Agenda

Introduction
TDR theory of operation
Real Example: Samtec Golden Standard Board
  • Single Ended Impedance
  • Coupling Effects
  • Odd & Even Modes
  • Differential Impedance
Relating TDR/TDT & S-Parameters
  • TDR – more than reflections
  • 4-Port Single Ended vs 2-Port Mixed Mode (Differential)
Important Factors in DTDR Accuracy
Signal Integrity Challenge

Data Rates Increase >1Gbps

- Risetimes become faster
- Reflections get larger
- Frequency Domain Data is Now Required

Trend to Differential Topologies

- Ideal differential devices
  - Low voltage requirements
  - Noise and EMI immunity
  - Virtual grounding
- Non-ideal devices are not symmetric
  - Can be identified by signal-conversions
    - Differential → Common
    - Common → Differential
- Differential signal integrity design tools are needed
What About Non-Ideal Devices?

Undesirable signal conversions cause emission or susceptibility problems

- **Differential-stimulus to common-response conversion**
  - Imperfectly matched lines mean the electromagnetic fields of the signals are not as well confined as they should be, giving rise to generation of interference to neighboring circuits.

- **Common-stimulus to differential-response conversion**
  - Imperfectly matched lines mean that interfering signals do not cancel out completely when subtraction occurs at the receiver. Measured by stimulating common-signal to simulate interference.

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Theory of Operation - TDR

*Impedance*

![Diagram of TDR Theory of Operation](image)
Impedance Mismatch Terms

\[
Z_L = Z_0 \frac{1 + \rho}{1 - \rho}
\]

Impedance Calculated from Source Impedance and Reflection Coefficient.

\[
\rho = \frac{V_r}{V_i}
\]

Reflection Coefficient, rho: How much was reflected?

What is the value of \( Z_{\text{load}} \)?

The DCA automatically calculates this for us.

The Samtec Golden Standard Reference Board

![Diagram of the Samtec Golden Standard Reference Board]

Details on www.samtec.com
Basic Microstrip Example

• As Positive Voltage Step is launched into conductor, positive charge is added to the conductor creating a current.

• Impedance is defined by the geometry and material properties – independent of the voltage applied.

• Wider conductor or thinner dielectric increases capacitance, decreases impedance

• If Voltage is doubled, current is doubled, \( Z = \frac{v}{i} \)
Coupling Effect on Single Ended Impedance

- Adding other nearby conductors causes field lines to couple to the other conductor instead of the return path.
- Capacitance to ground is reduced slightly.
- Single Ended Impedance of primary conductor is increased slightly.
- Induced Voltage & Currents on adjacent conductor create Near and Far End Crosstalk, NEXT/FEXT.

Single Ended Impedance, $Z_{SE}$ of A

- Stimulus on Port 1 only.

$V_r=8\text{mV}, V_i=200\text{mV}, Z_0=50\Omega$

$Z_A^{SE}=54\Omega$

$V=22\text{mV}$
Single Ended Impedance of B

- Exactly same as A
- Can be measured with either positive or negative voltage step at various amplitudes (linear)

Single Ended Impedance, $Z_{SE}$ of B

- Stimulus on Port 3 only

V = 23mV, $V_r = 7mV, V_i = 200mV, Z_0 = 50\ \Omega$

$Z_{SE}^B = 54\ \Omega$
Vector Addition of Field Lines

Simultaneous Stimulation

• Since the voltages/currents add/cancel, results can be calculated from independent measurements

"The amount of voltage that might couple onto a quiet net from an active net is completely independent of the voltage that might already be present on the quiet net"

Dr. Eric Bogatin – Signal Integrity Simplified
Prentice Hall
Differential Circuit Terminology

- **Odd Mode Impedance**
  - Impedance of a single line, while the pair is driven in the odd mode (only differential signal, no common signal).

- **Even Mode Impedance**
  - Impedance of a single line, while the pair is driven in the even mode (only common signal, no differential).

