

Errata

Document Title: TDR Techniques for Differential Systems (AN 62-2)

Part Number: 5989-6184EN

Revision Date: October 1990

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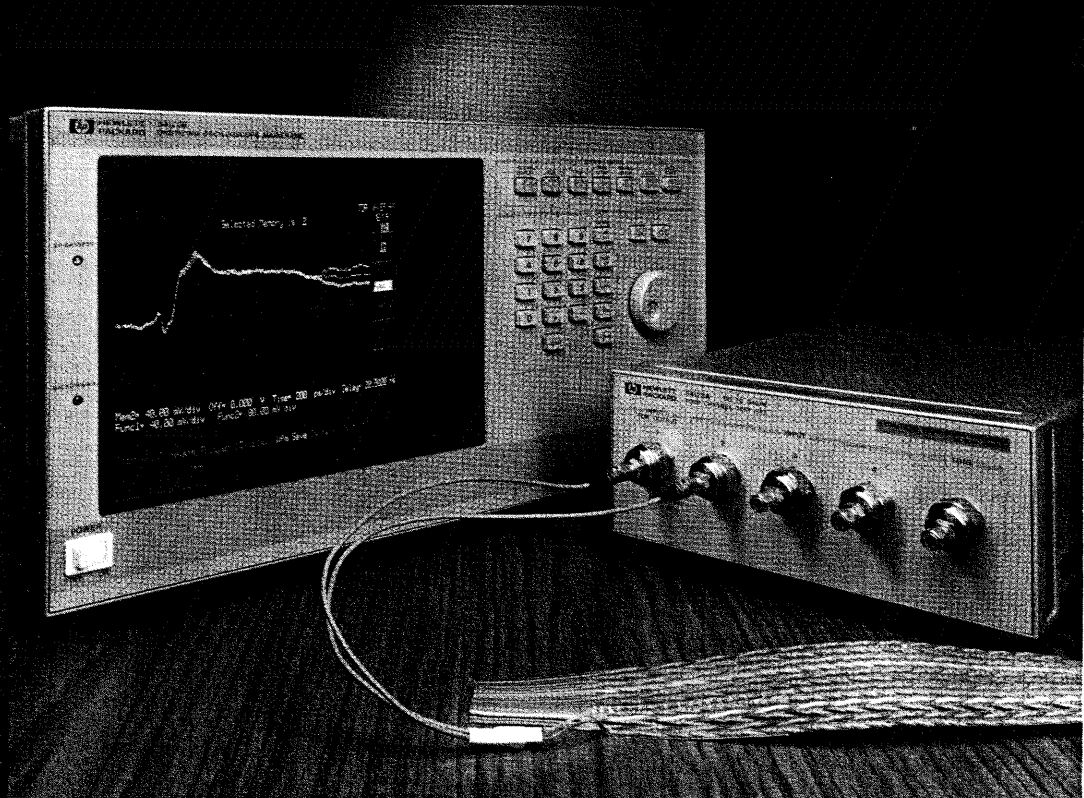
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Application Note 62-2

*For use with the HP 54120
Family of Digitizing Oscilloscopes*

October 1990



**TDR
Techniques
for
Differential
Systems**

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Introduction

This application note describes time-domain reflectometry (TDR) techniques for differential systems. To avoid confusing standard TDR using one oscilloscope channel with TDR for differential systems which uses two scope channels, the latter shall be referred to as differential TDR (DTDR). The note is divided into two sections and an appendix. In section I, the terminology and background for DTDR measurements are reviewed and descriptions of both the single and dual step generator methods of performing DTDR are provided. Section II contains the procedures for performing the single-step method of DTDR and techniques for interpreting the results. SPICE model simulations which theoretically verify the single step generator technique are provided in the appendix.

Section I

DTDR Terminology and Methods

DTDR Terminology

To provide a common base of understanding, several key concepts and definitions pertaining to DTDR are covered next.

Differential System

A differential system comprised of a differential drive, a balanced transmission line, and a differential receiver can be represented by the block diagram shown in figure 1.

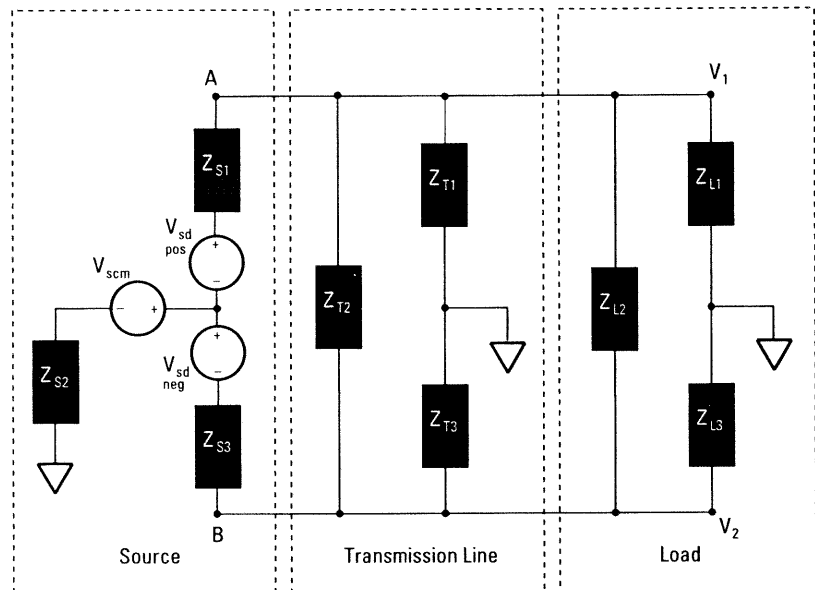


Figure 1. Differential system block diagram

Ideally, a differential system responds only to a potential difference between its balanced input terminals and suppresses outputs from common-mode voltages at the input. This is only true if there are no imbalances in the system. An imbalance could be demonstrated in figure 1 by making $Z_{S1} \neq Z_{S3}$, $Z_{T1} \neq Z_{T3}$, or $Z_{L1} \neq Z_{L3}$.

