2006-480: EFFECTIVE INTEGRATION OF ELECTROMAGNETIC COMPATIBILITY AND SIGNAL INTEGRITY IN ELECTRICAL AND COMPUTER ENGINEERING CURRICULA

Edward Wheeler, Rose-Hulman Institute of Technology

Edward Wheeler is Associate Professor in Electrical and Computer Engineering at Rose-Hulman Institute of Technology. He received a Ph.D. in electrical engineering from the University of Missouri-Rolla in 1996. His interests include electromagnetic compatibility, the electrical and optical properties of materials, and engineering education.

JianJian Song, Rose-Hulman Institute of Technology

Jianjian Song is Associate Professor of Electrical and Computer Engineering at Rose-Hulman Institute of Technology. He received a Ph.D. degree in electrical engineering from the University of Minnesota in 1991. His interests include electromagnetic compatibility, high-speed digital system design, microcontroller-based system design, embedded and real-time systems, electronics design automation, and algorithms and architecture for parallel and cluster computing.

David Voltmer, Rose-Hulman Institute of Technology

David Voltmer is Professor of Electrical and Computer Engineering at Rose-Hulman Institute of Technology. He received a Ph.D. in electrical engineering from Iowa State University in 1961. His interests include electromagnetics, microwave metrology, systems engineering, and entrepreneurial student projects.

Effective integration of electromagnetic compatibility and signal integrity in electrical and computer engineering curricula

Abstract: The frequencies and switching speeds used by today's high-speed electronic systems require engineers who understand electromagnetic compatibility and signal integrity for system design and layout. At Rose-Hulman, we are responding to this emerging need by introducing courses which effectively integrate high-speed design into our undergraduate curricula. Initial steps include one new required course and one redesigned elective course for our computer engineering curriculum and redesigning our required two-course electromagnetics sequence in our electrical engineering curriculum.

Introduction

Fifteen years ago, clock speeds on personal computers were 33 MHz. Today, clock speeds have reached 3 GHz—an almost hundred fold increase. This trend will continue with the International Technology Roadmap for Semiconductors calling for on-chip frequencies of 12.4 GHz and chip-to-board frequencies of 7.6 GHz by 2009. At 7.6 GHz, wavelengths are between two and three centimeters. Engineers working in this environment—from design to application to installation—require a thorough understanding of the electromagnetic principles that provide the basis of effective high-speed design.

Most electrical and computer engineering departments do not adequately prepare their undergraduate students to work in high-speed design. The result is that electrical and computer engineering (ECE) departments will soon face the prospect of having a majority of their graduating electrical and computer engineers ill-prepared to work effectively in this emerging high-speed environment. With increasing speeds and frequencies, needs in this area will only grow and engineering education in the United States must begin responding to this challenge, beginning at the undergraduate level. To this end, one of the first steps needed is to integrate topics which support high-speed design into core undergraduate ECE curricula

At Rose-Hulman Institute of Technology (RHIT), we are developing a high-speed design program in which the educational foundations of our high-speed design program are provided by courses that explore electromagnetics, electromagnetic compatibility and signal integrity. System-level issues are then discussed in courses in high-speed design and are extended via applications in wireless systems. Planned courses include a laboratory-based course in modeling and measurement and a course in RF integrated circuit design.

In this paper we report on courses in electromagnetic compatibility (EMC), signal integrity (SI), and high-speed design that will provide the foundations of the high-speed design program being developed . The needs of both disciplines, electrical engineering and computer engineering, must be kept in view. In the discussion below, therefore, keep in mind that, since electrical engineering and computer engineering students typically have backgrounds which differ significantly in electromagnetic fundamentals, any practical program designed to integrate EMC and SI into ECE curricula must address these differences to ensure plans are practical and so that both groups benefit to the greatest extent possible.

