HEWLETT
PACKARD

DIFFERENTIAL TDR USING A SINGLE STEP GENERATOR

Interest has been on the rise for making differential TDR measurements on balanced systems like twisted pair cables, both shielded and unshielded, on dual trace microstrip lines, and on dual conductor stripline. Under certain conditions, such balanced transmission paths offer improved performance over unbalanced lines, particularly in terms of common mode noise rejection and immunity to crosstalk.

The question arises on whether standard TDR can be used effectively to analyze balanced systems, and if so, how? This note explores these questions and will describe how differential TDR is easily accomplished using a standard TDR if a few special considerations are made. These are different considerations than those required with dual step source differential TDR. Equivalent circuits of dual and single step source TDR's are compared along with SPICE model simulation results to support this claim. Finally, actual measurements are performed on a number of standard devices and on a twisted pair cable to verify the technique. A view of the twisted pair cable using a dual pulse differential TDR is compared to these results and shown to have very close agreement, while standard TDR with no special considerations is shown to be error.

Dual pulse generator method:

Differential TDR can be accomplished by using two step generators to stimulate the DUT. One step generator outputs a pulse from 0 volts to some positive DC level with a fast edge. The other step generator has opposite polarity, and steps from 0 volts to a negative level. Each generator is single ended coaxial, but a differential pulse exists between the center conductors of the output cables of these generators. This differential signal is applied to the differential inputs of the DUT, a scope channel is attached to each input, and the difference of the channels is displayed on screen.

A block diagram of the differential stimulas is shown in Figure 1. This technique relies on step generators being synchronized in time, and identical in pulse shape.

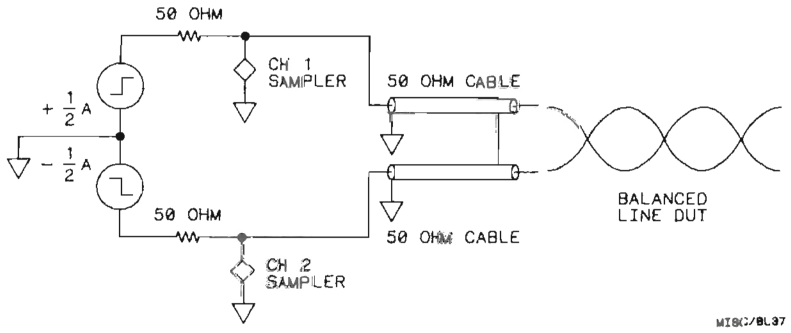


Figure 1. Dual generator differential stimulus

Single generator method:

Differential TDR is also possible using a single pulse generator and taking advantage of its common mode and differential mode components. Waveform math in the oscilloscope can be used to subtract the common mode component to view the differential mode reflections.

The HP 54120T TDR step is produced by a current source attached to the scope input sampler which is back terminated in 50 ohms. This can be represented with a Thevanin equivalent circuit like shown in Figure 2 with a step generator in channel 1 and no step in channel 2. This can again be redrawn to show the common mode and differential mode components of the step source. An equivalent circuit, which contains the desired dual source differential generator pair is shown in Figure 3. Notice it's similarity to the true differential source in Figure 1.

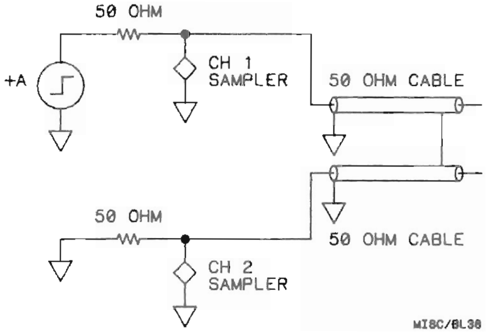


Figure 2. Single ended pulse generator built into Ch 1, and Ch 2 input with no step

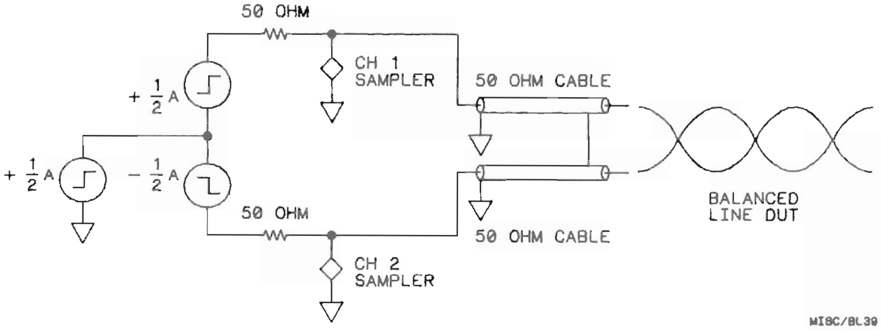


Figure 3. Equivalent circuit of TDR step and scope inputs represented by common mode and differential mode step sources.

The single step generator has been redrawn into its common mode (CM) and differential mode (DM) equivalents. 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 positive going and negative going pair of sources.

