TDR Measurements for Rambus

RAMBUS®
DEVELOPER

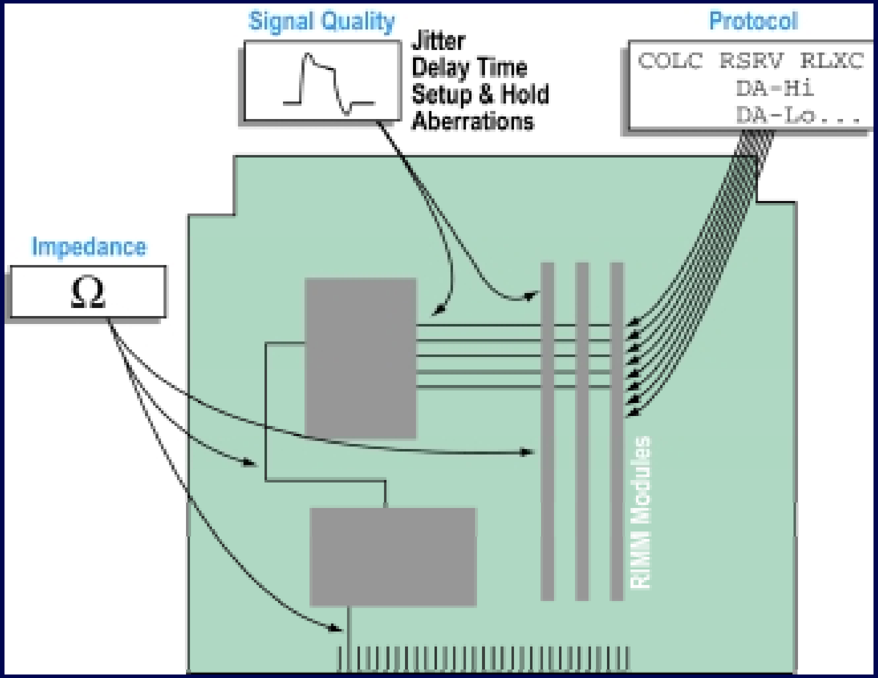
Tektronix®

Agenda

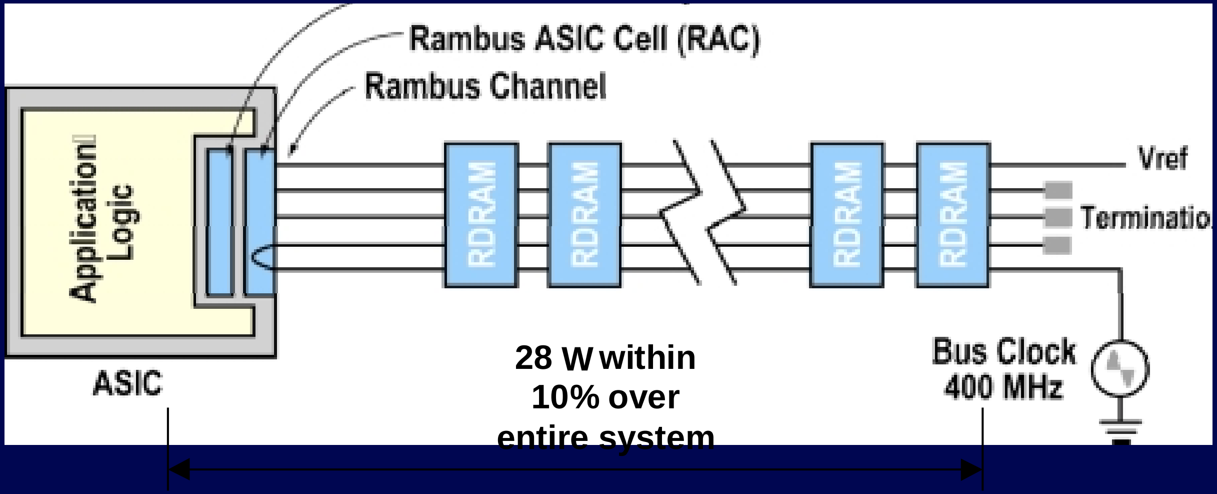
- Impedance effects in Rambus
- Introduction to TDR
- TDR error control with Rambus
  - ρ reference level error
  - Inadequate resolution
  - Stimulus amplitude error
  - Stimulus / Sampler aberrations
  - Launch resistance
  - Launch inductance
  - Device coupling error
  - Multiple reflections
  - Line loss
- Recommended TDR measurement technique

Rambus Challenges

- Tight Impedance Control
- Rambus Signaling Level (RSL) environment
  - 400 MHz differential clock/800 MHz data rate
  - 800 mV signal level around 1.4V ref
  - 200 ps setup and hold times
  - Bi-directional data flow
- Complex Protocol with high data rates



Rambus Impedance Control Implementation



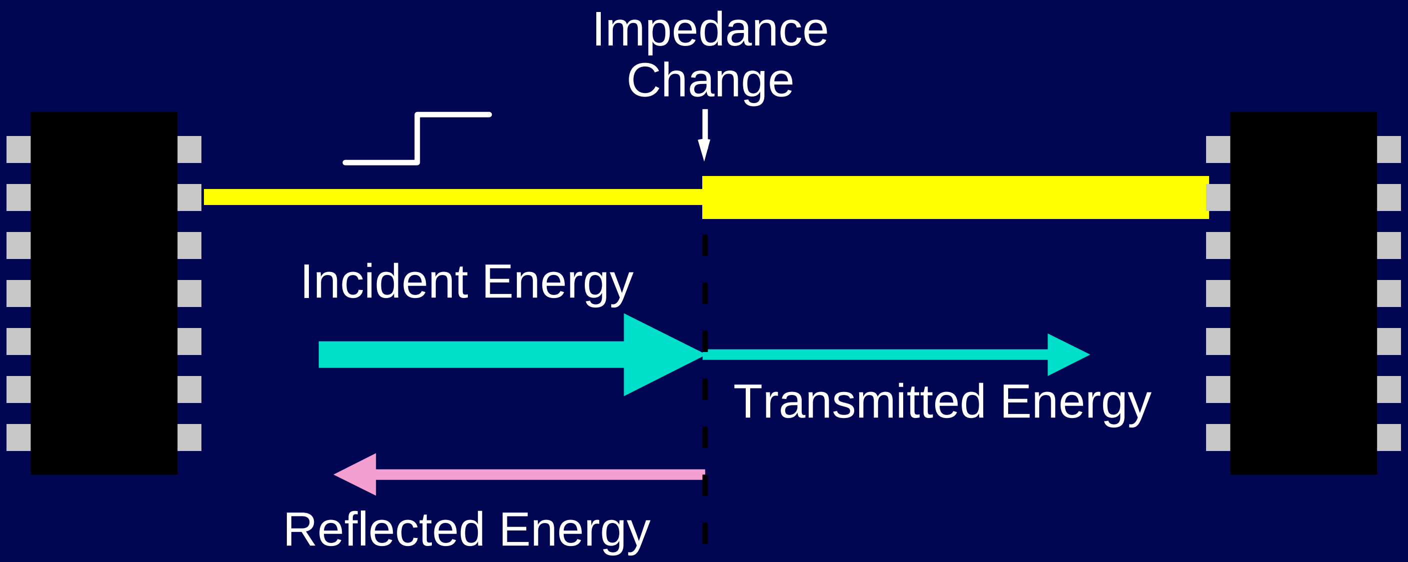
Important points:

- 28 Ω System specification (single-ended and Z_{odd})
- Control not like IC fab environment
- Individual components along bus may be different designs, technologies, tools, processes, vendors, lots, and expertise

Rambus Interconnect Issues

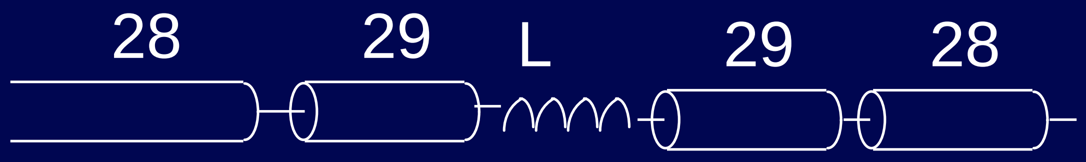
- Whenever signals encounter a change in impedance, some of the energy is reflected back toward the source; the remainder is transmitted
- Previous memory technologies were vulnerable only to lumped circuit effects
- With Rambus, the 200 ps edge speeds are fast enough relative to the typical lengths of the discontinuities that reflections and reduced transmitted energies from these discontinuities can contribute to signal aberrations

Rambus Interconnect Issues



- These aberrations can cause noise problems and compromise system margins.
- It is desirable to characterize Rambus components early in the design phase.

Signal Aberrations and Impedance



- Worst case, aberrations from different discontinuities may constructively interfere
- Lumped discontinuity on top of transmission line error is almost entirely additive
- Individual components within 10% doesn’t necessarily guarantee system is controlled 10%

The Rambus Specification Solution

- Overall impedance specification 28Ω ±10%
- Subcomponent specifications dictated by top-down specification much tighter
  - Circuit traces 28Ω ± 0.5Ω
- Some parasitic absorption necessary in RIMM modules due to package capacitances in RDRAM modules to stay within 28Ω ± 10%

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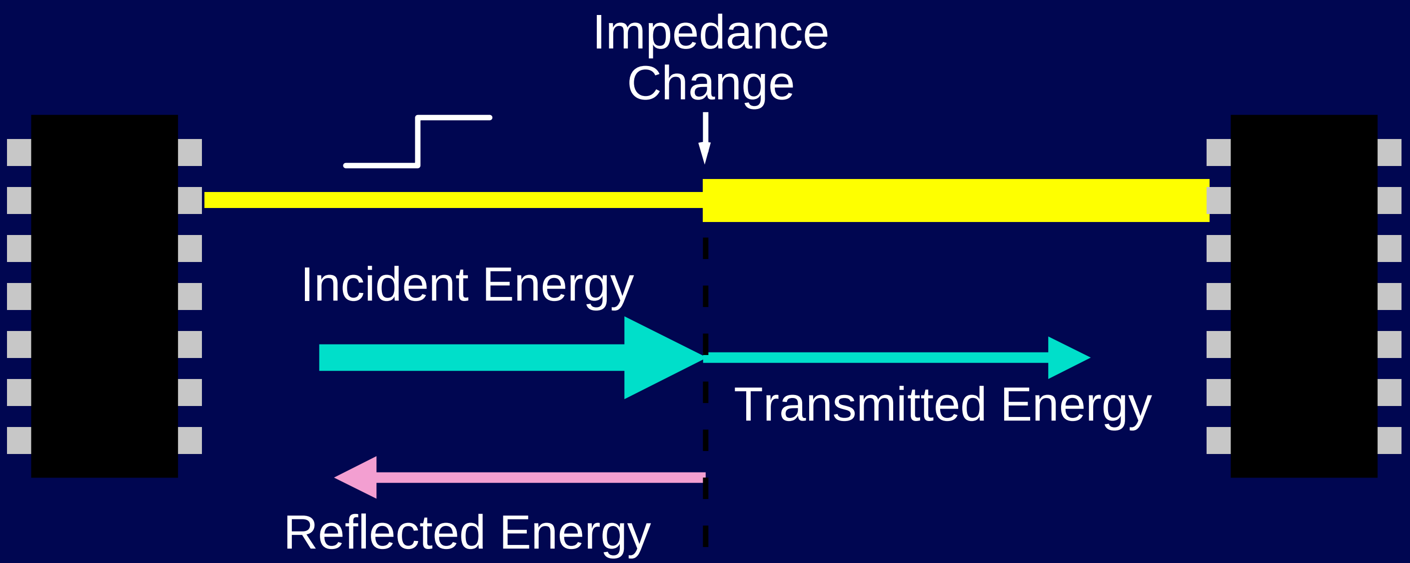
TDR and Interconnect Issues



- At high-speeds, interconnect limits system performance.
- It is desirable to characterize and model interconnect to predict the performance early in the design phase.

