Technology-based Analog and Digital Microsystem Design

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Abstract

The telecommunications industry is one of the fastest growing industries in the United States. Fueling this growth is the high degree of computational power made possible by advances in microelectronic fabrication and design. To contribute to this technology upon graduation, our students must have the necessary background that includes digital and both baseband and high frequency analog design skills. This paper describes a senior sequence in digital and analog microsystem design that uses a unique mix of lecture, projects and laboratory measurements to address telecommunication microsystem technology. The course material emphasizes the design and operation of key components and subsystems of telecommunication systems.

Introduction

The advent of low cost telecommunication equipment and related systems brings new challenges to engineering faculty asked to educate engineers in these new technologies. Our students must have the necessary background that includes both digital and analog microsystem design skills to contribute to this technology upon graduation. To gain an appreciation of the magnitude of these challenges, consider the block diagram of a generic telecommunication system illustrated in Figure 1. The receive side is the upper branch, while the transmit side is the lower branch. In systems such as these, there are high frequency analog components in the front end (left section), a signal processing section that most likely includes complex digital signal processors and data conversion devices (middle section), and a low frequency analog section (right) that provides the interface with the user. As indicated in the figure, the graduating student must have a diverse background in microsystem design to appreciate and address the issues involved in the creation of products based on this system topology. This paper describes a senior electrical engineering sequence in digital and analog microsystem design that uses a unique mix of lecture, projects and laboratory measurements to address the education of these topics to undergraduate students. The discussion that follows describes a senior sequence in microsystem design at the University of Massachusetts Dartmouth that addresses some of these challenges. The first course in the sequence, digital microsystem design, is a required course for computer engineering students and a popular technical elective for electrical engineering students. The second course in the sequence, analog microsystem design, is a technical elective for both majors.

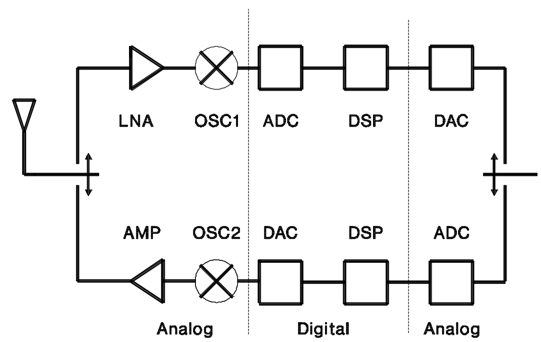

Figure 1. Block diagram of a typical telecommunication system. Graduate engineers will be required to be able to design systems using fully integrated technologies.

Microsystem and Telecommunication Design at the Undergraduate Level

During the 1980s, many universities introduced courses in digital microsystem design at the undergraduate level. These courses owed their origin to the landmark textbook on digital microsystem design by Mead and Conway [1]. These introductory courses continue to cover much of the same material, including a review of digital systems, the integrated circuit design process, standard cell design (usually digital logic primitives and programmable logic arrays), memory and digital systems design using examples such as microprocessors and microcontrollers. CAD tools that allow complex designs to be readily undertaken take a front seat in a first course so that students receive a first hand look at the power of these tools and the complexity of system design that they facilitate. Students have the opportunity to fabricate their full custom designs using various mechanisms such as the NSF-sponsored broker MOSIS.

The recent shift towards other rapid prototyping options for digital design based on new technologies such as the field programmable gate array (FPGA) has reduced the need for full custom designs and FPGAs and are widely used for proof of design concept (POC). New courses have been introduced based on FPGA technology at many schools. FPGAs, while excellent tools for POC and rapid turnaround from design to product, do not provide engineers the important background needed for full custom integrated circuit design that the new emerging products and markets will demand.

The increasing market for engineers knowledgeable in the field of telecommunications, specifically in the area of low cost, high volume products that are physically small but with complex functionality, is presenting new challenges for those educating the next generation of engineers. These new systems require high levels of system integration that can only come about with full custom systems on a single chip. These digital systems will have to interface with input and output analog circuitry, making a second course in analog microsystem design a necessity. Courses in analog design at the undergraduate level are not as widespread, but as indicated in Figure 1, are key systems that must be understood for full appreciation of these systems. The next section provides a detailed look at the microsystem design course sequence offered at the University of Massachusetts Dartmouth.

The Digital Course

The new focus on microsystem design for telecommunications changes some aspects of the traditional microsystem design education, but material crucial to the understanding of the entire integrated circuit design and fabrication process is still retained. The material in this first course focuses on the digital processing and control represented by the middle section of the generic system shown in Figure 1. The presentation of material important to microsystem design, such as a review of digital system principles as well as the integrated circuit fabrication process, is still an important part of the digital course. Standard cell and layout design are discussed since they are integral parts of any system design. Design case studies are frequently used to illustrate design, layout and fabrication concepts. Telecommunication subsystem blocks that are covered include digital filters, controllers and error correction and detection circuits. An extensive capstone design project is used to bring all the material in to focus. A full list of topics that are covered in the introductory digital course is listed in Appendix A.

The use of CAD tools is a necessary part of the design process that can not be learned strictly through lecture material. The choice of CAD tool suite varies from university developed tools (MAGIC, SPICE) to commercial tools (Mentor, Cadence), with the ultimate choice dependent on constraints usually outside the scope of the course. The digital microsystem course at the University of Massachusetts Dartmouth uses full custom university-based tools (MAGIC, SPICE) since the follow-on analog course requires the use of full custom layout. The importance of using CAD tools for a microsystem design course brings a real-life experience to the students. The design of a complex circuit, including its layout and simulation, brings to the surface many issues that are covered in lecture but are not appreciated by the students until the actual design process begins.

