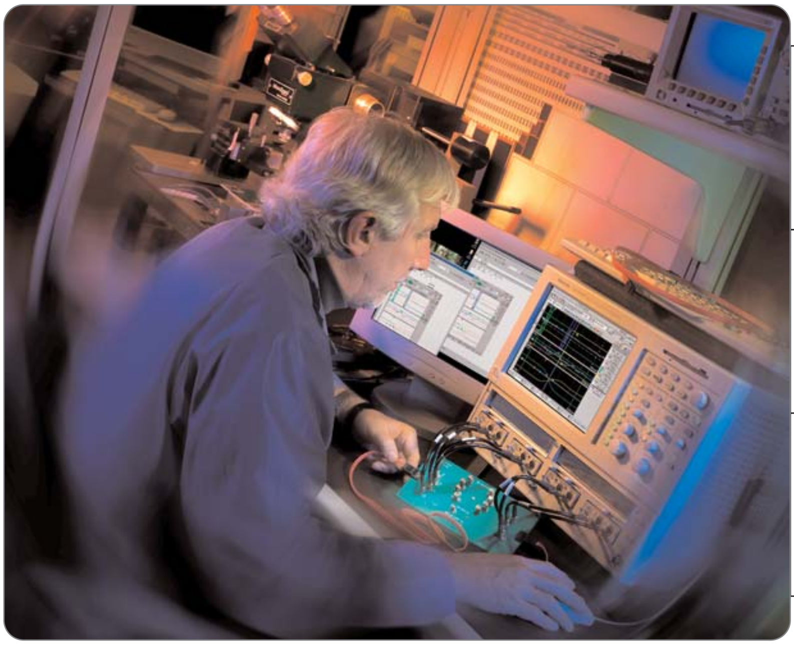
# Differential Impedance Measurements with the Tektronix 8000B Series Instruments



The fast transmission data rates of today require differential transmission lines in order to maintain signal integrity. Impedance characterization is often the first step in designing and testing of these lines.

This application note discusses these impedances and describes how Tektronix 8000B Series instruments are well equipped to take the measurements needed to characterize them. Discussion of these impedances will occur in three parts:

1. **Impedance types**. Clarifies the meaning of the variety of impedance types, terms, and concepts commonly used to describe differential circuit impedances, and then focuses on two useful types, Odd-mode and Even-mode impedance.
2. **Odd-mode and Even-mode measurements.** Describes how the Tektronix 8000B Series instrument, with the TDR-equipped 80E04 Electrical Sampling Module installed, measures Odd-mode and Even-mode impedances.
3. **Impedance calculations.** Details how the Average-differential and Average common-mode impedances can be calculated from the Odd-mode and Even-mode impedance measurements respectively, using the Define Math function that the Tektronix instrumentation provides.

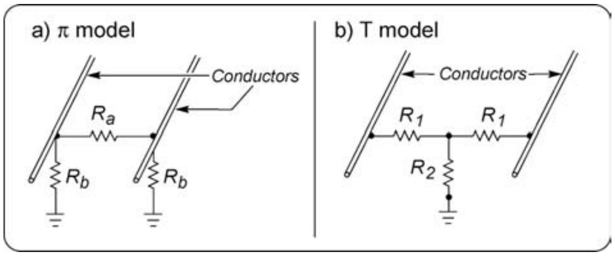


***Figure 1.*** *Models of a differential line*

## Impedance Types

This section defines Characteristic impedance, Differential impedance, Common-mode impedance, Odd-mode impedance, and Even-mode impedance. The descriptions use two models in describing these impedances, the π (pi) model and the T (tee) model. The descriptions, in order to simplify the models and concepts, assume balanced lines, which are equally referenced to ground.

**Characteristic impedance, $Z_0$,** is the impedance between two conductors when there is no coupling to ground. $Z_0$ is a term commonly used to specify cables.

The π and T models in Figure 1 show that when the ground reference is removed, $R_b$ (π model) and $R_2$ (T model) disappear.

Figure 2 shows the respective π and T models when coupling to ground is removed. $R_a$i and $R_1$i represent the new values of $R_a$ and $R_1$. These models show that Characteristic impedance, $Z_o$, equals $R_a$i (p model) or $2R_1$i (T model).

