Wireless Communications Laboratory

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***Abstract*—Wireless communications technology is one of the most rapidly growing disciplines and is experiencing unprecedented market growth. The 21st Century will witness the widespread deployment of all kinds of public and private wireless networks. Many graduating seniors and graduate students are finding themselves in careers relating to wireless information technology. In addition, practicing engineers, computer specialists, and managers have to re-educate themselves in the area of wireless technology. Polytechnic University (Brooklyn Poly), Brooklyn, NY, recognized the need to prepare its students for careers in wireless and successfully developed one of the first instructional wireless information networks laboratories. The laboratory has provided more than 800 students during the past decade with the opportunity to acquire both in-depth theoretical understanding and hands-on experience in this rapidly growing discipline. The laboratory experience can play an important role in motivating students and stimulating their interest in a specific discipline such as wireless communication systems. It both complements and supplements the other theoretical courses taken by the students. Reading about signals plus additive white Gaussian noise in a textbook and actually observing such signals in a laboratory oscilloscope can be two very different experiences for many students. This paper describes this instructional laboratory, which is replicable by other universities.**

***Index Terms*—Spread-spectrum communications, undergraduate laboratory, wireless communications.**

I. Introduction

POLYTECHNIC University is a private university formed in 1973 by the merger of the Polytechnic Institute of Brooklyn (Brooklyn Poly) and the New York University School of Engineering and Science, both of which date back to 1854. The name was changed from Polytechnic Institute of New York to Polytechnic University in 1985. Academic programs in electrical engineering, computer engineering, and computer science enroll more than half of the students in the university. Many of these students are minorities. In fact, the majority of the students are first- or second-generation immigrants. Wireless communications technology is one of the most rapidly growing disciplines in the telecommunications industry. It is experiencing unprecedented market growth, as evidenced by the rapid increase in the number of cellular phones, paging, mobile data, and wireless local area networks. The telecommunication industry is shifting away from nearly exclusive reliance on wired networks to an era of wireless technology. The computer industry is also moving toward integration of distributed and portable devices in a mobile environment. This rush to the wireless technology will revolutionize the concept of communication and information processing for business, professional, and private applications. As a result, many engineers, computer specialists, and managers have to educate themselves in the area of wireless technology, and many graduating seniors and graduate students are finding themselves in careers dealing with wireless information technology.

Polytechnic University has foreseen the need and has successfully developed both graduate and undergraduate curricula in wireless communications. To fulfill its commitment to equip its students with the most modern and the best training in the most advanced disciplines and to help its students stay at the forefront of various cutting edge technologies, the Wireless Lab was developed with the help of a National Science Foundation (NSF) instrumentation and laboratory improvement grant. The laboratory has provided more than 800 students in the last decade with hands-on experience in this rapidly growing new discipline. The education program combines the most updated course training with the state-of-the-art laboratory activities. These students not only achieve in-depth theoretical understanding but also acquire hands-on experimental experience. Upon completion of these curricula, many students have been employed by corporations such as AT&T, IBM, United Technologies, Raytheon Company, GE, GTE, NYNEX, Northrop Grumman, BAE, Symbol Technology, Computer Associates, and Telephonics. They have formed a major working force for many local high-tech industries.

The student interest in the Wireless Information Networks Laboratory has been overwhelming. The course is offered every Fall, Spring, and Summer session. Multiple sections have been offered each semester, and the laboratory course offering has frequently been fully enrolled during the preregistration period. In summer 1995, 1999, 2000, and 2001, Polytechnic University held a five-day workshop sponsored by the NSF Undergraduate Faculty Enhancement Program. During the workshop, faculty members from various universities were trained to conduct the experiments in the Wireless Information Networks Laboratory. They were encouraged to set up a similar laboratory and curricula in their own institutions.

II. Literature Survey

A review of the published literature over the past decade reveals that a number of other schools also offer laboratory courses relating to wireless communications. Among these are the University of Colorado (Boulder) [1], [2], the University of Utah [3], [4], Virginia Polytechnic Institute and State University [5], [6], Carnegie Mellon [7], UCLA [8], and the University of Southern California (USC) [9]. Some laboratories are project oriented [3], [10]–[12]; others focus on wireless networks [9], [10], radio-frequency (RF)/microwaves [3], [4], antennas [12], radar [13], and optical communications [14].

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Some are hands-on hardware-related labroatories, while others emphasize modeling and MATLAB simulations [10]. Others offer laboratory courses related to wireless but, to the best of this author's knowledge, have not published their experiences, although some information can be found at their websites.[1] Polytechnic's Wireless Lab provides a hands-on learning experience at the *physical layer* of wireless communication systems. In addition to the formal laboratory experiments, it includes lectures on each experiment to develop the theoretical concepts and the project-oriented work.

III. Pedagogical Issues Addressed

One of the objectives of the Wireless Lab is to provide the students with a hands-on laboratory experience that includes an in-depth theoretical understanding of this rapidly growing discipline. The laboratory experience can play an important role in motivating students and stimulating their interest in a specific discipline, such as wireless communication systems. Reading about signals plus additive white Gaussian noise in a textbook and actually observing such signals on the laboratory oscilloscope can be two very different experiences for many students. Witnessing the power of a matched filter in detecting such signals buried in noise are examples of how the laboratory experience both complements and supplements the other theoretical courses taken by the students.

Among the specific topics addressed in the laboratory include pseudonoise (PN) codes, direct-sequence spread spectrum, frequency-hopped signals, acquisition and tracking, code-division multiple-access (CDMA) wireless computer communications, UHF channel propagation characteristics, bit-error-rate (BER) measurements, and time-division multiple access (TDMA). In addition to lectures and formal weekly laboratory experiments, all students are required to complete a design project related to wireless information networks, make oral presentations, and submit written reports. Their laboratory grades reflect not only technical merit but also the communication skills exhibited.