Differential-Mode

A differential-mode stimulus to a differential system would be applied across the input terminals A and B of figure 1. The differential-mode response seen by the load is the difference of V_1 and V_2 .

The magnitudes of V_{sd} positive and V_{sd} negative are equal for DTDR measurements. Using DTDR for characterization of the differential-mode impedance of the system, V_1 minus V_2 provides a view of the impedance between the two conductors.

Common-Mode

The general definition from the I.E.E.E. Standard Dictionary of Electricity and Electronics Terms for common-mode is "the instantaneous algebraic average of two signals applied to a balanced circuit, both signals referred to a common reference."

A common-mode stimulus to a differential system applies the same signal to both inputs. Ideally such a signal is rejected at the receiver since the difference of the signals is zero.

Common-mode impedance of a differential system is the parallel combination of both connectors measured to ground. For a balanced system, both connectors see the same impedance to ground. To measure the common-mode impedance with DTDR, either one step generator or two identical steps of the same polarity must be used. The common-mode impedance measurements are made from V_1 plus V_2 . See figure 1.

Common-Mode Imbalance

A common-mode imbalance results from unequal impedance between the two conductors of a differential system and their common reference plane. In figure 1, an imbalance results if Z_{S1} and Z_{S3} , Z_{T1} and Z_{T3} , or Z_{L1} and Z_{L3} are not equal.

With an imbalance in a system, the algebraic average of the signals on the conductors will no longer be zero when the inputs are equal. A net current introduced from a common-mode imbalance develops a differential-mode voltage at the receiver. Common-mode conversion is the process of developing differential-mode interference from a common-mode interference (imbalance).

The end result of an imbalance is that the common-mode and differential-mode DTDR results are coupled and the system will not reject all extraneous common-mode signals.

Balanced Transmission Line

Balanced transmission lines consist of two identical conductors that are symmetrical with reference to ground. These include twisted pair cables, both shielded and unshielded, dual-trace microstrip lines, and dual-conductor strip line. Ideally, currents in the conductors of a balanced line are equal in magnitude and opposite in direction.

External interferences (noise and crosstalk) generally act equally on both conductors of a balanced transmission line. Thus extraneous signals produce common-mode interference. Since the currents in the conductors of a balanced line travel in opposite directions, the resulting induced common-mode voltages tend to cancel each other at the receiving end. Cancellation of induced voltages eliminates common-mode interference.

Discontinuity

Discontinuities result from any non-uniform impedances. In differential systems discontinuities can be common-mode, differential-mode, or both. Typically, discontinuities are noticed at connectors. Figure 2 shows discontinuities and impedance mismatches.

Techniques for measuring the values of discontinuities are covered in HP Application Note 62, TDR Fundamentals for Use with HP 54120T Digitizing Oscilloscope and TDR. The procedures are written for standard TDR; however, the calculations are applicable for DTDR displays.

Impedance Mismatch

Observing figure 2 and referring back to figure 1, a differential-mode impedance mismatch results if the differential impedance of the source, transmission line, and/or load are not equal (i.e. if $Z_{T1} \parallel (Z_{T2} + Z_{T3}) \neq Z_{L1} \parallel (Z_{L2} + Z_{L3})$). Measurement techniques for impedance mismatches are presented in section II of this application note.

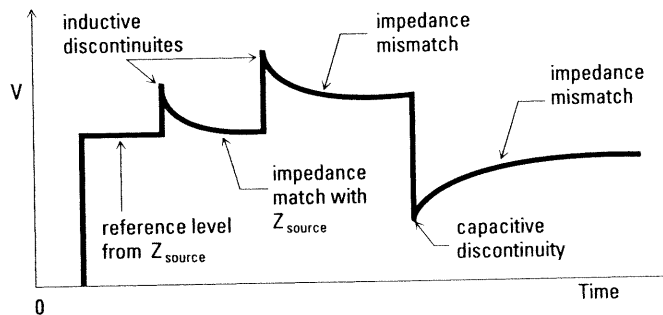


Figure 2. Discontinuities and impedance mismatches.

Unbalanced Transmission Line

Any transmission line with two conductors that are electrically unequal with respect to a reference point (usually ground) is unbalanced. An unbalanced transmission line is typically considered to be a single conductor signal path with a ground conductor.

Single-Ended System

Single-ended systems reference a signal between one conductor and ground. A single-ended system, including an unbalanced transmission line, is shown in figure 3.

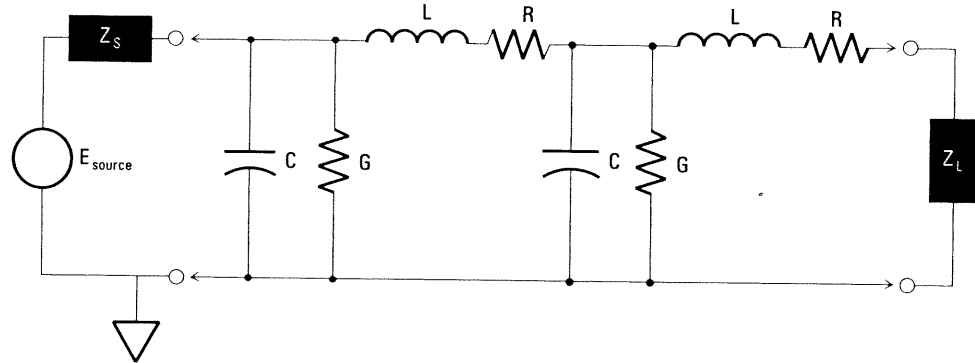


Figure 3. Single-ended system with an unbalanced transmission line.

