

Differential Time-Domain Reflectometry Module for a Digital Oscilloscope and Communications Analyzer

The HP 54754A differential TDR plug-in in conjunction with the HP 54750 digital oscilloscope or the HP 83480 digital communications analyzer significantly improves the speed and ease of making critical measurements in today's high-speed systems.

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With the advent of higher-speed systems, the issue of signal fidelity has become increasingly important. To maintain signal fidelity at these higher speeds, designers must be able to reduce discontinuities in the signal path and reduce coupling effects between different signal paths. To this end, many newer designs make use of differential transmission lines. An important tool in analyzing signal paths is time-domain reflectometry (TDR). Differential TDR makes this task easier and less time-consuming for differential transmission lines.

To analyze and optimize a differential transmission line system easily, the TDR system should have certain features:

- **Fast display throughput.** A standard technique in TDR is to observe the TDR trace while probing the line with a small capacitance. This helps locate the various points along the line. If the display throughput is too low, this process is tedious, especially if averaging is used to see small effects.
- **Full stimulus/response matrix.** To fully characterize a differential transmission line, the TDR system should allow control of both the stimulus and the response. Examples of possible needed measurements are differential response to differential-mode stimulus, differential response to common-mode stimulus, common-mode response to differential-mode stimulus, single-side response to differential-mode stimulus, and so on. Unbalanced differential lines and imperfect terminations can cause one mode to couple into the other, making it difficult to understand signals on differential lines. Being able to look at different corner cases of the stimulus/response matrix can be a big help in understanding these effects.
- **Automatic calculation of parameters.** The usefulness and ease of use of a TDR system are greatly enhanced if the system combines the various waveforms to get the desired responses. Also, it should be possible to have the response plotted as voltage, reflection coefficient, or ohms.
- **Easy calibration of the TDR measurements.** This includes establishing the reference planes and measuring the step heights so measurements can be made accurately.

The HP 54754A differential TDR plug-in for the HP 54750 digital oscilloscope and the HP 83480 digital communications analyzer (which share the same mainframe) achieves these goals through the use of optimized acquisition hardware, a rich firmware feature set, and flexible TDR hardware. This TDR system significantly improves the speed and ease of making critical measurements in today's high-speed systems.

Hardware Design

The samplers and TDR step generators for the HP 54754A plug-in are leveraged from the HP 54120 oscilloscope system. The samplers are a microwave design using state-of-the-art GaAs Schottky barrier diodes in a beam-lead package mounted on a thin-film microcircuit. The microcircuit is mounted in a machined cavity using 3.5-mm precision connectors. The step generators use a step-recovery diode to drive an anti-series pair of GaAs Schottky diodes, which switch an 8-mA current into the transmission line leading to the samplers. Like the samplers, the microcircuit is also implemented with beam-lead components on thin film in a machined cavity. This hardware produces a typical system rise time of 35 ps with a step top that is flat within $\pm 5\%$ for the first nanosecond after the edge and within $\pm 1\%$ after that.

The HP 54754A TDR plug-in has two TDR step generators to allow faster and easier differential TDR measurements. One possible hardware architecture would make the rising edges of both step generators coincident in time, as shown in Fig. 1a. Then, to switch from common-mode stimulus (shown) to differential-mode stimulus, the polarity of one of the step generators could be reversed. In practice, this system may have drawbacks. Typically, if the bias and setup of a step-recovery diode TDR step generator are changed, it takes time for the system to settle. This can take many seconds, which could be an issue for the measurement time. Also, the step may settle at a new time position, which would mean that different calibrations would be required for the positive and negative states of the step generator.

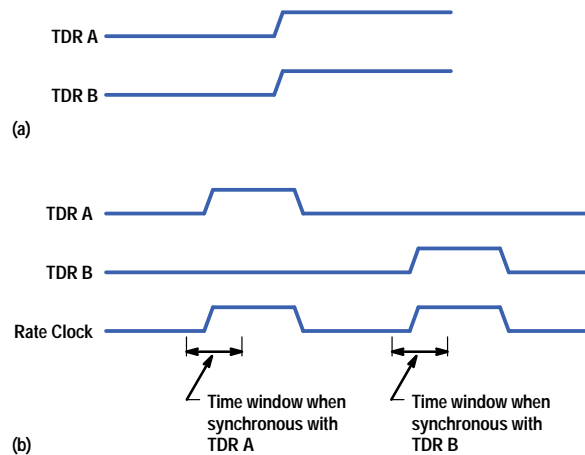


Fig. 1. (a) One possibility for a dual-step-generator TDR system is to have the rising edges of the two TDR step generators coincident in time. (b) The HP 54754A plug-in pulses the first step generator while the second is quiet, and then pulses the second step generator while the first is quiet.