The laboratory course achieves many of Accreditation Board for Engineering and Technology (ABET) objectives. By designing the course to include lectures, formal laboratory experiments, and project work, one integrates and applies many of the basic and widely used techniques and skills learned in other engineering courses (e.g., circuits; electronics; signals, systems, and transforms; and analog and digital communication systems) and mathematical techniques learned in calculus, differential equations, and probability courses. Laboratory experiments are specifically designed to require students to perform mathematical analysis, including BER probabilities for wireless communication systems and cumulative distribution functions for wireless communication channels. In the projects portion of the laboratory, students design wireless communication systems, identify important technical issues, develop a strategy, formulate, and solve resulting problems. Their required laboratory reports, project reports, and oral presentations are all designed to help develop their communication skills. In addition, the laboratory/project experience help students learn how to work in teams. ABET objectives are assessed by Polytechnic's Office of Assessment and Institutional Research, which conducts online course evaluations each semester. Results are presented in Section VI of this paper.

Fig. 1. Wireless Lab station.

IV. Description of Wireless Laboratory Experiments and Projects

Polytechnic's Wireless Information Networks Laboratory is a formal three-credit senior-level instructional laboratory consisting of weekly four-hour experiments accompanied by one-hour lectures. The lectures discuss any new theoretical concepts associated with the experiment. In addition, a design project is required by each student. A total of six laboratory stations are available with two students at each station. Each laboratory station is equipped with a spectrum analyzer, digital storage oscilloscope, RF signal generator, noise generator, true root mean square (rms) voltmeter, dc power supplies, function generators, printers, desktop computer, frequency/event counters, double-balanced mixers, and power splitters. A photo of a typical laboratory station is illustrated in Fig. 1. The course outline is shown in Table I.

Formal written laboratory reports are required by each student for all experiments. A written report and a formal oral presentation using PowerPoint is required for the project. Two or three 30-minute quizzes and a final written exam based on the experiments are also given. For the project, the laboratory is run as an "open lab," where students can come in during scheduled hours and work on their projects. Below is a description of each laboratory experiment. More details can be found in the laboratory notes, which the author would be pleased to share with any interested reader.

[1]Georgia Tech ECE 4602—Communication Systems Laboratory, available at http://www.ece.gatech.edu/PHP/undergrad/course_outline.php?prmCourse=ECE4602; Stanford University, EE 144 Wireless Electromagnetic Design Laboratory, available at http://eeclass.stanford.edu/ee144/; University of Texas at Austin Bits and Bytes, New Undergraduate Wireless Lab Offered at UT Austin, available at http://www.ece.utexas.edu/Wncg/bitsbytes/may2005/undergrad.php; University of Texas at Austin EE379K-WC: Wireless Communications Lab, available at http://www.ece.utexas.edu/~/heath/courses/wirelesslab/index.php; University of Maryland ENEE 429W Indoor Wireless Project, available at http://www.ee.umd.edu/Academic/Under/ucourses2.htm#ENEE%20428; University of Illinois, ECE463 Digital Communications Laboratory, available at http://www.ece.uiuc.edu/courses/couredes.asp?463; Cornell University's ECE488 RF Circuits and Systems, available at http://cuinfo.cornell.edu/Academic/Courses/CoSdetail.phtml?college = ENG&number = 488&prefix=ECE&title = RF+Circuits+and+Systems

TABLE I
WIRELESS INFORMATION NETWORKS LABORATORY

WIRELESS INFORMATION NETWORKS LABORATORY	
Experiment No.	Experiment Title
1	Equipment Orientation
2	Pseudo-noise Codes
3	Direct Sequence Spread Spectrum Communication Systems
4	Frequency Hopped Spread Spectrum Communication Systems
5	CDMA Wireless Computer Communications
6	Bit Error Rate Measurements
7	Multipath Channel Propagation Characteristics
8	Time Division Multiple Access (TDMA)

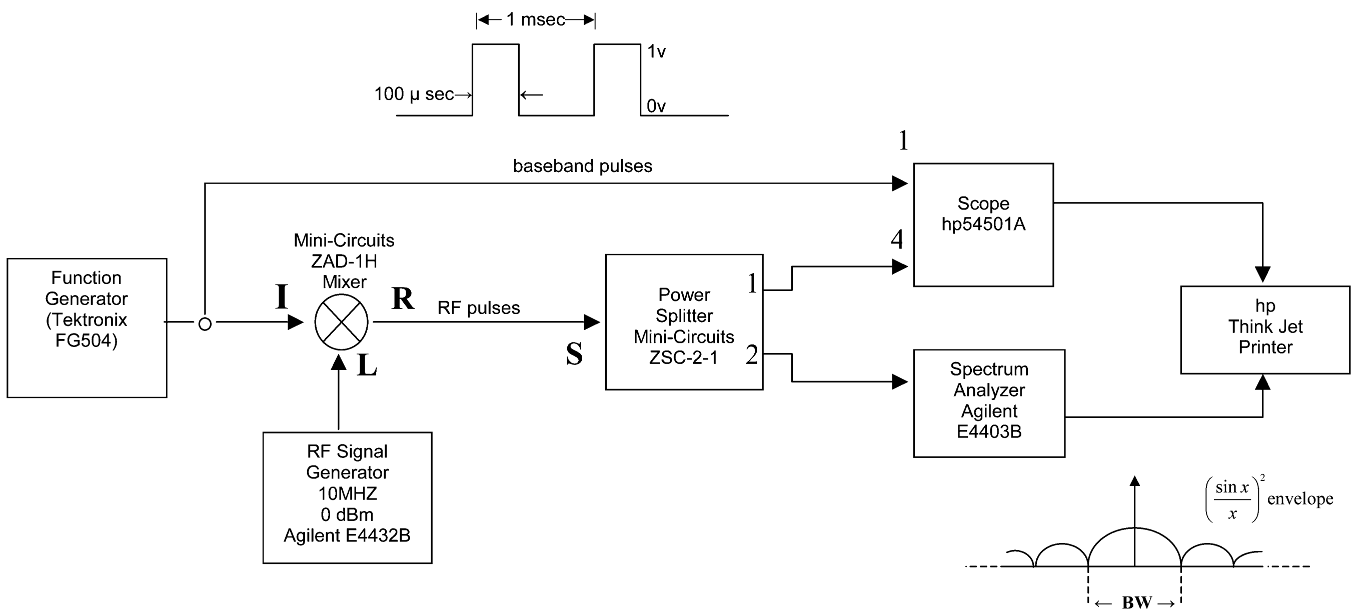


Fig. 2. Block diagram of experimental setup.

