

## CURRICULUM INNOVATION FOR SIMULATION AND DESIGN OF WIRELESS COMMUNICATIONS SYSTEMS

**Theodore S. Rappaport<sup>1</sup>, William H. Tranter<sup>2</sup>, Jeffrey H. Reed<sup>1</sup>, Brian D. Woerner<sup>1</sup>, Donna M. Krizman<sup>1</sup>**  
<sup>1</sup>Virginia Polytechnic Institute and State University / <sup>2</sup>University of Missouri - Rolla  
<http://www.ee.vt.edu/mprg/education/nsf/nsf.html>

### ABSTRACT

The U. S. telecommunications industry is experiencing an unprecedented demand for trained electrical engineers with the expertise to design and deploy new wireless communications services, encompassing the high growth areas of cellular telephone, personal communications, paging services, and wireless local area networks. The project described in this paper teams electrical engineering faculty from Virginia Tech's Mobile and Portable Radio Research Group (MPRG) and from the University of Missouri-Rolla to develop an innovative communications curriculum which draws from current research on radio signal propagation modeling, computer-aided design and simulation of wireless communication systems, and digital signal processing techniques to improve the performance and spectral efficiency of wireless modems.

### INTRODUCTION

Throughout the world, there is an unprecedented demand for trained engineers with knowledge and expertise in the communications and computer areas. The demand is particularly acute in wireless communications, which encompasses activities associated with the wireless revolution.<sup>1</sup> Growth in all sectors of the wireless communications industry has been staggering, with growth rates on the order of 50% or more per year for the past four years. As a result, the wireless industry has had an extremely difficult time finding newly graduated engineers with sufficient academic backgrounds to make an immediate impact.

In March, 1995, the Federal Communications Commission (FCC) concluded the largest single sale of public property in the history of the United States when \$7.7 billion was paid by wireless service providers for the rights to use 60 MHz of personal communications systems (PCS) radio spectrum in the 1800/1900 MHz band. The winners of the auction are hiring aggressively, and the industry now faces an even greater shortage of young, trained technical experts who can make contributions in this rapidly growing field. New graduates who have been exposed to research and modern communications topics are urgently needed to develop and deploy new products.

As part of the NSF combined Research-Curriculum Development (CRCDD) program, Virginia Tech and University of Missouri-Rolla faculty will develop a three-course sequence which integrates wireless communications concepts into the electrical engineering curriculum at the senior undergraduate and first-year graduate levels. Course 1 introduces digital and analog communication system design from a wireless perspective. Course 2 presents a hardware-based design experience on the implementation of wireless modems using digital signal processing technology. Course 3 is a graduate course covering simulation and computer-aided design concepts for wireless communication systems. All three courses emphasize design and the combination of fundamental concepts with current industry practice, while attempting to convey to the student the entrepreneurial spirit which permeates today's wireless industry. The three electrical



engineering courses are being incorporated into the curricula at both Virginia Tech and the University of Missouri-Rolla, and the instruction materials are being developed for dissemination in the form of textbooks, MATLAB<sup>®</sup>-based software modules, and “design studies.” A World Wide Web site has been established for this project.

## **PROJECT OVERVIEW**

### **The Wireless Trilogy**

Faculty involved with the NSF CRCRD program have made significant research contributions in the wireless industry, and they are investigating research topics that offer potential for improved radio link quality and increased capacity of radio-frequency resources. These research contributions fall into four main areas: 1) Radio channel measurements and modeling; 2) Modulation and multiple access analysis; 3) Interference rejection algorithms and simulation; and 4) Communication system design through analysis and simulation. All four of these areas are essential to the design, analysis, and deployment of modern wireless communication systems. Unfortunately, these topics are not offered in today’s academic curricula.

Because these four research areas are highly interdependent, it is important that students be exposed to all four areas in order to acquire a sufficiently broad perspective of wireless communication problems. To achieve the goal of effective system design, it is first necessary to have effective simulation tools. In order to create effective simulation tools, realistic modulation, filtering, and interference rejection algorithms are required. Finally, realistic algorithms depend on accurate channel models, developed from physical channel characteristics and empirical measurements. Thus each research area, from channel modeling through system design, builds upon the more basic research from which it was derived. As the research areas become more complex, students will require a broader understanding of the problems and design compromises which must be well understood for the effective deployment of wireless communications systems. While graduate students, through hands-on research, are able to develop problem-solving skills and a broad understanding of communication systems, it is much more difficult to develop the same skills and understanding in a classroom setting. To transfer this knowledge to the student in the classroom, it is vital to develop a curriculum that provides exposure to all four research areas in the communications curriculum.