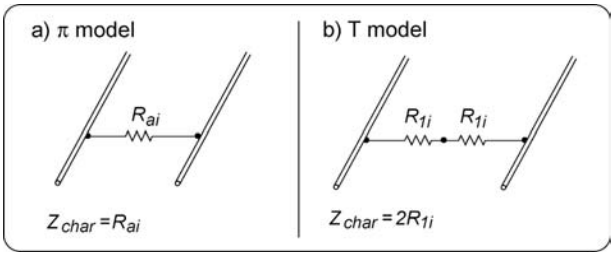


***Figure 2.*** *Models for measuring the Characteristic Impedance*

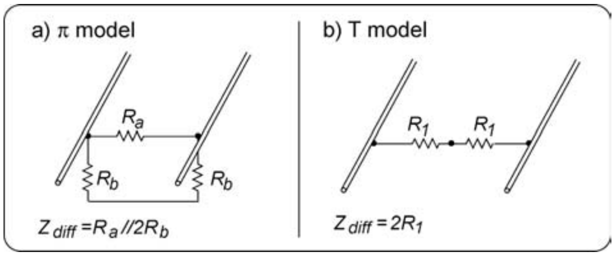


***Figure 3.*** *Models for measuring the Differential Impedance*

**Differential impedance, $Z_{diff}$,** is the impedance between the two conductors. Figure 3 shows the respective p and T models used to calculate the differential impedance ($Z_{diff}$). $Z_{diff}$ equals RaII(2Rb) (p model) or $2R_1$ (T model). In the special situation for which there is no coupling to ground, Differential impedance equals the Characteristic impedance, $Z_o$.

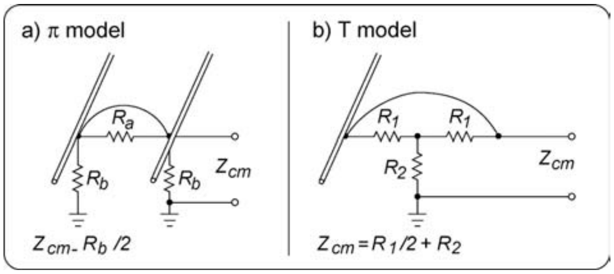


***Figure 4.*** *Models for measuring the Common-mode Impedence*

**Common-mode impedance, $Z_{cm}$,** is the impedance between the two conductors and ground when the conductors are connected to each other. Figure 4 shows the equivalent π and T models used to calculate $Z_{cm}$. $Z_{cm}$ equals $R_b/2$ (p model) or $R_1/2 + R_2$ (T model).

*Note. Use care in applying the definitions for Common-mode impedance and Differential impedance given here to other applications; such applications might assume different definitions for these terms.*

**Odd-mode impedance, $Z_{\phi o}$,** is the impedance of one conductor to ground when the pair is driven differentially. Odd-mode impedance and Even -mode impedance (defined below) are often used in the design of transmission lines, especially in microwave technology. Figure 5 displays the equivalent π and T models used to calculate Odd-mode impedance. Vg represents the virtual ground created by the line when conductors are driven with opposite polarities. The models show that Odd-mode impedance, $Z_{\phi o}$, is equal to $(R_a/2)IIR_b$ (π model) or to $R_1$ (T model).

Even-mode impedance, $Z_{\phi e}$, is the impedance of one conductor to ground when the pair is driven with equal polarity signals. Figure 6 shows the equivalent π and T models needed to calculate Even-mode impedance. $V_o$ represents the virtual open created by the line when conductors are driven with same signal and no current flows between them. The models show that Even-mode impedance $Z_{\phi e} = R_b$ (π model) or $Z_{\phi e} = R_1 + 2R_2$ (T model).

