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# Measuring Controlled-Impedance Boards with TDR

by Mark D. Tilden

**Advances in IC technology call for PCBs with controlled-impedance traces.**

Recent advances in high-speed integrated circuit (IC) technology have dramatically improved the performance and decreased the cost of many electronic products, from personal computers to cellular telephones. The proliferation of this technology brings with it an increased demand for PCBs with controlled-impedance traces.

Higher-speed ICs produce signals with faster rise times. As the rise time of the signals becomes short with respect to the length of the interconnect between ICs, it is increasingly important to control the impedance of the circuit board runs (see "Transmission Line Basics"). Many PCB manufacturers are finding that controlled-impedance testing is a competitive advantage, if not a requirement, with an increasing number of customers.

Time Domain Reflectometry (TDR) is a powerful, accurate tool for measuring impedance and length in PCB traces. Unfortunately, TDR is often regarded as a sort of mystical art useful only to microwave engineers. Early TDR instruments were difficult to operate and required a skilled operator to interpret the results. Modern instruments, however, make TDR a practical, efficient tool for process monitoring and production testing. With proper attention to calibration and test methodology, TDR can provide consistent, accurate results without highly skilled operators or "eyeball" judgements.

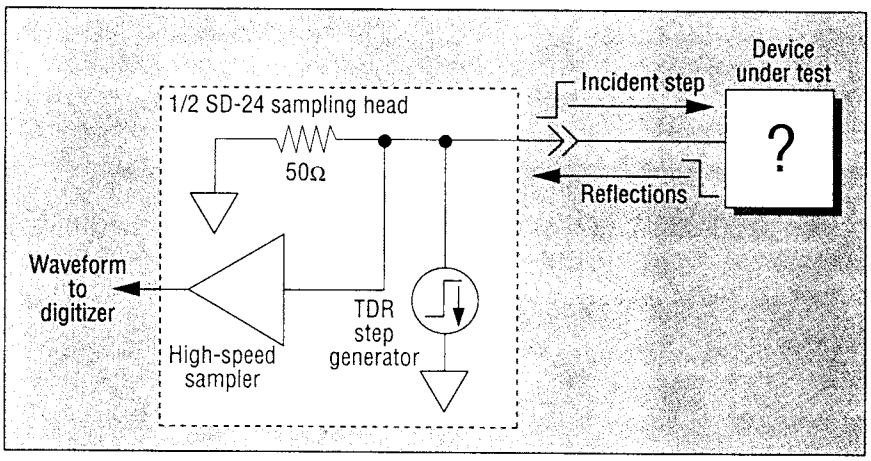



**Figure 1.** *A typical TDR instrument.*

## TDR FUNDAMENTALS

TDR is based on a very simple concept: Whenever energy transmitted through any medium encounters a change in impedance, some of the energy is reflected back toward the source. The amount of energy reflected is a function of the transmitted energy and the magnitude of the impedance change. The time lapse between energy transmission and the reflection returning is a function of the distance from the source to the impedance discontinuity and the energy's propagation velocity.

The effects of this phenomenon are evidenced through echoes that occur when sound encounters a change in impedance, such as a wall. In electrical systems, a similar phenomenon occurs when electrical energy travel-

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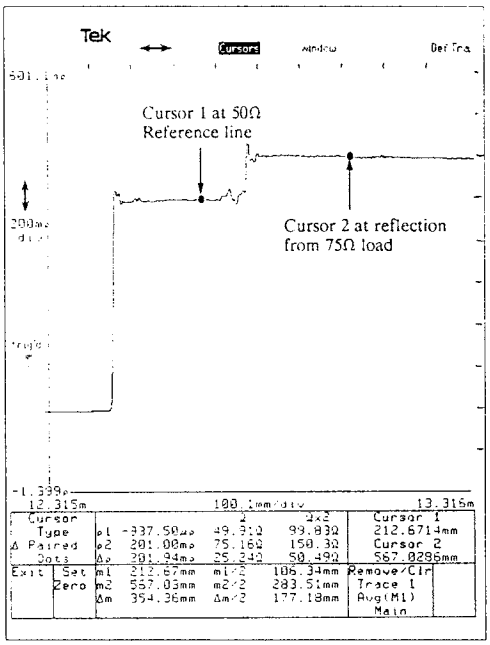



**Figure 2.** *A Time Domain Reflectometry measurement display from a digital sampling oscilloscope/TDR.*

ing in a transmission line encounters a change in impedance. Any change in the impedance of the transmission line, such as a variation in the width of a circuit board trace, causes a reflection with an amplitude proportional to the magnitude of the impedance change.

A TDR instrument measures the impedance of a circuit board trace or other transmission line by transmitting a very high-speed voltage step through a transmission line with a known impedance into the device under test—in this case, the circuit board trace. When the step energy encounters the transition from the known impedance to the circuit board trace, any difference between the known impedance and the trace impedance will cause a reflection. By measuring the amplitude of the reflection and applying a simple formula, the impedance of the circuit board trace can be calculated. Fortunately, modern TDR instruments with on-board microprocessors do these calculations for you.