The three-course sequence being developed includes, throughout the sequence, aspects from all of the key research areas in wireless communications. Course materials will be driven directly by past and present research results in the literature and from faculty research.

In order to cover the four research areas identified above, it was decided to develop a three-course sequence in wireless communications that straddles the senior year of electrical engineering and the first year of graduate study. The sequence under development consists of the following courses:

- Course 1: Fundamentals of Wireless Communications
- Course 2: DSP in Wireless Communications
- Course 3: Computer-Aided Design of Wireless Systems

Because of the necessity for students entering this sequence to have a firm understanding of linear system theory as well as some basic knowledge of digital signal processing, communications theory, and random processes, it is not practical in most curricula to initiate the proposed three-course sequence prior to the first semester of the senior year. Course 1 can therefore be offered at the senior level. Course 2 can be taught at either the senior level or at the beginning graduate level. Course 3 requires that the student have a



firm grasp of stochastic process theory, which is taught as a beginning graduate-level course in most programs. Course 3 must therefore be a graduate-level course in most universities. Course 1 serves as a prerequisite for both courses 2 and 3. The student will derive maximum benefit by taking the three courses in order, but Course 3 can be taken without Course 2 as a prerequisite.

## The teaming of VT and UMR

This venture teams electrical engineering faculty at two universities, Virginia Tech and the University of Missouri - Rolla, who have initiated efforts to modernize the communications curriculum in response to growth in the personal communications industry. Virginia Tech's MPRG was one of the first university programs to focus on research and curriculum development in the area of wireless communications. Founded in 1990, MPRG has mentored over 100 undergraduate, M.S., and Ph.D. students who now work in the wireless communications industry. Recruiters actively seek MPRG graduates for entry level positions in the wireless industry, and work at MPRG has produced a textbook for wireless communications.<sup>2</sup> At the University of Missouri-Rolla (UMR), there is an active research and curriculum development program for communications systems which is highly regarded. Simulation software tools, textbooks, and techniques for undergraduate and graduate communications courses have been developed.<sup>3,4,5</sup>

## COURSE 1 (Fundamentals of Wireless Communications)

While wireless communications share a common base of fundamental theory with other communications disciplines, educational material which teaches the design of wireless systems at the undergraduate level is not available. In addition, most engineering programs do not fully capture the set of skills required to succeed in emerging business fields such as wireless communications, characteristics which are often associated with *entrepreneurialism*. These skills include:

- \* the ability to work well in teams
- \* the ability to communicate effectively in written and oral forms
- \* the ability to solve open ended problems
- \* persistence
- \* the ability to solve a small number of problems thoroughly rather than a large number of problems superficially

## Objectives of the course

Course 1 will be a senior level course on Digital and Analog Wireless Communications, which will provide the strong foundation in basic communication theory required in undergraduate courses, while introducing the student to wireless communications applications through a series of open-ended "Design Studies." Each Design Study will apply the analytical tools of communication theory to the design of one block of a wireless communications system. The student will then further refine the design using simulation modules, developed in MATLAB<sup>®</sup>, which will allow the student to fully appreciate the results of the selected design. For example, the student will be able to listen to a short segment of speech before and after transmission through the simulated system. Course 1 also emphasizes entrepreneurial skills such as teamwork, solution of open-ended design problems, the cumulative integration of ideas, as well as both oral and written communication skills. The supplementary material for the course will include a videotape seminar series which relates practical technical issues to business decisions in the wireless field, and a series of MATLAB<sup>®</sup> software modules that the students develop.



## **Entrepreneurial flavor**

The students must feel like entrepreneurs who are actively seeking and learning the material needed to solve technical problems in order to build a product. On the first day of class, every student will be welcomed to a “start-up company” with a mission to develop PCS products. Nearly every aspect of the class will focus on that underlying theme, although technical material will not be sacrificed. Students will be assigned to design teams, with each team responsible for developing solutions for one homework problem assigned during the previous week. Each team will also be required to present its solutions to the class, and hold office hours to teach others in the class.

Enthusiasm will be maintained by handing out weekly progress reports, and a couple of “company picnics” will be held for the entire class. A series of supplemental seminars addressing current industry practice and business issues associated with the wireless communications industry will enhance the entrepreneurial flavor of the course. These seminars will feature prominent speakers from the wireless industry. Possible topics for seminars include: FCC licensing and auction procedures, business strategies for wireless communication projects, siting and deployment of wireless base stations, starting a wireless business with venture capital, standards processes in the wireless industry, and the manufacturing and packaging of wireless products.