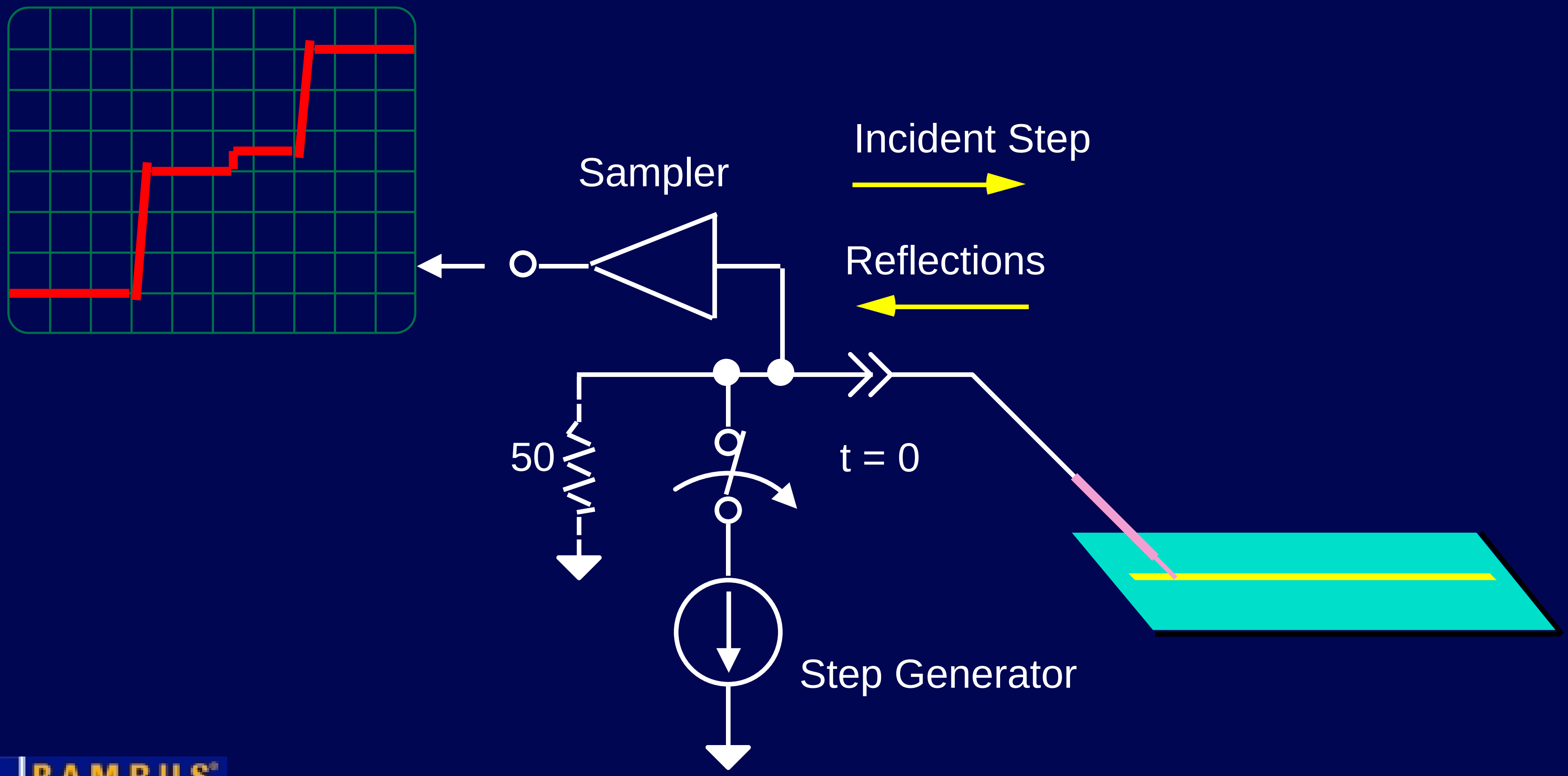
Key TDR Issues

- Whenever a signal encounters a change in impedance, some of the energy is reflected back toward the source; the remainder is transmitted
- The amount of energy reflected is a function of the transmitted energy and the magnitude of the impedance change
- The time between the transmitted energy and the reflection return is a function of the distance and velocity of propagation

TDR Overview

- Time Domain Reflectometry - a measure of reflection in an unknown device, relative to the reflection in a standard impedance.
- Compares reflected energy to incident energy on a single-line transmission system
  - Known stimulus applied to the standard impedance is propagated toward the unknown device
  - Reflections from the unknown device are returned toward the source
  - Known standard impedance may or may not be present simultaneously with the device or system under test

TDR Overview - Typical System



Sampler

Incident Step

Reflections

50

t = 0

Step Generator

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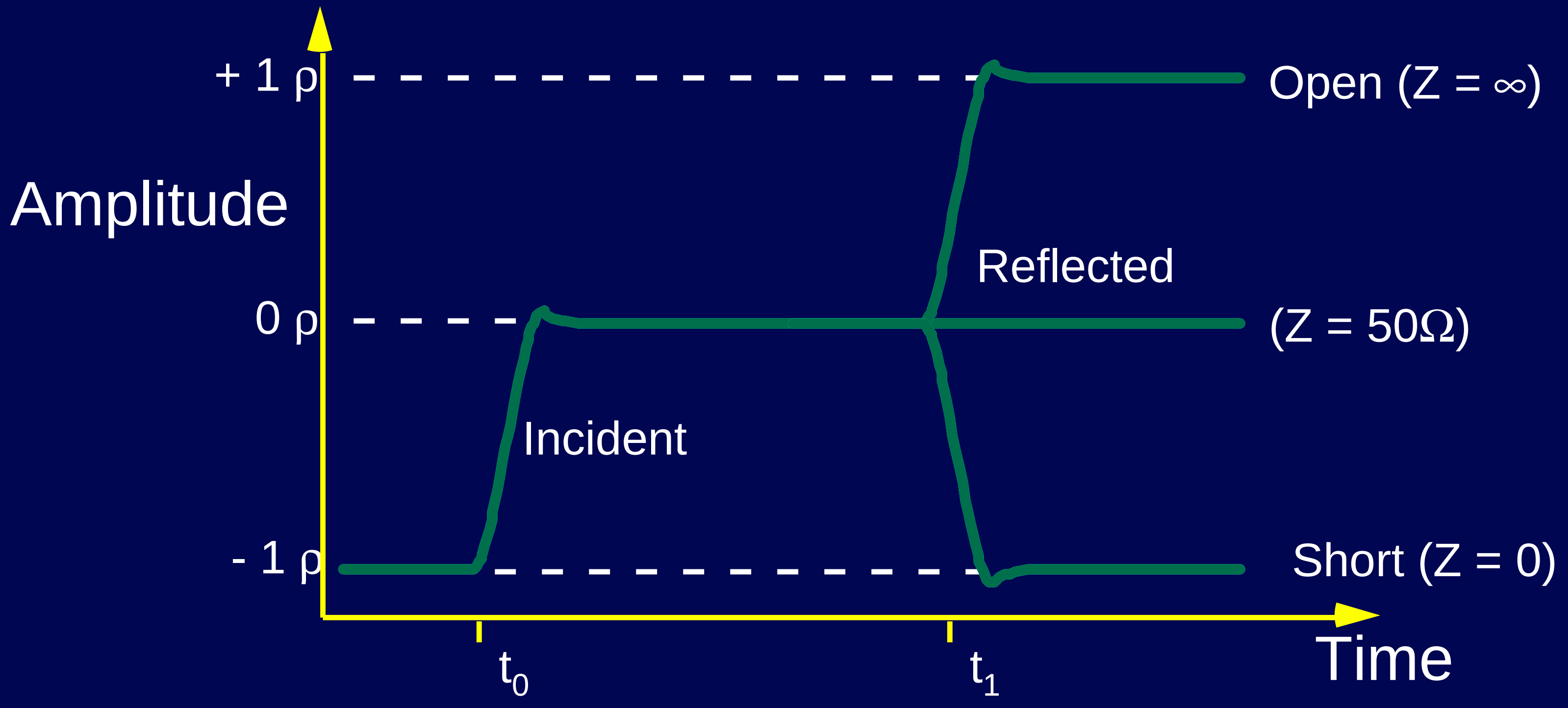
TDR Overview

Elements

- High speed stimulus, usually a step generator
- High speed sampling oscilloscope
- Back (internal) termination
- Interconnect system
- Device launch
- Known standard impedance

TDR Overview



TDR Waveforms - Open, Short and 50Ω terminations

Reflection Coefficient and Impedance

$$Rho(\rho) = \frac{reflected}{incident} = \frac{Z - Z_0}{Z + Z_0}$$

$$Z = Z_0 \frac{1+\rho}{1-\rho}$$

Where Z represents the test impedance
Z_0 is the reference impedance
ρ is measured by the oscilloscope

Measuring Impedance

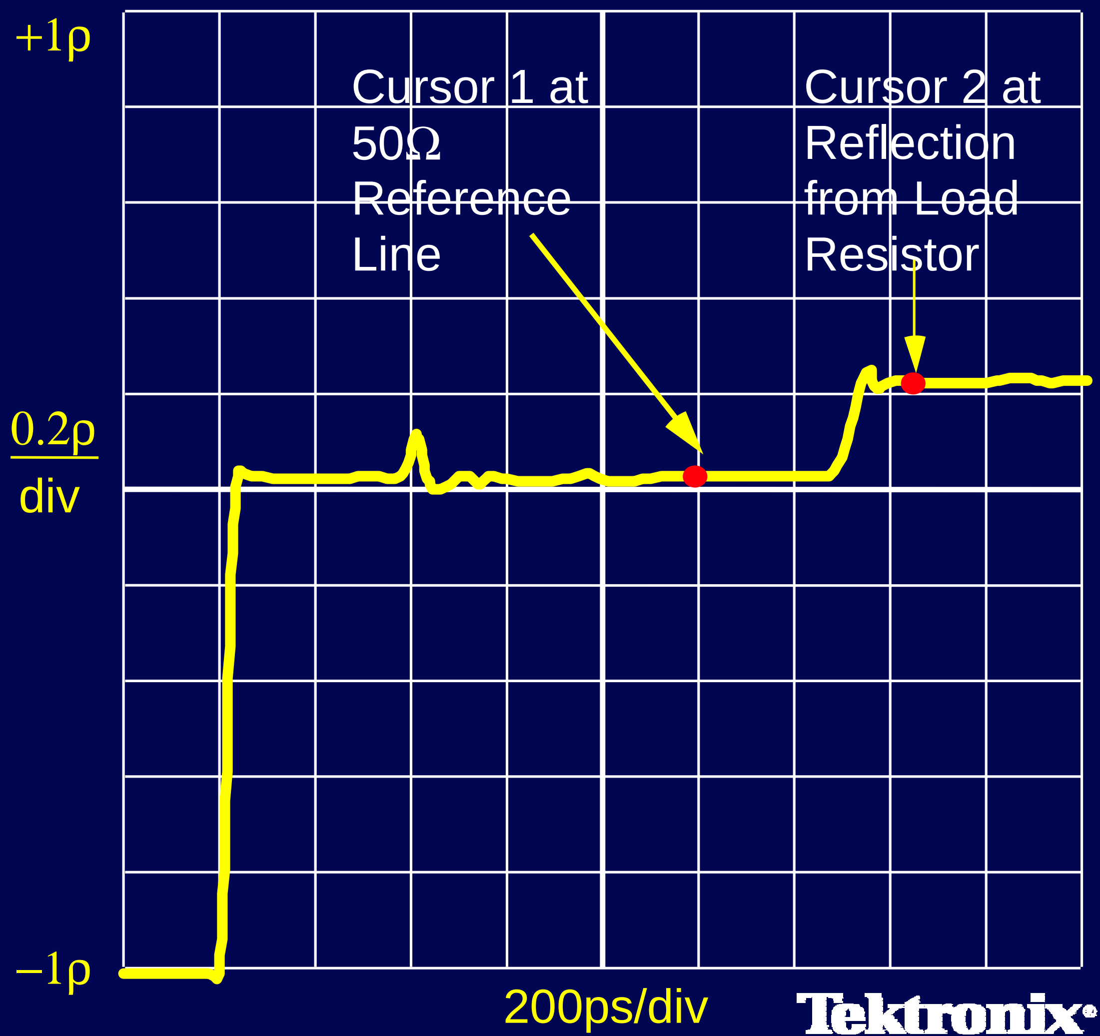
$$Rho(\rho) = \frac{reflected}{incident}$$

