

Time-Domain Reflectometry (TDR) in Graduate Courses

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Abstract:

A time-domain reflectometer is an instrument composed of a fast pulse generator and a broadband oscilloscope, usually a coherent sampling oscilloscope. Most textbooks used for graduate courses involving high frequency electronics and electromagnetic compatibility do not cover Time Domain Reflectometry (TDR). This is a significant omission, as TDR measurements form a popular and important method for signal integrity verification of transmission lines in broadband radio-frequency and microwave systems, including high frequency printed circuits. TDR methods are also important in non-electrical areas such as geology and optics. This paper presents a brief description of TDR issues, as taught in graduate level electrical engineering courses at Oakland University to make up for the gap in standard textbooks. We also include a discussion of the demonstrations we have developed with TDR; these include software simulations which enhance the interpretation of measurement results. Instrumentation involving two major types of TDR are described here: short pulse time-domain, and step pulse time-domain. Each type is involved in measurements of discontinuities of various types of cables, and is used to evaluate measurement errors and limitations.

I. Introduction

A time-domain reflectometer is an instrument composed of a fast pulse generator and a broadband oscilloscope, (often this latter device is a coherent sampling oscilloscope) [1-3]. Surprisingly, TDR methodologies are not covered in most standard textbooks related to high frequency electronics and electromagnetic compatibility [4-7]. The time domain reflectometer can be used in two ways—as a short pulse or a step pulse. The short pulse time domain reflectometer sends fast, very short pulses into the transmission line network under investigation—the resultant incident and reflected pulses are observed on the scope to determine the transmission line delay and possible network discontinuity locations. When the transmission line is properly matched, no reflections are observed. The time resolution of such a system is limited to the incident pulse width, which is close to a doubled value of the incident pulse rise time. Discontinuity types can be determined from the shape of the reflected pulses, although the interpretation process can be difficult.

In contrast to short pulse TDR, step pulse TDR sends long, step-like pulses into the network under investigation—the resultant reflected waves are observed superimposed atop the incident pulses. Time resolution for this approach is limited only by the rise time of the incident pulses. This improves the system resolution—an improvement over the constraints of the short pulse approach. In step-pulse TDR, it is easier to interpret discontinuity types. Moreover, in modern TDR systems, supporting software can be used to help identify discontinuities.

At Oakland University, we have integrated material related to TDR into two graduate courses—High Frequency Electronics, and Electromagnetic Compatibility (see Appendices A and B). Indeed, concepts of TDR have become vital, “backbone” subjects for these courses.

II. Principles of Time Domain Reflectometry

Figure 1 shows the basic structure of TDR as implemented using a high input-impedance oscilloscope. A step generator sends its pulse into the transmission system under test. The step generator’s impedance matches that of the transmission-line connection, so the only reflections expected are from the circuit under test. The incident wave, which is one-half the open-circuit step voltage, is transmitted toward the circuit under test. When this signal encounters any discontinuity, including unmatched impedance of the circuit under test, a reflected voltage wave is produced. This reflected voltage is propagated back to the generator and added to the incident wave. The reflected wave can be positive or negative.

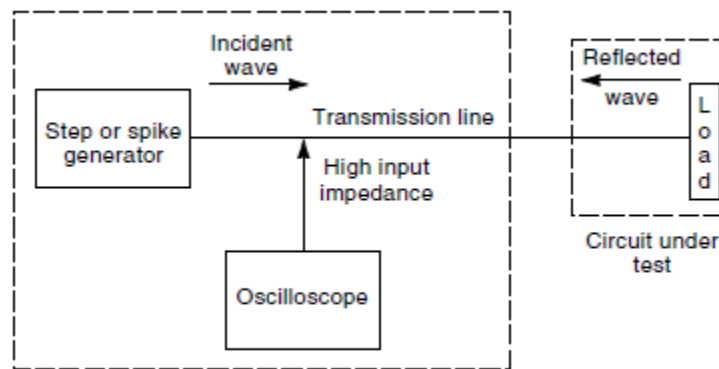


Figure 1: Basic structure of TDR.

III. Applications of Time Domain Reflectometry and Time Domain Transmissometry

As early as 1939, geologists identified a relationship between the dielectric properties of soil, rock, and their moisture content. Time domain reflectometry offers a methodology for capitalizing on these dielectric relationships [8-13]. Primary applications of time domain reflectometry and transmissometry include the following [1-3].