## **COURSE 2 (DSP in Wireless Communications)**

Communication systems are now being implemented using digital signal processing (DSP). A principal motivation for this approach is that receivers can decode a multitude of cellular standards and be reconfigured easily to match any future changes to the standards. Base stations can update the software of the mobile units to provide flexibility for future growth. DSP techniques also provide interference rejection, which improves cellular communication capacity.

## **Objectives of the course**

The course will focus on the implementation of DSP in communication systems. It will include a laboratory component, and will provide instruction and design experience in the implementation of communication system components such as modulators, demodulators, equalizers, array processors and controllers, and interference cancellation. Students will learn the design tradeoffs necessary when converting theoretical algorithms to actual hardware platforms. Specific tradeoffs that will be covered include: 1) computational complexity vs. power consumption; 2) floating point vs. fixed point computation architectures; 3) antenna diversity vs. signal channel processing; and 4) the overall comparison of algorithms to perform a specific task.

Students will select specific algorithms throughout the semester that will culminate in the implementation of a working wireless modem. The lab will be organized into teams of two students and each team will belong to one of two groups. Each group will design a modem and each team will be responsible for the design and construction of modem subsystems. Innovation and creativity in design will be emphasized. Performance of the modem under a variety of conditions will also be an important factor in student evaluation. Teams will be assigned to critique designs of other team members in a formal, industry-like review. Representatives of industry will also participate in the design reviews, providing a bonding between the industrial visitors and the students.

The lecture portion of the class will have three distinct goals. The first is to have the student understand the classical DSP approaches to implementation of basic modem functions such as equalization,



demodulation, voice coding, timing recovery, antenna steering, etc. Second, the student will learn about the design and analysis tools available for creating DSP-subsystems, such as SPW, COSSAP, SPOX, C-language compilers, ASIC design programs, etc. Finally, the student will examine design alternatives and judgments, including A/D strategies for trading noise and distortion for sampling speed, floating point versus fixed point benefits, antenna diversity combining versus single channel processing, and relative merits of algorithm structures.

### **Floating point versus fixed point implementations**

When developing a DSP laboratory to investigate implementations of systems, such as wireless communication systems, one must make a choice between fixed-point and floating-point implementations. Development systems are readily available for floating-point DSP chips such as those manufactured by Texas Instruments, Motorola, and Analog Devices. Most DSP functions used in communication systems are easily implemented using floating-point hardware, because wordlength effects (quantization error) and overflow are not considerations in floating-point implementations. Unfortunately, basing a DSP laboratory solely on floating-point implementations sends the wrong message to the student since communication system components designed for the mass market (e.g., cell phones) must be placed on the market at the lowest possible cost. Low cost dictates fixed-point implementations. Several of the affiliate companies working closely with MPRG have provided input on this issue, and the corporate world seems to desire students who have experience with the more practical fixed-point implementation.

As a result, there can be no doubt that we desire to develop the laboratory for Course 2 around fixed-point implementation of wireless system components. Because of the difficulties involved, this is not considered a short-term activity, and the laboratory will initially be developed using floating-point implementations. This will allow experiments to be developed quickly and allow us to offer the course sooner. Students will, of course, be made aware that they are seeing only part of the problem and that in an industrial setting, one would wish to use fixed-point implementations for economic reasons. After the laboratories are developed using floating-point hardware, we will begin the move to fixed-point implementations. This two-step approach will allow an orderly development of the laboratory without solving all of the problems of implementation at once.

### **Philosophy of experiments**

The lab component will consist of seven experiments. Due to time limitations, not all experiments may be performed by each group. Information and experience about a particular experiment can be conveyed to other students through the design review meeting. Students who did not participate in the design will be given the opportunity to critique the designs of those who did participate. Lab experiments planned include:

- \* Creation of a signal modulator using direct digital synthesis
- \* Design and implementation of a coherent demodulator
- \* Design and creation of a non-coherent demodulator
- \* Design and implementation of a symbol timing recovery system
- \* Design and implementation of a spread spectrum direct sequence synchronizer
- \* Implementation of an adaptive filter for equalization and interference rejection
- \* A voice coder and decoder.

