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The design of RF labs using Mini-Circuit modules to improve the quality of teaching in a course on wireless communications and systems

James Z. Zhang, Robert A. Adams & Kenneth Burbank

Western Carolina University
Cullowhee, United States of America

ABSTRACT: Recent development in wireless technologies has generated a high demand for wireless communications professionals. Marketable engineers and technologists should possess skills including a solid understanding of wireless communications theories, as well as a reasonable amount of hands-on experience. However, a thorough theoretical understanding of wireless communications requires a strong mathematical background, an accumulation of hands-on experiences, and costly experimental systems and test equipment. This article presents the authors' efforts and results of developing a modular approach to improve the teaching quality of a senior level course called *Wireless Communications and Systems*. Cost-effective Mini-Circuits RF modules have been used for function block testing and the system implementation of a point-to-point 915 MHz wireless communication system. This approach has enabled students to improve their understanding of wireless communications theories through experiential exploration, and to acquire hands-on experience of wireless communication functional block testing methods and system implementation techniques.

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. The rapid development of wireless technologies, such as wireless sensor networks, *last-mile* solutions and ubiquitous wireless computing environments, has generated a high demand for wireless communications professionals.

The ramification of this demand is a call for marketable engineers and technologists with the needed skill sets. The skill sets include a solid understanding of wireless communications theories, a reasonable amount of hands-on experience, as well as some understanding of wireless communications standards. In their efforts to improve the teaching quality of communications courses, the authors proposed and implemented a *system approach* to teaching communications fundamentals, as well as a *modular approach* to teaching wireless communications [1][2]. The goal of these efforts is to enable students to obtain a balanced knowledge of the desired skill sets.

This article presents the authors' recent efforts and results of RF experiments design for 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 five parts, as shown in Table 1.

Part I is a review of digital modulation schemes with an emphasis on wireless communications. Part V addresses wireless standards associated with wireless networks, such as cellular and 802.11x networks. Parts II through IV constitute the core of this course, and the modular design focuses on helping students to understand the various concepts listed in these parts.

Table 1: Course contents and teaching timeline.

Part	Content	Time
I	Modulation schemes for wireless comm.	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

DESIGN RATIONALE AND ISSUES ADDRESSED

RF theory and implementation skills are known to be hard to master. A thorough understanding of theory requires a strong mathematical background of Maxwell equations and various statistical distribution models that describe wireless communications system and channel properties. System implementation, on the other hand, requires years of hands-on experience to master design, layout and testing skills. The researchers' main goal is to design some key experiments to help students understand the theoretical concepts, while accumulating some design and testing skills through experiential exploration.

Considering that most students do not have any experience in building RF boards, Mini-Circuits modules were selected as the system building blocks. These modules can be tested as stand-alone components and are thus effective for students to learn functional block testing techniques. In addition, because these modules are well designed to have 50 ohm impedance, it is relatively easy for students to interconnect the modules to form a wireless system for performance testing.

Key Mini-Circuits modules incorporated in the design are listed in Table 2. RF transmitter and receiver block diagrams using Mini-Circuits modules are shown in Figures 1 and 2, respectively.

Table 2: Mini-Circuits modules used for lab design.

Part	Description	Frequency Range (MHz)
ZFMIQ-10M	I/Q modulator	9 - 11
ZFMIQ-10D	I/Q demodulator	9 - 11
ZOS - 1025	VCO	685 - 1025
ZFM – 4S	Frequency mixer	IF: 0.01-500, RF: 0.1-1000
ZFL – 500N	Amplifier	0 - 500

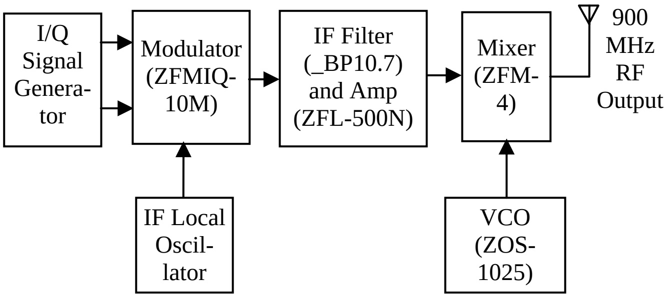

Figure 1: RF transmitter block diagram.