To avoid these potential problems, the HP 54754A TDR system uses a *staggered* step generator architecture. This architecture pulses the first step generator while the second one is quiet, and then pulses the second step generator while the first one is quiet, as shown in Fig. 1b. Using this approach, all information needed for either common-mode stimulus or differential-mode stimulus is present without changing the bias or setup of the TDR step generators. The hardware simply selects which edge of the rate clock to send to the oscilloscope's trigger. Each TDR step generator is run at a constant rate, so once it has settled (after initial turn-on), it is stable.

Another requirement for a TDR system is that the trigger-to-TDR-step edge timing have low jitter and be stable. The rate clock signal's rising edge is the source for this timing. This signal has two critical paths. One is through buffer gates to the oscilloscope's main trigger and the other is through buffer gates and a delay line to the TDR step generators. The delay line is necessary to get the step generator's rising edge onscreen. In the HP 54754A system, there is the additional requirement that the system be able to select which TDR generator is synchronous with the trigger. This hardware is shown in Fig. 2. The hardware is set up so that the gates in each signal path are minimized and signals are as fast and as clean as possible to minimize jitter. Also, to minimize the timing drift between the two step generators, the path to the step generators goes through a dual ECL flip-flop. This better matches thermal and bias conditions for these paths. Trigger-to-TDR-step jitter for this system is ~ 1.4 ps rms.

In most TDR measurements it is desired to define a reference plane at the input to the system under test so that measurements can be made relative to that point. In differential TDR measurements, it is important to have the edges from the two step generators arrive at the reference plane simultaneously. To accomplish this, the step-recovery diode bias in each step generator (bias determines the stored charge on the step-recovery diode and therefore determines when it will fire) is controlled by a DAC to produce a ± 400 -ps range over which the TDR step can be moved onscreen. This allows connection to the system under test with cables that are as much as 800 ps different in electrical length. The reflected or transmitted signals from the reference plane can be lined up onscreen using the skew adjustment provided for each sampling channel. Having the ability to adjust both the TDR position and the channel skew allows quicker and easier calibration for differential TDR even if the connection cables are not perfectly matched in electrical length.

When the HP 54754A plug-in is not being used for TDR, the two channels can be used as normal high-bandwidth sampling channels. To provide the normal external trigger path needed for non-TDR uses, the trigger path through the plug-in to the main trigger in the mainframe must be preserved. This means that it must be possible to turn off the trigger injected into the trigger path for TDR without affecting the normal external trigger. One way to achieve this would be to use a mechanical microwave switch, but this would add significant cost, take up valuable space, be an additional reliability concern, and add weight. A preferable solution is to use a p-i-n diode to switch in the trigger signal when TDR is on (see Fig. 2). When the p-i-n diode is forward-biased, it has low impedance and drives the trigger path through a coupling capacitor. When the p-i-n diode is reverse-biased, it has very high impedance and low capacitance. This allows the external trigger signal to flow through the trigger path with only a minor discontinuity at the TDR trigger injection point. This injection point is implemented on the printed circuit board using SMA board connectors, a surface mount capacitor, and a p-i-n diode.

The rest of the hardware in the HP 54754A differential TDR plug-in is similar to the other plug-ins for the HP 54750 and HP 83480 systems (see article, page 1). This includes the low-noise front-end amplifiers, temperature-compensated sample strobe generation circuits, and feedthrough compensation circuits. The low-noise amplifiers are optimized to achieve a very low noise floor of ~ 260 μ V rms at 12.4 GHz and ~ 660 μ V rms at 18 GHz. The temperature-compensated sample strobe generation circuits allow good vertical accuracy stability (0.6% for 12.4 GHz and 1.2% for 18 GHz over $\pm 2^\circ\text{C}$) without using feedback sampling.