$$= 0.2$$

$$Z = Z_0 \frac{1+\rho}{1-\rho}$$

$$= 50 \frac{1+0.2}{1-0.2}$$

$$= 75$$



Cursor 1 at 50Ω Reference Line

Cursor 2 at Reflection from Load Resistor

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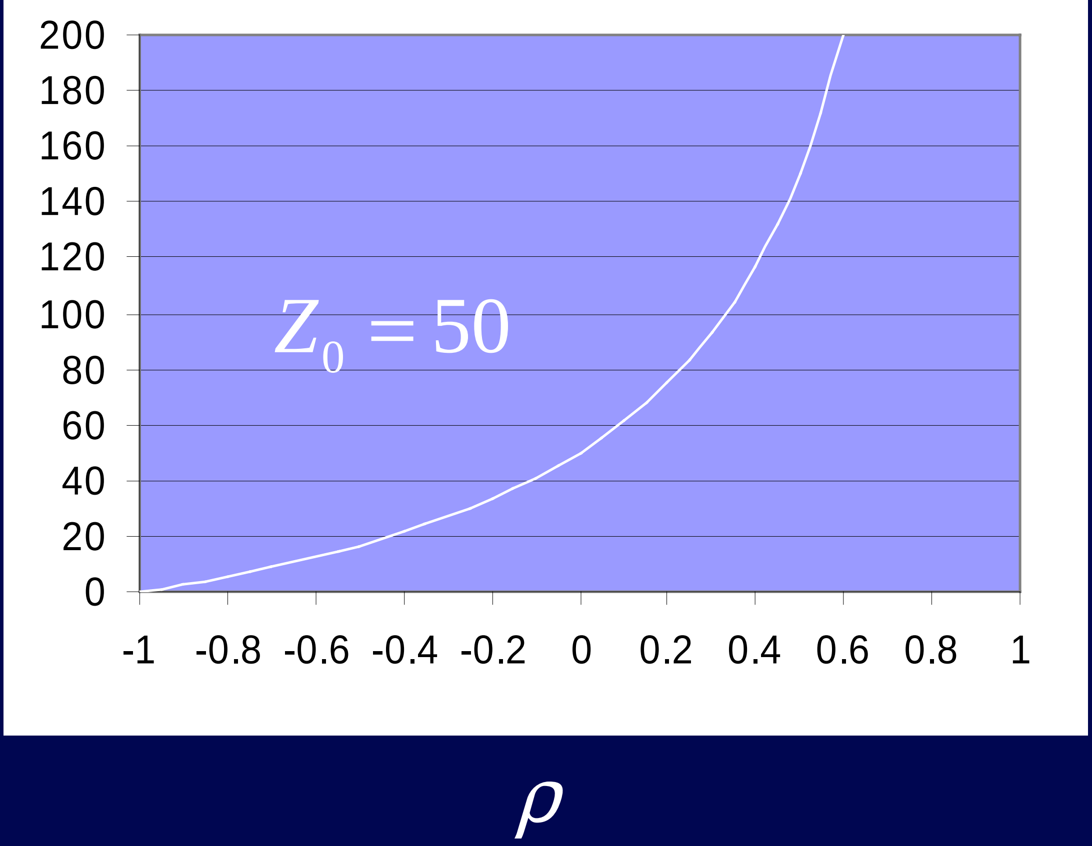
Measuring Impedance

$$Z = Z_0 \frac{1+\rho}{1-\rho}$$



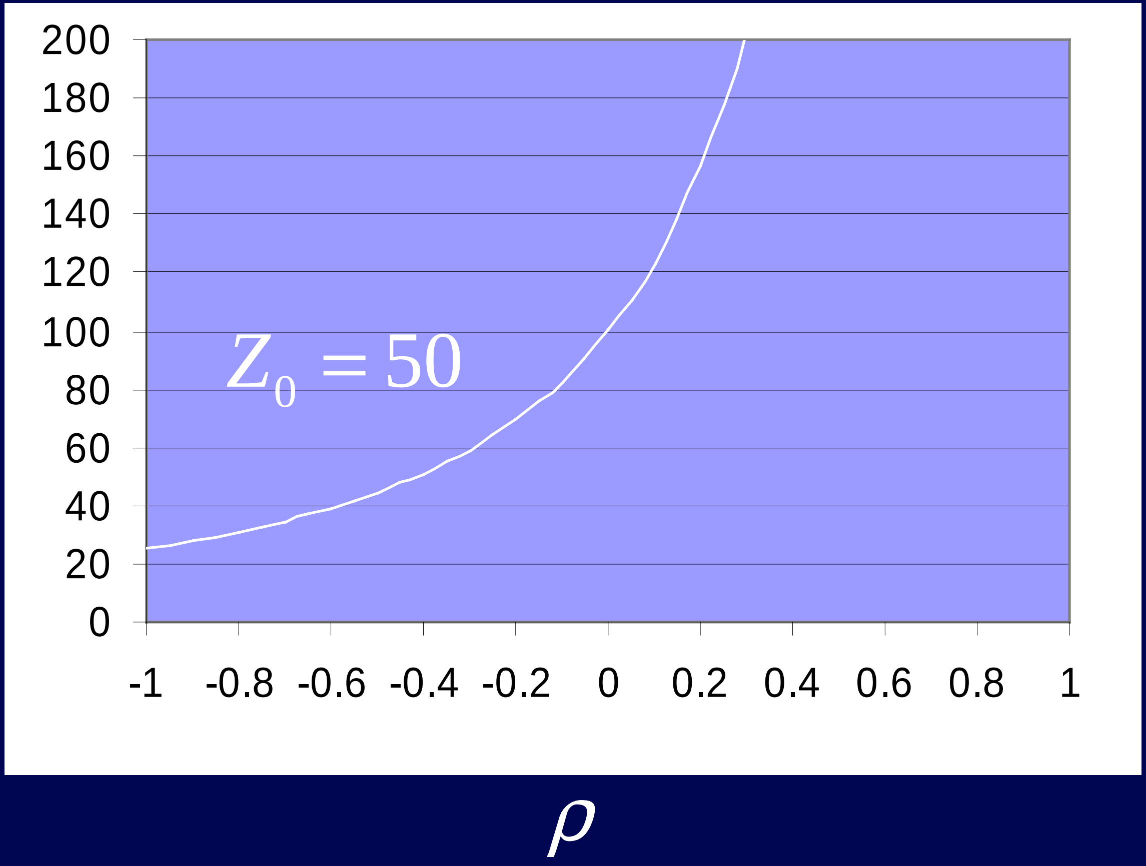
For Z = 28 Ω, ρ = -0.282

Nonlinear Impedance /ρ Mapping

- Everything else equal, lower impedance line measurements can tolerate more ρ error for a given impedance tolerance
- Assumed conditions
  - 250 mV step
  - 50 Ω Reference Line
- 1 mV or 4 mρ error equates to:
  - 0.40 Ω for a 50 Ω test line
  - 0.24 Ω for a 28 Ω test line <<< Rambus testing
  - 0.79 Ω for a 90 Ω test line
  - 1.23 Ω for a 125 Ω test line

Measuring Impedance

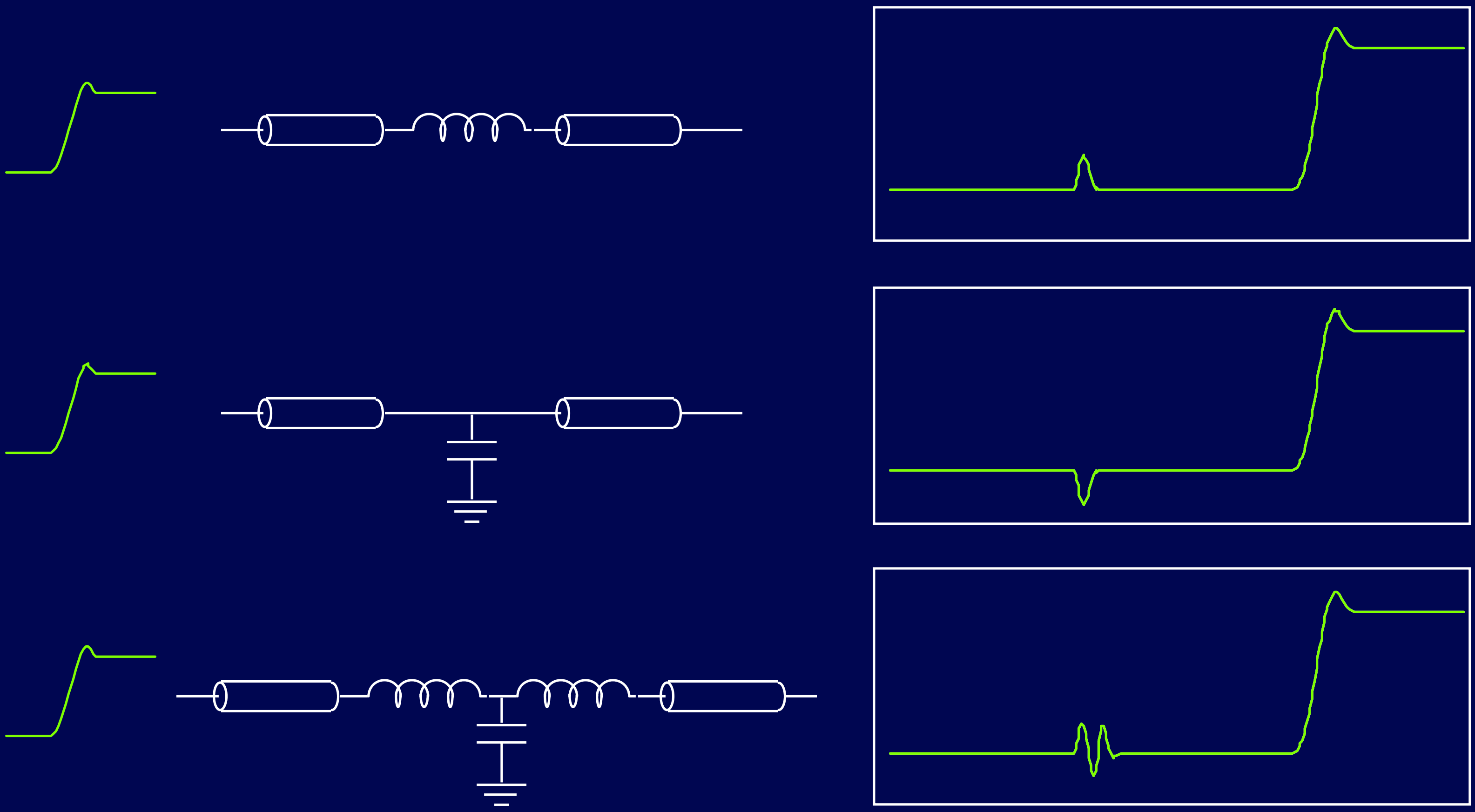
$$\frac{\partial Z}{\partial \rho} = \frac{2Z_0}{1 - 2\rho + \rho^2}$$