1. Conductor length and return loss determination
2. Finding short and open connections in cables
3. Location of bad splices, loose connectors, and crimps
4. Location of moisture and water in cables
5. Measurement of cable parameters, such as characteristic impedance, losses, and propagation velocity
6. Determining signal integrity, and performing failure analysis of printed circuit boards used in high speed digital and analog circuits
7. Evaluation of micro strip connections
8. Computer network cable tests

9. Characterization of integrated circuit packages
10. Sensing liquid levels.

IV. Simulation

As shown in the accompanying figures, simulation provides unparalleled ability to explain the dynamics underlying TDR. The line length used to reproduce the waveforms for all of the figures shown here is 14 meters; the unit delay is 23.3 cm/ns. Figure 2a shows a PSpice/MultiSim simulation circuit for a matched source. Figure 2b shows the temporal simulation result. Figure 2c provides an oscilloscope screen picture of the waveforms affiliated with an open ended transmission line input. In Figure 2c the input – Channel 2 (upper curve) shows the incident step and reflected step. The time between the incident and reflected step is the delay time introduced by signal as it passes through length of the line and then returns the length of the line—a doubled TL delay. The “Output – Channel 4” signal, (the lower curve), shows the doubled incident wave level with a long pulse applied by the source, delayed about 60 ns due to the length of the line. The distance between steps of Channel 2 is double the transmission line delay time.

Figure 3 reveals similar results in relation to an unmatched load. Figure 4 shows the use of a narrow pulse reflectometer to test the signal integrity of longer cables applied in computer networks.

Figures 5a to 5i show input and output waveforms affiliated with various loads. In Figure 5a, the results pertain to step pulse TDR in relation to an open ended transmission line. “Input – Channel 2” shows both the incident and reflected step, separated by a doubled transmission line delay—the source is matched to the line. “Output – Channel 4” shows the doubled incident wave level, delayed (60 ns or 23.3 cm distance from generator), with a long pulse applied by the signal generator. The distance between steps of Channel 2 are twice the transmission line delay time. (Again, as with all these measurements, the line length is 14 meters, and the unit delay is 23.3 cm/ns.)

Figure 5b shows step pulse TDR in relation to a reflection from the shorted load of the transmission line, where the source is matched to the line (in this case, R_{load} is a short consisting of one inch of wire).

Figure 5c shows a screen shot in relation to an open-ended transmission line, with a short pulse applied to show a “radar effect,” or echo. (Channel 2 – input; a doubled amplitude output is observed on Channel 4). Note the effects of the losses due to the transmission line, the echo is slower and smaller. The distance between pulses of Channel 2 are twice the transmission line delay time. The measured unit delay yields 20cm/ns.

Figure 5d shows a shorted transmission line, observed using narrow pulse TDR. Note that the “short” (Channel 4) is not really a short at high frequencies. Also observe the change of polarity of the reflected pulse (Channel 2 – Input). Figure 5e shows the transmission line results with an inductive load, while the source resistance is matched (50- Ω). Figure 5f shows the transmission line with capacitive load; the source resistance is matched (50- Ω), with the display adjusted to calculate the time constant and capacitance ($C = 10\text{nF}$). Figure 5g shows step pulse TDR with reflection from the unmatched load of the TL ($R_{load} = 27 \Omega$); the source is matched.

Figure 5h shows step pulse TDR revealing a reflection from the unmatched load of the transmission line ($R_{load} = 100\Omega$); the source is matched. Figure 5i shows step pulse TDR

revealing the reflection from the shorted load of the transmission line, (the source is matched, R_{load} is a short consisting of one inch of wire). Observe the effects of the transmission line losses: an elevated “tail” follows the pulse, and there is also the step of the output signal. Figure 6a shows simulated TDR (PSpice), where block HB1 comprises a step generator and a PSpice calculator which evaluates the value of the capacitance in volts (pV corresponds to pF). Block HB2 is used to evaluate the impedance.

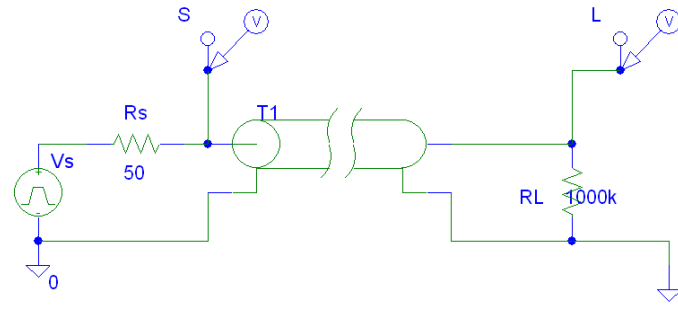


Figure 2a: PSpice/MultiSim model of an open ended transmission line (TL) with a long pulse applied. The source is matched.

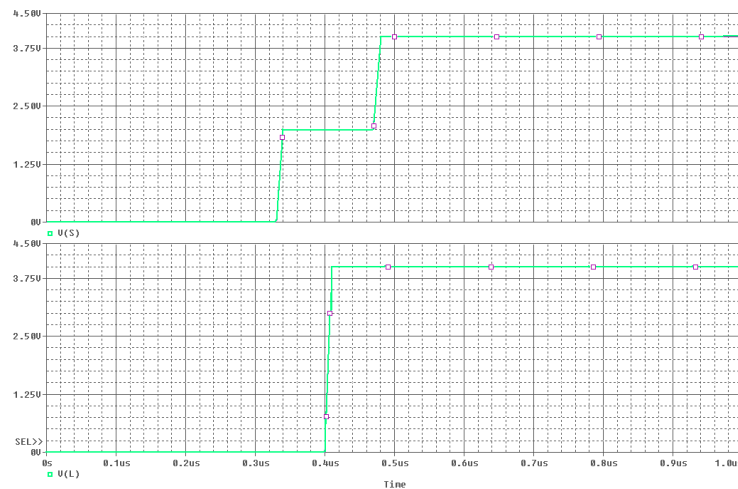


Figure 2b: PSpice/Multisim simulation results for the circuit shown in Figure 2a.

