A computer controlled time domain reflectometry multiplexer
by Rodney David Carlson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
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Second, the multiplexer had to be designed with a large bandwidth and flat frequency response to prevent skewing caused by harmonic distortion. This allowed resolution of closely spaced reflections. All of these were resolved by carefully constructing good matches with the circuit board and high frequency relays. Nevertheless, the device still demonstrated fairly large power losses when taking into account several reflections, resulting in error for conductivity measurements made with the Giese and Tiemann analysis. A more complete formula was derived to account for the multiplexer in the TDR sytem, thus the multiplexer reflection and loss were modeled into the Giese and Tiemann theory. Experimentation verified the new formulas for calculating conductivity with the multiplexer present.

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APPROVAL

of a thesis submitted by

Rodney David Carlson

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 5-17-95

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ABSTRACT

This paper discusses the design, implementation, and experimental verification of a one to thirty-two Time Domain Reflectometry (TDR) switch. The results of the investigation can be summarized. First, the device required a PC as a controller. Two separate programs were written for device drivers of the multiplexer. A C program permitted a TSR (Terminate Stay Resident) mode, while a Basic program allowed portable code with existing conductivity programs already written in that language.

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CHAPTER 1

INTRODUCTION

The following project originated as a joint venture between the Electrical Engineering and the Plant and Soil Departments at Montana State University, consisting of the development of a computer controlled Time Domain Reflectometry (TDR) multiplexer. Specifically, measuring soil conductivity with TDR at several locations required the operator to manually connect the probe of interest into the instrument. A high frequency multiplexer controlled by a PC and discussed in this paper reduced the amount of manual switching and thus the measuring times. In addition, the multiplexer increased the capacity of a single TDR instrument by the number of multiplexing channels for a fraction of the cost of buying more TDR instruments.

The high frequency performance of the multiplexer was critical. Insertion loss and mismatch between the instrument and multiplexer needed to be as low as possible. These losses were minimized by keeping the transmission lines as short as possible and making a fifty ohm microstrip match between the TDR, multiplexer, and soil probes. In addition, when a multiplexer had small reflections coupled with losses, the effect of reflection and loss drastically changed conductivity measurements. Existing multiplexer technology had to be studied to improve the insertion loss and bandwidth of this product.

A TDR multiplexer, from Cambell Scientific, consisted of four output channels. Its design employed high frequency switching relays embedded in a 50 ohm microstrip matched circuit board. Although the switcher worked for automated measurements, it was limited to only four probes. According to Dr. Jon Wraith (a soil scientist at MSU), more than twenty soil probes should be measured at numerous locations so that an accurate statistical sample can be calculated for conductivity in the field. Likewise, if an environmentalist wanted to check for leakage from nuclear containment facilities, he or she would sample a grid of points surrounding the container. The existing one to four multiplexer design wasn't sufficient to meet either test case so a new multiplexer was designed to multiplex the TDR signal from one input to one of 32 output probes.

A serious design problem resulted from the BNC contact fatigue, caused from connecting probes to the connectors on the circuit board. The fatigue resulted in loose BNC connectors, thus epoxy was added around the base of the BNC connectors to distribute the connecting forces across the board surface. Furthermore, since the multiplexer was to be used in the field, prolonged battery power consumption had to be avoided. A car battery was an acceptable field power supply. But if the continuous current consumption was too large, even a heavy duty car battery would become dead within a few hours of use.

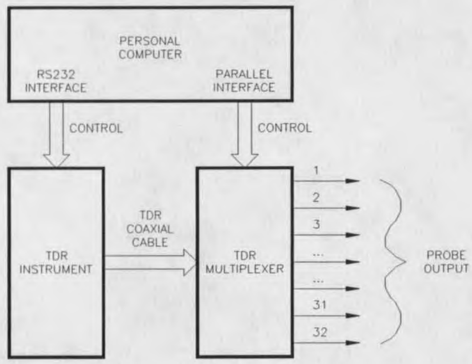


Figure 1. Block Diagram of PC Control

Figure one displays the block diagram for the operation of the entire TDR system. Notice that the multiplexer was designed to operate from the parallel port (25 pin D-subminiature) of the PC. This allowed word serial communication with the Tektronix 1502C TDR instrument through the RS232 port. The programs to support switching the TDR consisted of Basic function calls, since most of the conductivity algorithms were written in that language. However, C device controlling programs were used to implement a DOS and Windows visual toggling interface.

To summarize, the predominant issues of need in this TDR multiplexer design included: minimizing loss and reflections, PC controlling software, resistance to contact fatigue, and portability with respect to power consumption.