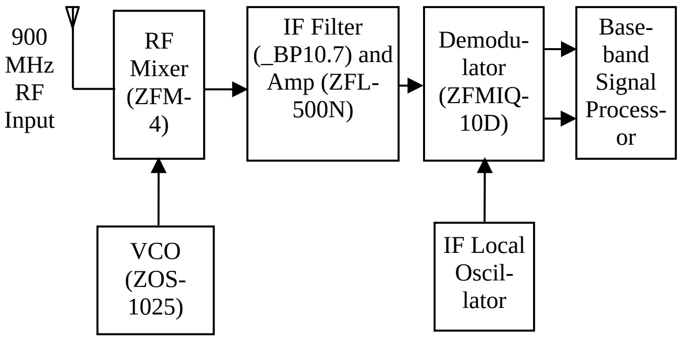

Figure 2: RF receiver block diagram.

The operating frequency of the RF system is set at 915 MHz. This is because many of the existing wireless systems operate in the 900 MHz Industrial, Scientific, and Medical (ISM) band. Choosing this operating frequency allows students to observe the performance characteristics of a real-world system.

Aside from the above, it is worth mentioning the cost-effectiveness of this approach. Even though there are well designed experimental systems available, most of them cost over US$10,000 per set, and the authors are not aware of any operating at an RF frequency over 200 MHz. By using the Mini-Circuits modules listed above, the cost is around US$600 per set, which makes it much more affordable.

DESIGNED LABS AND EXAMPLE RESULTS

There are six lab modules designed to achieve the goals of this project. These labs emphasise the functionality and parameters of the building modules, as well as system performance parameters of a wireless communication system. Because of the complexity of each lab, most of the lab modules are conducted in two 2-hour lab sessions, which extends the experiments to 8 to 10-week sessions (one session per week). A list of lab topics and Mini-Circuits modules used is provided in Table 3. These lab sessions include three module parameter test sessions that focus on the key components (modulator and demodulator, voltage controlled oscillator, and frequency mixer) and three system performance testing sessions of wireless communications systems.

Table 3: Designed RF lab modules.

Lab	Description	Mini-Circuits Parts Used
1	Modulator	ZFMIQ-10M
2	IF system performance	ZFMIQ-10M, ZFMIQ-10D
3	Voltage controlled oscillator	ZOS-1025
4	RF frequency mixer	ZFM-4
5	RF system performance	All parts from labs 1-4
6	Propagation and path loss	All parts from labs 1-4

Detailing the theory of operation, lab set-up and test procedures is out of the scope of this article. Interested readers may find this information elsewhere [1][2]. Figures 3 and 4 show the transmitter and receiver that correspond to the block diagrams shown in Figures 1 and 2, respectively. The rest of this section summarises the parameters to be tested for each lab session, alternative experimental methods, tips for expanding lab session content, and some example results of the project.

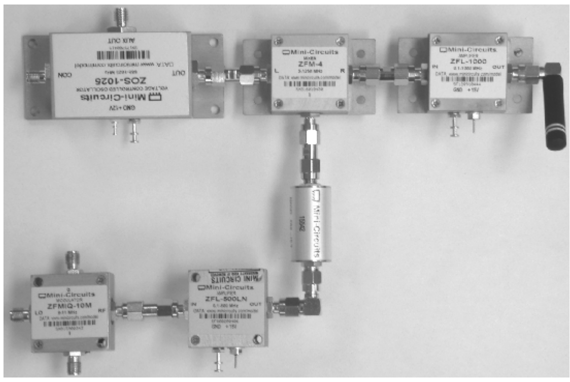

Figure 3: Transmitter using Mini-Circuits modules.

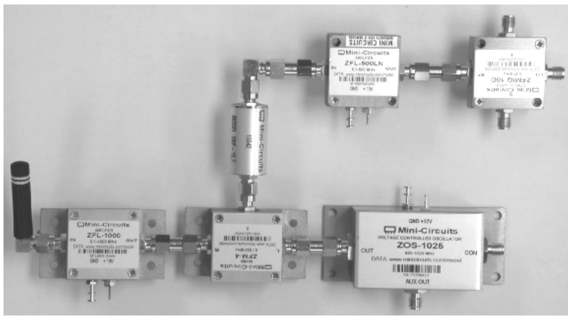

Figure 4: Receiver using Mini-Circuits modules.