Figure 1 shows a simplified block diagram of a typical TDR instrument connected to an unknown impedance. The TDR instrument includes both a high-bandwidth oscilloscope and a high-speed pulse generator. The oscilloscope monitors the voltage at the front-panel connector of the TDR. When the pulse generator sends out a pulse, the oscilloscope display shows the rising edge as it leaves the TDR unit. Some time later, this rising pulse edge reaches the device under test. Any resulting reflections travel back toward the pulse generator. When they arrive at the input to the TDR, the oscilloscope displays the reflection. Thus, the oscilloscope display shows the round-trip time between the incident edge and the reflections.

## TDR MEASUREMENT UNITS

All TDR impedance measurements are based on the ratio of transmitted voltage to reflected voltage. As a result, measurements are not generally made in absolute units, such as volts. Instead, TDR measurements are made on a relative scale, called reflection coefficient and abbreviated as $\rho$. The definition of $\rho$ is the reflected signal amplitude divided by the incident signal amplitude. For example, if a 100-millivolt reflection is observed from a 1-volt incident pulse, the reflection is called a 100 milli-$\rho$ reflection:

$$\rho = \frac{E_{reflected}}{E_{incident}} \qquad 100m\rho = \frac{100mV}{1V}$$

Given a known impedance and a measured reflection coefficient, the unknown impedance that caused the reflection can be calculated from the following equation:

$$R_L = Z_0 \frac{(1 + \rho)}{(1 - \rho)}$$

where $Z_0$ is the known impedance, $\rho$ is the measured reflection coefficient, and $R_L$ is the unknown impedance.

Figure 2 shows a typical waveform from a Tektronix 11801A Digital Sampling Oscilloscope equipped with an SD-24 Sampling/TDR head. In this case, the instrument is connected through a 50Ω coaxial cable to a 75Ω device under test. The incident step is about 5 divisions in amplitude, and the reflection from the device under test is about 1 division high. These numbers equate to a reflection coefficient of 0.2$\rho$ (1 division divided by 5 divisions). Plugging the known 50Ω level and the reflection coefficient into the above equation yields the 75Ω value:

$$R_L = 50\ \Omega \frac{(1 + 0.2)}{(1 - 0.2)} = 75\ \Omega$$

Notice that the instrument automatically performs this calculation and displays the impedance and reflection coefficient for each cursor and the difference between the two cursors at the bottom of the display. Two impedance columns are shown: a normal single-ended impedance (Ω) and a differential impedance (Ω × 2). The Ω × 2 column is used in differential TDR.

The bottom of the cursor readout also shows the physical distance (scaled in millimeters) to each cursor from a user-set reference point and the distance between the cursors. The m1/2, m2/2, and Δm/2 readouts show the distance divided by 2 to compensate for the fact that the signal displayed had to travel the distance twice—from the sampling head out to the device under test and back again.

## MAKING ACCURATE TDR MEASUREMENTS

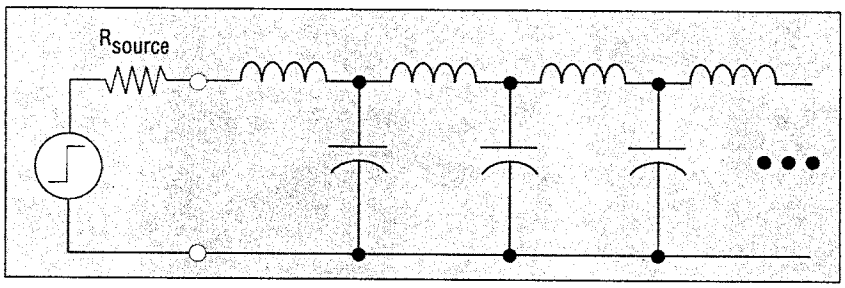
While the fundamental concepts behind TDR are relatively simple and modern instruments take care of most of the math, a number of issues mist be considered to make accurate measurements. In general modern instruments make it relatively easy to make impedance measurements near the reference impedance (usually 50Ω) with about 4% accuracy ( ± 2Ω).

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# Transmission Line Basics

Controlling the impedance of circuit board traces is important for high-speed circuits. At high speeds these traces cease to be simple interconnects that the circuit designer can ignore. As circuit speeds increase, the traces increasingly behave as transmission lines, and their effects must be considered in the circuit design.

The figure shows an electrical model of an ideal transmission line. When the rising edge of a pulse enters the transmission line, current begins to flow through the inductance to charge the capacitance. The pulse edge propagates down the line, charging the capacitance as it travels. Even if the transmission line is open at the far end, current will flow for some short period of time while it charges the capacitance of the line.