CHAPTER 2

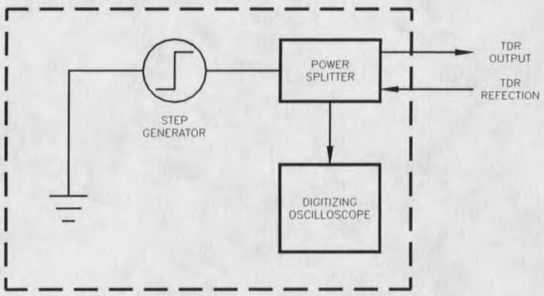
BACKGROUND INFORMATION ON THE TDR MULTIPLEXER

Theory of Time Domain Reflectometry

This section begins by discussing the basics of reflection theory employing TDR. Most of the theory traces back to Tektronix laboratories, in the early 1960's. Allen Zimmerman, Gordon Long, George Frye, and James A. Strickland were considered some of the fathers of the TDR pulse technique [1]. Initially, TDR was developed for testing the impedances of coaxial transmission lines. But, like most other technologies, it has since migrated into several fields. It's common to find TDR in fiber optics, power electronics, and even soil science applications.

Time Domain Reflectometry displays amplitude of reflection versus time of propagation on the y and x axes respectively. A simple model of TDR would be something like a "radar" detector. An initial electromagnetic pulse is emitted and the time required for the wave to travel to, reflect off a distant object, and return is recorded. Likewise, TDR instruments generate voltage pulses and the amplitude and reflection times are recorded and graphed.

The genius behind pulsed TDR involves splitting a repetitive square wave into two separate wave propagations. Part of the initial square wave amplitude is delivered directly to the oscilloscope. This establishes an amplitude and time reference to which all reflection events are compared. The other, propagating wave, continues to travel down the unknown transmission line, and when it encounters a change in impedance, a reflected wave returns to the oscilloscope. The initial and reflected voltages superimpose at some time $t_0 + 2 \cdot \Delta T$, where ΔT represents the total time of the pulse wave to travel to the discontinuity in impedance. The variable t_o denotes the time when the pulse achieves its 90% rise time for a matched load. A typical TDR device consists of a pulser, a power divider, and an oscilloscope as depicted in the Figure 2 below.



.Figure 2. The TDR Instrument

A conventional DC resistance circuit model can help one to derive reflection expressions for TDR [1]. Suppose that a battery source of 1 volt has an internal resistance R_G and is connected to a transmission line of resistance R_{LINE}, as portrayed by Figure 3. Furthermore, applying matched conditions for maximum power transfer to the transmission line requires R_G and R_{LINE} to be equal. Since the battery is 1 volt, the voltmeter inserted across R_{LINE} will indicate a half a volt when the switch is closed.

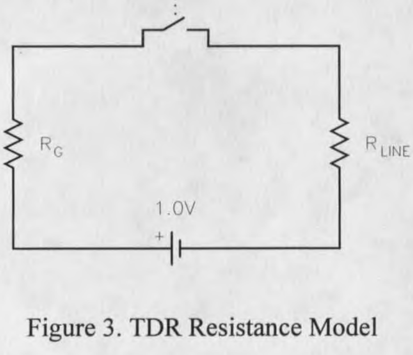


Figure 3. TDR Resistance Model

The time dimension can now be added to the existing DC circuit by addition of zero resistance wires. Replacing the battery source by a stepped generator gives a DC circuit the appearance of TDR (Figure 4).

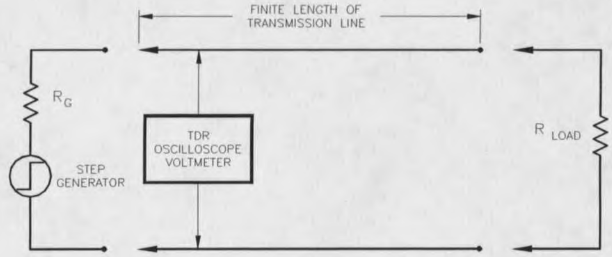


Figure 4. Model with Extension of Transmission Wires

Suppose that the resistance R_{LOAD} at the end of the zero resistance wires is infinity. The pulse generator then steps positive by one volt, but since the forward propagating wave hasn't reached the open at the end of the circuit, the voltmeter reads a half a volt. The forward moving wave reaches the open and the reflection will have the same magnitude and sign as the forward propagating wave [1]. At some time $t_o + 2 \cdot \Delta T$ the voltmeter will measure one volt, the sum of both the reflected and initial waves.