A. *Experiment 1—Equipment Orientation*

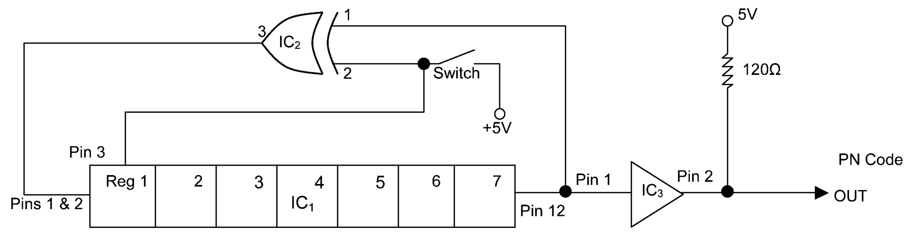
In this experiment, the student becomes familiar with the equipment that will be used in the wireless communications laboratory throughout the semester. The student investigates RF pulses in both the time and frequency domains using the function generator, RF signal generator, double-balanced mixer, power splitter, digital storage oscilloscope, spectrum analyzer, and printer to determine the relationship between pulsewidth and signal bandwidth for both baseband and RF pulses. A block diagram of the experimental setup used is illustrated in Fig. 2. This experiment complements material students learned in accompanying theoretical courses, such as Fourier transforms of a single pulse, Fourier series of periodic pulse trains, and modulation theory.

B. *Experiment 2—PN Code Sequences*

PN code sequences are generated using feedback shift register implementations. The experimental setup is illustrated in Fig. 3. Their autocorrelation, cross correlation with other codes, and spectral properties are examined in the laboratory in the time and frequency domains and compared with theory. Different codes are generated by altering the feedback connections on the shift register. Once again, the laboratory experience complements material covered in accompanying theoretical courses, such as the relationship between autocorrelation and power spectral density of a signal.

C. *Experiment 3—Direct-Sequence Spread-Spectrum Communication Systems*

Spread-spectrum technology has become very important in wireless information networks. In such systems, each user is assigned his or her own PN code. The PN code spreads the bandwidth of the transmitted signal. This spread may be accomplished by phase-shift keying a high-frequency RF sinusoidal carrier using the bipolar PN code sequence (direct-sequence spread spectrum) or by frequency hopping the RF carrier



IC_1	74164	V_{cc} = pin 14	Ground = pin 7	clock = pin 8
IC_2	7486	V_{cc} = pin 14	Ground = pin 7	
IC_3	7407	V_{cc} = pin 14	Ground = pin 7	

Fig. 3. Seven-stage linear-shift register sequence. PN code generator.

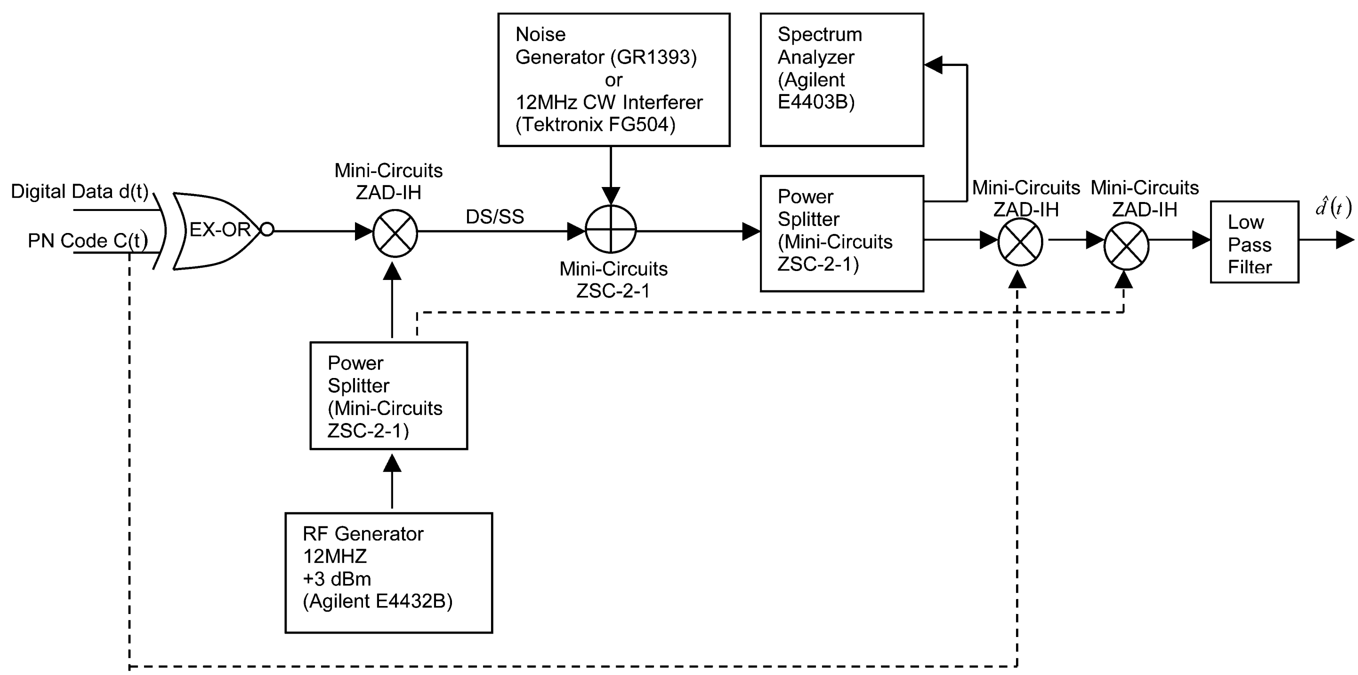


Fig. 4. Direct-sequence spread-spectrum transmitter/receiver.