- **Differential Impedance**
  - Impedance the differential part of a signal will see. (Sum of the Odd Mode Impedances)

- **Common Impedance**
  - Impedance the common part of a signal will see. (Sum of Even Mode Impedances/4)

Odd Mode Impedance

- Defined as Impedance of a single line when voltage on A is opposite polarity of voltage on B
- Can be measured either by stimulating both lines simultaneously OR combining currents/voltages from independent measurements
- $Z_{odd}$ is less than $Z_{SE}$ due to induced currents combining (more current = less impedance)
**Even Mode Impedance**

- Defined as Impedance of a single line when voltage on A is identical to voltage on B.
- Can be measured either by stimulating both lines simultaneously OR combining currents/voltages from independent measurements.
- $Z_{\text{even}}$ is more than $Z_{\text{SE}}$ since induced currents oppose each other (less current = more impedance).

**Odd Mode Impedances**

- $-(T_{33}-T_{31}) = T_{B\text{ odd}}$
- $T_{11} - T_{13} = T_{A\text{ odd}}$

Vr=-14mV, Vi=200mV, $Z_0=50\,\Omega$

$Z_A^{\text{Odd}}=43\,\Omega$

Vr=15mV, Vi=-200mV, $Z_0=50\,\Omega$

$Z_B^{\text{Odd}}=43\,\Omega$
Even Mode Impedances

\[ T_{11} + T_{13} = T_{\text{even}}^A \]
\[ T_{33} + T_{31} = T_{\text{even}}^B \]

V_r = 30mV, V_i = 200mV, Z_0 = 50 \Omega

\[ Z_{\text{Even}}^A = Z_{\text{Even}}^B = 67 \Omega \]

Differential Impedance

\[ \frac{(T_{\text{odd}}^A + T_{\text{odd}}^B)}{2} = T_{\text{CD11}} \]
\[ T_{\text{odd}}^A - T_{\text{odd}}^B = T_{\text{DD11}} \]

V_r = -29mV, V_i = 400mV, Z_0 = 100 \Omega

\[ Z_{\text{Diff}} = 86 \Omega \]

• Samtec simulated \( Z_{\text{Diff}} = 86.6 \Omega \)
Common Impedance

\[ Z_{\text{Comm}} = \frac{Z_{A_{\text{even}}} + Z_{B_{\text{even}}}}{4} \]

- \( V_r = 30 \text{mV}, V_i = 200 \text{mV}, Z_0 = 25 \Omega \)
- \( Z_{\text{Comm}} = 33 \Omega \)

“Try using your single-ended TDR to make any two of the following measurements. From these measurements, you can work out the true differential impedance:

- The impedance of one trace while the other is reasonably well-terminated at both ends.
- The impedance when both traces are ganged together in parallel.
- The near-end crosstalk induced on the second trace when the first is driven.

The necessary equations are pretty hairy, but you don’t have to know them.”

Howard Johnson, PhD – EDN Article, 8/22/2002

http://www.edn.com/article/CA238428.html
Understanding S-Parameters

**Optical Device (Lens)**
- Incident signal
- Transmitted signal
- Reflected signal

Reflection $\rightarrow S_{11}, S_{22}$
Transmission $\rightarrow S_{21}, S_{12}$

**Electrical Device (PCB)**
- $S_{21}$
- $S_{11}$
- $S_{22}$
- $S_{12}$

Reflection $\rightarrow$ stimulus
Transmission $\rightarrow$ response

Theory of Operation – TDR/VNA

**Impedance**
- Time Domain Reflectometer (TDR)
- Vector Network Analyzer (VNA)

**S-parameters**
- Reflection
- Transmission
- Magnitude & Phase

Network Analyzer
- Step Generator
- Receiver
- Ei
- Et

TDR
- Receiver
- DUT
- Ei
- Et

Optical Device (Lens)
- Electrical Device (PCB)