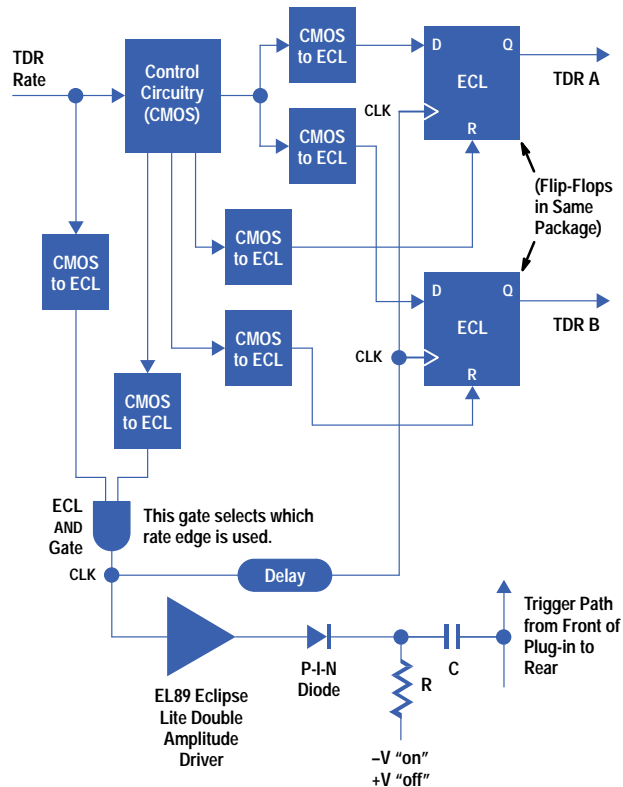


Fig. 2. Hardware diagram of the HP 54754A differential TDR plug-in.

Firmware Design

The goal of the HP 54754A firmware was to take full advantage of the power of the hardware and provide an easy-to-use interface to it. Many of the features of the HP 54754A were leveraged from the HP 54120 oscilloscope.¹⁻⁴ This product offered single-ended TDR with normalization capabilities and the ability to read out ohms and distance using cursors. The HP 54754A expands upon this foundation, providing full differential characterization in addition to single-ended measurements.

Single-Ended Control. To characterize a single-ended TDR signal, the instrument must be capable of reading out any point along the trace in distance and impedance or reflection coefficient. It also must provide filtering, typically in the form of normalization, which limits the bandwidth through the system so that edges traveling at different speeds can be characterized. Finally, the instrument must be flexible and easy to use.

For the instrument to convert voltage into impedance, a calibration must be performed to determine the signal amplitude and offset at 50 ohms and with a short circuit. The samplers used in the HP 54754A module are subject to drift with changes in temperature. If the temperature has drifted more than $\pm 2^\circ\text{C}$, a calibration should be performed before any critical measurements. Determining these offsets allows any signal voltage to be converted into impedance or reflection coefficient. Reflection coefficient is a normalized percentile such that 100% represents an open circuit, -100% represents a short circuit, and 0% represents 50 ohms. Reflection coefficient ρ is determined by:

$$\rho = (V_{\text{in}} - V_{50})/V_{\text{amp}}$$

where V_{in} is the voltage to be converted to ρ , V_{50} is the voltage of the step with a 50-ohm termination, and V_{amp} is the amplitude of the step into a short circuit.

Voltage can also be translated into impedance using ρ :

$$\text{ohms} = Z_n \times (1 + \rho) / (1 - \rho),$$

where ρ is the reflection coefficient to be converted to ohms and Z_n is the nominal impedance of the system, 50 ohms.

The HP 54754 provides a variety of ways to translate voltage into impedance or reflection coefficient. Waveform markers can be placed on the voltage waveform and set to read out in impedance or ρ . This allows the signal to be viewed in voltage, which is most familiar for many users, but permits any point to be translated to the appropriate units. Additionally, the entire signal can be displayed and controlled in impedance or ρ (Fig. 3). This obviates the need to run the marker down the signal, mapping every point from volts. When the signal is displayed in impedance, the scale and offset controls change to ohms per division and ohms offset.