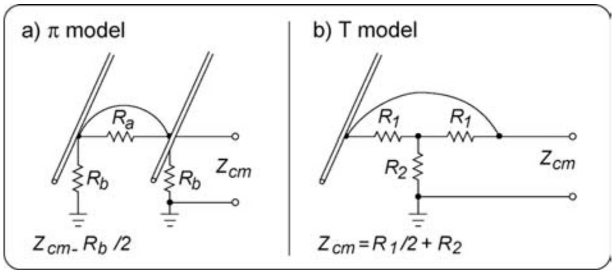


***Figure 5.*** *Models for calculating the Odd-mode Impedance*

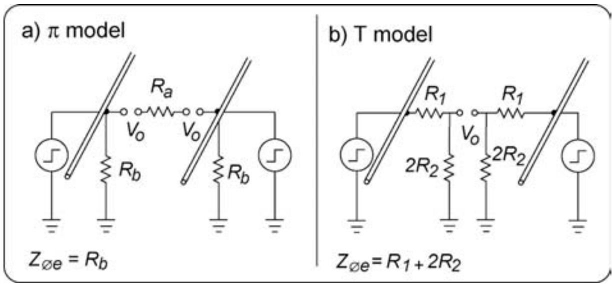


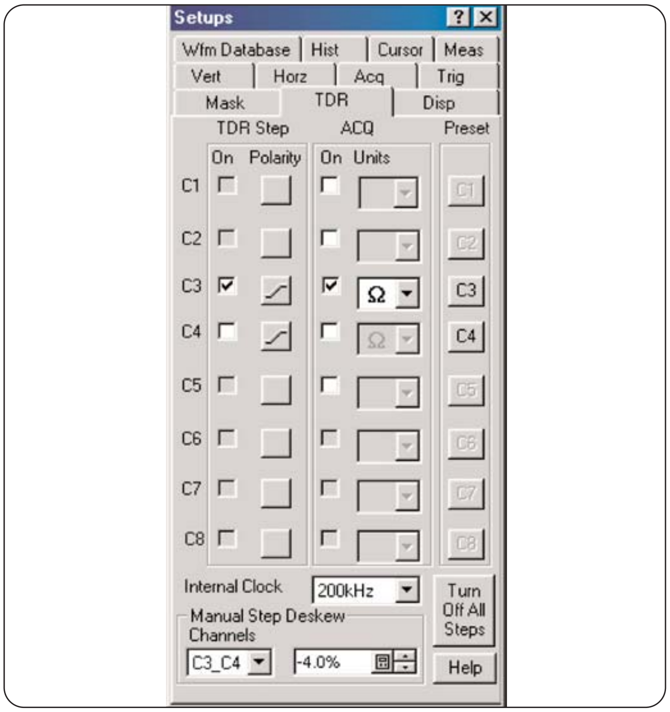
***Figure 6.*** *Models for Calculating the Even-mode Impedance*

Impedance relationships: Comparing Figure 5 with Figure 3 and Figure 6 with Figure 4 shows the following equivalences:

1 Odd-mode impedance is half of Differential impedance

2 Even-mode impedance is twice the Common-mode impedance

3 Odd-mode impedance is half of Characteristic impedance, for the special case in which both conductors are decoupled from ground



|  | TDR Step On | TDR Step Polarity | ACQ On | ACQ Units | Preset |
|---|---|---|---|---|---|
| C1 | ☐ |  | ☐ |  | C1 |
| C2 | ☐ |  | ☐ |  | C2 |
| C3 | ☑ | ⟋ | ☑ | Ω | C3 |
| C4 | ☐ | ⟋ | ☐ | Ω | C4 |
| C5 | ☐ |  | ☐ |  | C5 |
| C6 | ☐ |  | ☐ |  | C6 |
| C7 | ☐ |  | ☐ |  | C7 |
| C8 | ☐ |  | ☐ |  | C8 |

Internal Clock 200kHz

Manual Step Deskew
Channels C3_C4 -4.0%

**Figure 7.** *TDR setup*

## Odd-mode and Even-mode Measurements

The 8000 Series instrument , with the TDR-equipped 80E04 Electrical Sampling Module installed, provide 20 GHz bandwidth and TDR step pulse with a 17 ps rise time. This section describes, at a high level, how this instrument can measure Odd-mode and Even-mode impedances.

The TDR Setup dialog box of the instrument, shown in Figure 7, is used to specify the TDR measurements, and provides presets for each TDR channel. Pushing a preset button turns on the TDR step generator for the selected channel and positions the signal to see the incident edge of the TDR step signal.