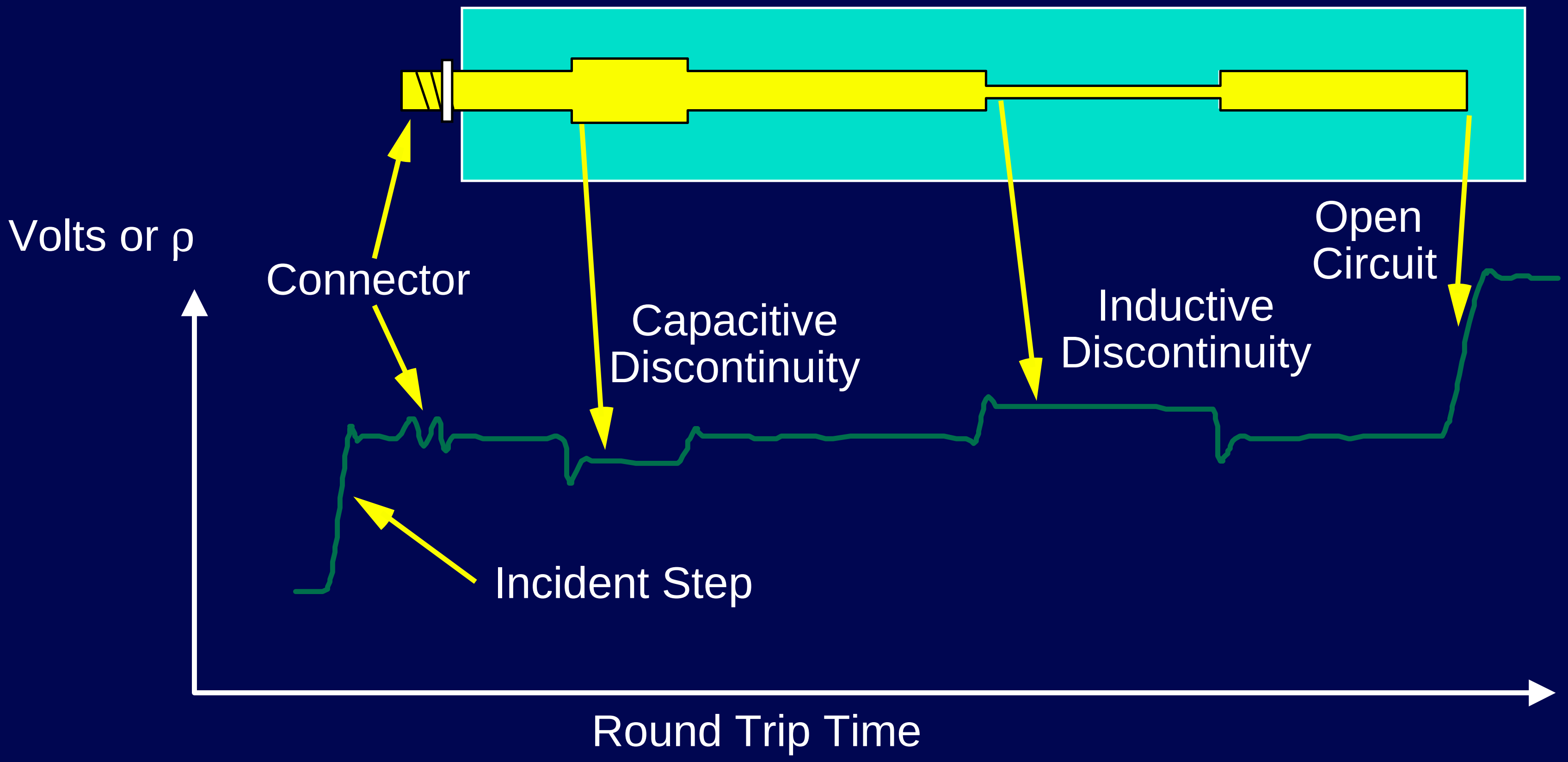
For Z = 50 Ω (ρ = 0), this sensitivity is 100 mΩ/mρ

For Z = 28 Ω (ρ = -0.282), this sensitivity is 60.8 mΩ/mρ

TDR Overview - Lumped Discontinuities



TDR Overview - Distributed Discontinuities



Volts or ρ

Connector

Capacitive Discontinuity

Inductive Discontinuity

Open Circuit

Incident Step

Round Trip Time

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TDR Calibration and Error Correction with Rambus - Reasons

- Tightly toleranced impedance measurements
- Many vendors and processes
- TDR system errors
- Connector uncertainties
- Launch uncertainties
- Test methodology differences

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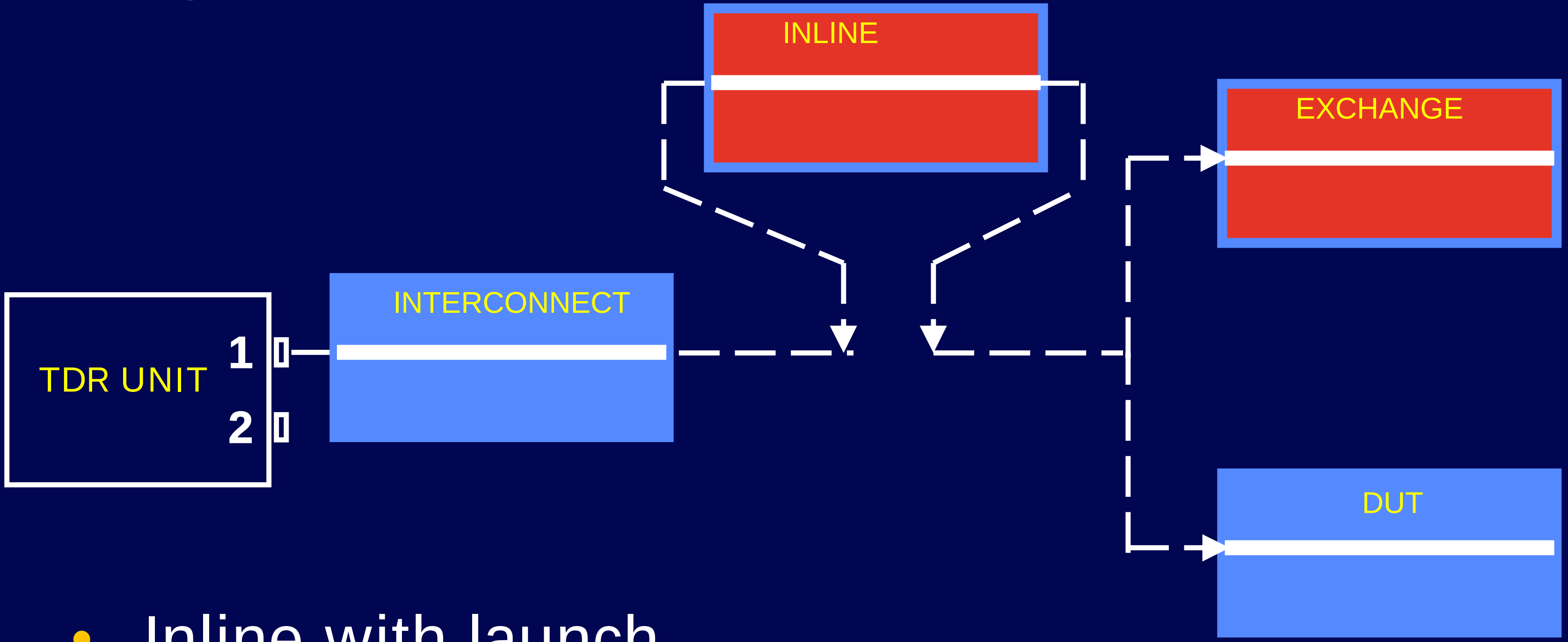
ρ Reference Level Error

- TDR is a comparative reflection technique- reflection in device being tested is always relative to some reference level
- Most TDR systems employ an assumed 50 Ω (zero ρ) reference level in the back termination
- Better accuracy can be attained by comparing device reflection with a separate standard impedance device
- Quality of standard impedance becomes first-level error control

Employing a Standard Impedance with TDR



- Inline with launch
- Exchange with device under test

Standard Impedances

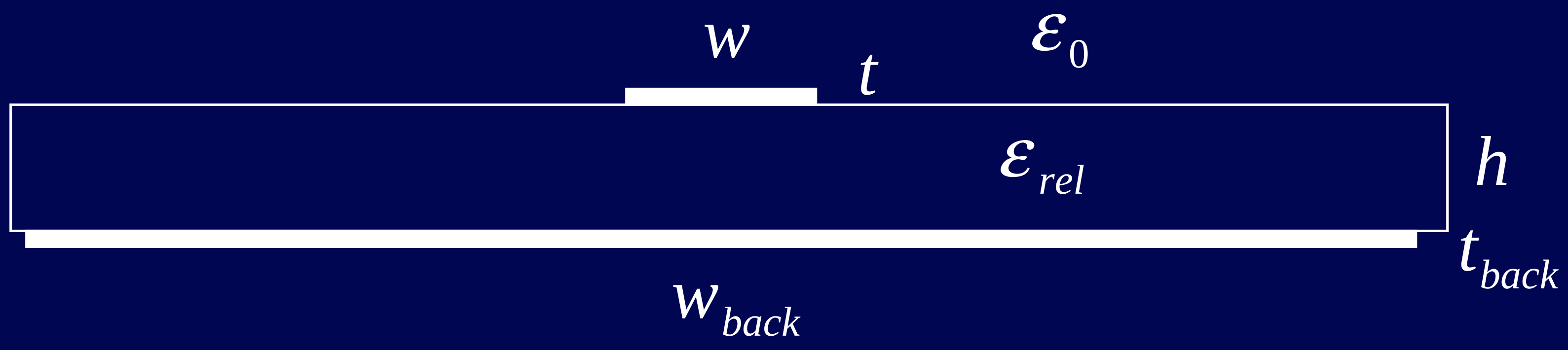
- Absolute Standards
  - Usually air lines built with extreme care employed for control of physical dimensions
  - Easily disassembled for checking dimensions
  - Standards Labs can characterize and periodically check
  - Based on physical equations like coaxial expression

$$Z_0 = \frac{\eta}{2\pi} \ln \frac{R_{outer}}{R_{inner}}$$

Standard Impedances

- Golden Standards
  - Absolute accuracy less important
  - Can be anything stable, repeatable, portable
  - Often need several sets depending upon supply chain
  - Characterization needs “round robin” or similar redundant checking

Microstrip Standards - Typically Rambus Test Coupons



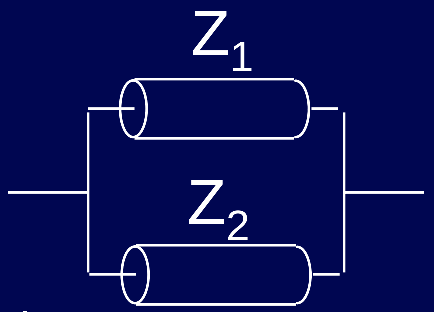
- Microstrip standards depend on many parameters with dispersed controls
  - Physical dimension (width w, thickness t, height h)
  - Dielectric media (glass and epoxy characteristics, glass/epoxy ratio, homogeneity)
  - PCB processes

Inline Versus Exchange Standard

Inline	Exchange
Always in place - remains primary standard in system	Substituted for DUT - interconnect becomes secondary standard
One connector change	One connector change
Two connector aberrations	One connector aberration
Measurement zone after standard location	Measurement zone at standard location
Loss in standard can affect accuracy	No affect from loss in standard
Additional multiple reflection compounding	No additional multiple reflection compounding

Tektronix recommends using an exchange standard

Standard Impedances



- For reasons that will become apparent, best comparison is with a standard impedance close to device under test
  - Error on device measurement is primarily additive
- 50Ω is the most commonly available and least expensive line
  - Can Parallel Two Lines for 25Ω, Using Tee(s)
  - Very close to 28Ω Rambus standard