These individual experiments shall be combined to produce a fully functioning modem. A channel simulator will be made available to the students to help test the robustness of their designs. The use of



development systems will allow us to efficiently design modem projects that will provide insight into code creation, synchronization, and clock recovery techniques.

## **COURSE 3 (Computer Aided Design of Wireless Systems)**

### **Objectives of the course**

As communication systems, especially wireless systems, become more complex, some level of computer-aided design and/or analysis is necessary in order to accurately predict the performance of a given design in a given environment. Fortunately, computer resources are currently available that make it possible for wireless communications engineers to do detailed computer-aided design and analysis studies at their desks. The power of modern workstations and PCs, and the availability of various simulation packages, make this possible. In order to use these simulation-based resources effectively, however, the system designer must understand the various steps involved in moving from a physical model of the system of interest to a simulation model.

### **The role of projects**

Simply stated, the objective of Course 3 is to give students the tools necessary to develop accurate simulations of wireless communication systems and the insights necessary to use these tools effectively. Unfortunately, this is a tall order since wireless communication systems are usually complex and operate in a random (stochastic) environment. Stochastic simulation is a difficult subject that draws from many fields of study including number theory, estimation theory, probability and stochastic process theory, and linear and nonlinear system theory, to name only a few. Students must appreciate the fact that there is a fundamental difference between mathematical analysis and simulation. The result of mathematical analysis is usually a fixed constant, i.e., a number. The result of a simulation is a random variable, and the properties of this random variable must be understood in considerable detail if the simulation is to provide useful results. Students must understand the tradeoff that exists between the detail and accuracy of the simulation model and the efficiency of the simulation. Simulations based on highly detailed models certainly provide very accurate results, possibly results that are more accurate than needed for the problem at hand, but take excessive execution time. Students must learn that, in some ways, a well-developed simulation is much like a hardware prototype. Experiments and parametric studies can be performed. We can play “what if” games with various system parameters or, for that matter, with the entire system architecture. Students learn that iteration is an important step in the design process.

In order to use simulation effectively, students must be able to define the problem to be solved very precisely so that the simulation contains the system models germane to the problem at hand and nothing more. This will result in the most efficient simulation. As an example, if bit synchronization is not an issue, perfect synchronization may be assumed and those models dealing with bit synchronization may be eliminated from the simulation model. Students must look ahead to the products to be generated by the simulation so that after the simulation has executed, the data generated is sufficient to answer the questions originally posed. In addition, students must be able to use basic theoretical tools and concepts to “validate” a simulation. In other words, one must be able to show that a simulation produces reasonable results for the problem at hand.

It is easy to see that Course 3 will present to the student a set of questions and concerns that are quite different from those questions and concerns raised in other courses.



It is certainly true that “we learn by doing,” and learning the art of producing efficient and accurate simulations of complex communication systems is no exception. Student projects are, therefore, an important component of the simulation course. The student will develop simulations of systems in which the student has an interest. As a result, the student not only has an opportunity to apply the various theoretical tools developed in class, but also has the opportunity to explore the manner in which these tools are applied to specific systems operating in a particular environment. In order to develop a successful project, the student must be able to accomplish the following:

1. Gain a complete understanding of the system to be studied.
2. Identify those attributes of the system that are to be studied and identify the simulation products (BER curves, waveforms, spectra, etc.) which allow the questions of interest to be answered.
3. Develop a software model of the system and understand the approximations involved in moving from the physical system to the software model. Obviously, the model must focus on the attributes identified in (2) above.
4. Gain an understanding of the environment in which the system is to operate (SNR, fade rate, delay spread, etc.).
5. Develop a software model of the environment complete with an understanding of the approximations and error sources involved with the model.
6. Develop a simulation of the overall system, including the environment model.
7. Use theory, bounding techniques, linearization techniques, etc., as necessary to predict system performance, as well as waveforms (time and frequency), histograms, etc., present at various points in the system.
8. Combine theoretical and simulation results in a way that allows one to gain confidence that the system simulation is operating correctly.
9. Use the simulation to study the system attributes and answer the questions identified in (2) above.

This is an ambitious list, but by considering the steps identified above through the course of a semester, the student gains an appreciation of the role of simulation in the design and analysis process.

Each project begins life as a proposal submitted by the student early in the semester. The proposal identifies the system to be studied, the scope of the proposed project, the motivation for selecting the proposed project, the simulation methodology (Monte Carlo, semi-analytic, etc.) to be applied, the computer language to be used (along with a justification), simulation products (BER curves, eye diagrams, etc.) to be produced, and the computer resources to be used. The proposal also contains a statement that identifies any unusual requirements, outside of those normally supplied by the department, and a statement of how these resources are to be obtained.