To View Differential TDR

By applying the center conductor of channel 1 and channel 2 to the inputs of a balanced line DUT, and shield ground to the DUT ground (if one exists, such as a shield around a twisted pair), and defining a Function in the Waveform Math menu of the HP 54120T as channel 1 - channel 2, a differential response appears on screen. The common mode element of the channel 1 driving source and associated reflections are subtracted out, except for reflections caused by any imbalance effect 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. This effect can be very helpful to determine if and where imbalance is present in a DUT. In the event it is not desired to see such effects and desired to match results that would be obtained from a differential TDR step source using two pulse generators, this can be easily accomplished.

One must only view and store the Ch 1 - Ch 2 response with scope channel 1 attached to one side of the device, and then view and store the response with the leads reversed. Adding these two responses yields the same result as when using a differential step source. Required waveform math functions are available in the HP 54120T.

SPICE modeling for differential TDR:

Hpspice simulations illustrate dual and single pulse generator methods of differential TDR, and show theoretically that the single pulse generator method is effective in viewing differential and common mode impedance of balanced DUT's, and results compare exactly to that of the two pulse method. Further, for systems with imbalance, Spice indicates the single pulse method is cabable of identifying an imbalance and displaying the differential impedance as would be seen with a dual pulse method by using waveform storage and math functions.

The simplest SPICE results are presented here for a balanced delay line with different common mode and differential mode impedances and delays, and with a balanced termination. More complicated SPICE results with imbalance effects and their removal are included in the appendix, as well as additional SPICE model circuit equations.

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 Cdiff, and common mode capacitances Ccm with ground reference between each capacitance. This is shown in Figure 4. T lines X1 and X2 are formed by cascading 20 of these T sections together, resulting in a common mode impedance and delay for each X1 and X2 of 26.5 ohms and 2.12 nsec. The differential impedance and delay for X1 and X2 is 83.27 ohms and 5 nsec respectively. Derived calculations can be found in the appendix. All simulations use the same delay line DUT; cases vary in the way the line is driven and terminated.

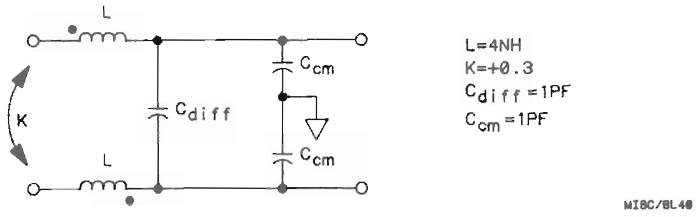


Figure 4. Basic T line section circuit model

True Differential Stimulus Drive

In the first SPICE experiment, the delay line formed by X1 and X2 is stimulated with dual step sources, and the delay line is terminated in 50 ohms to ground on each output as shown in Figure 5. Voltages V(1) and V(2) are shown in Figure 6, as well as v(1) - V(2) in Figure 7 which would correspond to the display on a TDR with differential pulsers. No common mode information is available because that mode is not stimulated unless one fo the pulsers is turned off. It is crucial that the two pulsers be accurately time synchronized.