in a pseudorandom fashion using the PN code sequence. Such systems employ CDMA to allow many users to share the same wireless radio channel simultaneously without interfering significantly with each other. Spread spectrum is noted for its many advantages. Among these are its immunity to multipath, ability to suppress interferers, low-power spectral density, and efficient use of the RF spectrum. It also does not require as much network synchronization, such as in the case of TDMA, and special RF bands [Industry, Scientific, Medical (ISM) bands] have been allocated by the FCC specifically and exclusively for commercial applications of spread spectrum.

This experiment describes the complete direct-sequence spread-spectrum transmitter and receiver implementations and examines many of the aforementioned advantages. The experimental setup is illustrated in Fig. 4. Waveforms are examined in both the time and frequency domains to observe the effect of "spreading" using the PN code and the despreading that takes place in the receiver when the broad-band received signal is cross correlated with a synchronized replica of the PN code used in the transmitter.

Perfect code and carrier synchronization are assumed in this experiment by using the same PN code generator and sinusoidal carrier signal generator in both transmitter and receiver. Practical techniques for generating coherent reference signals at the receiver directly from the received waveform are investigated in the projects portion of the laboratory.

Interference and broad-band Gaussian noise are also used to corrupt the transmitted signal. By observing the signal at the output of the receiver's PN code correlator on a spectrum analyzer, one can readily observe how the undesired signals are spread in the receiver while the desired signal is "despread," demonstrating the power of spread spectrum in suppressing interfering signals and noise. The amount of interference that can be tolerated (jamming margin) is also measured and compared with theoretical prediction. The interferer could be narrow band or continuous wave (CW) or could, in fact, be another spread-spectrum user operating with different orthogonal PN code. The latter case demonstrates the application of CDMA, where many spread-spectrum users may share the same RF band simultaneously without interfering significantly with each other.

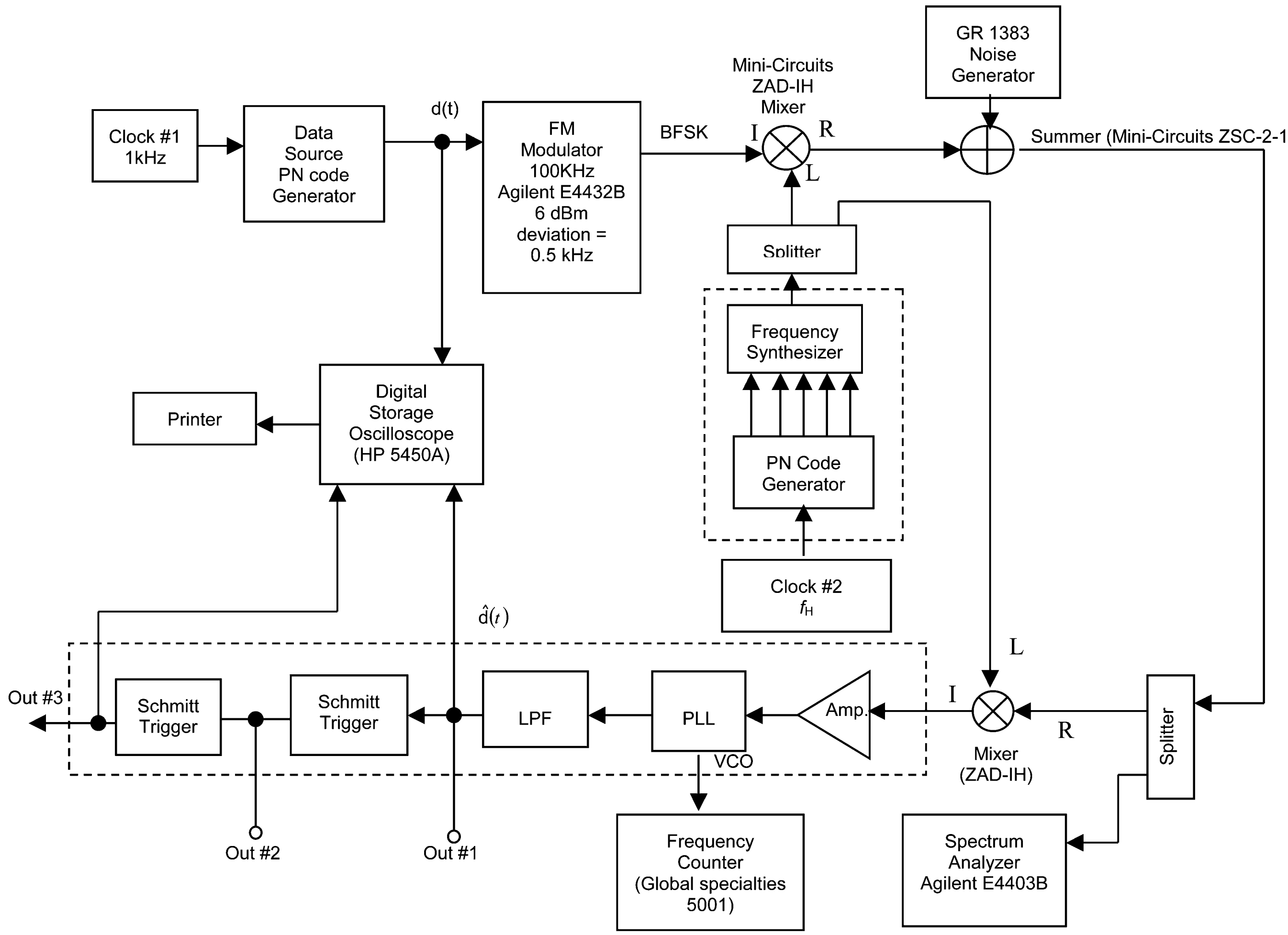


Fig. 5. BFSK/frequency-hopping transmitter and receiver.