The proposed project can be original or it can be a project selected from a “project notebook.” This “project notebook” is supplied by the faculty early in the semester in order to help students identify a project and appropriately establish the scope. For each project in the “project notebook,” the following is provided:

- Statement of objectives for the project
- Basic theoretical background
- List of suggested deliverables
- List of important references

Example projects identified in the project notebook include the following:



- \* Signal-to-Noise Ratio Estimation in Communication Systems
- \* Simulation of Asynchronous CDMA Systems
- \* Simulation Studies of Convolutional Coders and Decoders
- \* Multiuser Receivers for Synchronous CDMA Systems
- \* Voice Quality Assessment
- \* Data Compression Using the Lempel-Ziv Algorithm
- \* Simulation and Testing of a RAKE Receiver
- \* An Implementation and Study of Importance Sampling Using MATLAB<sup>®</sup>

Each student develops a formal written report presenting the results of the project. Oral reports are also required. We have allowed students to work individually, but team projects are preferred. The three-course sequence has a heavy emphasis on solving problems relevant to industry in a setting as close to an industrial atmosphere as can be accomplished in a university environment. Thus, teamwork is an essential part of the process.

### **Simulation tools developed for the course**

A number of simulation tools are being developed for Course 3. A suite of MATLAB<sup>®</sup> models relating to the various components of a wireless communication system have been developed and more are under development. A complete simulation of an asynchronous CDMA system, together with a RAKE receiver, has been developed as a result of a student project. Various simulation-based tools for channel modeling and wireless system performance prediction have been developed by MPRG faculty and graduate students over the past few years. These serve as resources for developing new tools of a similar nature targeted for Course 3. In addition, an end-to-end simulation of a wireless communication system, containing a rich library of modulators, receivers, coders, decoders and channel models, is under development. This system will feature a MATLAB<sup>®</sup>-based postprocessor.

## **OTHER ATTRIBUTES OF THE WIRELESS CRCO PROGRAM**

### **The role of MATLAB<sup>®</sup>**

MATLAB<sup>®</sup> is now a standard tool for the analysis of complex systems, and has been integrated into the engineering curricula of many departments. In addition, MATLAB<sup>®</sup> code is used in an increasing number of textbooks to document signal processing algorithms and to illustrate the operating characteristics of complex systems. MATLAB<sup>®</sup> is very well supported and a number of books are available illustrating the clever use of MATLAB<sup>®</sup> for problem solving and for system design. The available documentation is excellent. In addition, the processing power of MATLAB<sup>®</sup> and its rich library of routines make it the ideal candidate for this type of project. The code is very concise, which is an advantage for dissemination.

The senior level course (Course 1) will use MATLAB<sup>®</sup> simulation modules which will allow students to see and hear the results of their designs. By using audio files or speech or music, the students can hear the effect of changing system parameters. These modules will also allow students to specify design parameters based on analysis, and to iterate that design based on simulation results. Exposure to simulation as a design methodology will provide important background to students who eventually take the graduate course (Course 3) on simulation.

The graduate course (Course 3) will use MATLAB<sup>®</sup> simulation modules to provide simulation problems and a wide range of exercises that permit students to explore a large collection of communication





systems (optical fibers, satellites, microwave links, mobile radio communication systems). Experiments will be carried out to visualize communication system performance. System parameters, such as filter bandwidths and signal powers, can be readily changed, allowing students to see how system performance is altered, and how certain system designs may be more robust than others.

### **Web pages and dissemination strategy**

WWW pages have been established for this project. The purpose of the Web pages is to inform other schools of our work and to pass along to them wireless examples, demonstrations based on simulation of wireless systems, and MATLAB<sup>®</sup> exercises and simulations. The URL for the Web page is:

<http://www.ee.vt.edu/mprg/education/nsf/nsf.html>

It is hoped that schools will use these materials to present examples based on wireless communication systems in their basic communications courses and in their DSP courses, even if they do not elect to dedicate a three-course sequence to these subjects as we have done. It is our strong desire that those who have interest in wireless systems, both as an academic subject and as a research interest, will access these pages and provide us with feedback on the material provided.