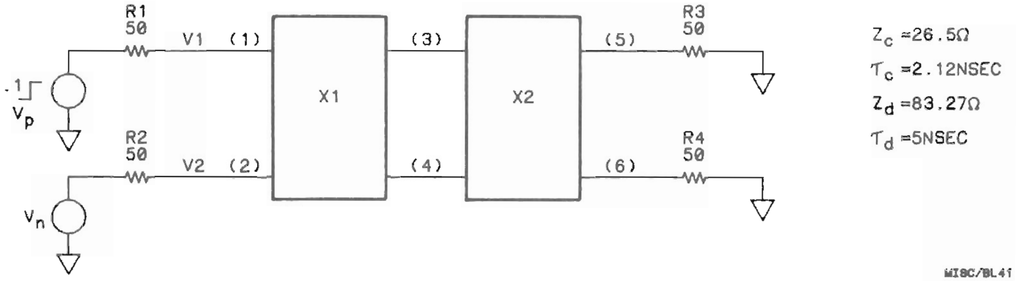


Figure 5. Configuration for differential drive, balanced termination

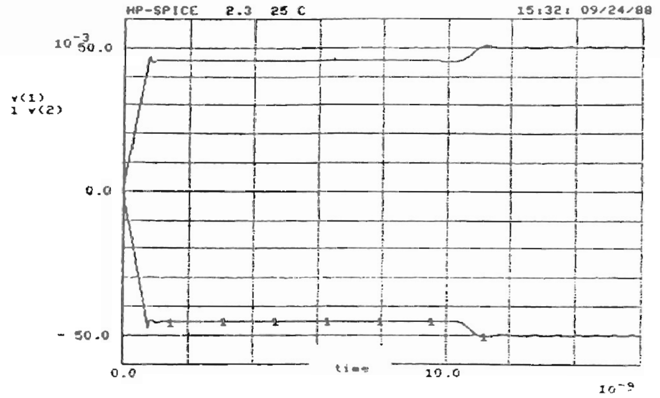


Figure 6. V(1) and V(2) responses, differential drive, balanced termination

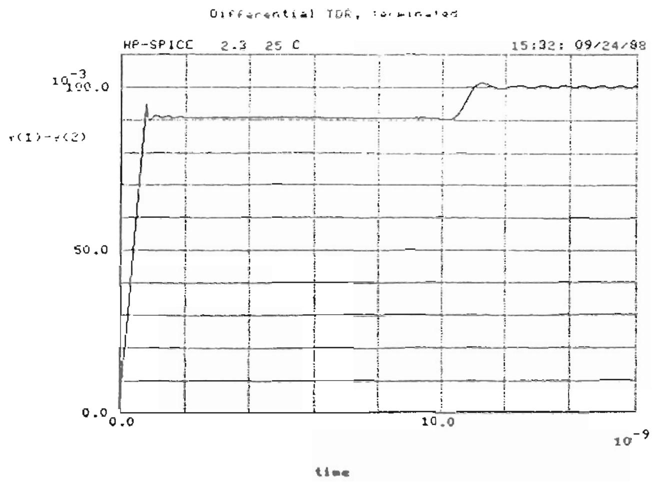


Figure 7. V(1) - V(2) response, differential drive, balanced termination

Single-ended Stimulus Drive

Next, the same device is driven by a single pulse generator as would be available in a standard TDR like that in the HP 54120T. Notice, this differs from simply taking center conductor and ground from the source and attaching to the DUT, but rather includes using a second scope channel to subtract the common mode. The configuration is shown in Figure 8, and results of V(1) and V(2) can be seen in figure 9.

The TDR display of V(1) - V(2) is shown in Figure 10 and can be seen to be identical to results from the dual pulse generator method. Switching to Ch 1 + Ch 2 would show the common-mode characteristics like presented in Figure 11.

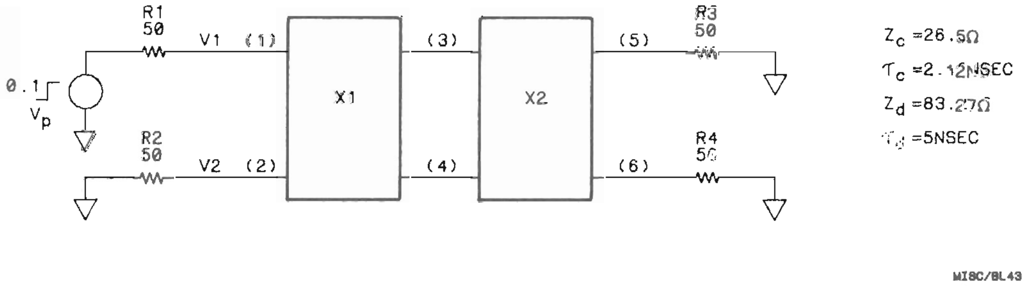


Figure 8. Configuration for single ended drive, balanced termination

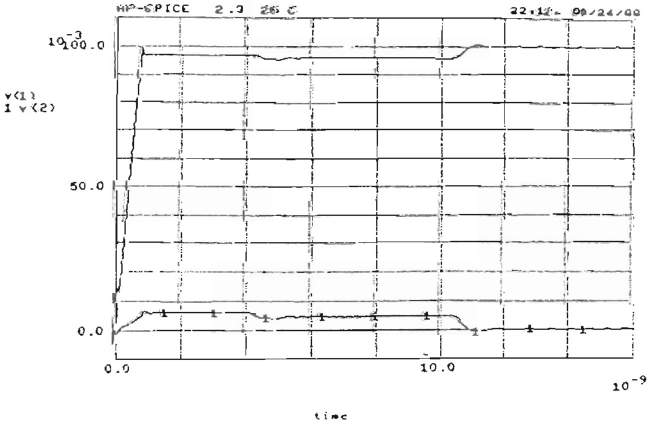


Figure 9. V(1) and V(2) responses, single edged drive, balanced termination

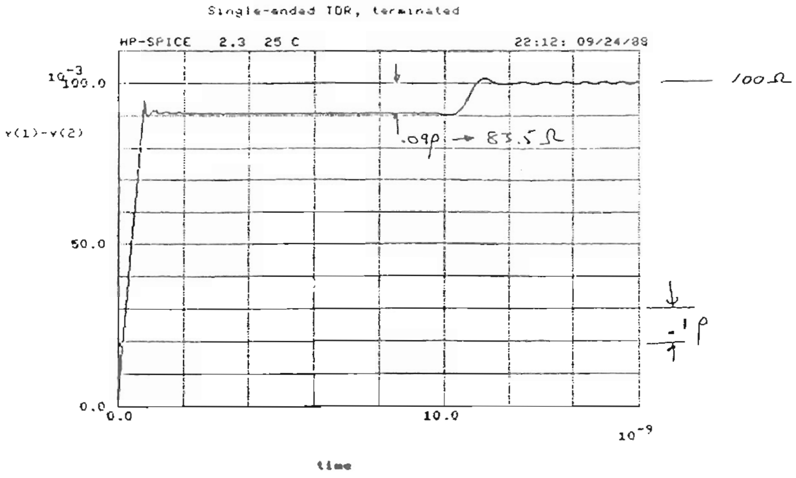
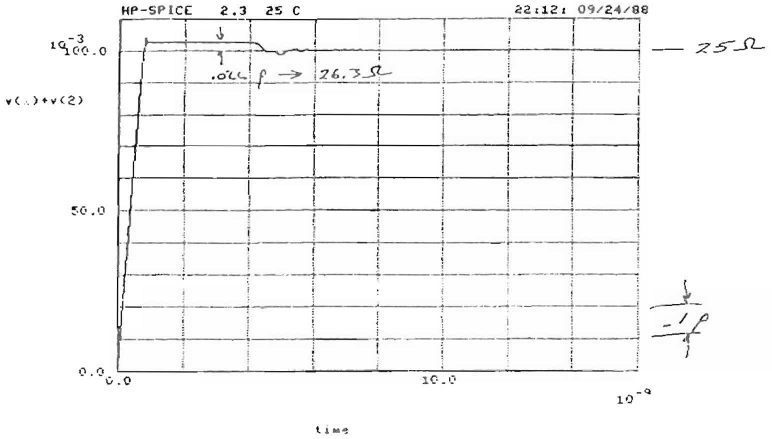