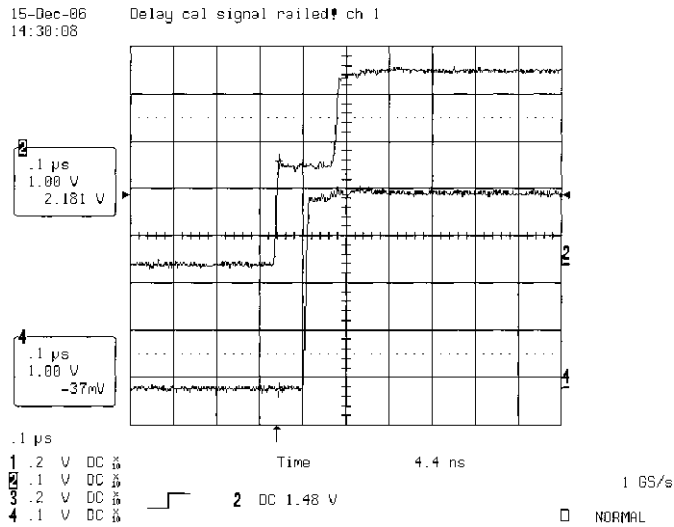


Figure 2c: Oscilloscope scope screen shot of voltage waves affiliated with an open-ended transmission line with a matched source.

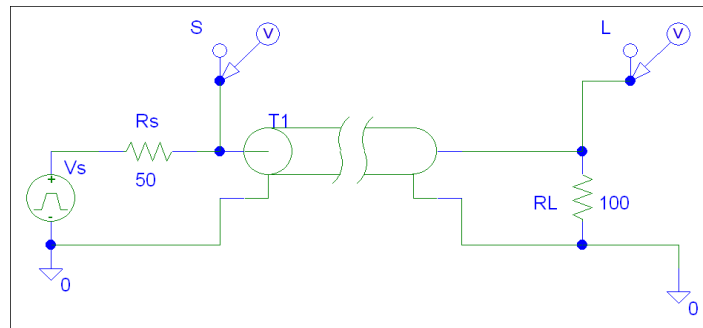


Figure 3a: PSpice/Multisim circuit to test reflection from the unmatched load of the transmission line ($R_{load} = 100\Omega$). The source is matched.



Figure 3b: Temporal simulation of the circuit of Figure 3a using PSpice/Multisim.

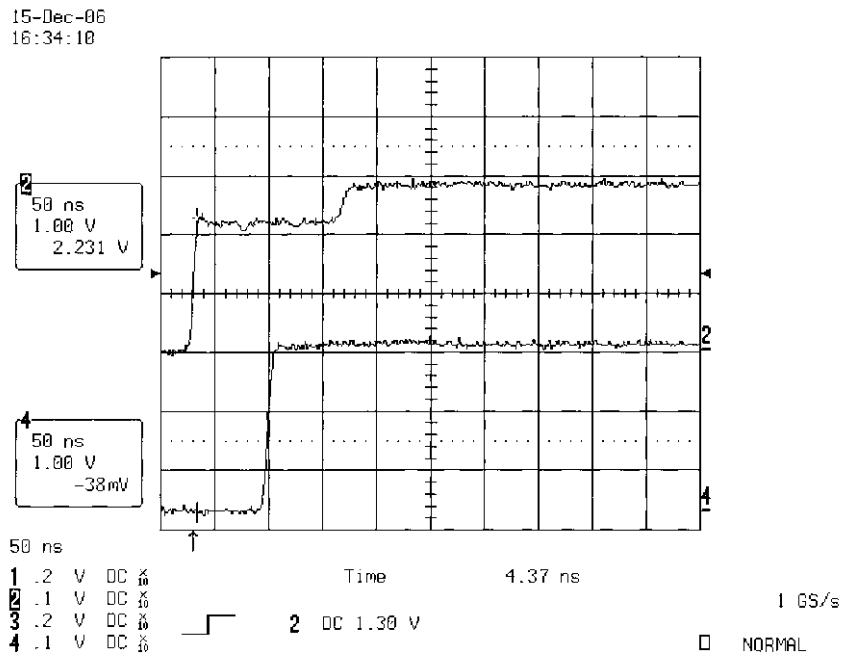


Figure 3c: Oscilloscope screen shot of waveforms affiliated with the circuit of Figure 3a.