To add more realism to the microsystem design process at the University of Massachusetts Dartmouth, students in this first microsystem design course are encouraged, but not required, to use the course design project as part of the senior capstone design project. These students are encouraged to bring their full custom design to fabrication. This course of action provides a real-life engineering experience that allows the student to design an integrated circuit as part of a larger system, requiring *a priori* knowledge of the system requirements. This process also imposes realistic constraints of project deadlines defined by external forces (fabrication foundry) rather than the simple academic calendar. The effects of schedule slippage must be worked in to their project, so the students must have a "fallback" system. The benefit in this approach is that students are heavily invested in their own integrated circuit as a key component of their senior design project rather than just as a project for the design course. Our experience has shown that senior capstone projects that have student-designed integrated circuits consistently have a much higher level of understanding.

The Analog Course

As illustrated in Figure 1, many subsystems involved in a telecommunication system are analog in nature. These analog components will still be key components of any system regardless of the modulation scheme (various worldwide standards use analog, digital or some hybrid schemes [2]) employed since some means for transmitting the data and interfacing with users is necessary. Many universities around the country are beginning to recognize this fact and are introducing analog microsystem design courses as either stand alone courses or coupled with the digital design course. These courses typically cover circuits and systems that are relatively low frequency in nature: operational amplifiers, switch capacitor (or switched current) networks and data conversion devices (see Appendix A for a more complete listing). These topics adequately cover the low frequency section (Figure 1).

In analog design, there are many more component variables that must be considered than in a digital design. Unfortunately, by the time sufficient material has been covered in class to do a significant project, the fabrication turn around time pushes the acquisition of the finished chip out of the course term (there is currently no FPGA equivalent for analog prototyping). What is needed is a means for students to learn the course material and then be able to simulate and test these circuits as soon as possible after the lecture as a method to enhance their understanding. One way we accomplish this task is to provide the student with a "resource kit" containing a set of pre-fabricated analog CMOS circuits and an accompanying set of tutorials and simulation laboratories aid in evaluation of analog circuits. This "Analog Design Resource Kit," supported by a grant from the National Science Foundation and available to engineering educators nationwide (see Appendix A), acts as a supplement to analog CMOS VLSI design courses, but does not prevent the assignment of individual student projects. Rather, the students will be able to undertake projects with a greater degree of understanding, which will translate into a more meaningful design experience for them. The students perform at least four measurement experiments each semester, in addition to three or four small projects and a final course design project.

Recent research and educational interests are now focusing on high frequency microsystem circuit design utilizing CMOS devices. This trend allows full "systems on a chip" by integrating the RF front ends, the digital signal processing and low frequency analog blocks using the same fabrication technology. To provide a complete view of the telecommunication system, this high frequency material must be introduced. New material has recently been introduced into the second semester analog design course to answer this trend. The new material focuses on low noise amplifiers, RF power amplifiers (100 mW or less) and integrated MOS mixer technology. Included in the discussion of these system blocks is nonlinear circuit operation, essential to understanding mixer operation as well as circuit distortion (intermodulation and distortion intercept points). The analysis of differential amplifiers and balanced mixers, with an eye toward integrated MOS design, are covered. The next phase of the course is to introduce simulation and measurement experiments to support understanding of these circuits.

Conclusion

This paper has presented a two semester senior course sequence that teaches electrical engineers the concepts in digital and analog microsystems design, with an eye toward fully integrated telecommunication systems. The high frequency analog component of the course has recently been introduced, but is an important part of understanding the entire system as shown in Figure 1. Further evolution of this portion of the course will focus on new simulation assignments as well as at least one new circuit on the analog design chip set to support this new course emphasis.

Acknowledgment

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4. Geiger, R., P. Allen and N. Strader, *VLSI Design Techniques for Analog and Digital Circuits*, McGraw-Hill Publishing Co., New York, 1990.

5. Gray, P. and R. Meyer, *Analysis and Design of Analog Integrated Circuits*, John Wiley and Sons, Inc., New York, 1993.

Appendix A

Topics Covered in the Introductory Digital Microsystem Design Course

The following list of topics is covered in the first digital microsystems course and the University of Massachusetts Dartmouth. Much of this material is covered in the many textbooks out on digital microsystem design. This list of material must be supplemented with additional notes.

Basic CMOS Digital Circuit Topologies, Review of Digital System Fundamentals, Electrical Properties of Silicon. Operation of MOS Field Effect Transistors, Fabrication of MOS Devices, Properties of Digital CMOS Circuits, CMOS and VLSI Design Rules, Chip Layout and Practical Realities, Circuit Characterization and Estimation, Scaling of MOS VLSI Circuits, Circuit Layout Hints, Circuit Examples and Design, Dynamic Logic Issues, Input/Output Structures, Design Case Studies: microcontrollers, ALUs, digital signal processors, Memories and Other Register Circuits, Testing

Topics Covered in the Introductory Analog Microsystem Design Course

The following list of topics is covered in the second course in the microsystems design course sequence at the University of Massachusetts Dartmouth. Much of this material is reviewed in textbooks such as indicated in References 3-5.

Device structures encountered in analog VLSI systems, simple analog circuit operation (active resistors, on-chip and RF switches, simple amplifier structures, current sources, sinks, mirrors), nonideal device behavior (noise, distortion), and voltage references, differential and operational amplifiers, comparators, analog system design (filtering, data conversion techniques, other analog signal processing). Included in the lecture material is a series of design and laboratory measurement projects using the Analog Design Resource Kit. This kit contains a prefabricated chip set and accompanying tutorials covering many of the basic analog circuits listed above, and may be retrieved over the World Wide Web at the following URL:
http://www.ece.umassd.edu/ece/studies/vlsi/vlsi.htm