Unbalanced transmission lines and single-ended circuits are susceptible to noise and crosstalk proportional to signal path length and bandwidth. Differential systems offer improved performance by basically eliminating induced common-mode currents generated by external electromagnetic interference (noise and crosstalk).

Standard TDR

Standard TDR uses a single step generator and a single scope channel to measure reflection characteristics and is performed on unbalanced transmission lines, such as coaxial cables. Standard TDR gives erroneous results when connected to a balanced line, since the response of only one of the two conductors is observed.

DTDR Methods

The two primary methods of performing DTDR with digital oscilloscopes, the dual step generator and single step generator methods, are presented in this application note.

Dual Step Generator Method of DTDR

DTDR can be accomplished by using two step generators to stimulate the differential system. One generator outputs a pulse from 0.0 V to some positive DC level with a fast edge. The second step generator is the complement of the first step generator. Each generator output is single ended coaxial; however, a differential pulse exists between the center conductors of the output cables. This differential signal is applied to the differential input of the system under test. A scope channel is attached to each input and waveform math is used to display the DTDR results.

Subtracting one channel from the other provides the differential-mode result to a differential stimulus. To obtain the common-mode result to a differential stimulus, the waveforms from the two channels are added.

Common-mode results to a common-mode stimulus are possible if both step generators are of the same polarity or one generator is disabled. The results from a common-mode stimulus can be used to view the common-mode rejection of a receiving system or locate imbalances.

A block diagram of dual step generator stimulus is shown in figure 4. The technique relies on the step generators being synchronized in time, and identical in pulse shape, height, and offset. It is difficult and expensive to build accurate dual step generators. Calibration of dual step generators is very difficult in general and especially so if the scope has analog feedback sampling with loop gain adjustments. Loop gain adjustment can separately alter the shape of each differential step. Thus, the adjustment varies with each individual user. Errors in matching the dual steps will be manifested as errors in DTDR measurements.

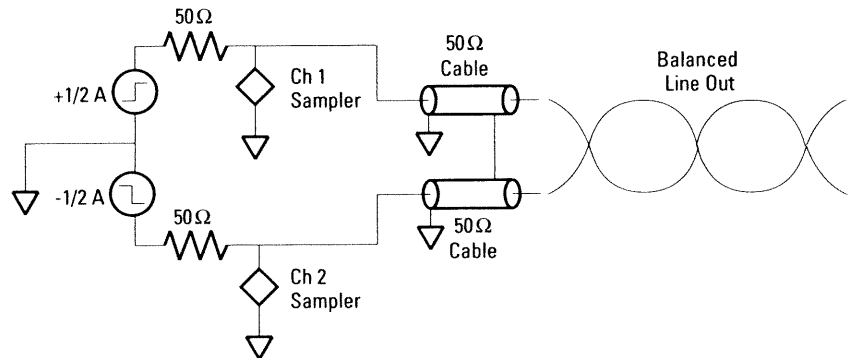


Figure 4. Dual step generator differential stimulus.

Insight on common-mode imbalances can be obtained using the dual step method if the waveforms are added rather than subtracted.

Systems with dual step generator capability can perform the single step method by disabling one step generator.

Single Step Generator Method of DTDR

Accurate DTDR results can also be obtained by using a single step generator and two scope channels. Taking advantage of the common-mode and differential-mode components of the overall circuit, waveform math is used to obtain the common and differential-mode reflections.

An example of the single step generator method of DTDR using the HP 54121T, HP 54123T, or HP 54124T digital sampling oscilloscope will be considered. The TDR step is produced by a current source attached to the scope input sampler, which is back terminated in 50 ohms.

The circuit for DTDR on a differential system can be represented by the Thevenin equivalent circuit shown in figure 5, where there is a single step generator in channel 1.

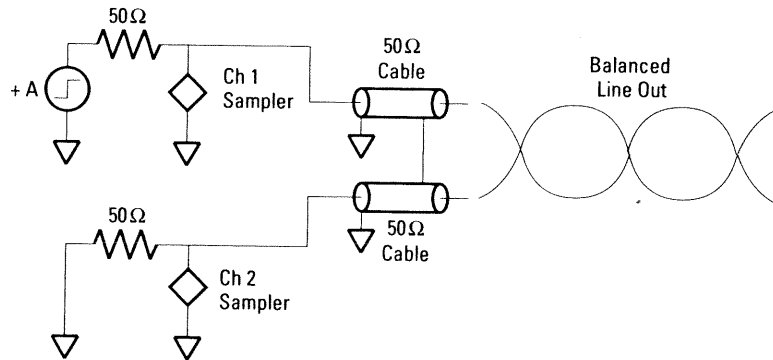


Figure 5. DTDR with a single step generator built into channel 1.

In figure 6, the single step generator has been redrawn into its common-mode and differential-mode components. In this equivalent circuit, both Channels 1 and 2 are simultaneously stimulated by the common-mode source. Channels 1 and 2 are also stimulated differentially by a complementary pair of sources.

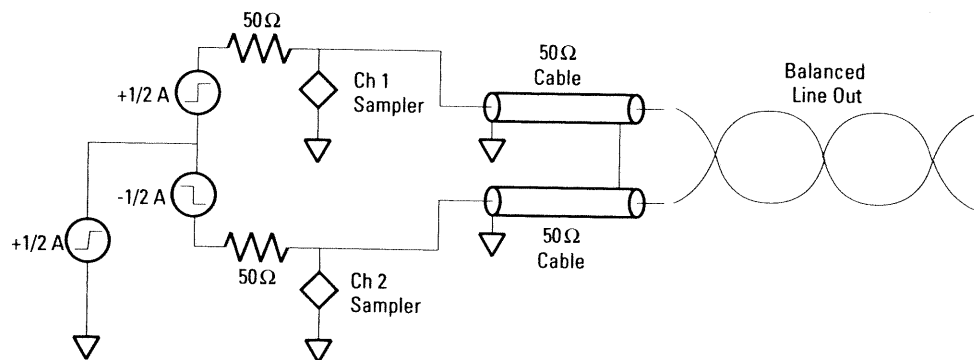


Figure 6. Equivalent circuit with the single step generator represented by common-mode and differential-mode components.