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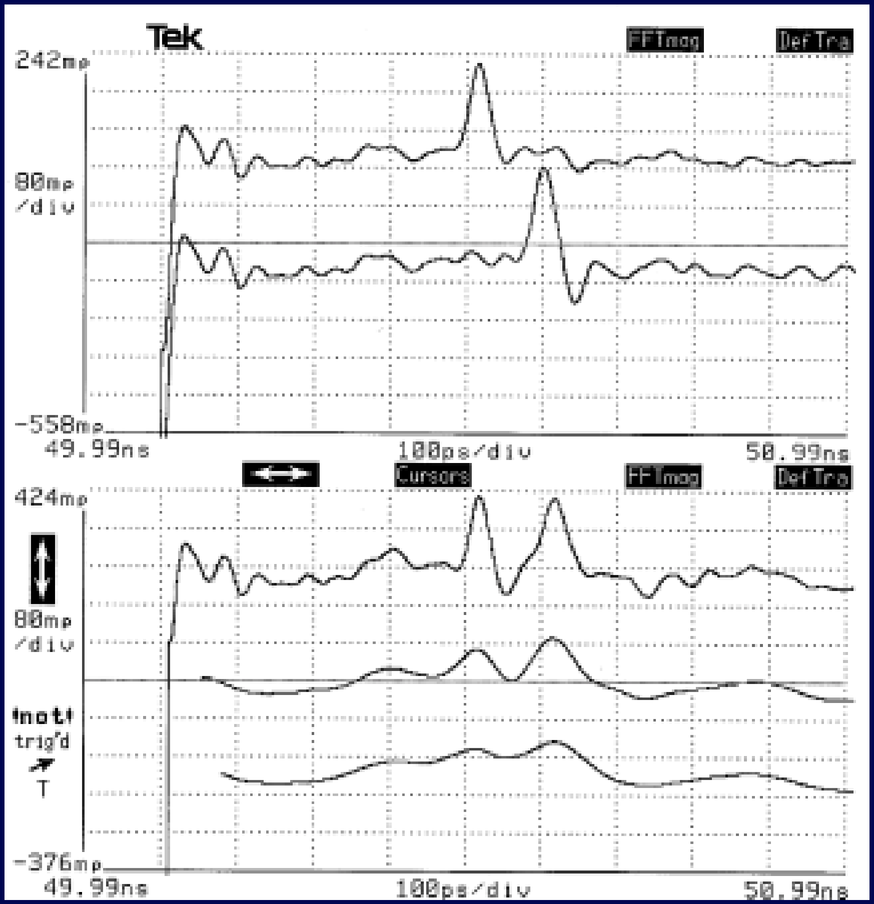
TDR Resolution

- Insufficient TDR resolution
  - Results from closely spaced discontinuities being smoothed together
  - Can miss details of device under test
  - May lead to inaccurate impedance readings

TDR Resolution



SMA through F-F barrel (8.6 mm dielectric)

Each end individually loosened 2.5 turns (1.8 mm)

Both ends loosened 2.5 turns; risetime limits

- –Top -- Full (~28 ps)
- –Mid -- 50 ps
- –Bottom -- 75 ps

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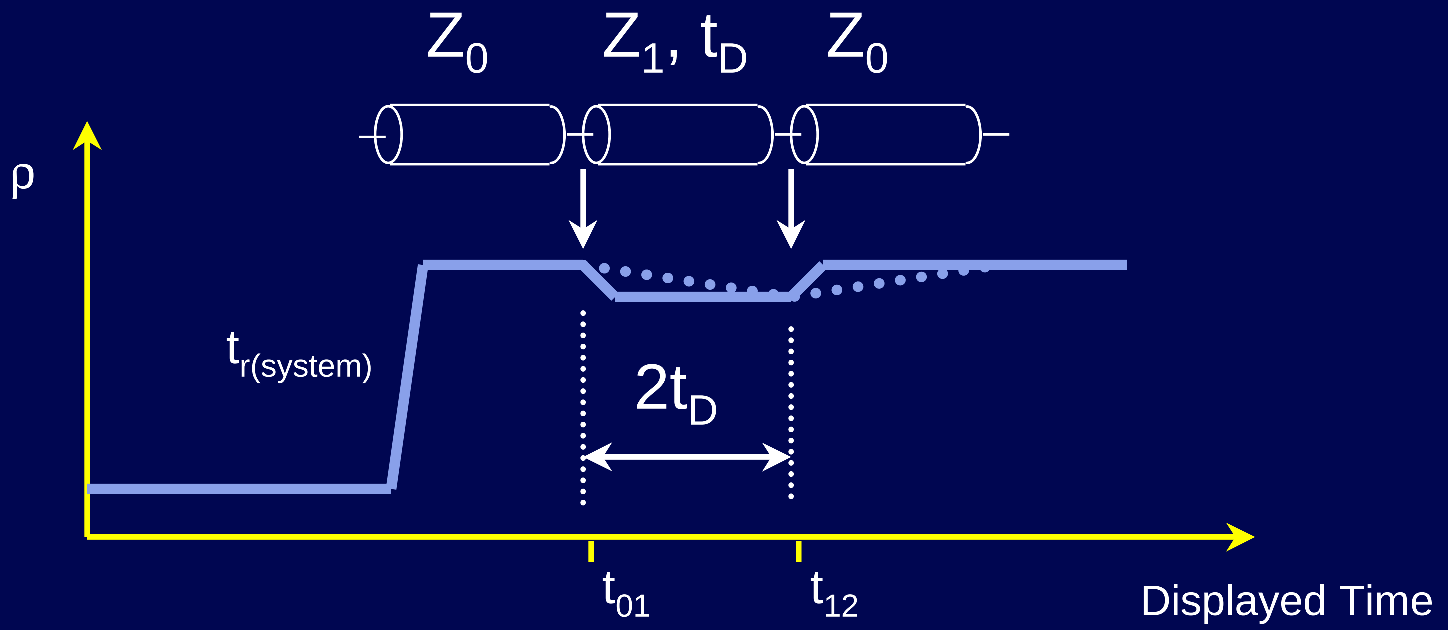
TDR Resolution



- TDR system risetime is related to resolution
  - Reflections last as long as the incident step and display as long as the system risetime

TDR Resolution

- First discontinuity reflection is witnessed at t_{01}
- Twice the one way propagation delay t_D between discontinuities elapses
- Second discontinuity reflection is witnessed at t_{02}
- Ideally, leading corner of reflection from second discontinuity arrives back at first discontinuity no earlier than lagging corner of reflection from first discontinuity, thus

$$T_{(resolution)} = \tfrac{1}{2} T_{R(system)}$$

TDR Resolution

Why is it important with Rambus technology and 200 ps edges?

- Mixed components and technologies add uncertainties to signal path - some quite short
- 200 ps Rambus edges still suffer from short discontinuities
- 17.5 ps resolution TDR instrument equates to discontinuity spacing of
  - 3.5 mm on surface etched board traces
  - 4 mm in most plastics
  - 5.5 mm in air
- Important to discern cause of discontinuity

TDR Resolution

- Note that
  - This rule assumes 0-100% ramp model; real world specifies 10-90% quadratic-type responses
  - System rise time is characterized by fall time of reflected edge from ideal short at test point
  - Other second order factors enter picture
  - System rise time approximated by:

$$T_{R(system)} = \sqrt{T_{R(stepgen)}^{2} + T_{R(sampler)}^{2} + T_{R(\text{int}\,erconnect)}^{2}}$$

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Stimulus Amplitude Error

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$$\frac{\partial Z}{\partial \rho} = \frac{2Z_0}{1 - 2\rho + \rho^2}$$

Amplitude impacts here

- Percentage Z error roughly doubles percentage ρ error near Z_0
- Can be entirely compensated by directly measuring incident amplitude

Stimulus Amplitude Compensation

- Measure incident amplitude during calibration cycle
- Calibration cycle check of incident amplitude can be same as standard impedance check
- Note that use of standard impedance close to device minimizes any residual errors

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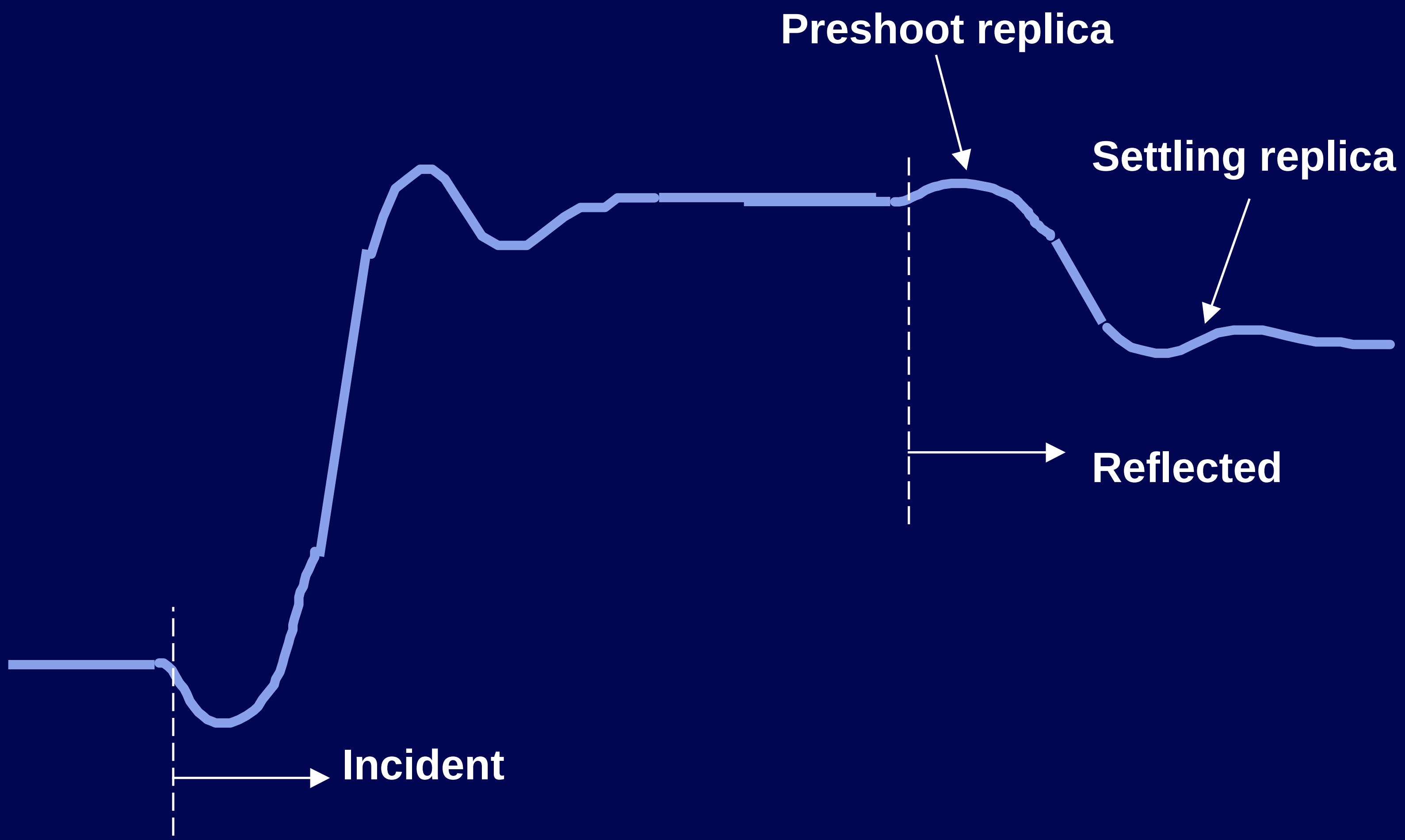
Stimulus / Sampler Aberrations

- Aberrations - foot, preshoot, ringing, longer term effects
  - Can amount to several percent
  - Short or long term
  - All reflections are replicas of the original step, filtered by reflecting device
  - Foot distorts response before the reflection, affecting establishment of baseline
- With linear devices, it doesn't matter how aberrations are apportioned between stimulus and sampler