In addition, the students examine experimentally how one can “hide the signal in the noise” and still successfully demodulate the digital data in the receiver. This exercise is usually met with surprise and excitement on the part of the students and demonstrates how laboratory experiments can help motivate students and stimulate their interest when studying a particular topic such as wireless communications.

D. Experiment 4—Frequency-Hopped Spread-Spectrum Communication Systems

In frequency hopping, the PN code is used to change the carrier frequency of a frequency-shift keyed (FSK) signal in a pseudorandom fashion. This step is usually accomplished with a frequency synthesizer. The block diagram of the experimental setup is illustrated in Fig. 5.

The data modulator used is a binary-frequency-shift-keyed modulator. The carrier frequency is shifted in a random fashion from a set of 2^k possible hopping frequencies spreading the bandwidth of the transmitted waveform. The received waveform is cross correlated with a synchronized replica of the frequency-hopping pattern used in the transmitter. This cross correlation despreads the desired signal while simultaneously spreading any unwanted interference or noise. Students monitor signals in both the time and frequency domains to observe these features. The data demodulation done in the receiver is a phase-locked-loop (PLL) binary-phase-shift-keyed detector. Students construct this complete communication system in the laboratory using the modules and equipment provided and demonstrate successful recovery of the message signal d(t) at the receiver’s output. The effects of additive white Gaussian noise, co-channel interferers, and fast-versus-slow hopping are also investigated. PN code and carrier synchronization are examined in the projects portion of the laboratory.

E. Experiment 5—CDMA Wireless Computer Communications

In this experiment, students build a complete wireless information network enabling two personal computers to communicate with each other using UHF radio waves. The experimental setup is illustrated in Fig. 6.

The UHF transmitter and receiver constructed by the students is similar in architecture to the direct-sequence spread-spectrum communication system used in Experiment 3. Transmitter power levels are limited to 10 mW. A bandpass filter and amplifier are connected at the output of the receiving antenna before the receiver’s PN code correlator. An RS232 D25 connector is used to interface the serial port of the computers to the transmitter and receiver. The data signal appearing at the output of the spread-spectrum receiver is connected to the receiving computer. Receiving and transmitting antenna locations are varied

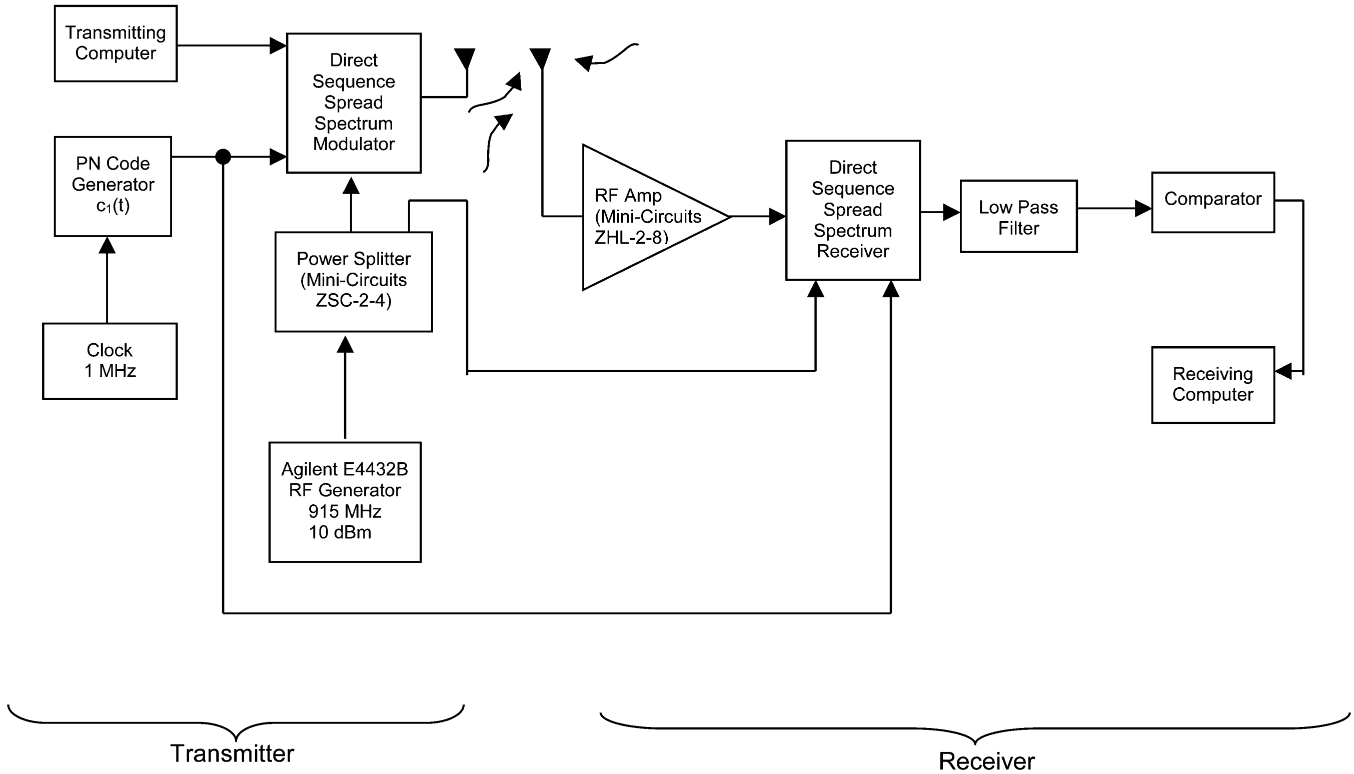


Fig. 6. CDMA BPSK/direct-sequence spread-spectrum communication system.

within the laboratory to note the effect of multipath and shadowing on system performance. Different laboratory groups use different orthogonal PN codes but transmit simultaneously over the same UHF radio channel (902–928 MHz) to simulate a complete CDMA wireless information network. The effect of multiple users sharing the same radio channel on system performance is evaluated both theoretically and experimentally. In addition, the "near–far" problem, where nearby transmitters can overpower signals being received from distant users, is also investigated.