Notice the similarity of figure 6 to the dual step generator source in figure 4 with respect to the differential components. To fully characterize and understand the system, both the common and differential modes must be viewed.

The procedures for viewing DTDR results from the single step method are covered in section II.

Section II

Procedures

Single Step DTDR Procedures on Differential Systems

Differential and common-mode responses to both differential and common-mode stimuli are obtained from the procedures presented in this section. The responses provide immediate insight on the nature of the system. Accurate distance and impedance measurements can be made from the resulting displays.

The procedures also produce a graphic display of common-mode imbalances in a differential system. Remember that when an imbalance is present in a system, the modes become coupled and the results from either the dual or single step method become complicated to interpret. Common-mode imbalances are undesirable in a differential system and they should be corrected before attempting to characterize a differential system.

Differential-Mode Results

Any multiple-channel digitizing oscilloscope with a built-in TDR step generator and waveform mathematics can be used for single step generator DTDR. The following steps apply for observation of the differential-mode response and location of imbalances.

- 1) Attach the center conductors of two channels of a digitizing oscilloscope to the inputs of a balanced line system with cables equal in length and impedance. One of the channels must have a step generator output.
- 2) Tie the ground, if one exists, such as a shield around a twisted pair, to the scope ground. Make the ground connection as short as possible.
- 3) Define a function in the waveform-math menu as channel 1 minus channel 2. This will be the actual differential-mode response of the system only if there are no imbalances. Store this trace in memory.
- 4) Reverse the leads to channels 1 and 2. View and store, in another memory, the response of channel 1 minus channel 2. If there are no imbalances, the trace stored from step 3 will overlap with this trace. At locations where there is an imbalance, the traces will diverge.
- 5) Using waveform math, add the two responses from steps 3 and 4 to get the same differential-mode result as would be obtained from using the dual step source method. Locations where the three traces from steps 3, 4, and 5 do not coincide represent the areas of imbalance.

Taking channel 1 minus channel 2 subtracts out the common-mode element of the driving source and associated reflections, except for reflections caused by any imbalance in the line, or from common-mode resonance where the line acts as an antenna. In the case of imbalance or resonance, reflections cause a slightly different response depending on whether the channel 1 source is attached to one side of the device or to the other. The effect of the common-mode element allows

identification of any imbalances present in a differential system. Imbalances coincide with areas where the traces do not overlap.

Simplified Procedures for Differential-Mode Results

When it is known that the system has no imbalances, it is only necessary to perform steps 1-3.

Viewing only the differential results from the dual step method or using only the simplified procedures of the single step method will not accurately characterize the system under test when an imbalance is present.

Common-mode Results

The common-mode response of a balanced system is obtained by using the same steps as for the differential-mode response only adding channel 2 to channel 1 in steps 3 and 4 instead of subtracting channel 2 from channel 1.

Time-Alignment Procedures Distance Measurements

The time delay between the device under test (DUT) reference plane and each scope input must be matched. The following alignment procedures apply for DTDR using a single step generator.

1) Replace the DUT with a power splitter (HP 11667B) as shown in figure 9.

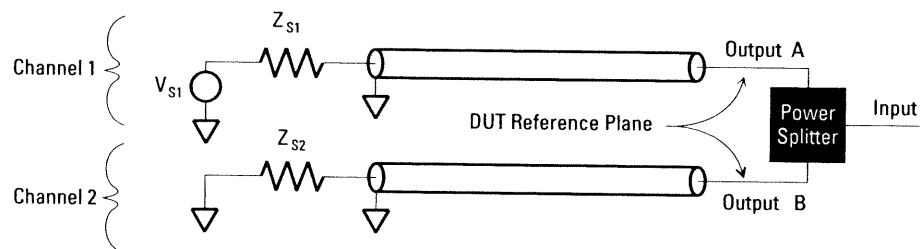


Figure 9. Setup for time-alignment.

2) Turn on the TDR step generator (V_{s1}) and align the positive edges of channels 1 and 2 using channel skew. Channel skew is available through the utility and cal menus on the HP 54120 family of digitizing oscilloscopes. Note the value of channel skew necessary to align the edges.

3) Reverse the output connections to the power splitter and repeat step 2.

4) Set channel skew to the average of the results from steps 2 and 3. The result from step 2 is within ± 3 ps (a limitation of the power splitter).

The result from step 4 provides channel alignment to within ± 1 ps (scope specification).

Distance Measurements

It is often desirable to locate discontinuities and impedance mismatches in a system. Distance measurements can be made from any TDR display using the following equation.

$$\text{distance} = (\text{velocity})(\text{time}) \quad d = \left(\frac{c}{\sqrt{\epsilon_r}} \right) \left(\frac{\Delta t}{2} \right)$$

c = velocity of light (2.997×10^8 m/s)

Δt = time between a reference point and a point of interest

ϵ_r = relative dielectric constant of the transmission line

The value of ϵ_r will usually be different for the common and differential modes of propagation on a balanced transmission line. Use the common-mode value to determine distances to common-mode discontinuities. Use the differential value to locate differential impedance discontinuities. ϵ_r also depends on the type of cable used. If ϵ_r is not known, it can be experimentally determined by holding the distance variable of the above equation constant, performing TDR measurements to obtain Δt to the known distance, and solving for ϵ_r .