Aberration Replication



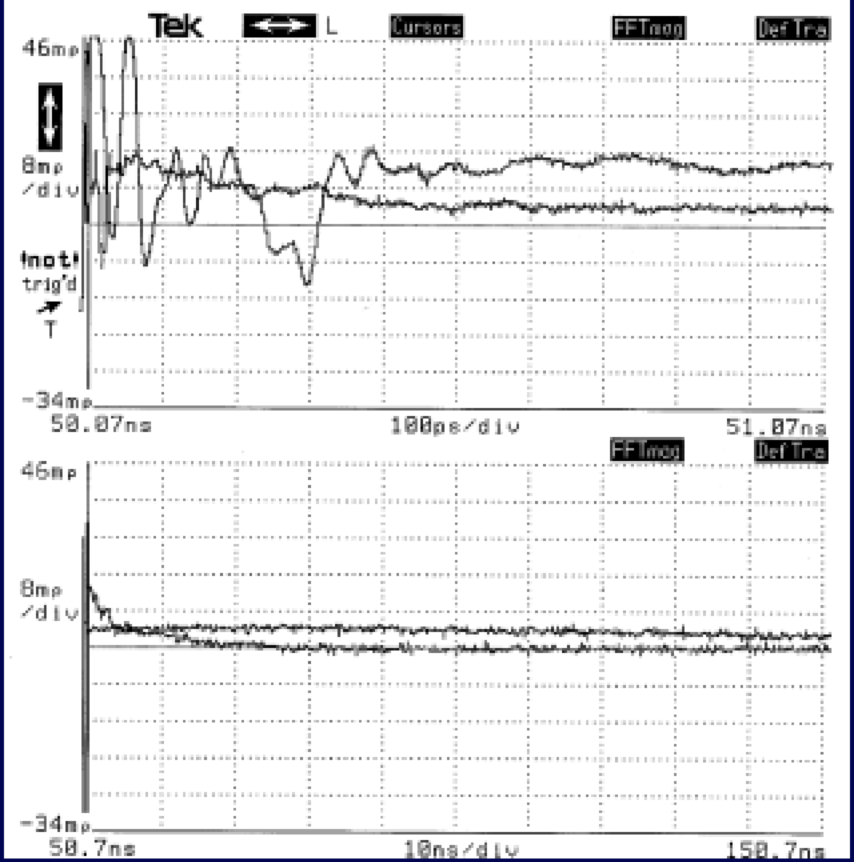
Preshoot replica

Settling replica

Reflected

Incident

Stimulus / Sampler Aberrations



100 ps/div

1 ns/div

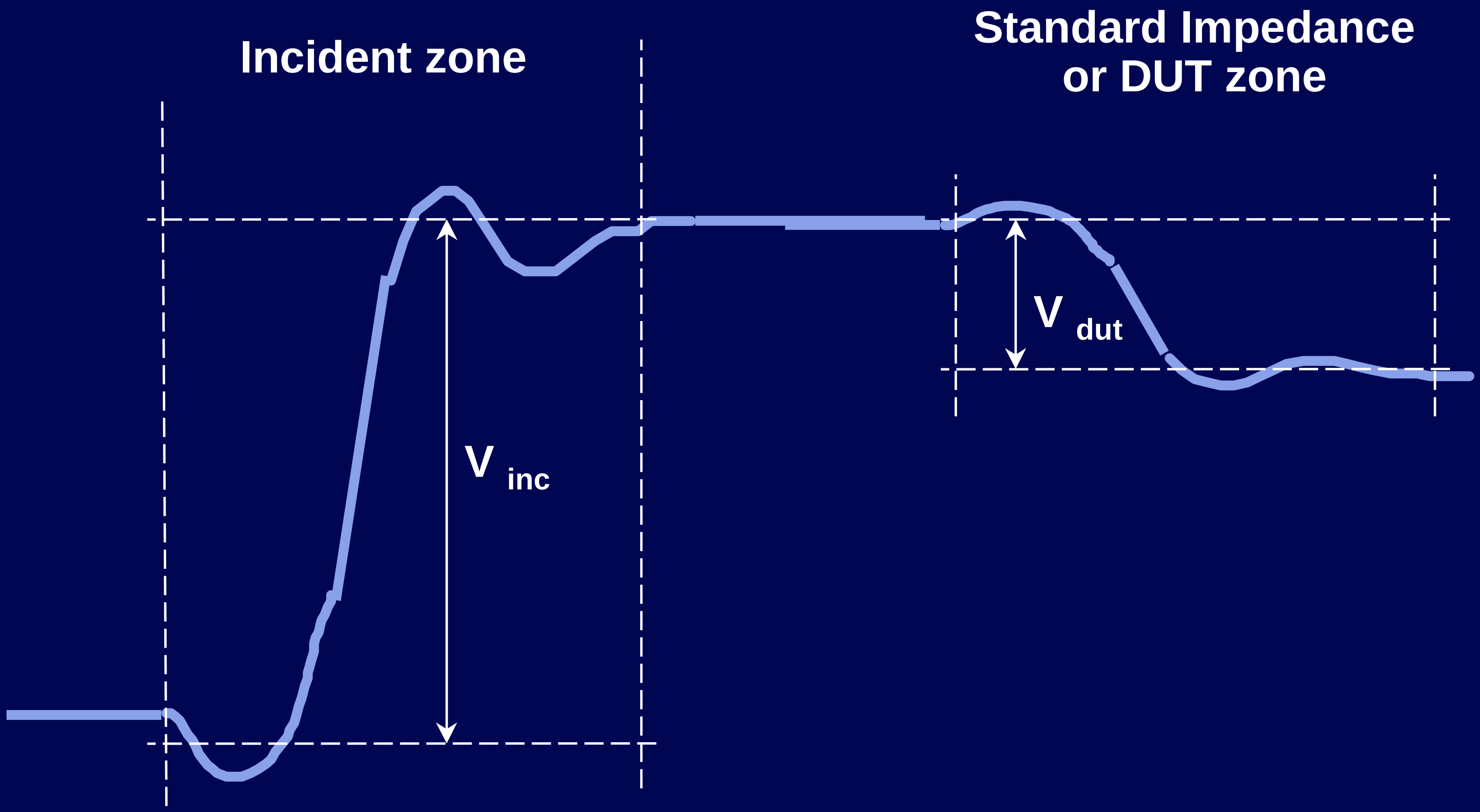
10 ns/div

100 ns/div

Stimulus / Sampler Aberrations

- Measurement over a zone to establish ρ levels and amplitude includes:
  - Device reflections
  - Stimulus / Sampler aberrations incident
  - Stimulus / Sampler aberrations reflected
- Recommended measurement technique will involve:
  - Use of exchanged impedance standard
  - Measurement over identical zones for incident edge and reflections from standard impedance and DUT
  - Amplitude measurement

Measurement Zones



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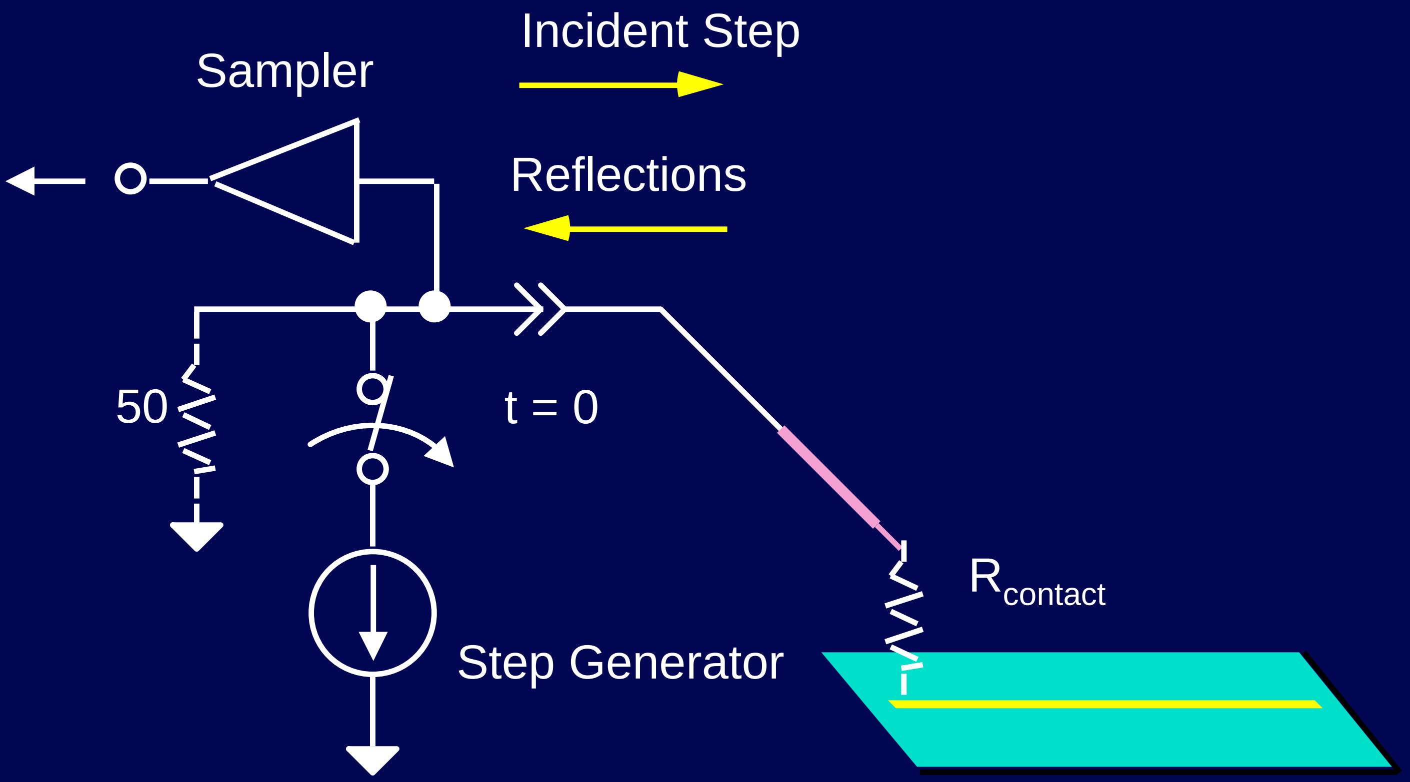
Launch resistance



- Indiscernible from device impedance
- Effect is additive, always positive, and similar to an equal amount of ρ reference level error

Launch resistance

- May not necessarily be repeatable
- Is a problem with lower impedance levels, e.g. 28Ω Rambus measurements
- Most often is reasonable bounded (tens of mΩ)
  - Can be measured with 4-wire measurement - replicate several in series if necessary
- May be present in both signal and ground contacts
- Use of exchanged standard impedance will cancel launch resistance provided it is constant

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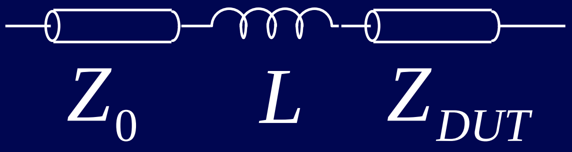
Launch Inductance

- Caused by
  - Non-characteristic launches
  - Air gaps at launch
  - contorted launch paths
  - Poor attention to ground attach
- Time constant is longer for smaller Z_0