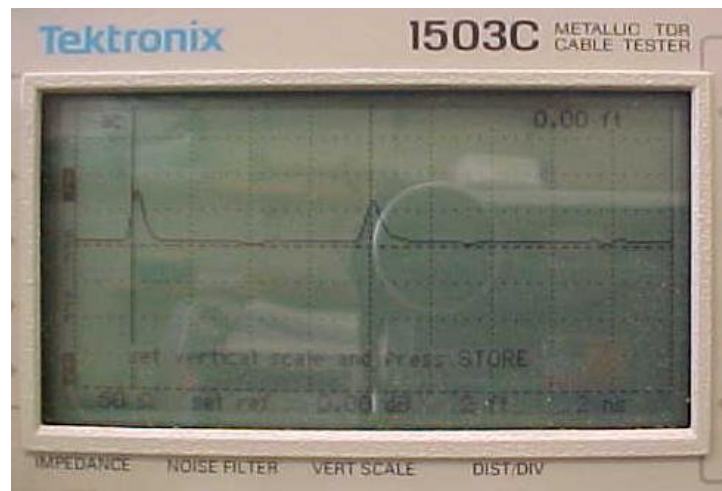


Figure 4: Test signal related to a narrow pulse TDR to test the signal integrity of longer cables applied in computer networks using a Tektronix oscilloscope.

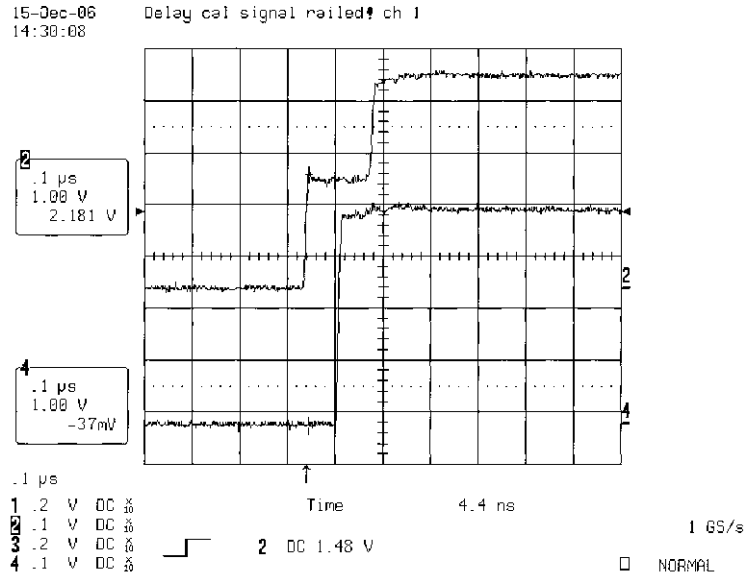


Figure 5a: Step pulse TDR for an open ended transmission line.

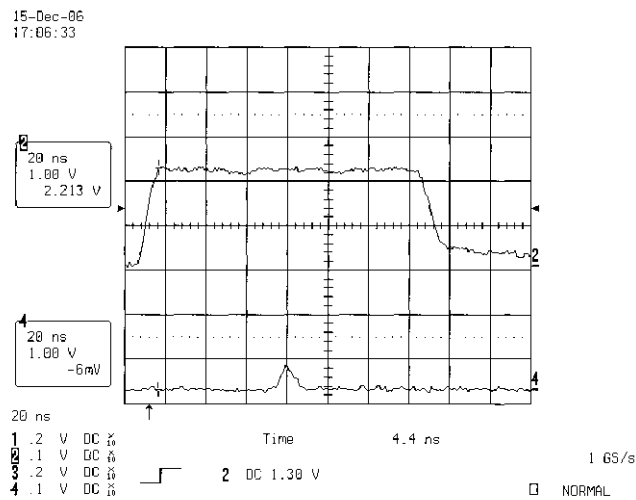


Figure 5b: Step pulse TDR in relation to reflection from the shorted load of the transmission line, where the source is matched to the line ($R_{load} =$ a short consisting of one inch of wire).

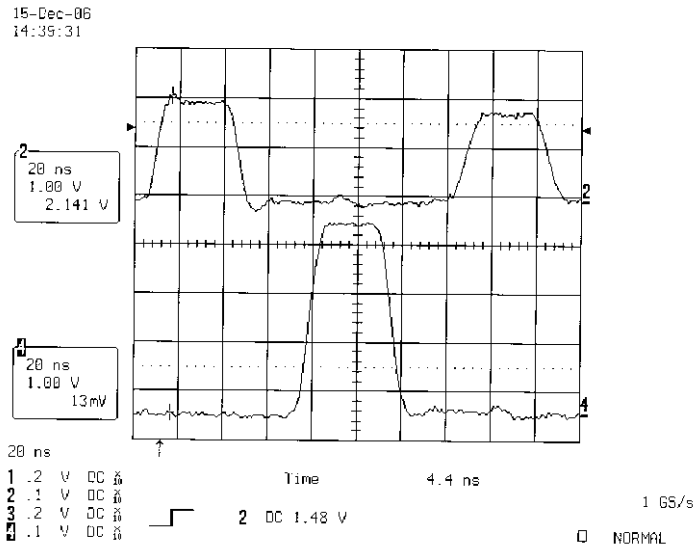


Figure 5c: Narrow pulse TDR in relation to an open-ended transmission line.