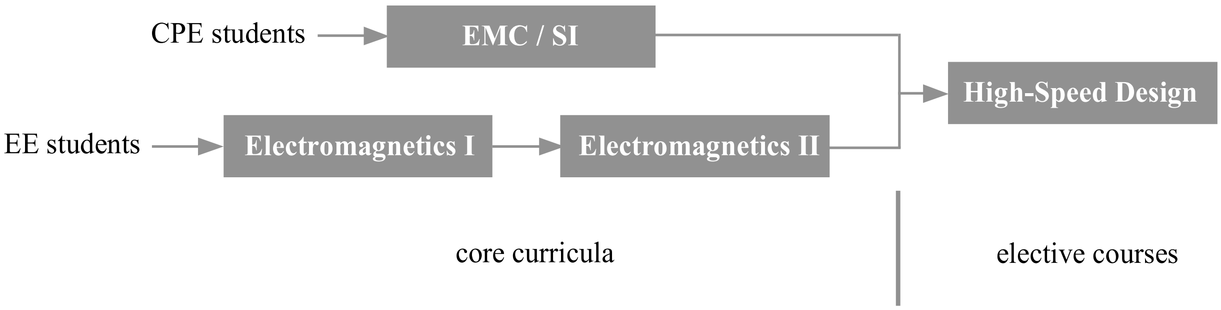

Figure 1: RHIT undergraduate high-speed design program foundations

Background and Present Status

At Rose-Hulman, the need to better prepare our students became apparent five years ago in an elective high-speed design course, which was taken primarily by our computer engineering (CPE) students and which has been offered at Rose-Hulman since 1999. A current topic listing for the high-speed design course is given in Table 1.

Table 1: Topics for elective high-speed design course for computer engineers

Week	Topics			Lab / Demo
1	Trends and issues in high-speed design	Driver and receiver, noise margins, setup and hold times, noise sources	Skew, jitter, timing margins, clock timing budget	
2	IBIS	Transmission line review	R_{PU} and R_{PD} example Bounce diagram	Hyperlynx tutorial
3	Review of RC circuits, bounce diagrams of multiple lines	Capacitive and inductive loading of transmission lines	Termination techniques, RAMBUS termination, multiport	Terminations
4	Eye diagrams, intro. to time-domain reflect.	TDR examples (RC and RL circuits)	TDR examples (RC and RL circuits) HP AN 1304-2	Orcad TDR simulation (individual lab)
5	Impedance profiling, spectral content for squarewave and trapezoidal signals	System freq. response Bode plots	EXAM 1	No lab
6	Crosstalk Hyperlinx examples	Three-conductor crosstalk modeling	Time-domain crosstalk, lumped-component models	TDR
7	Power planes	Simultaneous switching noise	Power-delivery system design	Decoupling with SPEED2000
8	SPEED2000 introduction project initialization	Differential design for high-speed applications	EXAM 2	Ground noise
9	EXAM 2	Project	Project	Project
10	Project	Project	Project	Oral presentation

At that time, our computer engineering curricula, like most other computer engineering programs, did not require courses in electromagnetics other than that contained in sophomore physics classes. The computer engineering students taking the high-speed design course were hampered by a lack of knowledge in electromagnetics, e.g., coupling mechanisms, passive component frequency variations, and transmission line fundamentals. The inadequate student background resulted in the class material being treated in a "cookbook" fashion that, not surprisingly, resulted in student learning outcomes that were insufficient to produce a foundation for future learning or work in high-speed design.

Our response was to design a *required* EMC/SI course for our CPE students. NSF has supported this effort which has resulted in better prepared students in the elective high-speed design class. Having better prepared students has, in turn, required the high-speed design course to be continually augmented and improved.

Computer Engineering Core: The intent in including the EMC/SI course in the core CPE curriculum is to ensure that all our CPE students have sufficient background to pursue a study of high-speed design with more success. The require EMC/SI course focuses on electromagnetic fundamentals, electromagnetic compatibility, and signal integrity. It serves as a kind of "electromagnetics for computer engineering students." A listing of topics in the required EMC/SI course for computer engineers is given in Table 2.