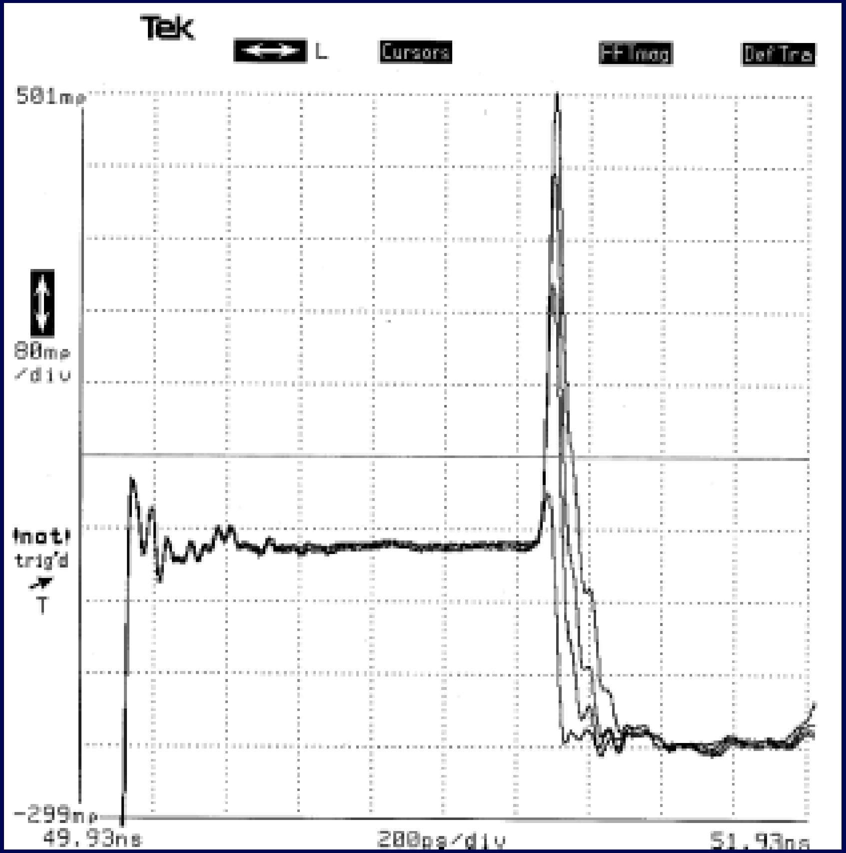


$$\tau = \frac{L}{Z_0 + Z_{DUT}}$$

Launch Inductance

- May affect measurement zone
  - Lumped time constant decay usually lasts much longer than propagation through inductance element
  - Multiple reflections carried into measurement zone
  - If C present, may have second order ring (though usually only a larger Z_{DUT} is more vulnerable)
- May be partially compensated
  - Must be absolutely repeatable attach geometry
  - Standard impedance Z_0 must be very close to Z_{DUT}

Launch Inductance



Launch from 0.141” semi-rigid coax to microstrip through center and ground wires, with gap

L-R: gap = 0/1/2/3 mm

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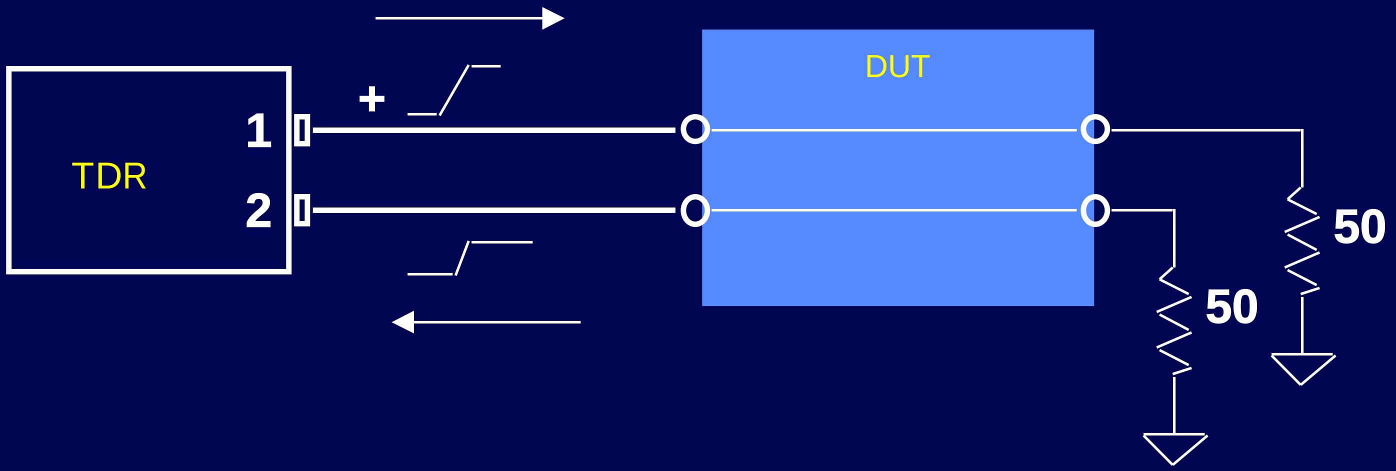
Crosstalk

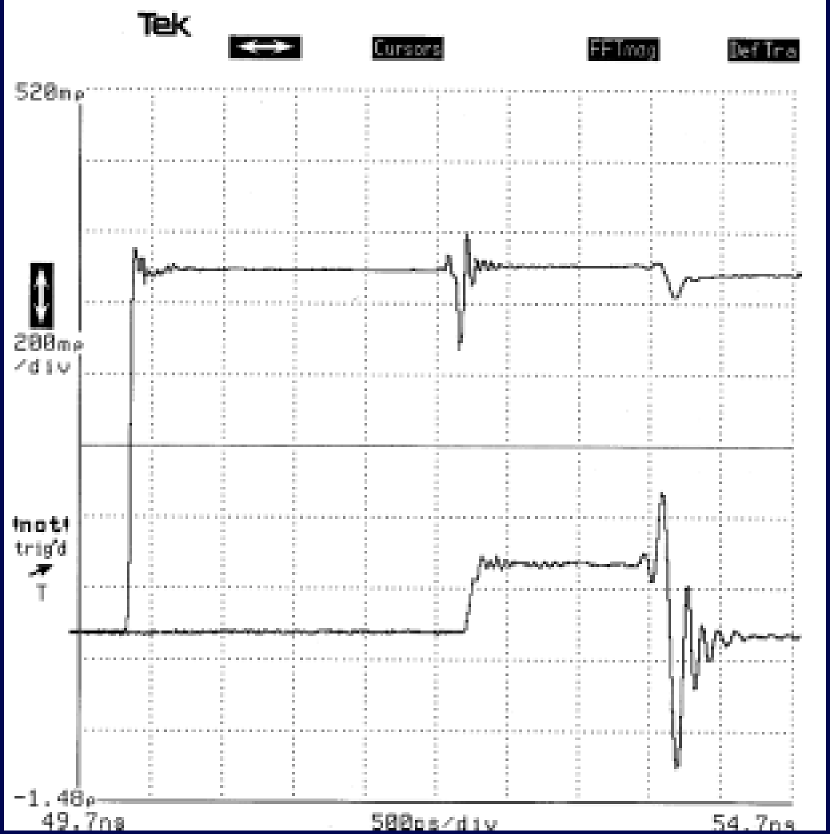
- The coupling of energy from one line to another
- Three Elements Contribute to Crosstalk:
  - Port terminations
  - Stimulus
  - Moding on transmission system
- Generalities:
  - Proportional to the line length
  - Proportional to rise time of driving signal
  - Can be positive or negative (inductive or capacitive)
  - Occurs in both forward (near-end) and backward (far-end) directions
  - Non-characteristic port terminations make it worse

Crosstalk Measurement Techniques



- Set up TDR on aggressor line
- Observe victim lines with TDT
- Take care to terminate all other lines

Crosstalk



Crosstalk between adjacent 50 Ω runs on FR4 with
W=2.5 mm
S=2 mm
Far end 50 Ω terminations

Aggressor: 200 mρ/div
Victim: 4%/div

Crosstalk

- Adjacent microstrips and striplines will always crosstalk to a degree if fringing fields overlap
- Impedance measurements include loading of adjacent lines, whether intended or not
- Three key questions:
  - Is the geometry measured representative of the geometry in the application?
  - Are the port terminations of adjacent lines representative?
  - Are the driving conditions of adjacent lines representative?

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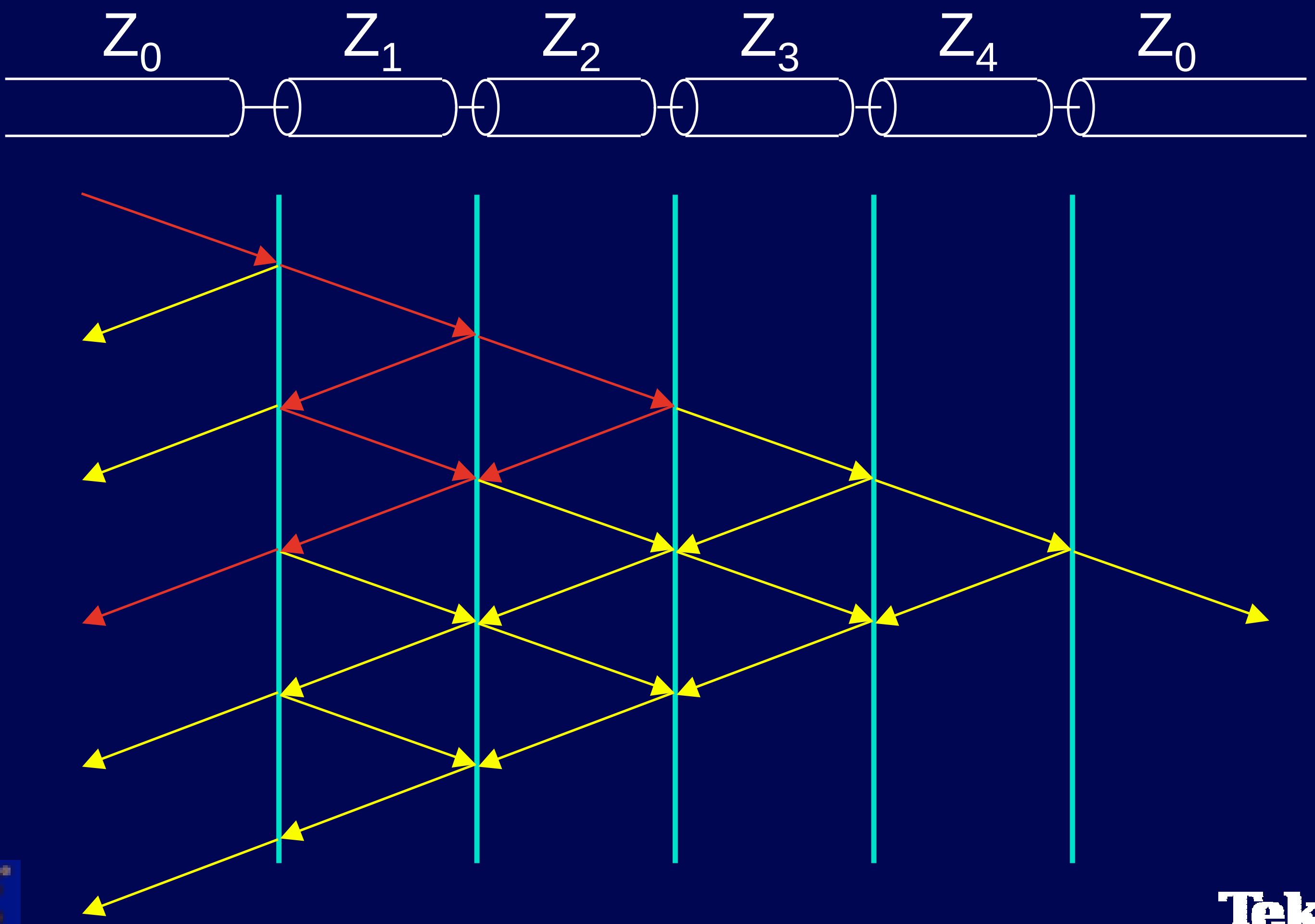
Superposition of Reflections

Effect of multiple impedance discontinuities



Problems with Multiple Reflections

- Multiple reflections
  - Can appear anywhere in a waveform
  - Can look like anomaly or Z-shift
  - Might be controllable, but always are predictable
- TDR trace is a reflection profile, not a true impedance profile
- Resolution may be lost due to rise time degradation

Problems with Multiple Reflections

- TDR trace may be difficult to interpret in the presence of multiple reflections
- Can be deconvolved with DSP if impedance profile and other information is needed
- Can be compensated with techniques using exchanged standard impedance, if only impedance is needed