Impedance Measurements

Differential or common-mode impedance measurements, on differential systems without imbalances, are possible from their corresponding displays with the following equation

$$Z_{\text{line}} = \left(\frac{1 + \rho}{1 - \rho} \right) \times Z_{\text{ref}}$$

$$\rho = \left(\frac{V_{\text{ref}}}{V_{\text{inc}}} \right)$$

$$V_{\text{ref}} = V_1 - V_2$$

For differential calculations $Z_{\text{ref}} = 100$ ohms. ($50 + 50$)

For common mode calculations $Z_{\text{ref}} = 25$ ohms. ($50 // 50$)

For standard TDR calculations, one step generator and one scope channel, $Z_{\text{ref}} = 50$ ohms.

Complications

The impedance equations provided are only valid for balanced systems. When an imbalance exists, the common and differential-mode impedance calculations become more complex. The impedance equations for use on a differential system with an imbalance are not provided in this note.

TDR measurements on any scope become more complex and results become less definitive as the number of reflections from impedance discontinuities and mismatches increases. TDR results to the first impedance mismatch will be accurate and measurements to preceding impedance levels will diminish in accuracy unless more complex calculations are performed. This is also true with the results obtained from the single and dual step methods of DTDR. As an example, a source to line mismatch complicates the impedance equations for the load.

Calculations for multiple impedance mismatches are provided in *Application Note 67, Cable Testing with Time Domain Reflectometry*.

The required waveform math functions for single step generator DTDR measurements are available on the HP 54121T, HP 54123T, and HP 54124T oscilloscopes. The HP 54121T, HP 54123T and HP 54124T Digitizing Oscilloscope Front-Panel Operation References, which are supplied with each instrument, provide details on TDR measurements and waveform mathematics.

Appendix

SPICE Modeling For DTDR

The following is a series of HSPICE simulations to illustrate the dual and single step generator methods of DTDR. The simulations show theoretically that the single step generator method is effective in viewing the differential and common-mode impedance of differential systems.

The differential results of the single step generator method for balanced systems compare exactly to the results of the two step generator method with no additional measurements or waveform math. Further, for systems with imbalance, SPICE indicates the single step generator method is capable of identifying an imbalance. SPICE also demonstrates that for a differential system with an imbalance, the single step method can display the same differential impedance as seen with the dual step generator method by using some additional waveform storage and waveform math functions.

In all cases the delay line is the same; the cases vary in the way the line is driven and terminated. The line has common mode characteristic impedance of 26.5 ohms and delay of 2.12 ns. Differential characteristic impedance is 83.3 ohms and delay 5 ns.

The SPICE T Section Model and Resultant Delay Line Model

The basic T line section model used consists of series inductors: L , with mutual coupling; K , a differential capacitance C_{diff} and common-mode capacitances C_{cm} with ground reference between each capacitance. This is shown in Figure A1.

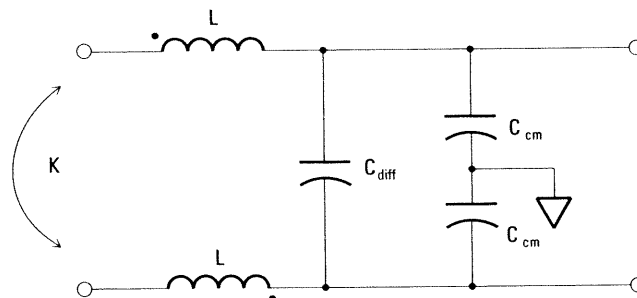


Figure A1. Basic T line section circuit model.

Each T line is formed by cascading twenty of the basic T sections together, resulting in a common-mode impedance and delay for each T line of 26.5 ohms and 2.12 ns. The differential impedance and delay for a T line is 83.27 ohms and 5 ns respectively.

All simulations use the same delay line device under test (DUT). Cases vary in the way the line is driven and terminated.

Dual Step Generator Differential Stimulus Drive

In the first SPICE experiment, a delay line formed by T line is stimulated with dual step sources. The delay line is terminated into 50 ohms to ground on each output as shown in figure A2. Voltages V(1) and V(2) are shown in figure A3. V(1) minus V(2) is shown in figure A4, which would correspond to the display on a TDR with dual step generators. No common-mode information is available because that mode is not stimulated unless one of the steps is turned off. It is crucial that the two steps be accurately time-synchronized and identical except for polarity.

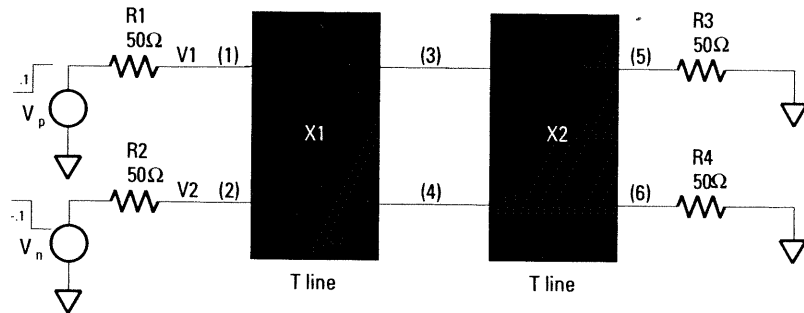


Figure A2. Configuration for dual step generator differential drive, balanced termination.