*A model of an ideal transmission line driven by a voltage step. $R_{source}$ represents the source resistance of the step generator.*

The amount of current that flows for a given voltage is determined by the impedance of the transmission line. This impedance is a function of the inductance and capacitance shown in the figure as follows:

$$Z_0 = \sqrt{\frac{L}{C}}$$

Keep in mind that this impedance is not the same as DC resistance. Clearly, a trace on a bare circuit board has an essentially infinite DC resistance to ground. The same trace may have a relatively low impedance according to the above equation. So what's the difference?

The difference is time. For the instant that the voltage step is propagating down a trace and charging the capacitance formed by the trace and its ground return, current flows according to the impedance ($Z_0$) of the trace. When the step reaches the end of the trace, there is no place for the flowing current to go, since there is no more capacitance to charge. As a result, the voltage at the end of the trace doubles and is now higher than the voltage nearer the source. The new higher voltage step begins to propagate back toward the source, canceling the current flowing out to the end of the trace. This phenomenon is a reflection—like the echo that returns when sound hits a wall.

When the reflected step from the open end of the trace reaches the source end, the voltage at the source end is equivalent to the open-circuit voltage of the source, and no current flows. This condition is exactly what we would expect with an open circuit. The only difference between this process and a standard DC ohmmeter is that the high-speed pulse generator and high-bandwidth oscilloscope in the time domain reflectometry instrument allow us to see the short time period (typically only a few nanoseconds) required to charge the transmission line to the open-circuit voltage.

If the end of the trace is terminated in a DC resistance equivalent to the impedance of the trace, current continues to flow indefinitely at the same level and no reflection occurs. A DC ohmmeter, measuring the DC termination would read the same resistance as the TDR indicates for the impedance of the trace. If, on the other hand, the trace has a short circuit at the end, a negative-going reflection occurs, and the voltage eventually settles to zero. This condition is consistent with what we would expect for a short circuit.

Typically, circuit designers will add a DC resistance to ground that is equivalent to the trace impedance at the end of longer traces. This resistance "terminates" the transmission line and reduces or eliminates reflections. Thus, it's important that the impedance of the circuit board trace be held constant so that the same value of termination resistor works on all boards. Mismatches between the DC termination resistance and the trace impedance will produce reflections that can cause a variety of circuit problems. ■

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$$T_{r\ system} = \sqrt{(T_{r\ step\ gen})^2 + (T_{r\ oscilloscope})^2 + (T_{r\ test\ fixture})^2}$$

**Equation 1.** *The combined rise time of the pulse generator, the oscilloscope, and the interconnect between the TDR and the circuit board equals the system rise time.*

Achieving higher accuracy or making measurements farther from the reference impedance requires more care. The following list covers a few key considerations in making accurate and repeatable impedance measurements.

### *System Rise Time*

It's important to remember that the system rise time determines the smallest impedance discontinuity that the TDR instrument can measure. If a discontinuity, such as a variation in the width of a trace, is small with respect to the system rise time, the reflection will not accurately represent the impedance of the discontinuity. In extreme cases, the discontinuity may effectively disappear. System rise time is the combined rise time of the pulse generator, the oscilloscope, and the interconnect between the TDR and the circuit board (Equation 1).

In general, the most significant limitation in circuit board impedance testing is the probe. However, for average trace impedance measurements, where small discontinuities are less important, a system rise time of around 100 picoseconds is usually sufficient. This rise time can generally be achieved using simple probing techniques.

### *Reference Impedance*

All TDR measurements are relative—they compare an unknown impedance to a known impedance. While modern instruments perform virtually all the math of making these measurements, the accuracy of the results depends directly on the accuracy of the reference impedance. Any error in the reference impedance translates to error in the measured impedance. Thus, a high-quality reference impedance is required for high-quality measurements.

It's also a good idea to use a reference impedance close to the expected measured impedance because a smaller difference between the reference and unknown impedance reduces uncertainty in the measurement. The reference impedance should also have the same DC resistance as the device under test to minimize other errors due to limitations in the TDR unit. Since circuit board testing is usually done on bare boards where the circuit board runs are open at both ends, a high-quality reference "air line" makes an ideal impedance reference. An air line is simply a piece of rigid coax with air separating the inner and outer conductors.

### *Noise*

System noise can reduce the accuracy and repeatability of the measurements. Fortunately, modern instruments usually provide convenient on-board signal averaging that can significantly reduce noise and improve the repeatability of the measurements. Some instruments even provide measurement statistics to help evaluate the stability of the measurements. Also, remember that signal averaging takes time. The rate at which the instrument can acquire waveforms and perform averaging can have a significant measurement throughput. A slow acquisition rate is particularly detrimental to averaging since many waveforms must be acquired.

### *Cable Losses*

The cable that connects the TDR unit to the circuit board not only degrades the system rise time, but can cause other aberrations in the system response that add to measurement error. Always use the shortest high-quality cable possible to connect to the test fixture. If possible, run the TDR/sampling head (which contains the TDR's high-frequency circuitry) on an extender cable to move the head closer to the test fixture. The extender cable does not degrade the system performance, and it allows the use of shorter cables between the head and the test fixture. ■

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