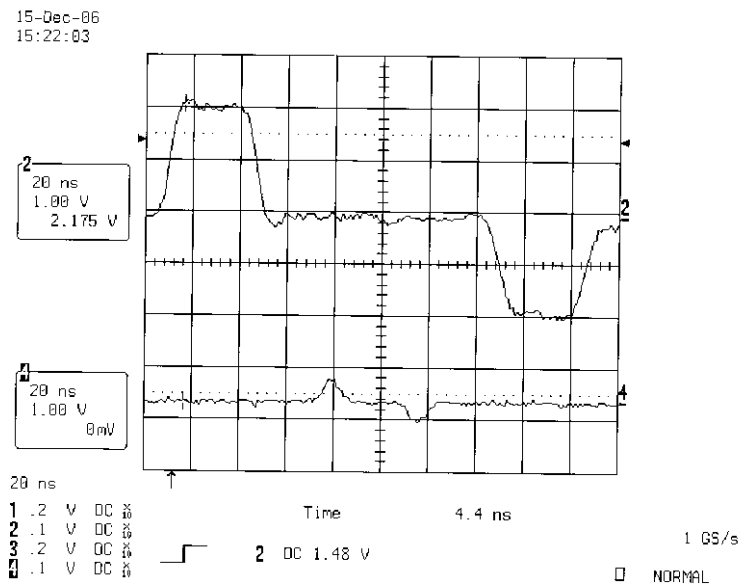


Figure 5d: Shorted transmission line, narrow pulse TDR. Note that the “short” is not really short at high frequencies (Channel 4).

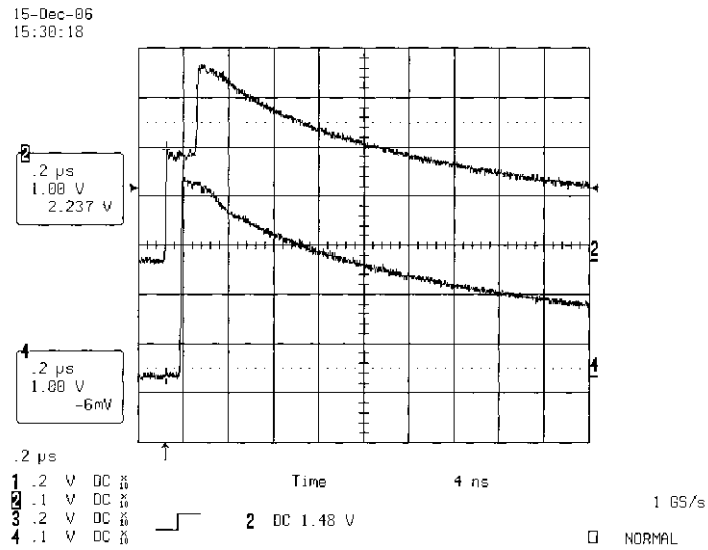


Figure 5e: Step pulse TDR with an inductive load.

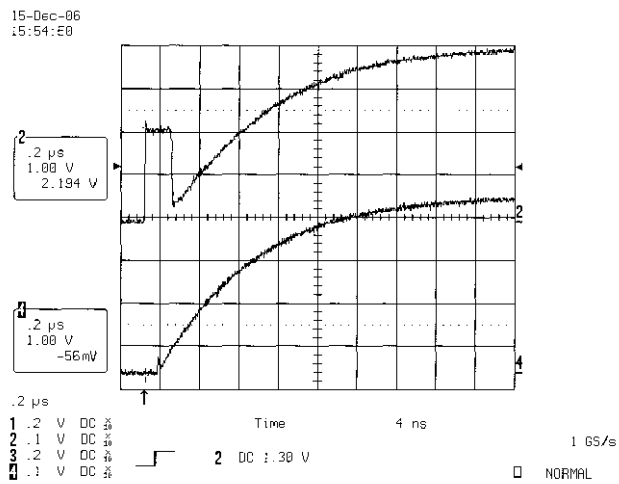


Figure 5f: Step pulse TDR with capacitive load.