Figure 10. V(1) - V(2) response, single ended drive, balanced termination



```
hpspice> 1:
Single-ended TDR, terminated
.options nolist nonode nomod nodeck
.options limpts=1001
.tran 20p  16n
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
.include xline
.end
```

Figure 11. V(1) + V(2) response (common-mode), single ended drive, balanced termination

Actual Measurements to Verify the Single-ended drive Technique

Actual Hardware Configuration:

High bandwidth Gore cables are attached to channel 1 and channel 2 scope inputs. Differential TDR probing is accomplished using two small lengths of 50 ohm semirigid cable with SMA male connectors on one end of each cable. The other end of each semirigid cable is stripped back to expose the center conductor. Ground shields on each cable end are soldered together, resulting in the two center conductors in close proximity to one another as a convenient probe, like shown in figure 12. If the DUT has a ground connector, a wire can be soldered to the semirigid ground to provide stimulus ground.

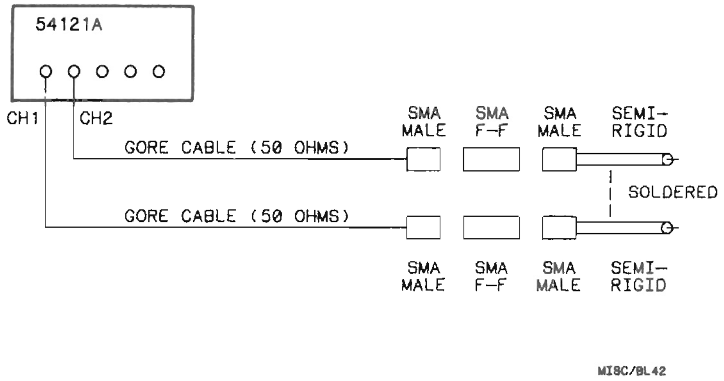


Figure 12. Hardware configuration for Differential TDR

Test results:

A number of tests are performed on standard DUT's such as shorts, resistive loads connected differentially, and standard 300 ohm twin lead transmission line to verify the single step generator method.

Tests are as follows:

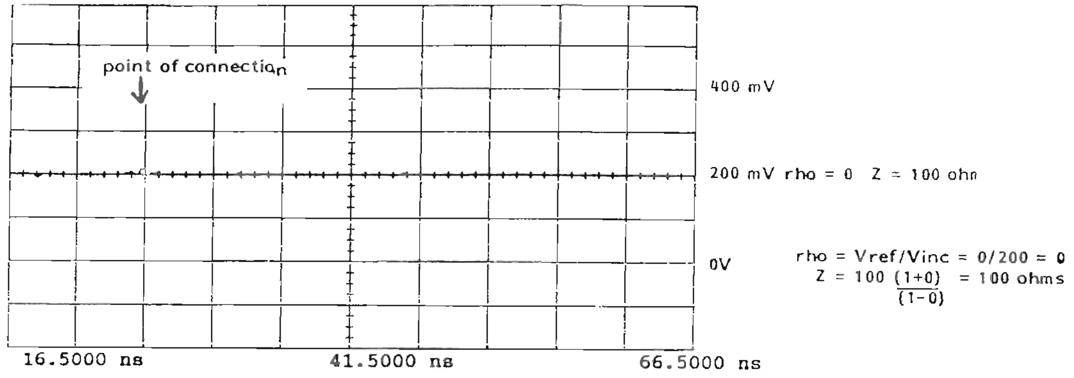
Differential TDR measurements:

Fig 13 * 100 ohm resistor (connected differentially across the center conductor of each semirigid cable, no ground connection)

Fig 14 * 25 ohm resistor (same config.)
Fig 15 * 300 ohm resistor (same config.)
Fig 16 * 300 ohm twin lead