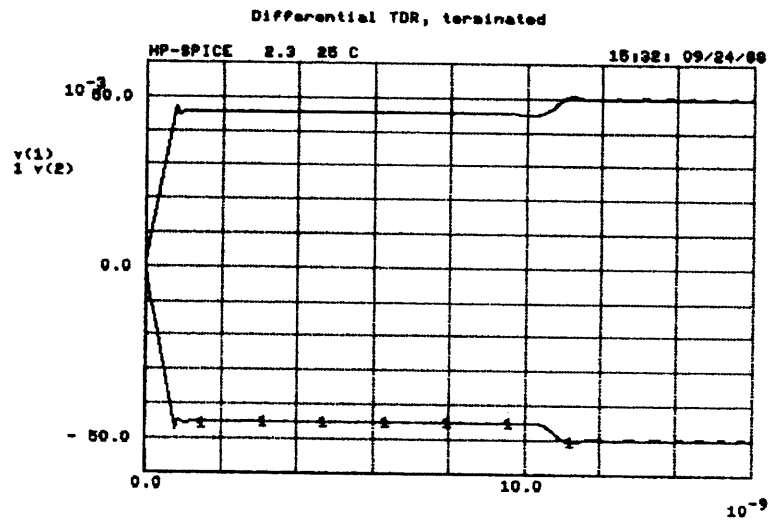


Figure A3. V(1) and V(2) responses, dual step generator drive, balanced termination.

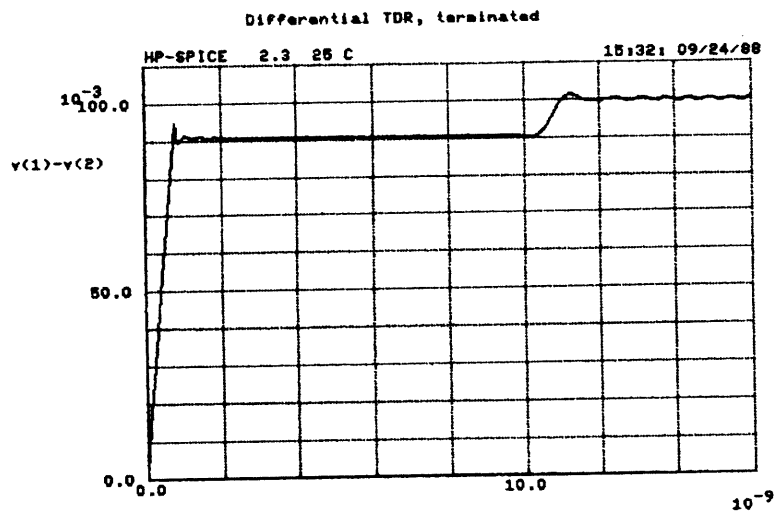


Figure A4. $V(1)$ minus $V(2)$ response, dual step generator drive, balanced termination.

One Step Generator Stimulus Drive

Next, the same device is driven by a single step generator like that in the HP 54120 family of digitizing oscilloscopes. The configuration is shown in figure A5, and results of $V(1)$ and $V(2)$ can be seen in figure A6.

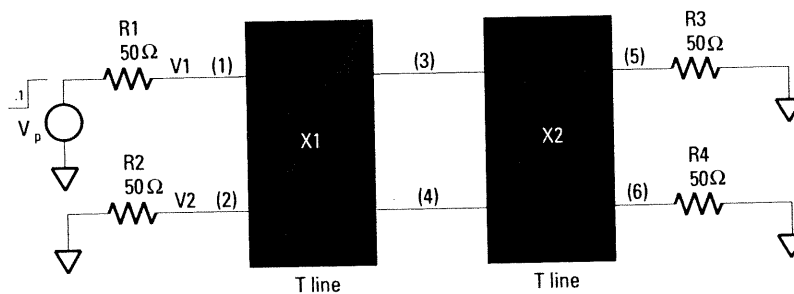


Figure A5. Configuration for single step generator drive, balanced termination.

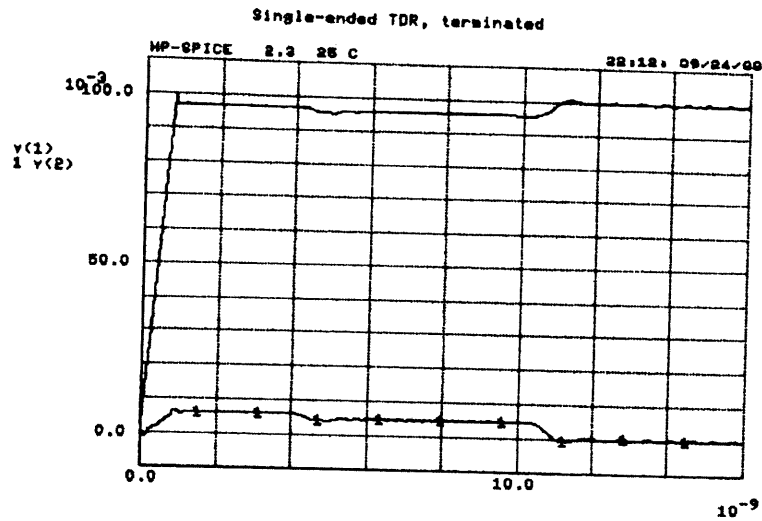


Figure A6. V(1) and V(2) responses, single step generator drive, balanced termination.

The TDR display of V(1) minus V(2) is shown in figure A7. The results are identical to results from the dual step generator method. Switching to Ch 1 plus Ch 2 displays the common-mode characteristics as presented in figure A8.

