of 10^{-5}. A typical receiver sensitivity test setup is shown in Figure 10. The BER tester is connected to the transmitted message signal and the reconstructed baseband signal for bit-to-bit comparison. The received signal is attenuated until the BER is close to the threshold level of 10^{-5} and the received signal power level P_{r_0}(dBm) is recorded at the receiver input. The receiver input signal is further attenuated by a factor of $L_{attenuation}$(dB) until the BER becomes higher than 10^{-5}. The receiver sensitivity can then be estimated as: *Receiver sensitivity* = $P_{r_0} + L_{attenuation}$ (dBm).

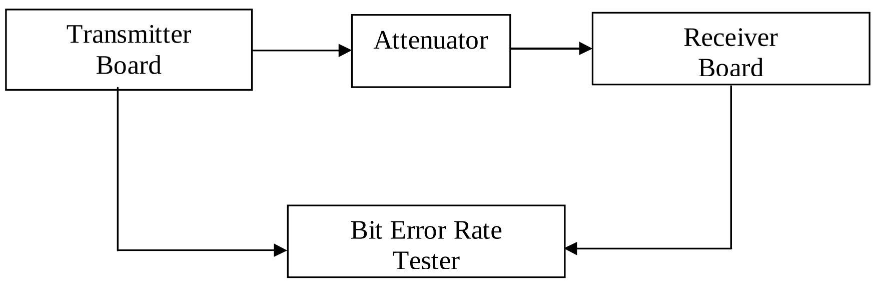

Fig. 10. A Typical Setup for Receiver Sensitivity Test

The setup shown in Figure 10 is also used for CIR testing. The received signal power is adjusted to P_{r_0}(dBm) so that the BER is 10^{-5}. A foreign carrier is transmitted at the same frequency as that of the intended carrier for demodulation. The amplitude of the foreign carrier is slowly increased until the BER is higher than 10^{-5}. The difference between the amplitudes of the foreign carrier and the intended carrier indicates the CIR (in dB).

Co-channel rejection can be tested by adding an uncorrelated, unwanted signal at the receiver frequency in Figure 10. P_{r_0}(dBm) is used as the reference. The unwanted signal power is increased to $P_{co-chan}$(dBm) so that the BER is higher than 10^{-5}. Co-channel rejection can be calculated as $P_{r_0} - P_{co-chan}$.

Adjacent channel rejection can be measured similar to co-channel rejection. Instead of an unwanted signal at the receiver frequency, an unwanted signal is transmitted either above or below the desired signal with pre-determined channel spacing. The channel spacing is dependent upon the transmission data rate. In either case, when BER is higher than 10^{-5}, unwanted signal levels P_{high} and P_{low} are recorded, respectively. The upper and lower adjacent channel rejection can be calculated as follows:

Upper adjacent channel rejection $= P_{high} - P_{r_0}(dB)$

Lower adjacent channel rejection $= P_{low} - P_{r_0}(dB)$

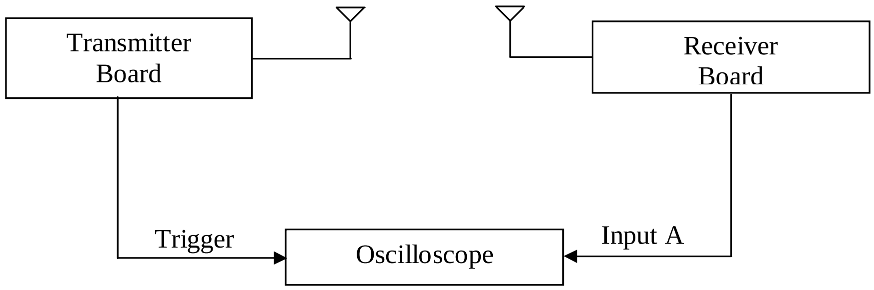

Fig. 11. Test Setup for Receiver Throughput Delay

Receiver throughput delay is the time that a receiver takes to produce a reconstructed signal. This test is very important for students to understand the latency problem in wireless communications networks. The test setup is depicted in Figure 11. In this test, the transmitted message signal is used as the trigger of the monitoring oscilloscope, while the reconstructed signal is connected to a channel input of the scope. The scope is set at a single sweep mode. In this configuration, the time elapsed between the trigger input and the start of the reconstructed signal can be measured. The average of ten such measurements represents a good estimate of the receiver throughput delay.

(6) Large Scale Fading - Path Loss

Investigation of channel fading characteristics helps the students understand the environments within which a wireless communication system operates. Because it is very difficult to separately categorize the effects of large-scale fading such as ground reflection and diffraction, and small-scale fading such as Rayleigh and Rician fading, we decide to measure overall path loss of the system and ask students to plot experimental data against theoretical path loss in this lab.

Theoretically, path loss can be calculated as follows:

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

where
- $P_r(d)$ is the received signal power at distance d
- P_t is the transmitted signal power
- G_t is transmitting antenna gain
- G_r is receiving antenna gain
- λ is the transmitted signal wavelength
- d is distance between the transmitter and the receiver
- L is the loss factor

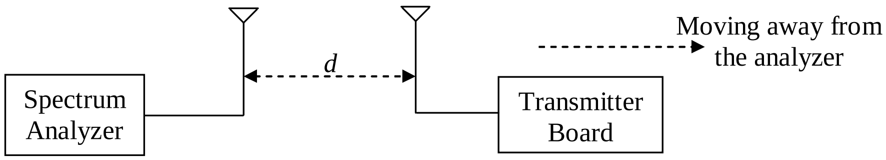

Fig. 12. Test Setup for Path Loss Measurement

The experimental setup is shown in Figure 12. The transmitter is moved away from the spectrum analyzer at pre-defined distance increments. The distance between two antennas and the signal power level at each distance are recorded. The $P_r(d)$ versus distance d can be plotted and compared with the theoretical plot generated from (4).

Conclusion and Future Work

The modular approach to teaching "Wireless Communications and Systems" focuses on the functionality and performance parameters of wireless communications system modules. This approach emphasizes the consolidation of student theoretical knowledge through experimental means. A point-to-point wireless system is built through lab experiments. Through module and system testing, students can better appreciate the characteristics of the building blocks, the factors affecting system performance, and the environments within which wireless systems operate. It is expected that students can easily extend their knowledge acquired from this course to large-scale systems such as wireless networks.

As indicated earlier this is an ongoing project. The authors realize that some test implementation can be further refined to improve the effectiveness of teaching. This project will continue as a senior design project in the spring semester of 2005, and is expected to be complete in April of 2005. Further results will be reported at the conference. Major areas for improvements include more robust system design, improved system performance, and measurement methods for small-scale fading.

The assessment plan for this teaching approach is also an important part of this project. Taking into account that this course is offered once a year, and most students taking this course do not have previous RF measurement experience, more time is needed to collect data and measure the effectiveness of this approach. However, preliminary implementation of this method has shown potential positive impact on students' learning activities of wireless communications. Especially, operating the system at 900 MHz brings students' understanding of theories specific to wireless communications to a new level.

Acknowledgment

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