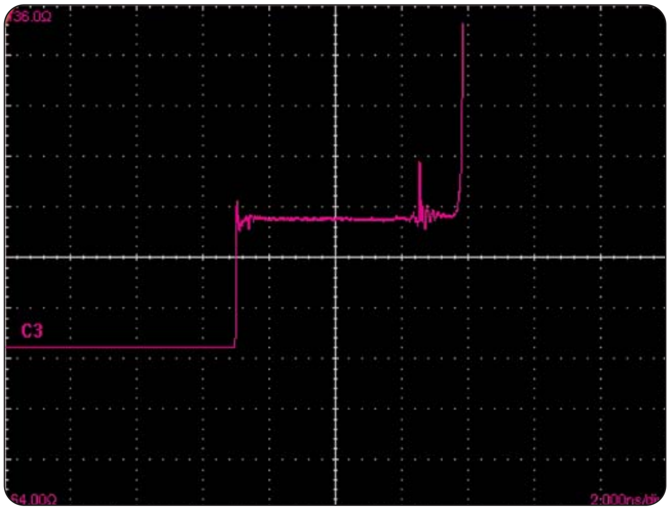
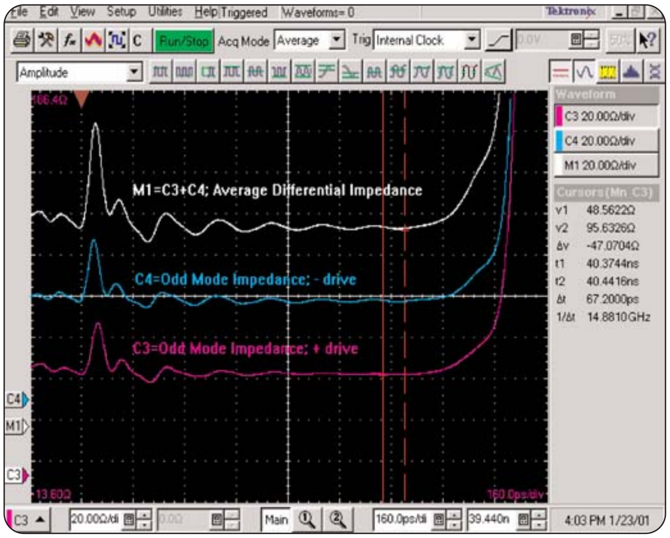


**Figure 8.** *TDR profile*

The TDR waveform in Figure 8 results from touching or clicking on the C3 Preset button in the TDR Setup dialog box. In time, from the left edge of the screen, the step edge occurs at 3.5 divisions, the coaxial cable response follows until reaching 6.2 divisions, where the cable connector and the PCB edge connector appear as spikes. The transmission line under study continues for about 0.5 division after the spikes. All waveforms in the following screen shots are expanded into this transmission line.

The differential measurement results in two impedance waveforms, one for each conductor. See Figure 9.



v1 48.5622Ω
v2 95.6326Ω
Δv -47.0704Ω
t1 40.3744ns
t2 40.4416ns
Δt 67.2000ps
1/Δt 14.8810GHz

***Figure 9.*** *Odd-mode and Average Differential Impedances*

*Note: The 8000B Series instrument displays Odd-mode impedance waveforms when the two conductors of the differential line are driven with opposite polarity steps from the TDR heads. When the polarities are the same, the instrument displays Even-mode impedance waveforms.*

Also note that for this discussion we will be using the Ohms (Ω) unit display mode.

If the transmission line is a perfectly symmetric differential line, and if the time delays for the generator pulses are exactly deskewed, both waveforms are the same. However, very often, the line conductors are not equal and the two acquired waveforms look different, which indicates unbalance and is of special interest to the designer. Care should be taken to match input cables to reduce unbalance.

v1 54.9190Ω
v2 27.5352U
Δv UNDEFINED
t1 40.3008ns
t2 40.4704ns
Δt 169.600ps
1/Δt 5.89623GHz