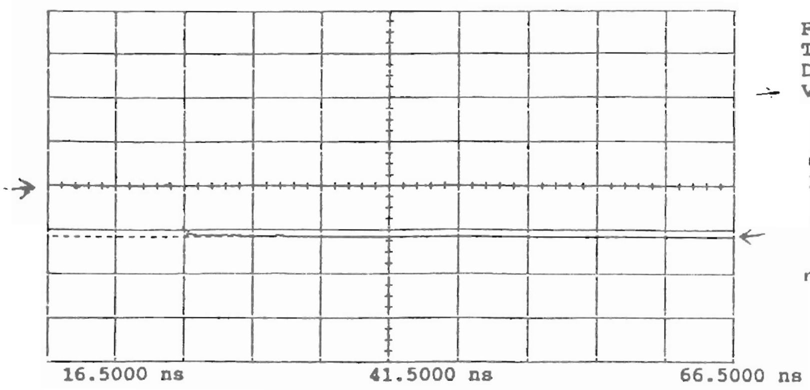
Common mode TDR measurement:

Fig 17 * 25 ohm resistor (connected common mode, one lead to both semirigid center conductors, the other lead to ground)



```
Function1 =  100.0 mVolts/div          Offset    =  200.0 mVolts
Timebase  =  5.00 ns/div               Delay     =  16.5000 ns
Delta V   =  200.00 mVolts
Vmarker1  =  0.0000  Volts             Vmarker2  =  200.00 mVolts
```

Figure 13. 100 ohm resistor connected differentially

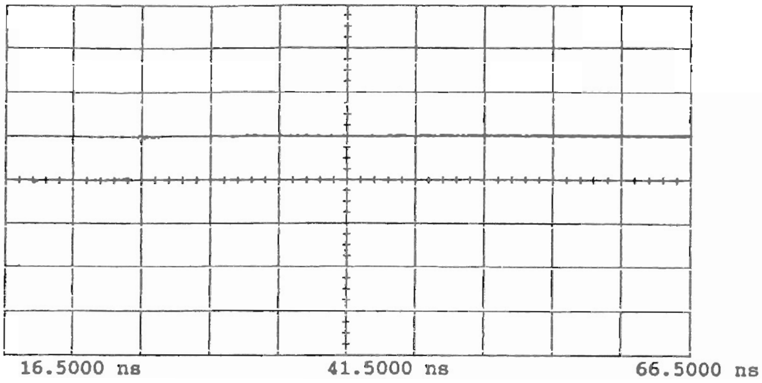


```
Function1  =  100.0 mVolts/div
Timebase   =  5.00 ns/div
Delta V    = -115.62 mVolts
Vmarker1   =  200.00 mVolts

Offset     =  200.0 mVolts
Delay      =  16.5000 ns

Vmarker2   =  84.375 mVolts
```

rho = Vref/Vinc = -115.62 mV/200 mV = -0.58

$$Z = 100\,\frac{(1+\text{rho})}{(1-\text{rho})} = 26.6 \text{ ohms}$$

Figure 14. 25 ohm resistor connected differentially

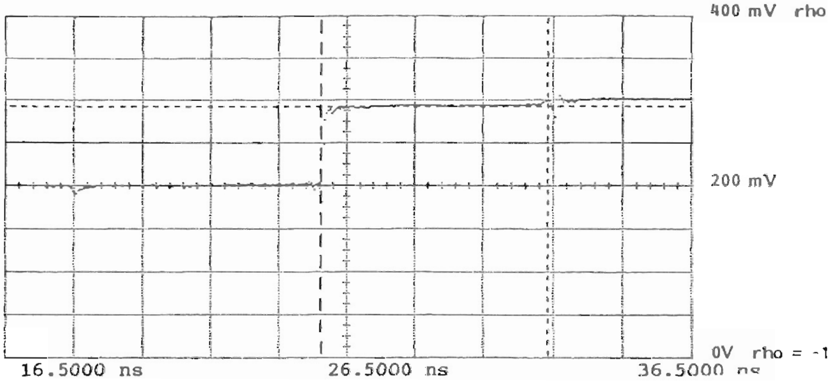


rho = Vref/Vinc = 100 mV/200 mV = +0.5

$$Z = 100\,\frac{(1+p)}{(1-p)} = 300 \text{ ohms}$$

```
Function1 =  100.0 mVolts/div          Offset    =  200.0 mVolts
Timebase  =  5.00 ns/div               Delay     =  16.5000 ns
Delta V   =  100.00 mVolts
Vmarker1  =  200.00 mVolts             Vmarker2  =  300.00 mVolts
```

Figure 15 300 ohm resistor connected differentially



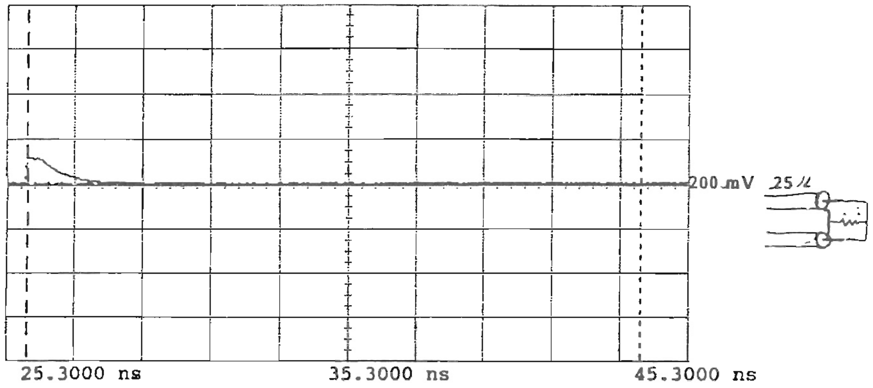
```
Function1 =  50.00 mVolts/div
Timebase  =  2.00 ns/div
Delta V   =  92.187 mVolts
Vmarker1  =  200.00 mVolts
Delta T   =  6.5678  ns
Start     =  25.7522 ns

Offset    =  200.0 mVolts
Delay     =  16.5000 ns

Vmarker2  =  292.18 mVolts

Stop      =  32.3200 ns
```