F. Experiment 6—BER Measurements

In this experiment, the student designs error-counting circuitry useful to monitor the BER performance of a digital communication system. The error-counting circuitry is capable of sampling and comparing two pulse trains (transmitter input versus receiver output) at a prescribed instant of time to determine whether they are the same. If at the sampling time a pulse exists in the transmitted data signal but not in the receiver output signal, or vice versa, the error-counting circuitry will produce a pulse indicating an error was made. If both data signals are identical, no error pulse is produced. The experimental setup is illustrated in Fig. 7.

Students also investigate the use of the integrate-and-dump matched filter to minimize the BER. The matched filter is connected to the output of the direct-sequence spread-spectrum receiver studied in Experiment 3. Broad-band Gaussian noise obtained from the output of a noise generator is used to corrupt the transmitted spread-spectrum signal. BER is then measured with the error-counting circuitry designed. Measurements of BER versus received signal-to-noise ratio (SNR) are compared with known theoretical results for binary-phase-shift-keying (BPSK) signals. The effect of processing gain on BER performance is monitored by varying the ratio of the PN code chip rate to the bit rate of the data. The effect of interferers (narrow-band and other broad-band spread-spectrum users) on the BER performance is also investigated.

This example again shows how a laboratory exercise plays an important role in motivating a student and stimulating his or her interest. The performance of the integrate-and-dump matched filter used in this experiment vividly demonstrates the power of the matched filter in successfully detecting digital signals buried in noise. The student's response is one of excitement and enthusiasm. This point is sometimes missed when reading a communications text or studying this topic from a purely theoretical viewpoint.

Fig. 8 illustrates the integrate-and-dump matched-filter performance in the laboratory. The upper waveform describes the baseband binary digital data used in the direct-sequence spread-spectrum transmitter. The second trace describes the signal buried in noise *before* the matched filter. The third trace describes the response of the integrate-and-dump matched filter, and the lower trace the decisions made by the matched filter (receiver output).

G. Experiment 7—Multipath Channel Propagation Characteristics

This experiment focuses on measurement techniques useful for determining the channel propagation characteristics of an indoor radio channel in the UHF radio band. Such a channel is typically characterized by numerous multipath reflections off

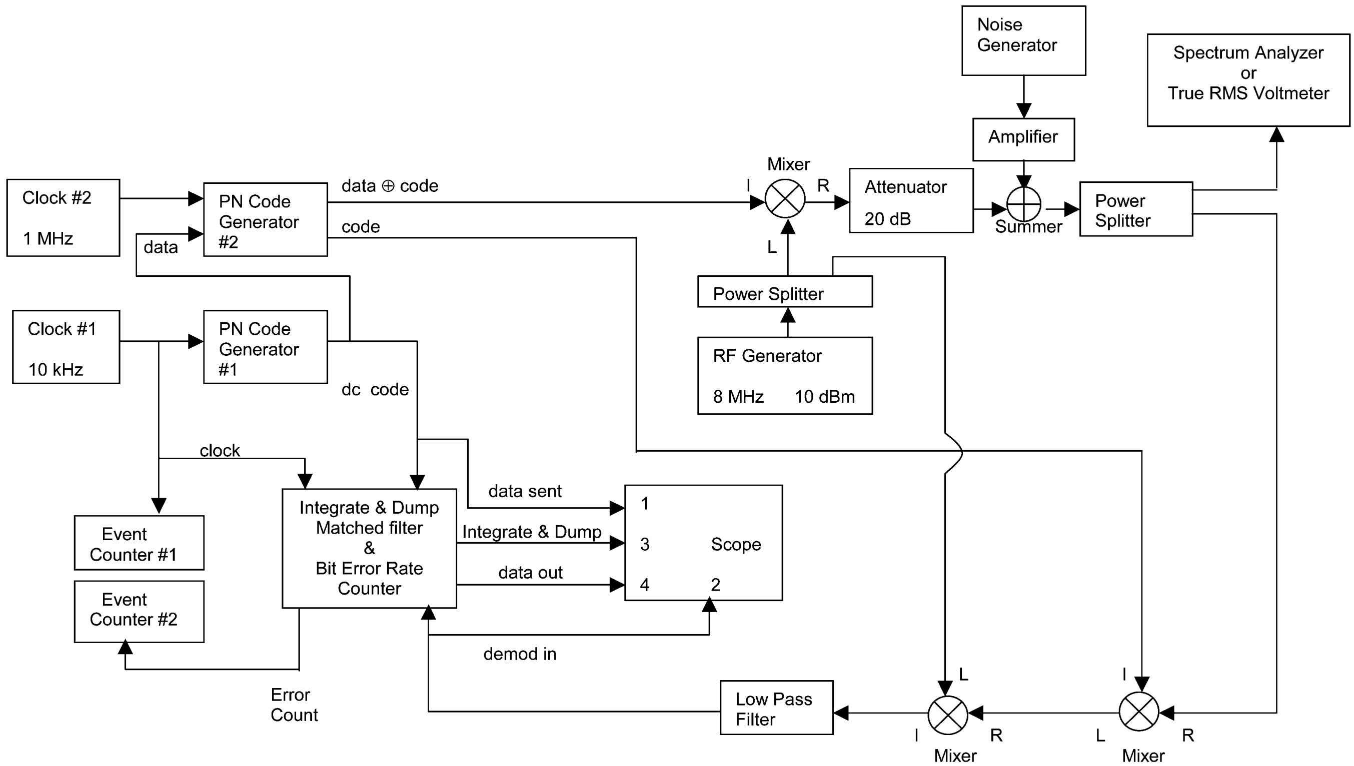


Fig. 7. Block diagram of direct-sequence spread-spectrum communication system and BER counter.