In addition to the Web pages discussed above, several new textbooks will be based upon the three-course sequence described in this paper [2]. A contract was recently signed with Prentice Hall for a textbook for Course 3. It should also be mentioned that MPRG (The Propagator) and UMR (Current Transmissions) have periodic publications that go to friends, supporters and alumni. The status of the curriculum development project will be updated in these publications. The combined circulation list for these two publications exceeds 10,000.

Other materials are also being developed as a result of the curriculum development effort. The "project notebook" previously mentioned in connection with Course 3 is a valuable resource for the student and for one teaching the course for the first time. At some point the project notebook may be submitted for publication but, in the interim, we are willing to share this resource. A file is maintained that contains the final reports for all completed projects.

### **The role of MPRG affiliates and IEEE Press**

A major strength of MPRG lies in its industrial affiliate program. There are now 14 industrial affiliate companies supporting the research efforts of MPRG. These affiliates come from all sectors of the wireless community including research groups, service providers, and hardware manufacturers and vendors. They work closely with MPRG faculty to ensure that the MPRG research program is appropriately focused. The affiliates therefore represent a unique knowledge pool to ensure that the three courses being developed as a part of this project are providing the necessary tools to allow students to be major contributors to the industry upon graduation.

The IEEE Press has also offered to support the curriculum development project by videotaping and distributing the videotapes of seminars presented as a part of this effort. The IEEE Press may also be involved in the publication of other materials that are developed.

### **CONCLUSIONS**



This paper has described a trilogy of electrical engineering courses being developed by faculty at Virginia Tech and UMR under the NSF CRCD program. The curriculum innovation is being developed in response to the growing demand for electrical engineers with the expertise to design and deploy new wireless communications services and products. The senior and graduate level courses include hardware and software components, along with a change in teaching style, and will be incorporated into the curriculum at both Virginia Tech and UMR. Textbooks, software modules, videotapes, and revolutionary laboratory/hardware experiences developed under this program will be made available to universities world-wide, over the Internet and through widely available texts and notes.

## REFERENCES

- <sup>1</sup> Rappaport, T. S., "The Wireless Revolution," *IEEE Communications Magazine*, Vol. 29, No. 11, November 1991.
- <sup>2</sup> Rappaport, T. S., *Wireless Communications: Principles and Practice*, Prentice Hall, 1996.
- <sup>3</sup> Tranter, W. H. and K. L. Kosbar, "Computer-Aided Design and Analysis of Communication Systems," Chapter 72 in *The Electrical Engineering Handbook* (R. C. Dorf, Editor), CRC Press, 1993.
- <sup>4</sup> Tranter, W. H., and K. L. Kosbar, "Simulation of Communication Systems," *IEEE Communications Magazine*, Vol. 32, No. 7, July 1994.
- <sup>5</sup> Ziemer, R. E. and W. H. Tranter, *Principles of Communications: Systems, Modulation, and Noise*, Houghton-Mifflin Publishing Company, 1976, 1985, 1990, 1995.

## BIOGRAPHICAL INFORMATION

THEODORE S. RAPPAPORT is a Professor of Electrical Engineering at Virginia Tech in Blacksburg, VA. In 1990, he formed the Mobile & Portable Radio Research Group (MPRG) of Virginia Tech. He was awarded the Marconi Young Scientist Award in 1990, the NSF Presidential Faculty Fellowship in 1992, and has authored the textbook *Wireless Communications: Principles & Practice* (Prentice Hall).

WILLIAM H. TRANTER is Schlumberger Professor of Electrical Engineering at the University of Missouri - Rolla. His research interests lie in the areas of digital signal processing and computer-aided design and analysis of communication systems.

JEFFREY H. REED is an Assistant Professor at Virginia Tech's Bradley Department of Electrical Engineering and has been a member of the Mobile and Portable Radio Research Group since 1992. Dr. Reed's interest is in DSP algorithm and hardware development for wireless communications. He has a special interest in DSP interference rejection techniques.

BRIAN D. WOERNER is an Assistant Professor of Electrical Engineering at Virginia Tech, where he teaches and conducts research in the field of wireless communications. He received his BSCEE degree from Purdue University in 1986 and his MSEE and Ph.D. degrees from the University of Michigan in 1987 and 1991 respectively. He has been director of the Mobile and Portable Radio Research Group since 1994.



DONNA M. KRIZMAN received her BSEE and MSEE degrees from Virginia Tech in 1983 and 1992, respectively. She is currently a Ph.D. candidate in electrical engineering, working with Prof. Rappaport and Prof. Tranter on simulation of wireless communication systems.