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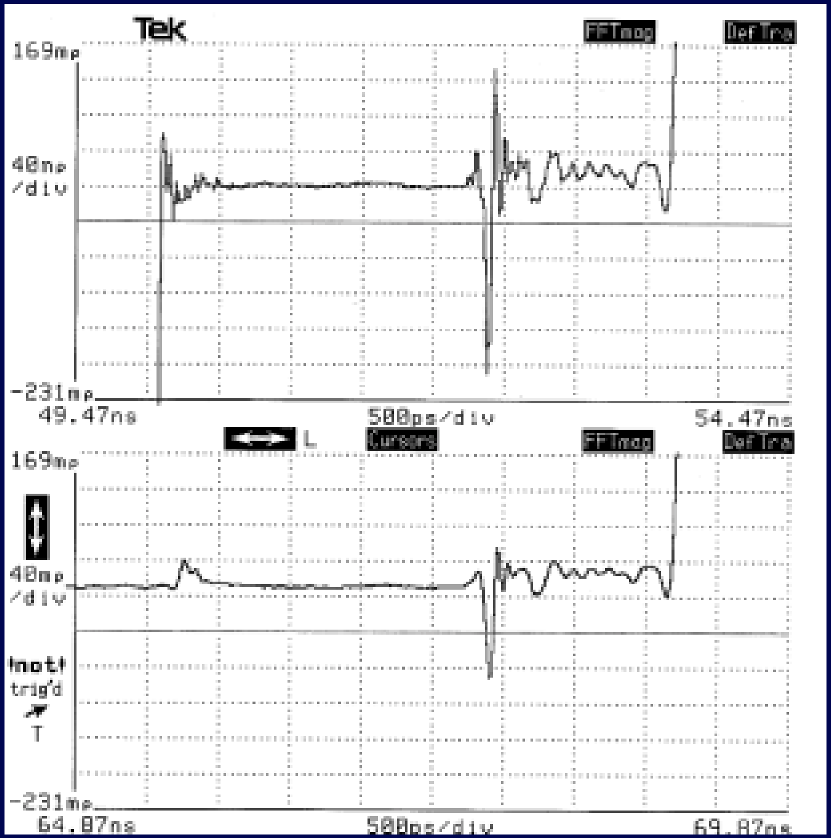
Transmission Line Losses

- Affects TDR and TDT measurements
  - Long dribble up time constants
  - Impedance accuracy affected
  - High frequency details attenuated
  - Risetime (and therefore resolution) increased
- Loss mechanisms
  - DC resistive losses
  - Skin effect losses
  - Dielectric losses
  - Coupled losses (crosstalk loss)

Transmission Line Losses



100 mm 50 Ω microstrip on FR4

Same with 1.5 meters RG58 inserted in front of DUT. The DUT error is about +10 mρ or +1 Ω.

Transmission Line Losses

- Generally, skin effect losses dominate at microwave frequencies
- Skin effect loss effect on impedance measurements can be compensated within reason
- Resolution cannot be regained easily

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  - Inadequate resolution
  - Stimulus amplitude error
  - Stimulus / Sampler aberrations
  - Launch resistance
  - Launch inductance
  - Device coupling error
  - Multiple reflections
  - Line loss
- <u>Recommended TDR measurement technique</u>

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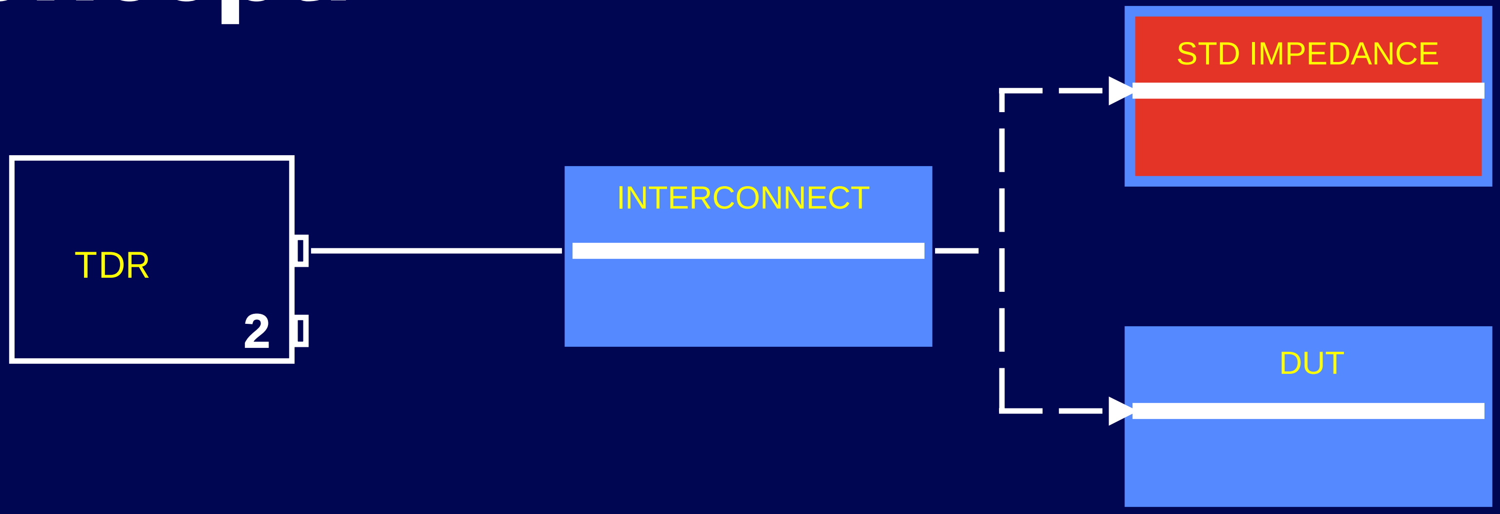
TDR Accuracy Improvement
IPC - TM - 650 Method

- Eliminates These Errors
  - Stimulus amplitude error
  - Most Stimulus / Sampler aberrations
  - Launch resistance and inductance, provided it is duplicated on the standard impedance
  - Multiple reflections up to exchange point
  - Line loss prior to impedance standard

TDR Accuracy Improvement - Concept:

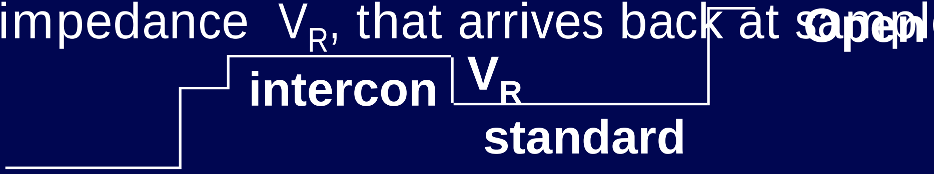


- TDR like a linear, homogeneous, isotropic system - implemented as a 1 port
- TDR edge from source experiences identical source, interconnect, and sampler imperfections with both standard and DUT present

TDR Accuracy Improvement

- Characterize interconnect as secondary standard
  - Disconnect standard impedance and measure size of step incident on standard impedance V_I that arrives back at sampler.

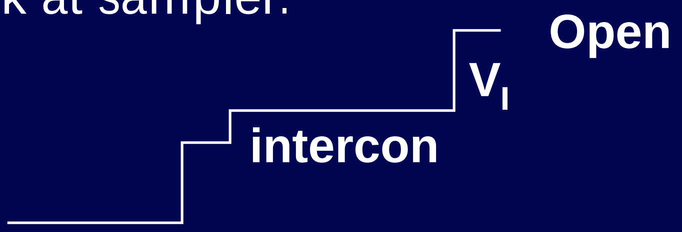
Re-connect standard impedance and measure size of step reflected from standard impedance V_R, that arrives back at sampler.



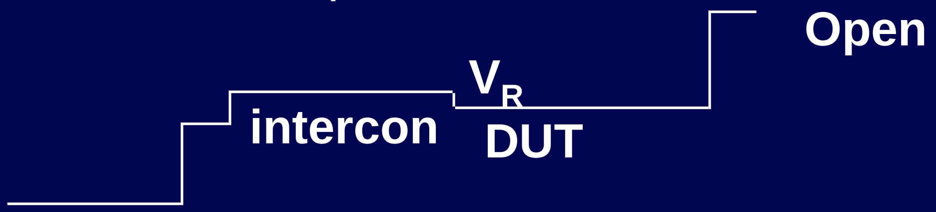
Calculate Z_{INT}: $Z_{INT} = Z_{STANDARD}(V_I - V_R) \ / \ (V_I + V_R)$

TDR Accuracy Improvement

- Measure DUT impedance against interconnect
  - Disconnect DUT and measure size of step incident on DUT V_I that arrives back at sampler.



Re-connect DUT and measure size of step reflected from DUT V_R that arrives back at sampler.



Calculate Z_{DUT}: $Z_{DUT} = Z_{INT}(V_I + V_R) \ / \ (V_I - V_R)$

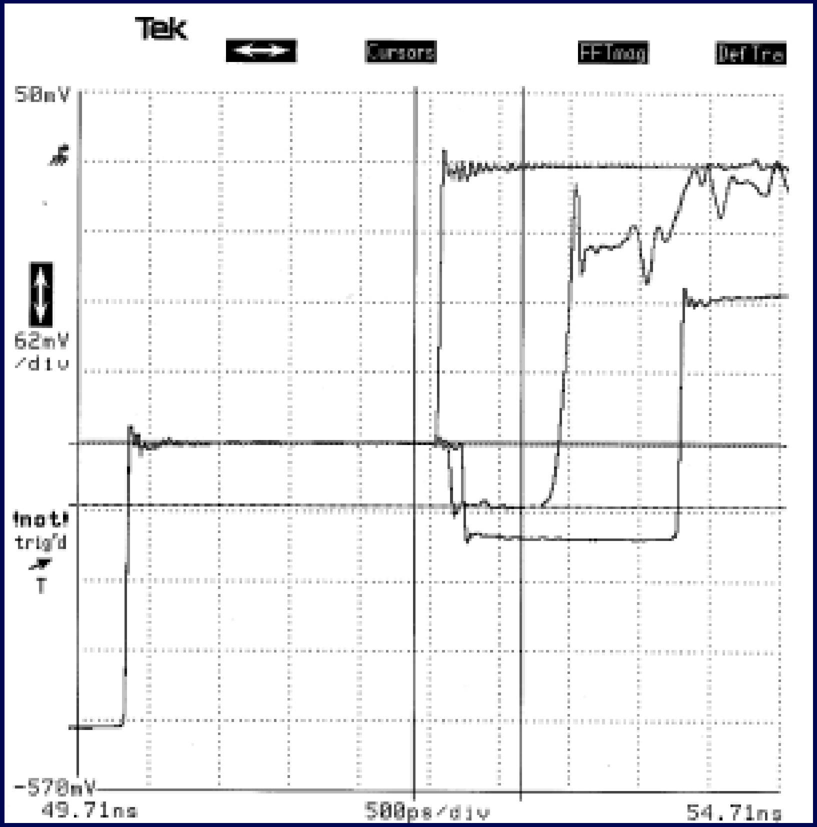
TDR Accuracy Improvement - Advantages

- Reduces problem to three critical measurements
  - Interconnect (secondary standard) impedance Z_{INT}
  - Incident step at DUT V_I
  - Reflected step from DUT V_R
- Employs primary traceable standard - exchange method
- Eliminates or minimizes most controllable sources of error

TDR Accuracy Improvement - Caveats

- Keep standard and device under test interconnect methods similar
- Use short, repeatable connector between interconnect and standard impedance or interconnect and DUT
- Always measure V_I and V_R over identical time zones
  - Reduces sensitivity to aberrations, dribble-up
  - Reduces chance of measuring re-reflections
- Minimize interconnect / TDR cable length and loss

TDR Accuracy Improvement Example



Standard (25 Ω)

VI = 243.04 mV

VR = -84.32 mV

DUT

VI = 243.04 mV

VR = -54.56 mV

Z_{INT} = 51.56 Ω

Z_{DUT} = 32.66 Ω

Conclusions

- Control as best as possible--or know limits of--those items that can’t be compensated:
  - ρ reference level error
  - Inadequate resolution
  - Connector repeatability uncertainties
- Employ stable, repeatable, and durable interconnect and launches
- Employ TDR accuracy improvement to compensate those items that can be dealt with