I/Q Modulator Test

This is a warming-up lab session. A similar lab may be conducted in a previous communications fundamentals course. Because carrier and sideband rejection are the most important parameters to measure the quality of any modulator, they are tested in this lab. Other parameters tested in this lab session include conversion loss, port-to-port isolation, amplitude and phase imbalance, and 3rd and 5th order products. Because the difference of a demodulator and a modulator is insignificant when they are operated at the same frequency, no separate lab is needed to test a demodulator's parameters. The functionality of a demodulator is examined in an IF system and is described in the next lab session.

Figure 5 shows the test result of carrier and sideband rejection of the modulator at 10.7 MHz. The measured rejections are 62.66 dBc and 9.87 dBc, respectively.

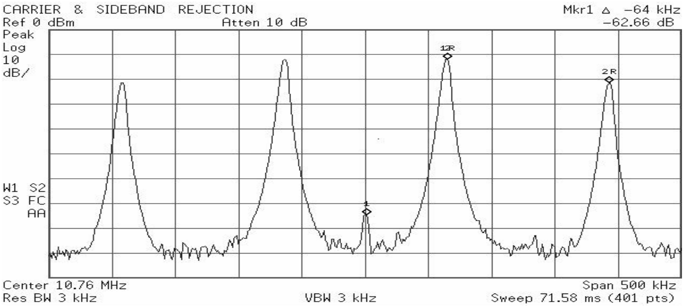

Figure 5: Carrier and sideband rejection.

IF System Performance

This lab serves as an intermediate step to investigating RF system performance. It focuses on the performance of an IF system operated at 10.7 MHz and the effects of IF performance on that of the RF section. The parameters tested in this lab session include receiver sensitivity, Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR), baseband signal reconstruction, and synchronisation.

Mini-Circuits ZFMIQ-10M is composed of two bi-phase modulators. Through experimentation, it was found that if a data stream is fed into either the I or Q port of the modulator, a resultant BPSK signal is generated. Those who lack equipment or time to conduct QPSK investigations may replace it with BPSK. Figure 6 shows the BPSK modulated signal. The modulating signal is a 128 kbps MP3 music data stream. Phase reversals at bit boundaries can be clearly observed in Figure 6.

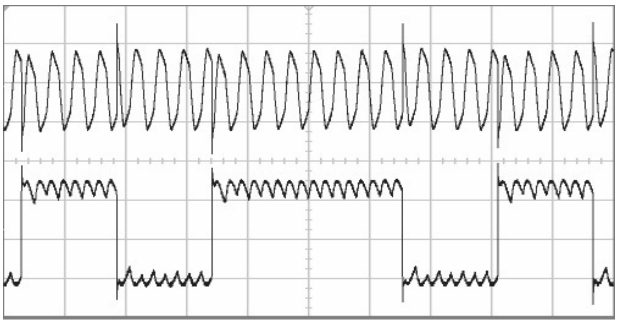

Figure 6: A BPSK modulated waveform.

One way of making students realise the importance of synchronisation is to compare the performance of using the same and different local oscillators for the modulator and demodulator. Using separate local oscillators for the modulator and the demodulator allows students to observe that the demodulated signal cannot be synchronised with the original signal. By utilising the same LO for both the modulator and demodulator, students can better understand the importance of synchronisation.

Another important aspect of the demodulator functionality is the fact that its outputs contain higher ordered frequency terms. In order to reconstruct the baseband signal, higher ordered terms need to be filtered out by a lowpass filter before the baseband signal can be obtained.

Figure 7 shows the original message signal used in Figure 6 and the demodulator output. It can be observed that the demodulated signal contains higher order harmonics that requires a lowpass filter implementation to reconstruct the original MP3 music signal.