Table 2: Topics for required EMC/SI course for computer engineers

Week	Topics			Lab / Demo
1	EMC definition, history, examples; electrical dimensions	EMC units, regulations, measurements, and instrumentation	Non-ideal behavior of components and spectrum analyzer	EMC measurements
2	Construct a LC model of a capacitor from its frequency response	Frequency behavior of an inductor, Coordinate systems	Low-pass filter design and measurement	Spectrum analyzer and freq. response of passive comp.
3	Electric field, work, voltages	Gauss' law, electric flux density, capacitance	Ampere's law, magnetic field, magnetic flux	Inductive coupling
4	Faraday's law and inductance, examples	Faraday's law and inductance, examples	Capacitive and inductive coupling	Coupling and shielding
5	Transmission lines, v_p, reflection coefficient	Bounce diagrams	EXAM 1	Transmission line simulations with PSPICE
6	Bounce diagrams	Antenna introduction	Electric (Hertzian) dipole, monopole	Antenna review and demo
7	Magnetic dipole, antenna tuning	Antenna factor, common and differential modes	Common and differential modes	A high-frequency low-pass filter implementation
8	Radiated emission for wires and PCB lands	Susceptibility for wires and PCB lands	Review	Review
9	EXAM 2	Shielding: far- and near-field sources	Shielding: far- and near-field sources	Apertures and EM shielding
10	Conducted emissions measurement	Power supply filters	Review and examples	Review and examples

Over 100 Rose-Hulman CPE students have taken the required EMC/SI course. [1,2] The CPE students from this course who take the subsequent elective course in high-speed design are much

better prepared to undertake a meaningful study of high-speed design. As mentioned above, these changes were instituted to improve student learning outcomes in high-speed design. Because of these changes, a first revision of the elective high-speed design course was required for the 2005-2006 academic year to raise the level of rigor and to include additional topics. A second revision is planned for 2006-2007. While more thorough assessment is planned, we conclude from this that our learning outcomes are improving! Students and employers report that the required EMC/SI course provides our computer engineering graduates a competitive advantage over graduates without similar background.

A draft version of an EMC/SI Concept Inventory Test is being developed for the CPE course and will be presented at the conference this summer.[3,4]

Electrical Engineering Core: Since 1999, many of our electrical engineering (EE) students have, along with CPE students, enrolled in the high-speed design course. In response, we have redesigned our required two-course electromagnetic sequence in our electrical engineering program so that our EE students are also well prepared to study high-speed design. This work is supported by the same NSF project as mentioned above. Initial plans for the redesign are complete and will be implemented in the 2006/2007 academic year.

A problem in many electromagnetic courses is that student learning is based on theoretical concepts and equations which students tend to memorize with little real understanding. There is a lack of student involvement with and observation of electromagnetic phenomena. To overcome these deficiencies, the classes described in this paper emphasize conceptual and experiential learning. Adapting the work of E. Mazur,[5] frequent *Concept-Quizzes* will be used to enhance student conceptual understanding and significant demonstration and simulation activities are included in the courses.

It is important to use CAD simulation tools in electromagnetics courses in order to demonstrate to students that electromagnetics is more than studying ever more challenging solutions to Maxwell's equations. CAD tools allow students to better appreciate the power and practicality of electromagnetics and demonstrates that electromagnetics is an integral part of their education as electrical engineers. Too many engineering students are presently being turned off by electromagnetics. In classes where CAD tools are not used and where there are no demonstrations or laboratories, many students develop a strong aversion to the study of electromagnetics simply because they cannot understand how electromagnetics can be applied or how it is used in design. With predictions of continuing increases in system speeds, this does not serve our students or our stakeholders well.

The redesign electromagnetic courses for EEs will include discussions of non-ideal behavior of components, coupling mechanisms, transmission lines, signal integrity, shielding. The learning environment in the two courses will include weekly reading quizzes, weekly conceptual quizzes, on-line materials including supplemental notes, detailed step-by-step examples, interactive examples on applications in text, and Camtasia tutorials. CAD tools include *CST EM Studio*, *CST Microwave Studio*, *PSpice* and *Hyperlynx*. The changes will not only better prepare EE students for high-speed design, but will also result in improvements in student understanding of and engagement in electromagnetics. A listing of planned topics for the EM two-course sequence is given in Tables 3 and 4.