DUT
- B
- R

Magnitude
- Phase

Sine Wave

Ei
Et
Ela

Receiver
- Reference
Scattering Parameters & Impulse Response

**Frequency Domain**

\[ T(j\omega) \ast H(j\omega) = R(j\omega) \]

(Phase not shown)

\[ T(t) \otimes H(t) = R(t) \]

**Time Domain**

Step Response (TDR/TDT) vs Impulse Response

\[ \frac{\partial}{\partial t} \]

A perfect impulse is equivalent to a differentiated perfect step

Therefore if we differentiate the Step Response we get the Impulse Response

**S-Parameter!** \((S_{21})\)
Single-ended S-Parameters and TDR/TDT

**Frequency Domain Parameters**
- Return Loss or TDR
- Insertion Loss or TDT
- Near End Crosstalk (NEXT)
- Far End Crosstalk (FEXT)

**Time Domain Parameters**
- FFT or IFFT

**Stimulus and Response**
- Port 1: Single-ended
- Port 2: Balanced
- Port 3: Single-ended
- Port 4: Balanced

**Naming Convention:**
- Single-ended S Parameters: $S_{SE}$
- Differential S Parameters: $S_{MM}$

**Network Analyzers typically use this method**

Single-ended to Differential S-Parameters

Network Analyzers typically use this method
Single-ended to Differential TDR/TDT Parameters

**Naming Convention:**

- Port 1: Single-ended
- Port 2: Balanced
- Port 3: Port 1
- Port 4: Port 2

**Stimulus:**

$$T_{SE}$$

- Single-ended: $T_{11}, T_{12}, T_{13}, T_{14}$
- Balanced: $T_{DD11}, T_{DD12}, T_{DC11}, T_{DC12}$

**Response:**

- Single-ended: $T_{41}, T_{42}, T_{43}, T_{44}$
- Balanced: $T_{CD21}, T_{CD22}, T_{CC21}, T_{CC22}$

**Conversion Matrix $M$:**

$$M = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 1 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} = \frac{1}{\sqrt{2}}$$

**Conversion Matrix $T_{MM}$:**

$$[T_{MM}] = [M]^* [T_{SE}]^* [M]^{-1}$$
The 4 Matrices of a 4-Port Device

All 4 Matrices can be calculated from any 1 of the 4 Matrices

DCAj – S-Parameters

Calibrated S-Parameters

• Real-time Update

• Built-in to the GUI
Correlation with Network Analyzer

S11

S21

• Blue = 20GHz PNA, Red = DCAj, Data compared with PLTS

Correlation with Network Analyzer

S31

S41

• Blue = 20GHz PNA, Red = DCAj, Data compared with PLTS
Differential Circuit Testing – What’s Important?

- Differential Steps must be well matched
- Differential Channels must be de-skewed
  - use the TDR De-Skew procedure prior to making measurements

Matching the Steps
When the TDR outputs are terminated with 50 Ω standards, there is no coupling so the Differential Impedance should be $2 \times 50 \, \Omega = 100 \, \Omega$

Mismatch or overshoot will affect the resolution of the Differential Impedance measurement

- DCAj has ~10 Ω (10%) variation
- Tek CSA has ~17 Ω (17%) variation
Agilent Calibration

Agilent’s built-in Calibration removes the effects of imperfect steps AND fixturing to give the Truest Differential Impedance.

DCAj has <1 Ω (<1%) variation

More Information

DCAj - www.agilent.com/find/dcaj

High Precision Time Domain Reflectometry (AN 1304-7)

Measuring Differential Impedance with TDR to Improve High-Speed Bus Designs, (AN 1382-5)

Improving TDR/TDT Measurements Using Normalization (AN 1304-5)

PLTS - www.agilent.com/find/plts

Signal Integrity Analysis Series

• Part 1: Single-Port TDR, TDR/TDT and 2-Port TDR - 5989-5763EN
• Part 2: 4-Port TDR/VNA/PLTS - 5989-5764EN
• Part 3: The ABCs of De-Embedding – 5989-5765EN