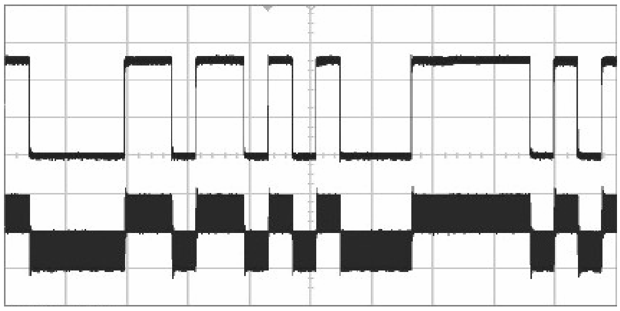

Figure 7: Transmitted message signal versus a demodulated signal.

Voltage Controlled Oscillator (VCO)

The quality of a Voltage Controlled Oscillator (VCO) used in the system directly affects the overall system performance. Important parameters to the quality of a VCO include its output power and frequency, tuning sensitivity, tuning linearity, harmonics and spurious levels, frequency pushing and pulling, modulation bandwidth, and phase noise. It was suggested that these parameters be tested in this two lab sessions. The VCO operates at 904.3 MHz. When mixed with 10.7 MHz IF, a 915 MHz RF signal can be generated with a 915 MHz bandpass filter.

Typical measurement set-ups can be found in ref. [2]. More detailed information about test set-up and measurement methods can be found in the Mini-Circuits application notes [3][4]. Figure 8 shows the measured VCO frequencies and tuning sensitivity.

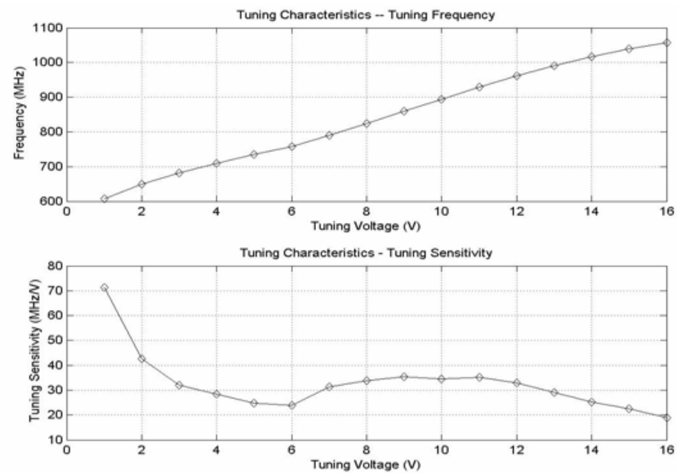

Figure 8: VCO tuning sensitivity test.

As this VCO is sensitive to tuning voltage, it is recommended that students use a high accuracy potentiometer to apply a control voltage to the VCO to obtain a stable and desired frequency.

RF Frequency Mixer Characteristics

The selection of the right mixer is imperative to the performance of an RF communications system. Among mixer performance parameters, conversion loss, RF-IF or RF-LO isolation, VSWR, and two-tone 3rd order distortion (IP3) are some critical factors that are tested in this lab session. Details of experimental procedures and methods can be found elsewhere [2][5][6]. Figure 9 shows an example result of two-tone 3rd order distortion measurement.

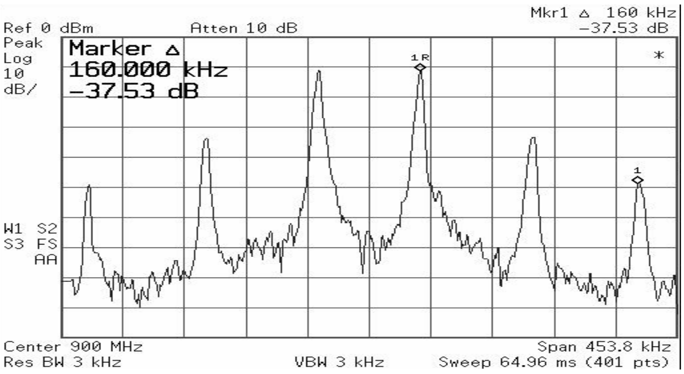

Figure 9: RF mixer two-tone 3rd order distortion measurement.