rho = Vref/Vinc = 92.187 mV/200 mV = +0.4

$$Z \approx 100\,\frac{(1+\text{rho})}{(1-\text{rho})} = 270 \text{ ohms}$$

Prop Delay = 6.5678 n sec

Figure 16. 300 ohm twin lead



```
Function1  =  160.0 mVolts/div
Timebase   =  2.00 ns/div
Delta V    =  0.0000  Volts
Vmarker1   =  205.00 mVolts
Delta T    =  18.0000 ns
Start      =  25.9000 ns

Offset     =  200.0 mVolts
Delay      =  25.3000 ns

Vmarker2   =  205.00 mVolts

Stop       =  43.9000 ns
```

rho = Vref/Vinc = 0/200 = 0

$$Z = 25 \frac{(1+rho)}{(1-rho)} = 25 \text{ ohm}$$

Figure 17 25 ohm resistor connected common-mode

Example Responses From a Twisted Pair

Consider the example of measuring the differential impedance and propagation delay on a length of twisted pair computer backplane cable as shown in Figure 18. Two measurements are shown where channel 1 is connected first to one side of the DUT, and then to the other. In this example, a differential impedance of 125.5 ohms is seen. Voltage markers are used to measure the size of the reflected waveform and to calculate rho. Here, delta V of 22.5 mV indicates Vrefl, so

$$\begin{aligned} rho &= Vrefl/Vinc \\ &= 22.5 \text{ mV}/200 \text{ mV} \\ &= +\ 0.113 \end{aligned}$$

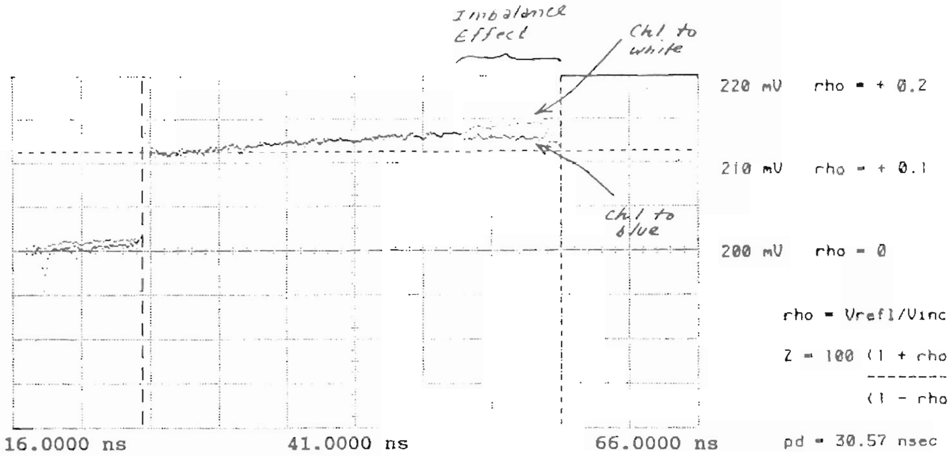
Impedance, Z, follows directly from rho, where

$$Z = 100 \frac{(1 + rho)}{(1 - rho)}$$

$$= 100 \frac{(1.113)}{(0.887)}$$

$$= 125.5 \text{ ohms}$$

At 20mV/div, which corresponds to 0.1 mrho/div (10% reflection/div), skin effect along the cable can be seen (the rising slope) and a slight variation in differential impedance due to a variation in the twist density. A difference in the two traces indicates where in time after a common mode edge the transmission line resonates.



$$\text{rho} = \text{Vrefl}/\text{Vinc} = 22.5 \text{ mV}/200 \text{ mV} = + 0.113$$

$$Z = 100\,\frac{(1 + \text{rho})}{(1 - \text{rho})} = 100\,\frac{(1.113)}{(0.887)} = 125.5 \text{ ohms}$$

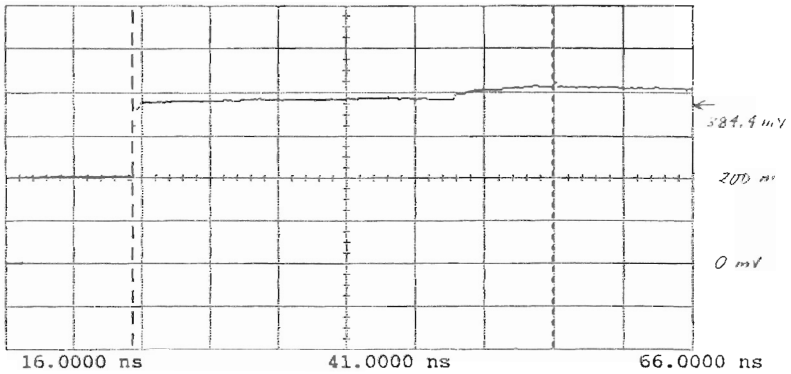
pd = 30.57 nsec

```
■Function1 =  10.00 mVolts/div        Offset     =  200.0 mVolts
 Timebase  =  5.00 ns/div             Delay      =  16.0000 ns
■Memory 1  =  10.00 mVolts/div        Offset     =  200.0 mVolts
■Timebase  =  5.00 ns/div             Delay      =  16.0000 ns
■Delta V   =  22.500 mVolts
■Vmarker1  =  200.00 mVolts           Vmarker2   =  222.50 mVolts
■Delta T   =  30.5680 ns
■Start     =  25.4320 ns              Stop       =  56.0000 ns
```