The actual experiment realistically approaches TDR by replacing the zero resistance wires in Figure 4 above with a transmission line having a constant impedance such as (50 ohm coaxial cable). The source must possess a 50 ohm resistance. A somewhat more complete method of handling signal reflections can then be explained. At the start of the pulse, the voltage would see 50 ohms from both the source and the coaxial line. The source supplies 1 volt but is split by the voltage divider according to the equation below:

$$V_o = V_G \cdot \frac{R_{LINE}}{R_G + R_{LINE}} = (1\ \text{Volt}) \cdot \frac{50}{50+50} = \frac{1}{2}\ \text{Volt}. \qquad (1)$$

Time proceeds and R_{LINE} changes from 50 ohms to infinity (R_{LOAD}), the resistance of the open at the end of the coaxial cable. Taking the limit as R_{LOAD} approaches infinity, the voltage divider equation shows the output voltage converging to one volt. Thus, the numerical result agrees with the wave propagation model developed earlier.

$$V_o = \lim_{R_{LOAD} \to \infty} \left[V_G \cdot \frac{R_{LOAD}}{R_G + R_{LOAD}} \right] = 1 \text{ Volt} \tag{2}$$

Another extreme in TDR would be to terminate the coaxial cable with a short. From a wave model, the introductory pulse height would again be a half a volt. Then, the forward moving wave encounters the short at the end of the cable. It is returned with the same magnitude but opposite sign, canceling the initial voltage at the meter. The resistance divider once again confirms the reasoning; as the R_{LOAD} approaches zero so does the measured voltage.

$$V_o = \lim_{R_{load} \to 0} \cdot \left[V_G \cdot \frac{R_{LOAD}}{R_G + R_{LOAD}} \right] = 0 \text{ Volt} \tag{3}$$

The extreme cases of an open and a short prove that any other load should have a superposition voltage between one and zero volts as illustrated in Figure 5.

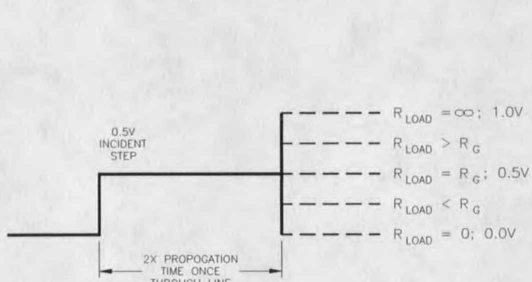


Figure 5. TDR Display for Various Load Resistances

A more convenient method of handling signal reflections is to define a reflection coefficient as the ratio of reflected to incident voltages

$$\rho = \frac{V_{REFLECTED}}{V_{INCIDENT}} = \frac{V_{OUT@LOAD} - V_{OUT@LINE}}{V_{OUT@LINE}} \tag{4}$$

The voltages $V_{OUT@LINE}$ and $V_{OUT@LOAD}$ are calculated from the divider equations listed below, before and after reflection from the load. Notice that these equations are derived from (1) and (2) assuming matched conditions between the source and line impedances ($R_G = R_{LINE}$).

$$V_{OUT@LINE} = \frac{1}{2} \cdot V_G \tag{5}$$

$$V_{OUT@LOAD} = V_G \cdot \frac{R_{LOAD}}{R_{LINE} + R_{LOAD}} \tag{6}$$

Substituting these equations into (4) and reducing produces (7) which is nothing more than the reflection coefficient common to microwave theory.

$$\rho = \frac{R_{LOAD} - R_{LINE}}{R_{LOAD} + R_{LINE}} \tag{7}$$

We therefore have the complete theory for a TDR system. As a final comment, the reflection coefficient (ρ) is usually expressed in impedances instead of resistances to account for inductance and capacitance

(8). In order to stay consistent with notation used later in this paper, the subscripts load and line will be replaced by s and μ in the general impedance equation.

$$\rho = \frac{Z_S - Z_\mu}{Z_S + Z_\mu} \quad (8)$$

With the basic theory explained, it is now appropriate to discuss the mathematics behind measuring conductivity with a TDR instrument provided by Giese and Tiemann [2], Dalton [3], and Topp [4]. The reader will then be familiar with the concepts and the key design parameters for a TDR multiplexer. Then, this chapter will continue with the high frequency matching techniques required. Functional design of software, hardware, and schematics is presented at the end of this section.

Theory for Measuring Conductivity and Water Content of Soil Samples

There are several methods of determining conductivity from TDR measurements, but the Giese and Tiemann analysis is by far the most prevalent in soil science [2]. It accounts for multiple reflections and loss inside the probe. In fact, due to its popularity, the other methods will only be mentioned in this article, not derived. After deriving the Giese and Tiemann conductivity equation, it will become obvious that only the initial and final voltages are necessary to determine the conductivity of any sample.

At this point, it would be wise to present a typical measuring configuration shown in Figure 6. As previously discussed, the TDR instrument consists of a spliter, pulser, and oscilloscope. The TDR is connected to the probe via a coaxial cable, and the probe can be one of two types. The first would be two parallel wire conductors, resembling a set of monopole antennas. One of these wires would connect to the cable's ground and the other to its center conductor (Figure 7). The second type of probe consists of an air core coaxial transmission line (Figure 8) filled with the sample to be tested.