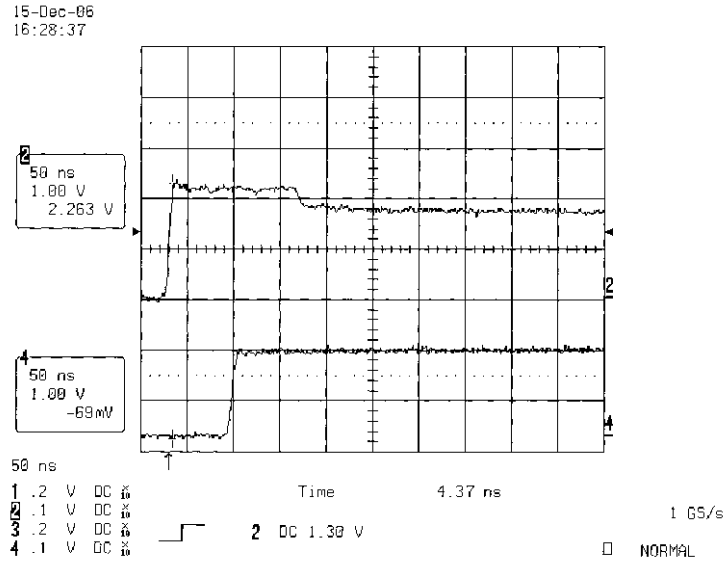


Figure 5g: Step pulse TDR illustrating a reflection from the unmatched load

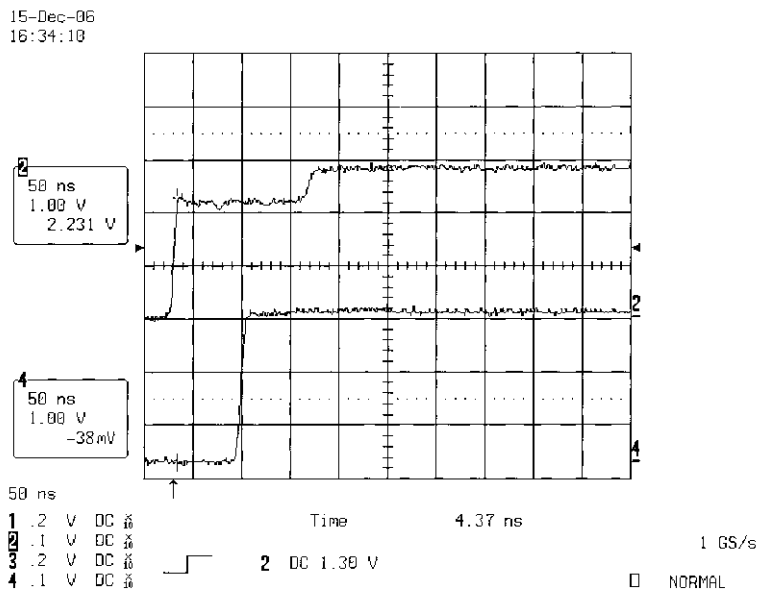


Figure 5h: Step pulse TDR revealing a reflection from the unmatched load of the transmission line.

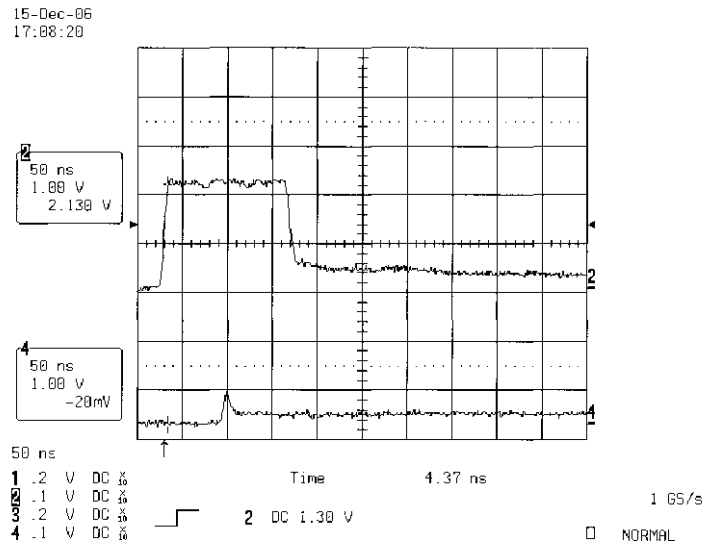


Figure 5i: Step pulse TDR revealing the reflection from the shorted load of the transmission line.

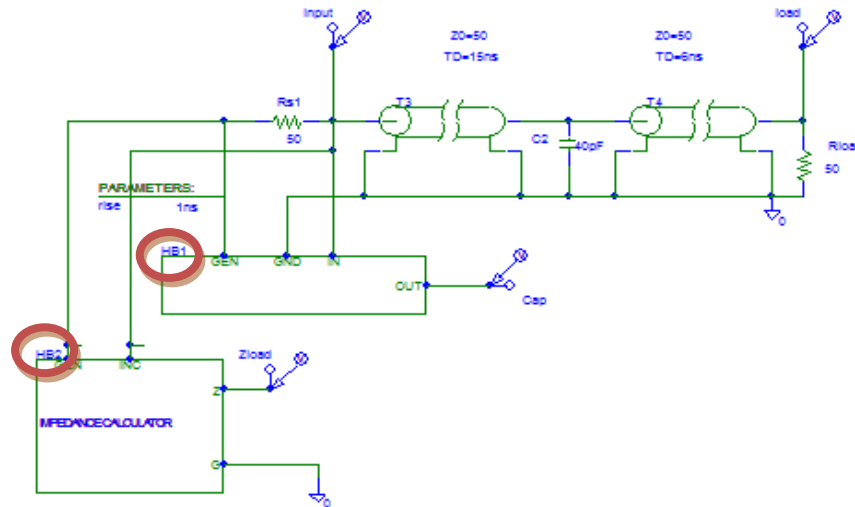


Figure 6a A simulated TDR generation system in PSpice. Block HB1 comprises a step generator and a PSpice calculator which evaluates the value of the capacitance, calculated in volts (pV corresponds to pF). Block HB2 is used to evaluate the impedance.