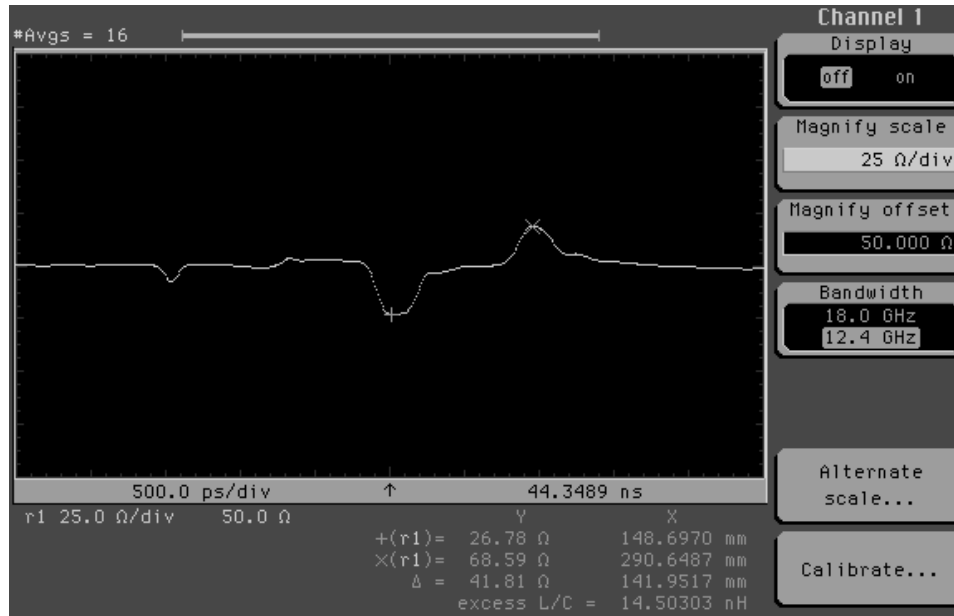


Fig. 3. Cursors can read out in units of distance in meters or feet along the horizontal axis. Waveforms can be displayed in units of volts, ohms, or reflection coefficient along the vertical axis. Scaling in ohms/division and ohms offset is provided.

To convert any point along the signal to distance, the reference plane is determined by the calibration. The reference plane is the point at which the TDR pulse is launched into the device under test. This allows any cabling up to the launch point to be eliminated from the distance measurement. The distance to any point after the reference plane is determined by:

$$\text{distance (meters)} = \frac{c}{\sqrt{\epsilon_e}} \frac{(t_{in} - t_{ref})}{2},$$

where c is the speed of light in meters per second, ϵ_e is the effective dielectric constant of the transmission medium, t_{in} is the time to be converted to meters, and t_{ref} is the time at which the TDR pulse is launched at the reference plane.

The constant 2 in the equation above accounts for the round-trip time of the pulse, since only the time from the reference plane to the event is typically desired. The HP 54754A allows the distance to be measured in meters or feet (Fig. 3).

Typically in single-ended TDR the user may see a small impedance variation in the signal and wonder how to flatten the signal. By integrating the reflection coefficient around the variation, the HP 54754A can compute the excess inductance or capacitance⁵ causing the impedance variation (Fig. 4). This can lead to trimming the part or adding inductance or capacitance to correct the variation. The waveform markers are used to define a portion of the trace to integrate, time t_0 and t_1 , and the following equation is used to compute excess L or C :

$$\tau = \int_{t_0}^{t_1} \rho dt.$$

If $\tau > 0$,

$$L = 2Z_0\tau \frac{(Z_0 + Z_n)^2}{4Z_0Z_n},$$

and if $\tau < 0$,

$$C = -\frac{2\tau}{Z_0} \frac{(Z_0 + Z_n)^2}{4Z_0Z_n},$$

where ρ is the reflection coefficient of the waveform, Z_0 is the impedance at t_0 , Z_n is the nominal impedance of the system (50 ohms), L is the excess inductance between t_0 and t_1 , and C is the excess capacitance between t_0 and t_1 .

Since the impedance of the first point is used as the reference impedance, these equations will work in environments that are not nominally at 50 ohms.