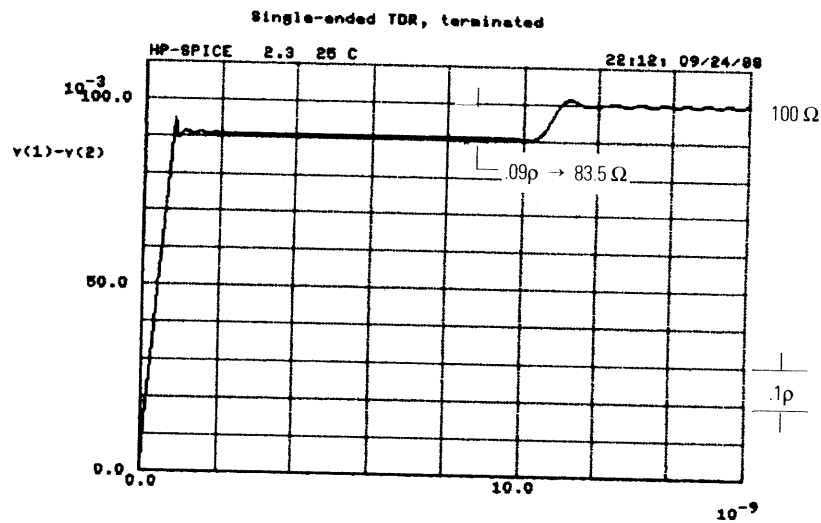
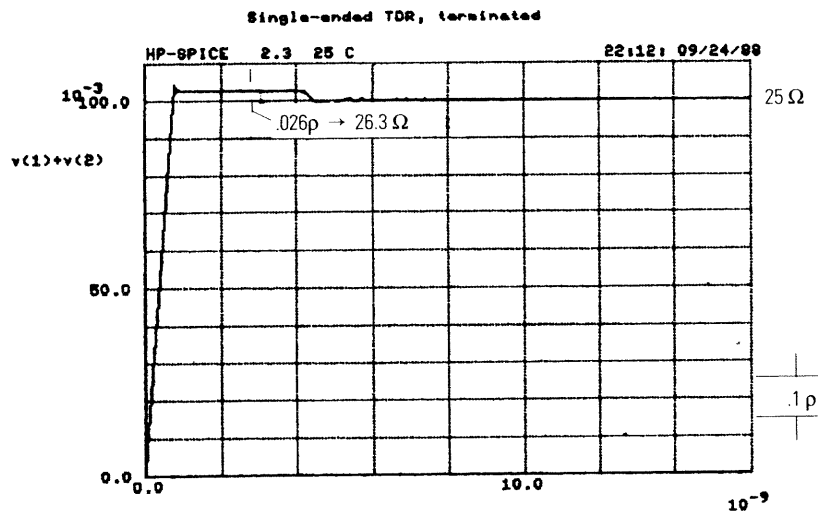


Figure A7. V(1) minus V(2) response, single step generator drive, balanced termination.



```

hspice> li
Single-ended TDR, terminated
.options nolist nonode nomod nodeck
.options limpts=1001
.tran 20p 15n
x1 1 2 3 4 0 xline (4n .3 1p 1p)
x2 3 4 5 6 0 xline (4n .3 1p 1p)
vp 11 0 pulse(0 .2 0 .8n .8n 30n 60n)
vn 12 0 pulse(0 -.0 0 .8n .8n 30n 60n)
r1 11 1 50
r2 12 2 50
r3 5 0 50
r4 6 0 50

```

Figure A8. V(1) plus V(2) response (common-mode), single step generator drive, balanced termination.

The DTDR results become more complicated if the structure is significantly unbalanced. In that case neither the differential or common-mode results give a very clear indication of the exact nature of the mismatch. The DTDR configuration for the dual step method on an unbalanced case is shown in figure A9. The differential results, from the dual step method, see figure A10, look innocuous. However, if the dual step generator responses are added as displayed in figure A11, the fact that the waveforms are not at a constant level, gives some indication that something is amiss.

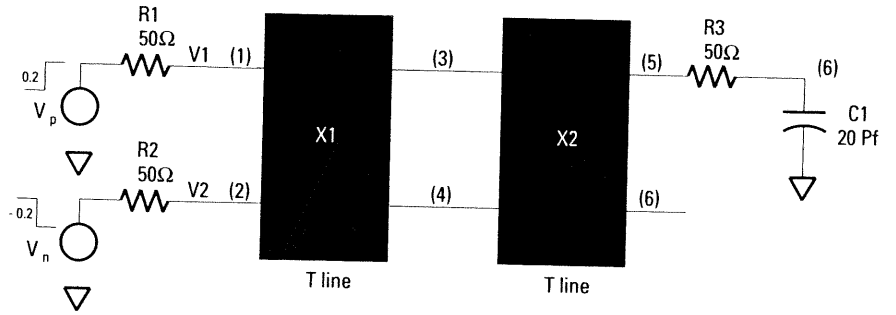


Figure A9. Dual step method, configuration for a balanced line with an unbalanced termination.

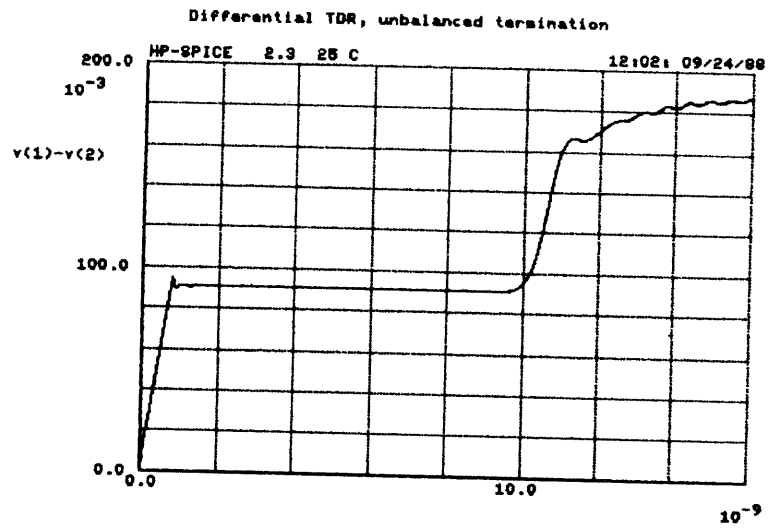


Figure A10. Dual step method, differential simulation results for a balanced line with an unbalanced termination.