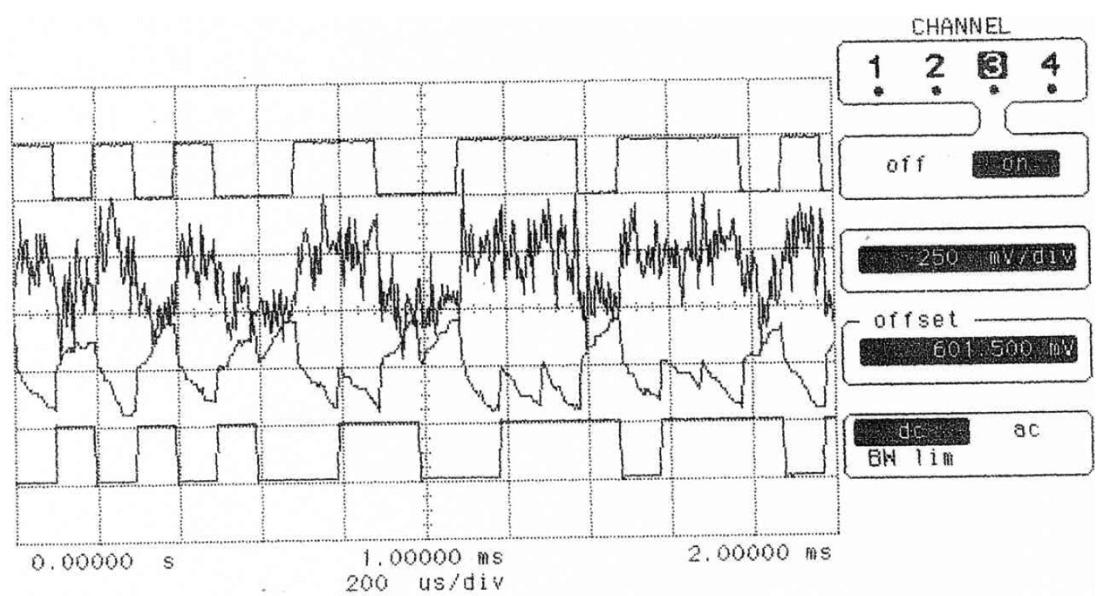


Fig. 8. Oscilloscope waveforms from BER experiment: (a) top trace: data sent, (b) 2nd trace: data sent + noise, (c) 3rd trace: integrate-and-dump matched-filter output, and (d) bottom trace: receiver output.

of the walls, ceiling, floor, office furniture, etc. Attenuation between transmitter and receiver antennas may be as large as 60 dB. In order to design indoor wireless information networks, one must understand the propagation within buildings and be able to predict signal levels.

Students measure the fast-fading and slow-fading characteristics of an indoor radio channel. A CW transmitter is set up in the hallway operating at 915 MHz (wavelength: 12.9 in). Using their spectrum analyzers connected to a half-wavelength monopole receiving antenna mounted on a mobile cart, students take 100 data points of signal strength in dBm (decibels above 1 milliwatt) versus distance (each measurement spaced 2 in apart) at each of six different sectors located 30–150 ft away from the transmitting antenna. Some sectors are line-of-sight (LOS) while others are non-LOS with respect to the transmitting antenna. Using data reduction, plots of sector average path loss (PL) in decibels versus distance (R) on a log scale between transmitter and receiver are obtained. Such plots are typically straight lines. The slope index, n, is calculated and compared for LOS versus non-LOS sectors and for vertical polarization

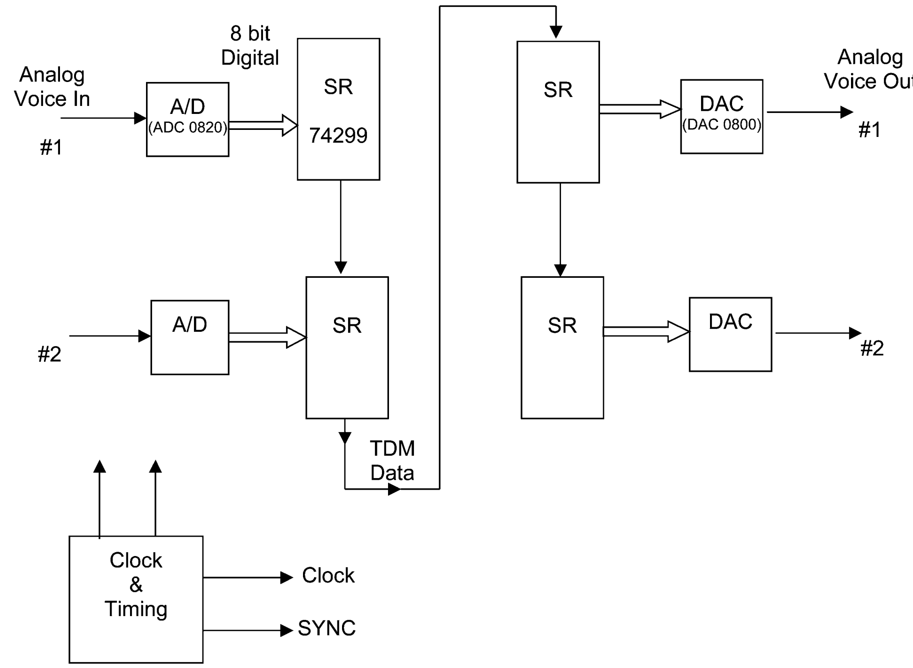


Fig. 9. MUX and DEMUX TDM transceiver.

versus horizontal polarization of the transmitting antenna. In addition, students construct from the data cumulative distribution functions to determine whether the fast fading follows Rayleigh or Rician statistics.