Table 3: Topics for ***first*** required EM course for electrical engineers

Week	Topics			
1	Charge, electric field	Force, energy, potential, conservative fields	Energy, potential gradient, electric field	Electrostatics simulation *CST EM Studio*
2	Conductivity, charge conservation	Boundary conditions for **E** and **J**	Examples and applications	Divergence, charge conservation
3	Line and surface integrals	Laplace, potential, electric field	Examples and applications	Resistance, analytic, numeric
4	Examples	Electric flux density, Gauss' law	Permittivity, BCs for **E** and **D**	Examples and applications
5	Capacitance, analytic, numeric	TEST 1	Examples and applications	*Demonstration:* direct determination of permittivity
	Ampere's law	Examples and applications	Magnetic fields, Biot-Savart	Examples and applications
6	Permeability, magnetic flux density	Forces and torques	Examples and applications	Magnetostatics simulation *CST EM Studio*
7	BCs for **B** and **H**	Magnetic circuits	Inductance	Inductance, analytic, numeric
8	Examples and applications	*Demonstration:* inductance, field containment	Continuity, relaxation time	Faraday's law
9	Examples and applications	TEST 2	Transformer and motional EMF	Ampere, displacement current, and Maxwell's equations
10	Examples and applications	Non-ideal behavior of Rs, Ls and Cs	Non-ideal behavior of Rs, Ls and Cs	*Demonstration:* non-ideal behavior of Rs, Ls, and Cs

A tentative list of CAD projects and demonstrations to be incorporated into the *first* required EM course for electrical engineering students follows:[6]

- Electrostatics – charge, potential, Gauss's law, the electric field and flux mapping, capacitance (CST EM Studio)
- Magnetostatics – current, Biot-Savart law, magnetic field and flux mapping, Ampere's law, signal current and signal current return, inductance (CST EM Studio)
- Faraday's law (CST EM Studio)
- Wave propagation (CST Microwave Studio)
- Current takes the path of least impedance (demo)
- Direct evaluation of permittivity (demo)
- Developing an equivalent circuit model for a wire-wound inductor connected to the source through lead inductance (demo)

- Magnetic field coupling through simple hand-size multi-turn loops, and identifying and quantifying coupling structures at the printed circuit board level (demo)

Table 4: Topics for ***second*** required EM course for electrical engineers

Week	Topics			
1	Electromagnetics	EM waves	TEM plane waves	Examples
2	Propagation in lossy materials	Propagation in lossless materials	Poynting's vector, polarization	Propagation in low-loss materials
3	Propagation in a good conductor and skin effect	Examples and applications	Reflection and transmission	Reflection and transmission: normal incidence
4	Reflection and transmission: oblique incidence	Examples and applications	Transmission lines, Telegrapher's equations	Lossless lines, low-loss lines
5	Terminated T-lines, power	TEST 1	Examples and applications	Smith chart
6	Impedance matching	Examples and applications	Stub tuners	Examples and applications
7	Transients, bounce diagrams	Time-domain reflectometry	Reactive loads	*Demonstration:* TDR, transmission line models
8	EMI, interference sources	Electric field coupling	Magnetic field coupling	*Demonstration:* crosstalk
9	TEST 2	Impedance control, signal integrity	Examples and applications	Decoupling, current control,
10	Conducted emissions	Conducted emissions, filtering	Shielding	*Demonstration*: shielding effectiveness

A tentative list of CAD projects and demonstrations to be incorporated into the *second* required EM course for electrical engineering students follows:[6]

- Capacitive & inductive crosstalk on an electrically short signal bus (Hyperlynx)
- Signal/pulse propagation on electrically long signal lines – quantifying electrically long in the time- and frequency-domains, and using lumped element modeling versus distributed transmission line models (Hyperlynx)
- Signal propagation on transmission lines (Hyperlynx)
- Shielding effectiveness of a PC enclosure (CST Microwave Studio)
- Multi-conductor transmission lines and cross-talk (Hyperlynx)
- Non-ideal effects of signal routing and transmission (CST Microwave Studio)
- Distributed systems vs. lumped element systems (demo)
- Capacitive & inductive crosstalk on an electrically short signal bus (demo)
- Signal/pulse propagation on electrically-long signal lines and using lumped element modeling versus distributed transmission line models (demo)
- Frequency dependence and modeling resistor, inductor, and capacitor impedances (demo)

- Shielding effectiveness of a PC enclosure and the importance of apertures and seams. (demo)

Class Examples

Example of time-domain reflectometry from 2nd required EM course for electrical engineers: A 10 volt pulse is introduced into a 75 Ω transmission line having $v_p = 10^8$ m/s. 11.3 μs later, a -2 volt pulse is observed at the TDR unit. What information is available about the discontinuity and its location?