Figure 18. Single step differential trace of twisted pair

Common Mode Response:

By looking at Channel 1 + Channel 2, the common mode impedance and time response can be seen as shown in Figures 19 and 20. Notice the exact time correlation from where the common mode ringing begins to where the two differential TDR traces indicated imbalance. This allows one to observe the effects from unwanted common mode components of a differential drive signal. To see only the differential response waveform math is again used.



Function 1 = Ch1 + Ch2, Ch1 to white wire

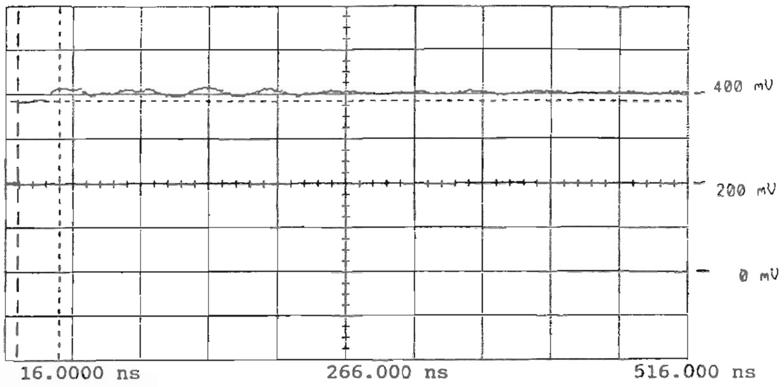
$$\text{rho} = \text{Vrefl}/\text{Vinc} = 184.4 \text{ mV}/200 \text{ mV} = + 0.922$$

$$Z = 25\,\frac{(1 + \text{rho})}{(1 - \text{rho})} = 25\,\frac{(1.922)}{(0.078)} = 616 \text{ ohms}$$

pd = approx 24 nsec

```
Function1 =  100.0 mVolts/div        Offset   =  200.0 mVolts
Timebase  =  5.00 ns/div             Delay    =  16.0000 ns
Delta T   =  30.6000 ns
Start     =  25.3000 ns              Stop     =  55.9000 ns
```

Figure 19. Common mode response from twisted pair



Function 1 = Ch1 + Ch2, Ch1 to white wire

$$\rho = V_{refl}/V_{inc} = 184.4\ \text{mV}/200\ \text{mV} = +0.922$$

$$Z = 25\,\frac{(1+\rho)}{(1-\rho)} = 25\,\frac{(1.922)}{(0.078)} = 616\ \text{ohms}$$

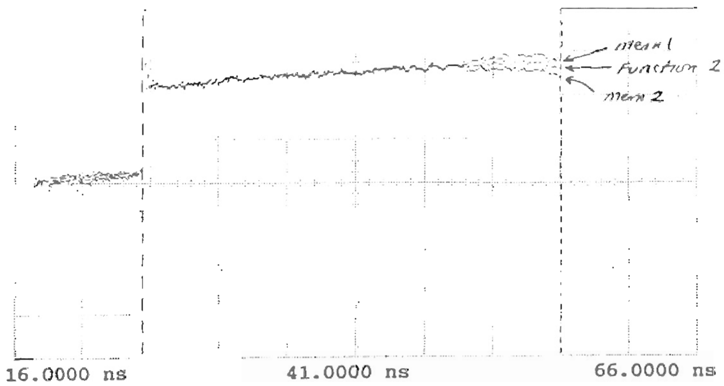
pd = approx 24 nsec

```
Function1 =  100.0 mVolts/div       Offset    =  200.0 mVolts
Timebase  =  50.0 ns/div            Delay     =  16.0000 ns
Delta V   =  184.37 mVolts
Vmarker1  =  200.00 mVolts          Vmarker2  =  384.37 mVolts
Delta T   =  30.5680 ns
Start     =  25.4320 ns             Stop      =  56.0000 ns
```

Figure 20. View of common-mode resonance as long wire antenna

Removing all Common Mode:

Three traces are shown in figure 21 including the response from connecting the channel 1 step center conductor to one side of the twisted pair, and then to the other side, and finally viewing the sum of both responses from waveform math on the two waveform memories. This can be compared to the response from TDR with two step generators with results presented in figure 22. Traces match very closely. The same measurement is achieved using a single pulse generator as with two.