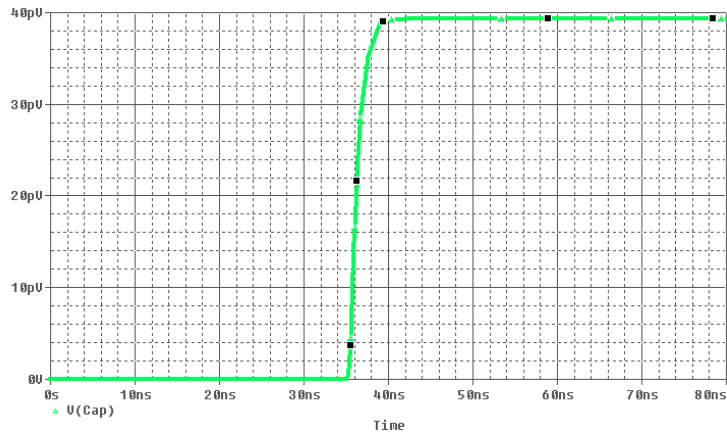


Fig. 6b: Recorded wave $V(\text{Cap})$ indicates the value of the capacitance. The “pV” units recorded by the PSPICE probe correspond to Pico farads (pF).

V. Assessment and Evaluation

Our graduate electromagnetics and high frequency electronics courses (ECE 546 and ECE 527, respectively) include short projects in which the students can appreciate real applications of TDR involving fast pulse generators, high-frequency oscilloscopes, and spectrum analyzers. In both courses, TDR helps in analysis of signal integrity issues in transmission line communication circuits.

Pulse transmission issues in transmission lines are initially introduced during lectures by applying basic tools such as bouncing wave diagrams (for linear source and load resistances), and the graphical method based on the Bergeron diagrams (for both linear and nonlinear sources and load resistances). In addition, we like to provide practical demonstrations of the various effects related to sinusoidal and pulse operations in transmission lines, as outlined in the various illustrations below.

This material also serves as a background for short student projects in which the students identify the transmission line load character and load locations based on the shapes and parameters of observed pulses. Single and multiple transmission line discontinuities are also detected and identified. Simple transmission lines, such as twisted pair lines, are constructed and measured using TDR methods so that students are able to learn more about transmission line parameters. Measurements are also simulated using PSPICE in order to help elucidate processes of transmission line load identification.

Use of TDR reinforces the learning objectives for both the courses. Appendix A gives the ECE 546 Electromagnetic compatibility course outline. One of the key outcomes is the “Ability to evaluate parameters of electronic components, including transmission lines at high frequency.” Appendix B gives the ECE 527 High Frequency Electronics course outline. Here, one of the key outcomes is “Understand the operation of transmission lines, both in frequency and time domain, including TDR.” End of course evaluations and student evaluations show that teaching TDR has helped students meet learning objectives and improve their understanding of a practical and useful electrical engineering phenomenon.

Conclusion

Time domain reflectometry is a critical, and underrated, component of electrical engineering education. Yet it is a relatively straightforward matter to provide students with the fundamentals they need to understand and use these important techniques. This paper provides an overview of how these fundamentals are taught at Oakland University, and provides a template for widespread dissemination of TDR in modern electrical engineering coursework.

VI. References:

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Appendix A

Re: ECE 546 Electromagnetic Compatibility Course Level: Graduate, Total Credits: 4

Textbook: C. R. Paul, *Introduction to Electromagnetic Compatibility*, J. Wiley, Recent Edition.

Topics:

- Overview of EMC
- EMC Requirements (i, j)
- Review of Electromagnetic Principles (a, e)
- Distributed and Lumped Components
- Signal Spectra and Spectrum Measurements (a, e, k)
- Intro to EMC Pre-compliance and Compliance Tests, Component and System Level Measurements (e, k)
- Radiated Emissions and Susceptibility (a, e)

- Conducted Emissions and Susceptibility (a, e)
- Crosstalk (a)
- Shielding and Guarding (a)
- Electrostatic Discharge (a)
- Introduction to System Design (a, e, i, j, k)
- Introduction to Signal Integrity (a)

Course Outcomes:

The students obtain the following competencies:

- Understanding of US and foreign EMC standards.
- Understanding of time and frequency representations of signals.
- Ability to evaluate parameters of electronic components, including transmission lines at high frequency.
- Ability to evaluate the design factors that contribute to conducted emissions, radiated emissions, and crosstalk.