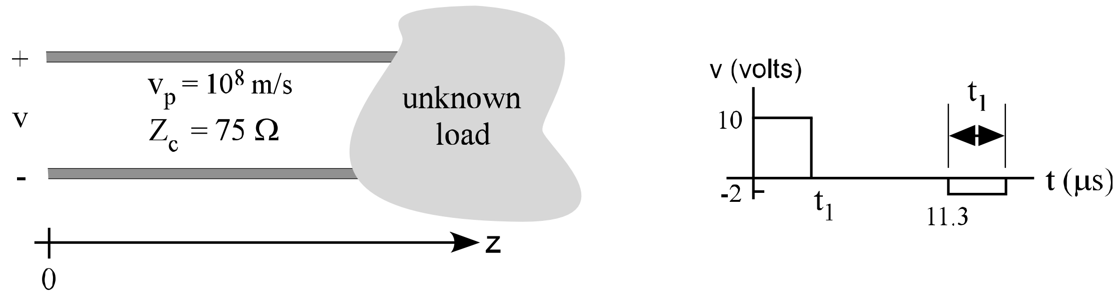

Figure 2: Time-domain reflectometry setup and measurement

Solution: From v(t) at the input to the transmission line, the reflection coefficient can be determined. From this measured Γ, the load impedance can be calculated.

$$\Gamma = \frac{v^-}{v^+} = -0.2 = \frac{Z_L - Z_c}{Z_L + Z_c} \qquad \Rightarrow \qquad Z_L = 50\ \Omega$$

From the time of the reflected pulse, the distance to the load (z = d) can be determined. Note that the time is the sum of the time required for the incident pulse to reach the load and the time required for the reflected wave to reach the input.

$$t_r = \frac{2d}{v_p} \qquad \Rightarrow \qquad d = \frac{t_r v_p}{2}$$

$$d = 56.5 \text{ m}$$

Note that a pulse can be considered as the sum of two step functions and that, likewise, the reflection can be considered as the sum of two step functions.

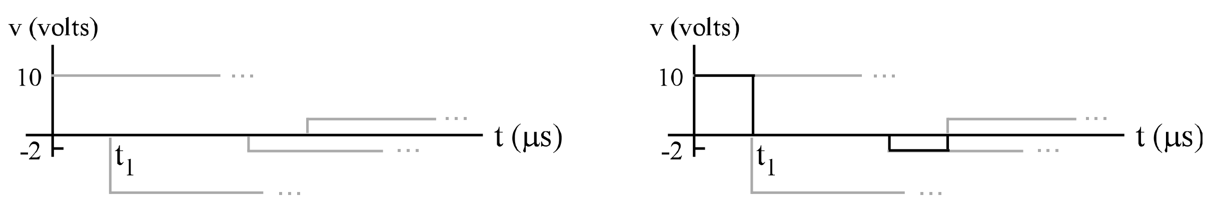

Figure 3: TDR measurement for a resistive load

This viewpoint is especially valuable when considering reflections from reactive loads. For example, consider the results when a pulse is applied to the above 75 Ω line with a load consisting of a capacitance in parallel with a 50 Ω resistance. In this case, Γ will initially be -1 and will decay to -0.2 as the capacitance is being charged.