Memory1 = Ch1 - Ch2 (Ch1 to white wire)
Memory2 = Ch1 - Ch2 (Ch1 to blue wire)

Function2 = Memory1 + Memory2

```
■Function2 =  20.00 mVolts/div      Offset  =  400.0 mVolts
 Timebase  =  5.00 ns/div           Delay   =  16.0000 ns
■Memory 1  =  10.00 mVolts/div      Offset  =  200.0 mVolts
■Timebase  =  5.00 ns/div           Delay   =  16.0000 ns
■Memory 2  =  10.00 mVolts/div      Offset  =  200.0 mVolts
■Timebase  =  5.00 ns/div           Delay   =  16.0000 ns
■Delta T   =  30.5680 ns
■Start     =  25.4320 ns            Stop    =  56.0000 ns
```

Figure 21. Waveform math used to remove all common mode a duplicate two step generator TDR method

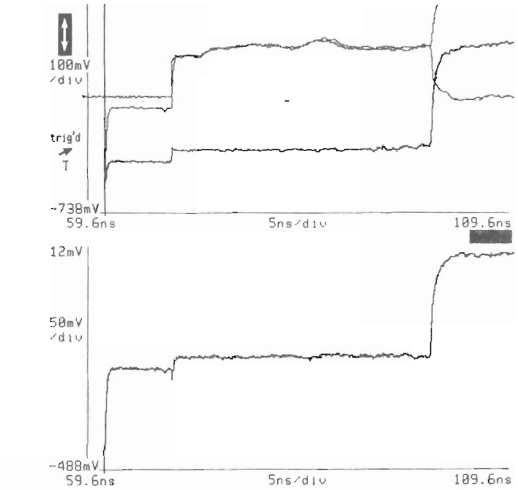
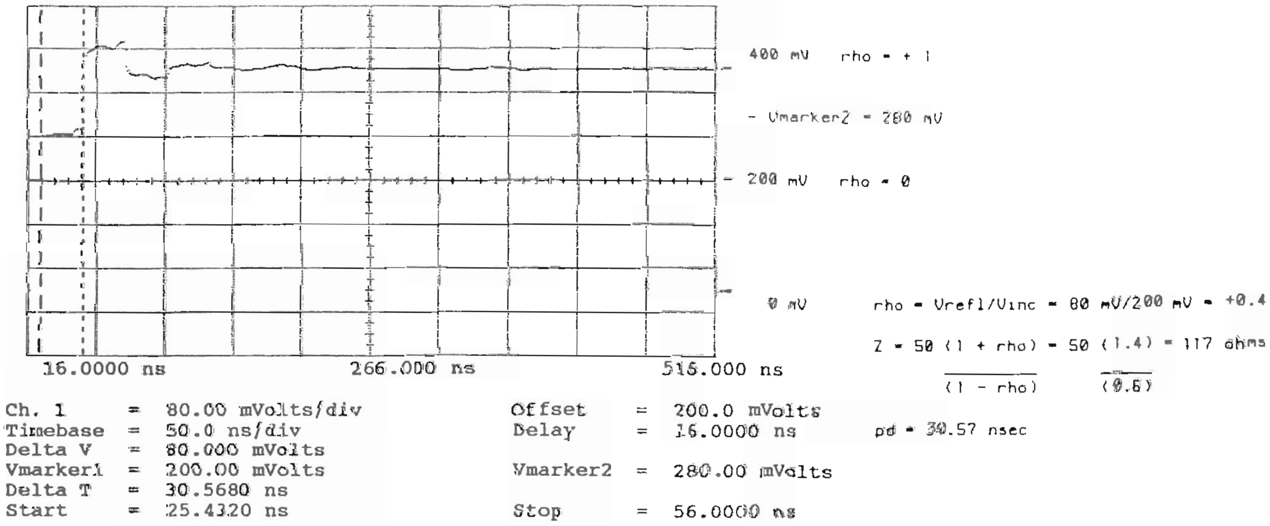


Figure 22. Dual step source differential TDR technique

A few comments of interest. Looking at the twisted pairs with a standard TDR like in Figure 23 yields a response which is a combination of differential mode and common mode. The cable length is seen, but the impedance measurement is incorrect and the response distorted by common mode reflections.



```
Ch. 1      =  80.00 mVolts/div      Offset    =  200.0 mVolts
Timebase   =  50.0 ns/div           Delay     =  16.0000 ns
Delta V    =  80.000 mVolts
Vmarker1   =  200.00 mVolts         Vmarker2  =  280.00 mVolts
Delta T    =  30.5680 ns
Start      =  25.4320 ns            Stop      =  56.0000 ns
```

Figure 23. Standard TDR Response, center conductor and ground of channel 1 connected directed to balanced DUT

Summary:

Over time, more and more systems will include balanced transmission lines which require analysis with TDR. Users of standard TDR measurement tools can still make such differential measurements by using dual inputs on an sampling scope with their standard pulse generator, and subtracting the common mode portion of the step source. Also of importance to the designer are common mode impedance and reflection characteristics of systems where unexpected imbalance effects are present within a balanced structure; this is conveniently provided by single step TDR. Alternatively, two step sources of opposite polarity can be used to drive a differential pulse for "true" differential TDR if pulse shape, size and timing skew can be well controlled. Both techniques allow valuable device evaluation capability.