H. Experiment 8—Time-Division Multiple Access

In TDMA, each user is assigned a specific time slot over which to transmit data. At any given instant of time, only one user is transmitting. A central network control assigns the time slots and establishes timing synchronization. Slots may be preassigned or demand-assigned (DAMA) to make more efficient use of the RF spectrum. In this experiment, students study the digital circuitry necessary to time-division multiplex signals in a transmitter and demultiplex in the receiver. A block diagram description of the time-division-multiplexed (TDM) transceiver hardware is illustrated in Fig. 9. Specific topics addressed include sampling theorem, Nyquist sampling rate, analog–digital converters, and digital–analog converters.

V. Design Projects

The project portion of the laboratory runs throughout the term. This portion of the laboratory operates as an "open lab," where students are permitted to work in the laboratory during certain scheduled hours. Projects must be approved by the course instructor. Many of the projects selected build upon the formal laboratory experiments. Examples include hybrid direct-sequence/frequency-hopped spread-spectrum communication systems, PN code acquisition and tracking for direct-sequence and frequency-hopped spread-spectrum receivers, PN Gold codes, PLL frequency synthesizer, and overlaying spread-spectrum CDMA signals with narrow-band users. Other students have selected wireless projects not directly associated with the formal laboratory experiments. Among these are radio-frequency identification (RFID) tags, orthogonal frequency-division multiplexing (OFDM), forward-error correcting codes, RAKE [15] receiver, differential-phase-shift-keying (DPSK) modulation, quadrature-phase-shift keying (QPSK), antenna design, UHF transistor amplifier design, and infrared wireless information networks. A written report and a 20-minute formal oral presentation using PowerPoint are required at the end of the semester by each student. Students enrolled in the laboratory are required to attend all project presentations, and interested faculty are also invited to attend.

VI. Assessment

Polytechnic's Office of Assessment and Institutional Research conducts online course evaluations each semester. All undergraduate students are required to complete the survey and provide feedback to the instructor. The questionnaire is extensive and includes 43 questions covering the areas of Procedures and Policies (course syllabus, grading policy, office hours, etc.), Instructor (prepared for lectures, knew material thoroughly, spoke clearly, lectures organized, etc.), Graded Assignments and Exams, ABET (a–k) Criteria, Overall Rating for the Course, and an Overall Rating for the Instructor.

The Wireless Lab received an average overall course rating of 4.10/5.00 over the past five years. When students were asked to rate the course on whether it was too hard (5), hard (4), fair (3), easy (2), or too easy (1), the Wireless Lab received an average rating of 3.23/5.00 over that same time period.

The Wireless Lab students were also asked whether they were provided the opportunity to learn and practice the following CORE skills: analytical skills—3.66; communication skills—3.99; lifelong learning skills—3.74; project management skills—4.00; research skills—3.66; and teamwork skills—4.12. They responded 5—To a Very Great Extent, 4—To a Great Extent, 3—To a Moderate Extent, 2—To a Limited Extent, and 1—Not at All.

Using the same rating scale, the Wireless Lab students were asked if they were required to do the following: 1) apply knowledge of math, science, and engineering 3.71; 2) design and conduct experiments as well as analyze and interpret data 4.28; and identify, formulate, and solve engineering problems 3.85.

They were also asked if the laboratory manual provided good support for the course curriculum. They responded with a score of 3.76, using the same scale described above.

Students were also given the opportunity to make specific comments regarding the course and/or instructor. The comments collected in recent semesters include the following:

> "This is a course from which I learned a great deal."
>
> "I thoroughly enjoyed the course."
>
> "I found the first eight weeks of this class highly educational; the next six weeks when I did my project was less so. I did learn a considerable amount... about the project that I undertook. I feel, however, that six more weeks of experiments done in the Wireless Lab would have trained me better for the engineering challenges I will surely face."

In addition to the online survey conducted by the students, the Department of Electrical and Computer Engineering also conducts its own survey of the faculty to identify any significant deficiencies in the course and specify actions to be taken to correct the deficiencies by whom and by when. Faculty are also asked to assess the students in their class to determine if their prerequisite background in electrical engineering, computer science, and math is adequate. Faculty are requested to assess the course syllabus, text or laboratory notes, and whether the published ABET a–k objectives are appropriate for this course. Responses and comments to the survey are forwarded to the department head, associate head for undergraduate studies, and the course director. The results of the faculty survey conclude that the Wireless Lab students are well prepared, provided they complete the prerequisite course EL3404: Fundamentals of Communication Theory before enrolling in the laboratory. Having EL3404 as a corequisite is not sufficient. Some laboratory instructors recommended a few changes in the laboratory note write-up to help clarify some of the experimental procedures, and these have all been implemented.

VII. Conclusion

Polytechnic's Wireless Lab has been immensely popular. During the past decade, over 800 students have enrolled. The laboratory experience clearly motivated the students, stimulated their interest, and complemented the theoretical topics they studied in their other communication courses. The students had the opportunity not only to achieve in-depth theoretical understanding but also to acquire an excellent hands-on learning experience as well. The hands-on learning environment proved invaluable to the students in preparing them for a career in wireless in the communications/computer/consumer electronics industries. Many graduating students commented that they received employment opportunities in industry and credit the practical experience they acquired at Polytechnic's Wireless Lab with helping them obtain the job offers and preparing them well for their professional career in wireless. The NSF Undergraduate Faculty Enhancement (UFE) Workshops provided an opportunity to bring this laboratory experience to a national audience.

The author would be pleased to share the laboratory notes with anyone interested in them. He can be contacted at cassara@rama.poly.edu.

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