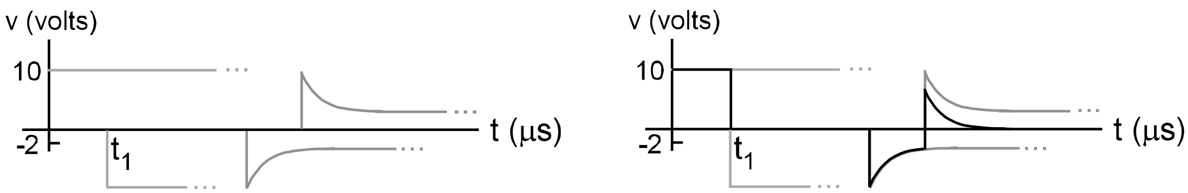

Figure 4: TDR measurement for a RC load

Laboratory exercise from required EMC/SI course for computer engineers: The objectives of this lab are to learn how to use a spectrum analyzer and to understand resonant frequency of a closed current loop with a discrete capacitor. A breadboard is used to connect two or three capacitors in parallel to form a low-pass filter. The filter is connected to a spectrum analyzer with a tracking generator. The low-pass filter is required to have 30-dB attenuation from 100 kHz to 100 MHz.

Students are asked to choose a capacitor to achieve a 30-dB reduction at 100 kHz as a pre-lab exercise. Other capacitors may be chosen with values that are about ten times part from each other so that they might have different resonant frequencies.

During the lab, the students learn how to operate a spectrum analyzer and to calibrate their test setup with the breadboard. They find the resonant frequency of each of several capacitors of different values and place them in parallel to ensure 30-dB attenuation from 100 kHz to 100 MHz through trials and error and by cutting leads on the capacitors as short as possible. Students are surprised to see the degree to which the resonant frequency of a circuit changes when they cut the leads of the capacitor in the circuit and are often amazed by how the test setup can affect their results. Representative laboratory results are shown in Fig. 5.

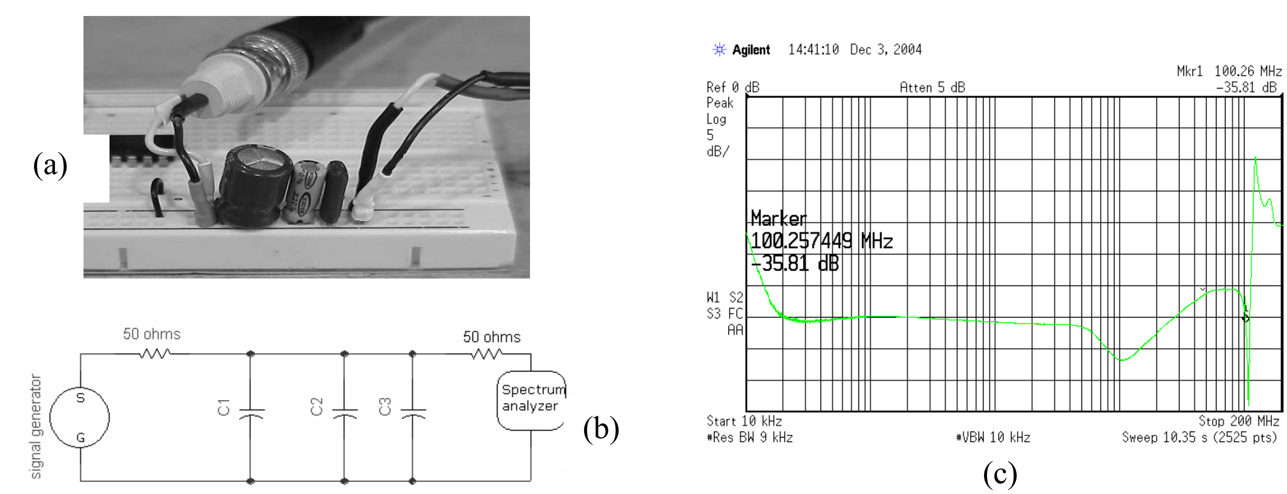

Figure 5: Low-pass filter with a minimum 30-dB attenuation from 100 kHz to 100 MHz, (a) breadboard, (b) model, (c) data from spectrum analyzer.

Summary

In this paper, the initial steps in the development of an undergraduate program in high-speed electronic design are presented. These include a required course in electromagnetic compatibility and signal integrity for our CPE curriculum and a redesign for our required two-course sequence in electromagnetics for our EE curriculum. The EMC/SI course for CPEs has been offered several times. The initial redesign for the EM courses for EEs is complete and will be implemented in the 2006/2007 academic year. Also included is an evolving elective course in high-speed design which has been offered since 1999.

Acknowledgement

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