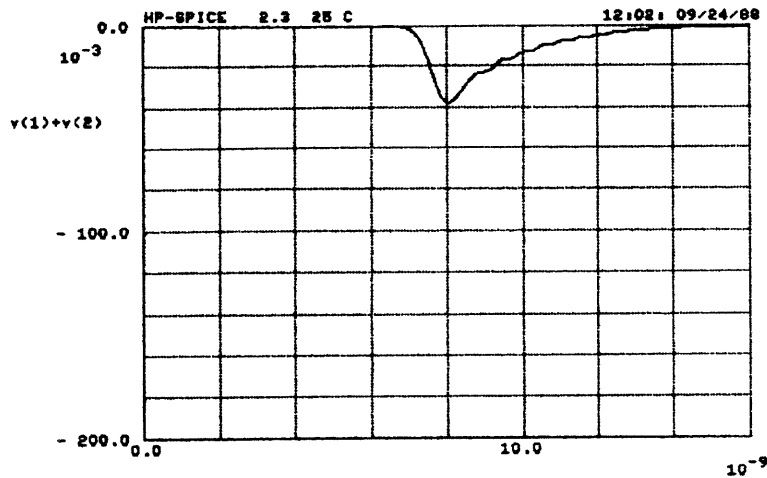


Figure A11. Dual step method, trace 1 plus trace 2 from responses of a balanced line with an unbalanced termination.

The single step drive with an unbalanced termination configuration is shown in figure A12. To get all the information, two measurements are taken, channel 1 minus channel 2 is displayed and stored, then the inputs are interchanged and the channel 1 minus channel 2 measurement is stored again in a different memory. The responses stored in the two memories are then added and the results are plotted in figure A13. Figures A10 and A13 are equally misleading because of the unbalanced structure being analyzed.

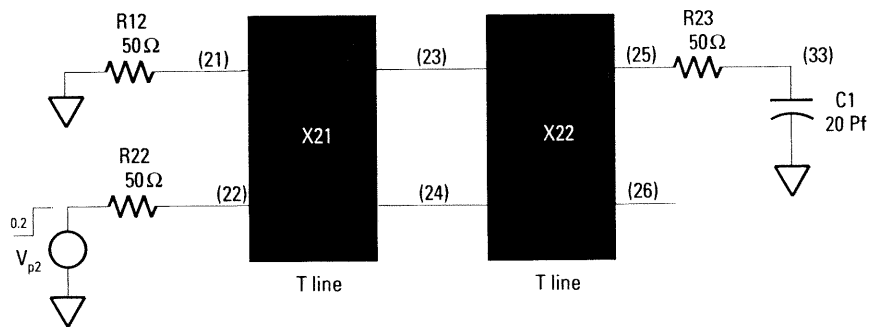


Figure A12. Single step method, configuration for a balanced line with an unbalanced termination.

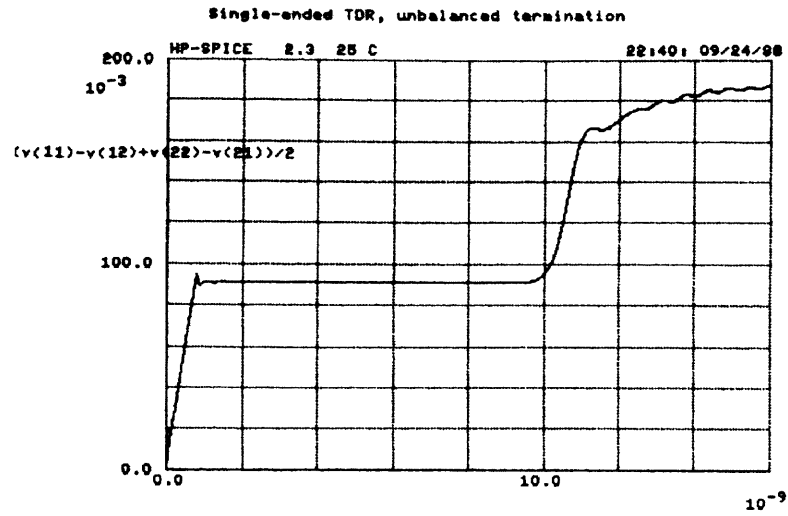


Figure A13. Single step method, differential simulation results for a balanced line with an unbalanced termination.

The common mode response, figure A14, can be displayed with the single step method by adding channel 1 and channel 2. The dual step method cannot produce common mode results unless both step generators are of the same polarity or one step generator is turned off.

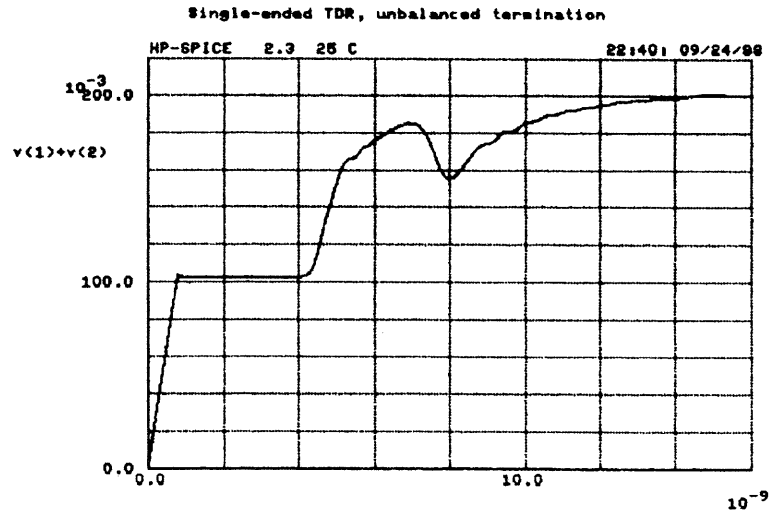


Figure A14. Single step method, common mode results from a simulation of a balanced line with an unbalanced termination.

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