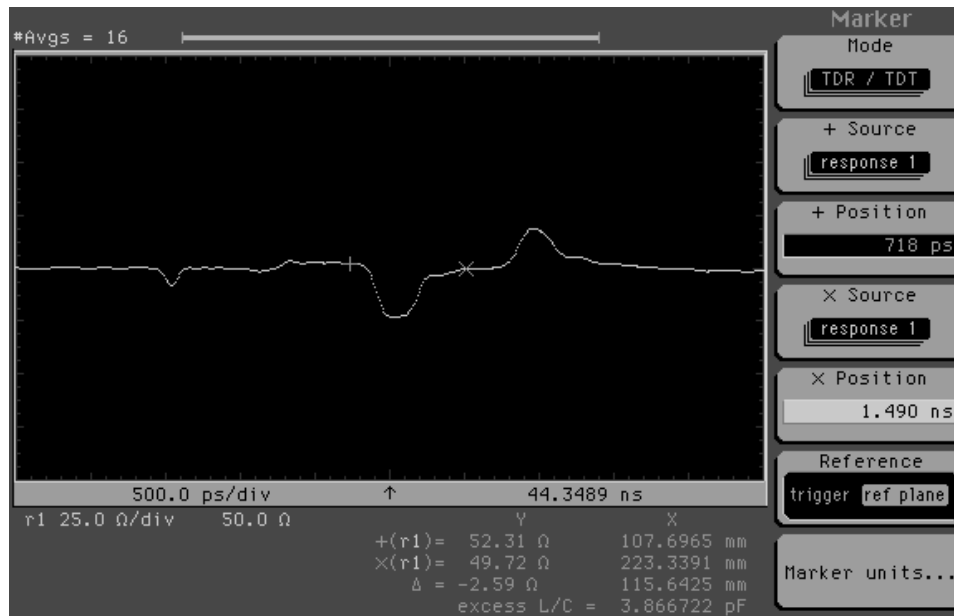


Fig. 4. The waveform is integrated between the + and × markers to yield an excess capacitance of 3.86 pF. Negative-going variations are capacitive and positive-going variations are inductive.

The rise time of the step generated by the pulse generators is fixed at 35 ps. Frequently a more realistic stimulus for the device under test is a slower step. Normalization allows the simulation of a slower-speed step through the device under test. If the full accuracy of normalization is not needed, a firmware digital filter can be used. This digital filter does not require calibration and can be applied to any waveform. The step speed can be specified by either rise time or 3-dB bandwidth.

The HP 54120 oscilloscope made measurements one waveform at a time and stored the results in a special waveform memory. The goal of the HP 54750 was to allow normalization and other advanced measurements in real time, updating for every waveform acquisition, without perceptibly slowing down the instrument. The HP 54750/83480 mainframe takes advantage of its dual-computer design and can perform normalization on real-time data. Many excellent articles have been written describing the normalization process, which will not be discussed in this article.²

For customers who require a quality step faster than 35 ps, Picosecond Pulse Laboratories makes a product capable of producing steps with 15-ps rise times in conjunction with the HP 54752B 50-GHz plug-in. The HP 54754A provides an external stimulus mode which allows easy control of this step generator.

Differential Control. Since the HP 54754A plug-in module contains two pulse generators that are staggered in time, differential and common-mode measurements can be made. The firmware in the product controls the pulse generators by synchronizing first with one, then with the other for every acquisition so that one TDR is silent while the other is pulsing. Waveforms are acquired for both the active, pulsing TDR and the nonactive, silent TDR. Since the active TDR signal can couple into the nonactive TDR and cause small variations, both the active and nonactive waveforms are acquired for each pulse generator on each acquisition.

If AA is the signal on line A caused by pulsing TDR A, AB is the signal on A caused by pulsing TDR B, BB is the signal on B caused by pulsing TDR B, and BA is the signal on B caused by pulsing TDR A, then for common-mode stimulus, the signal on line A, or signal A, is $AA + AB$ and signal B is $BB + BA$. For differential-mode stimulus, signal A is $AA - AB$ and signal B is $-(BB - BA)$. The negative sign in the last equation inverts stimulus B for differential TDR to arrive at a more customary differential stimulus consisting of a positive-going step for stimulus A and a negative-going step for stimulus B.

Table I
Derivation of Response Waveforms

Volt Units (A and B in volts)		
	Differential Response	Common-Mode Response
Differential Stimulus	$A - B$	$(A + B)/2$
Common-Mode Stimulus	$A - B$	$(A + B)/2$
Ohm Units (A and B in ohms)		
	Differential Response	Common-Mode Response
Differential Stimulus	$A + B$	$(A - B)/4$
Common-Mode Stimulus	$A - B$	$(A + B)/4$
ρ Units (A and B in ρ)		
	Differential Response	Common-Mode Response
Differential Stimulus	$(A + B)/2$	$(A - B)/2$
Common-Mode Stimulus	$(A - B)/2$	$(A + B)/2$

In addition to controlling the TDR stimulus through the pulse generators, the firmware constructs all of the TDR response waveforms. Differential and common-mode responses are available for both differential and common-mode stimulus. For voltage units, the differential response is the difference of the responses to the two stimulus signals, A and B. The common-mode response is the sum of the responses to the stimulus A and stimulus B waveforms divided by two. Table I lists the derivations of the common-mode and differential response waveforms for units of volts, ohms and ρ .

All of the unit conversion capabilities of the HP 54754A can be applied to differential and common-mode stimulus and response waveforms. The power of the HP 54750/83480 far surpasses any other product of its type. The flexibility with which units can be converted across all stimulus types coupled with the automatic computation of complex differential and common-mode responses provides full-featured characterization of differential lines. The real-time normalization and advanced features like excess L and C computation make the instrument ideal for single-ended TDR as well.

Acknowledgments

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