***Figure 10.*** *Even-mode and Average Common Impedances*

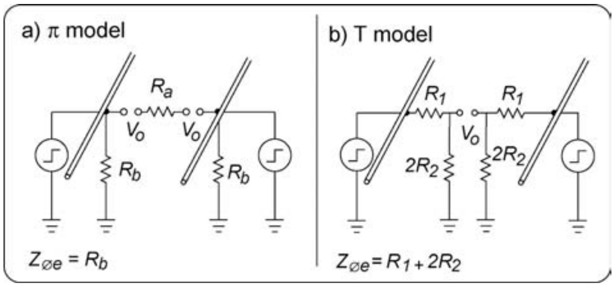


***Figure 11.*** *Math formula to calculate Common Mode Impedance.*

## Impedance Calculations

With the Odd-mode and Even-mode impedance waveforms acquired, the Define Math functions of the instrument can be used to calculate waveforms of the Average-differential, and Average common-mode, impedances. Figure 11 shows the Define Math dialog box, used to enter the calculations.

### Average-differential impedance

The Define Math dialog box can transform the acquired Odd-mode waveforms into a new math waveform of the Average-differential impedance, which equals the sum of the Odd-mode impedances (from Figure 3). The formula to enter follows:

M1 = C3 + C4, where:

- M1 is the calculated Average-differential impedance math waveform
- C3 and C4 are the acquired Odd-mode impedance waveforms

Figure 9 shows the Average-differential impedance waveform, M1. Although C3 and C4 are driven with opposite polarity steps, the instrument displays the negative channel as positive (because the instrument is set to display TDR units in ohms), and M1 displays the sum instead of difference. C3 and C4 each are at 50 Ω level, and M1 is at the 100 W level, which matches the actual conditions on the transmission line.

*Note: This averaged waveform does not indicate how balance differs between the two conductors. Furthermore, it is possible that existing imbalances may cancel out in the calculation of the math waveform. Examining the two Odd-mode impedance waveforms can reveal any imbalances in the transmission line.*

### Average Common-mode impedance

The Define Math dialog box can also transform the Even-mode waveforms that the instrument acquired into a new math waveform of the Average common-mode impedance. This impedance is equal to the two Even-mode impedances in parallel (from Figure 6). The formula to enter follows:

M2 = (C3*C4)/(C3+C4), where:

- M2 is the calculated Average Common-mode impedance math waveform
- C3 and C4 are the acquired Even-mode waveforms

Figure 10 shows Average Common-mode impedance waveform, M2, and the acquired Even-mode waveforms, C3 and C4. M2 is now at the 25 Ω level.

*Note: This averaged waveform does not indicate how balance differs between the two conductors. Furthermore, it is possible that existing imbalances may cancel out in the calculation of the math waveform. Examining the two Even-mode impedance waveforms can reveal any imbalances in the transmission line.*

## Summary

When taking your differential impedance measurements, you must ensure that your instrumentation setup creates the virtual short and the virtual ground on the transmission line during the step-pulse propagation. To do so, the setup make sure that the two steps used are equal and that they propagate exactly at the same time. Amplitude difference will be small with good quality cables, but time difference, or skew, between the edges (caused for example, by unequal length in cables) will cause very large differential error signal, which shows as a spike for every connector and impedance-change event on the waveforms.

The Tektronix instrumentation used to measure and compute the impedances in this application note supports the set-up requirements just described. The 80E04 TDR Electrical Sampling Module provides the steps from matched step-pulse generators, simultaneously running in parallel . The output polarity of each step is independently selectable for the desired impedance measurement. The output timing of the steps includes skew adjustment to compensate for differences in cable lengths from the step outputs to the transmission-line connection points. This high-resolution skew adjustment ensures that your setup creates the virtual ground and the virtual short in the measured transmission line.

Your setup, when using the 80E04, requires no complicated external termination or extensive calibration settings, since, with TDR units set to display ohms or rho, the instrument compensates to a known air line value kept internally in the 80E04 module. The impedance-measurement waveforms appear immediately and update as measuring continues—even for lines that do not have ground reference coupling, due to the virtual coupling of the simultaneous pulses. As long as your setup uses the highest quality connections and cabling, and adjusts the 80E04 timing skew to zero at the connection point, you will achieve top-quality, differential-impedance measurements.

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