Appendix B

ECE527 “High Frequency Electronics”

Catalog Course Description:

Transmission lines with sinusoidal and pulse excitation. Passive and active circuit components at high frequency. High frequency amplifiers, communications circuits, waveform generators and digital circuits. Introduction to high frequency measurements.

Course Contents:

1. Passive lumped components at high frequencies
2. Transmission lines with sinusoidal and pulse excitation, TDR
3. Active devices operating at high frequencies
4. Pulse operation of active devices
5. High frequency amplifiers
6. High frequency oscillators
7. High frequency communication circuits
8. Introduction to high frequency measurements and instrumentation

Software Applied: PSPICE, Serenade, MATLAB, SMITH 191, APPCAD

RE: ABET outcomes:

Engineering programs must demonstrate that their graduates have:

- (a) an ability to apply knowledge of mathematics, science, and engineering
- (b) an ability to design and conduct experiments, as well as to analyze and interpret data
- (c) an ability to design a system, component, or process to meet desired needs
- (d) an ability to function on multi-disciplinary teams
- (e) an ability to identify, formulate, and solve engineering problems
- (f) an understanding of professional ethical responsibility
- (g) an ability to communicate effectively

- (h) the broad education necessary to understand the impact of engineering solutions in a global and societal context
- (i) a recognition of the need for, and an ability to engage in, life-long learning
- (j) a knowledge of contemporary issues
- (k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Course Objectives (related to ABET outcomes: a, b, c, e, j, k)

By completing the course students will be able to:

1. Analyze the influence of parasitic parameters of passive components, such as resistors, capacitors and inductors on high frequency circuit performance (a, b).
2. Understand the operation of transmission lines, both in frequency and time domain, including TDR (a, b).
3. Understand the processes involving design and analysis of high frequency filters(a, b, c, e).
4. Analyze and design high frequency amplifiers, based on scattering matrix parameters of active components (a, b, c, e).
5. Verify the analytical problem solutions using PSPICE, Serenade, and/or MATLAB (k).
6. Understand the functions and analyze basic high frequency system blocks, such as mixers, demodulators, and voltage-controlled oscillators (a, b, c, k).
7. Understand operation and limitations of fundamental high frequency measurement instruments, including spectrum and network analyzers (b, j, k).

Biography



Andrew Rusek (rusek@oakland.edu) is a Professor of Engineering at Oakland University in Rochester, Michigan. He received an M.S. in Electrical Engineering from Warsaw Technical University in 1962, and a PhD. in Electrical Engineering from the same university in 1972. His post-doctoral research involved sampling oscillography, and was completed at Aston University in Birmingham, England, in 1973-74. Dr. Rusek is very actively involved in the automotive industry with research in communication systems, high frequency electronics, and electromagnetic compatibility. He is the recipient of the 1995- 96 Oakland University Teaching Excellence Award



Subra Ganesan (ganesan@oakland.edu) is a Professor of Electrical and Computer Engineering at Oakland University and Director of Real Time Embedded DSP Systems Lab. He joined the university in 1984. After graduating from Indian Institute of Sciences Bangalore India, he served at universities in Germany, and Canada and Indian research laboratory as a scientist. He does research work in collaboration with TI, Free Scale, and a few other semiconductor companies and US army. His research areas include DSP, Embedded Systems, Real Time Systems, Condition-based Maintenance, and Optimization.



Barbara Oakley is an associate professor of engineering at Oakland University in Michigan—she has won national awards from the National Science Foundation and others for her teaching. Dr. Oakley’s research focuses on the complex relationship between neurocircuitry and social behavior. Among her varied experiences, she has worked for several years as a Russian translator on Soviet trawlers in the Bering Sea during the height of the Cold War; she met her husband while working as a radio operator at the South Pole station in Antarctica; and she has gone from private to regular Army Captain in the U.S. military. Oakley is a recent vice president of the IEEE Engineering in Medicine and Biology Society, the world’s largest bioengineering society, as well as a Fellow of the American Institute of Medical and Biological Engineering. Her books include *Pathological Altruism* (lead editor, Oxford University Press, 2012), *Cold-Blooded Kindness* (Prometheus Books, 2011), *Career Development in Bioengineering and Biotechnology* (co-edited, Springer, 2008), *Evil Genes: Why Rome Fell, Hitler Rose, Enron Failed, and My Sister Stole My Mother’s Boyfriend* (Prometheus Books, 2007), and *Hair of the Dog: Tales from Aboard a Russian Trawler* (WSU Press, 1996).



Daniel N. Aloï (aloï@oakland.edu) received the B.S.E.E., M.S.E.E., and Ph.D. degrees (in electrical engineering) in 1992, 1996, and 1999, respectively, all from the School of Electrical Engineering and Computer Science, Ohio University, Athens. He is currently Chair of the Department of Electrical and Computer Engineering at Oakland University. His research interests have focused on antenna modeling and various aspects of location technology in the aviation and automotive telematics industries. In addition, he serves as a key technical advisor to the Federal Aviation Administration’s Satellite Program Office for the Local Area Augmentation System. He is a coinventor on three patents related to automotive navigation.