One tip when selecting the mixer is to choose one that requires lower LO input (eg Level 7 series). Even though a high level mixer (eg Level 23) may provide a higher RF output, inter-modulation products may cause performance degradation.

RF System Performance

The emphasis of this lab session is on the RF system performance and the effects of RF operating environments. Therefore, the parameters tested 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 a VCO was used in the RF transmitters, sources for CIR measurement, co-channel and adjacent interferences were easily generated.

Receiver sensitivity was tested with an attenuator to reduce the received signal power. When the received signal is -87 dBm, Figure 10 shows the original MP3 and the demodulated signal. When compared with Figure 7, it can be seen that this signal is irrecoverable. The receiver sensitivity is about -87 dBm.

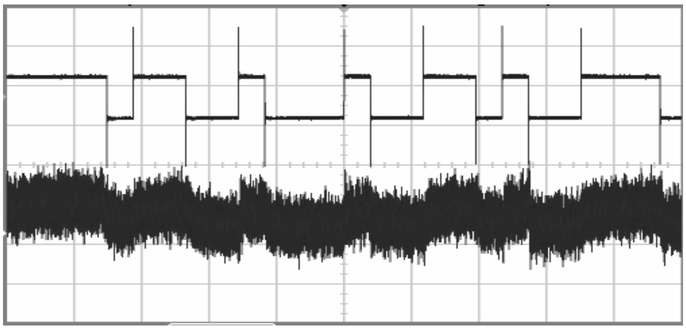

Figure 10: Receiver sensitivity test.

Propagation and Path Loss

The investigation of channel fading characteristics helps students to understand the environments within which a wireless communication system operates. Students are required to measure the overall path loss of the system and to plot experimental data against theoretical path loss in this lab. Details of lab procedures can be found in ref. [2].

Figure 11 is a plot of the measured and theoretical received signal power comparison. Path loss can be calculated by taking the difference between the transmitted and received powers.

For lab sessions (E) and (F), if a digitally modulated IF source is not available, an analogue modulated source, like an FM signal, can be used instead. For example, one can use an FM radio to receive a local station and feed the signal from the FM radio's front end into the RF mixer. The VCO can be detuned on the RF receiver end so that the mixer output is at an unused FM frequency, and an antenna can be connected at the output of the mixer to broadcast the FM signal. Students can utilise another FM radio to receive the FM signal and consequently evaluate the RF performance. This method permits simultaneous experiments of multiple student groups because each group can detune the VCO so that the output FM signals will not interfere with each other. Even though somewhat subjective, this method still helps students gain first-hand experience regarding RF system performance.

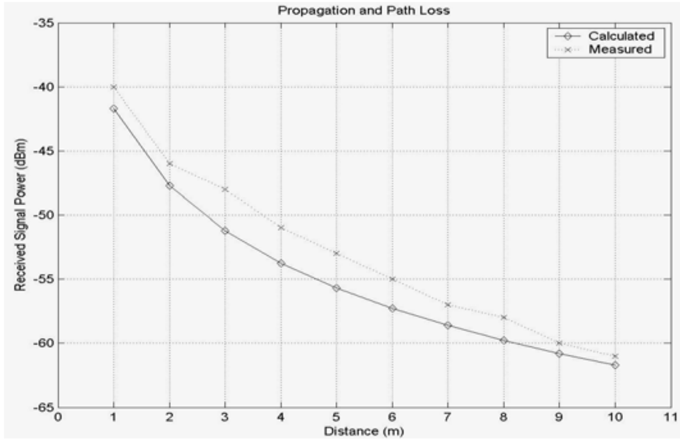

Figure 11: Measured versus theoretical path-loss comparison.

CONCLUSION AND FUTURE WORK

In this article, the authors have presented the concepts and example results of testing the functionality and performance parameters of wireless communications system modules using cost-effective Mini-Circuits components. This approach emphasises the consolidation of student theoretical knowledge through experiential exploration.

Potential future work includes the integration of baseband, IF and RF sections into one complete communications system. This task is being carried out through a senior design project and is close to completion. Assessment plans are being made to measure the effectiveness of this approach, as well as the benefits to students.

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