Propagation Delay Measurements with TDR in the Manufacturing Environment

Brian D. Butler
Introbotics Corporation
Albuquerque, NM

Abstract
This paper addresses the growing need in the Printed Wiring Board industry to measure and test propagation delay parameters of board interconnects within the fabrication process. The state of current art is detailed in discussions of four different methods of measurement including their respective advantages and disadvantages. Definitions and basic considerations for the measurement process are also discussed. The conclusion is that accurate and repeatable measurements of propagation delay in the manufacturing environment can be made with existing equipment technology and with a best known method.

Introduction
There is a growing need for making accurate and/or repeatable measurements of propagation delay in the manufacturing environment. Reasons cited are:

- Monitoring of PWB dielectric material permittivity (especially hybrid materials)
- Design Verification - ensuring timing margins are being met (based on actual interconnect signal flight times)
- Characterizing variability of the manufacturing process for design planning (improved modeling and simulation)
- Quantifying time delay skew across a set of interconnects (i.e., Automatic Test Equipment probe card channels, high speed buses, etc.) for product calibration.

Impedance of a given interconnect is a function of its width, its height and the properties of the dielectric material surrounding it (including the materials thickness and its permittivity). Propagation delay (in picoseconds/inch) is also an interconnect property whose value is solely a function of the dielectric material's permittivity. Propagation Delay can be calculated as follows:

Equation for PWB microstrips[1]
Propagation Delay (ps/in) = 85*SQRT(0.475Er + 0.67)

Equation for PWB striplines[1]
Propagation Delay (ps/in) = 85*SQRT(Er)

where: Er is the Bulk Dielectric Constant

Definitions
There are several terms associated with signal propagation in Printed Wiring Boards (PWB) interconnects which are defined below:

Flight Time (picoseconds) is a measured property of any given interconnect trace and represents the time it takes a signal to move from one end of an interconnect to other end. The value is typically represented in picoseconds (1 X 10^{-12} seconds).

Propagation Delay (picoseconds/inch) is a physical property of a PWB interconnect and typically is displayed in values of picoseconds/inch. Propagation delay is calculated by dividing the measured flight time (in picoseconds) of signal through the given interconnect by its measured length (in inches). A typical value for a PWB stripline interconnect with FR4 laminate is 172 picoseconds/inch. The accuracy of this value is dependant upon the accuracy of the measurement process to determine flight time and the ability to accurately measure the true electrical path length (in inches) of the interconnect.

It is worth noting that propagation delay values for shorter interconnect traces (i.e., 2") are more susceptible to measurement errors inherent in determining the values (flight time and interconnect length) which are used to calculate propagation delay. Longer traces (i.e., 20") also have inherent difficulties as is noted further within this paper.

Bulk Relative Permittivity (Dielectric Constant/Bulk Er/Dk)

Bulk Er is a property of a material (laminate – core or prepreg, soldermask) and defines several electrical characteristics of interconnect structure supported by the material including at what speed can signals propagate through the interconnect. Bulk Er is unit-less and all values are reported relative to the Er value of free space (which is given a value of 1).Values of Bulk Er are reported by the material suppliers and are typically determined using a Vector Network Analyzer (VNA). (Please refer to IPC TM-650 Test Method 2.5.5.3, 2.5.5.5, or 2.5.5.9).

Effective Relative Permittivity (Effective Er)
Effective Er defines the relative dielectric strength of all combined material surrounding a printed wiring board's interconnect. A surface microstrip, for example, would be surrounded by air and/or soldermask on its outer surface and board material on its inner surface. Even though air and the board material have significantly different dielectric properties both are combined to define an Effective Er. Values for Effective Er can be determined by taking TDR measurements of flight time on finished PWBs and calculating the propagation delay relative to the speed of light in a vacuum.

Effective Er values can be utilized as monitoring parameters during PWB fabrication, as input data in board parameter modeling equations or can be related to Bulk Er values provided by laminate suppliers.

Propagation Velocity (or Propagation Speed or Transmission velocity) (inches/picoseconds) is the inverse of propagation delay and represents a value which can be compared to the value of the velocity of light in a vacuum (0.0118 inches/picoseconds or 186000 miles/second).

Velocity of Propagation (%) is the ratio of the velocity of a propagating signal in an interconnect to the velocity of light in a vacuum. For example, a value of 65% would yield (0.0118 in/ps multiplied by 65%) 0.00767 inches/picoseconds (or equivalently 130 picoseconds/inch). High frequency coax cables typically include a Velocity of Propagation specification.

Risetime (picoseconds) of a Time Domain Reflectometry (TDR) test system is defined as the time it takes it's generated pulse (incident pulse) to rise from 10% to 90% of its amplitude total change. This is often referred to as the 10-90 risetime. A typical TDR pulse amplitude change is 250mV and a typical risetime value is 17 picoseconds.

The risetime in large part defines the resolution of the TDR system or its ability to detect physical changes (line width changes or dielectric material variations, etc.) which lead to impedance or propagation delay variations in the PWB interconnect

It is important to note that TDR system's risetime is greatly affected by the quality and length of the cables and probes utilized as part of the entire measurement system.

It is also important to note that as a TDR pulse propagates through an interconnect its risetime degrades. A TDR incident pulse of 17 psec injected into a six (6) inch interconnect could degrade to 100 psec at the end of the trace due to the skin affect and dielectric losses through the interconnect trace..

Important Measurement Considerations
This paper covers the use of Time Domain Reflectometry (TDR) equipment to make flight time measurements. Methods utilizing other equipment including Vector Network Analyzers (VNA) are not discussed.

TDR equipment specifications will have a significant affect on the quality of Propagation Delay measurements. Several of these are detailed below:

Time Base Accuracy: The accuracy of the TDR equipment's time base (X –axis on the display) will define the ability to accurately measure flight time. Accuracy will vary with equipment type between 1-50 picoseconds.

Time Base Jitter: The Time Base Jitter (repeatability) is defined as the ability of the TDR scope to repeatably in time reproduce a constant step pulse and affects both the repeatability and accuracy of flight time measurements. Time Base Jitter will vary with equipment type between 2-40 pseconds.

TDR Risetime: The sharpness of TDR system Risetime will also affect the quality of the measurements. In most methods of determining flight time, estimates of where on the TDR display the interconnect trace begins and ends is critical to an accurate measurement. A shorter risetime significantly improves this estimate. TDR complete system Risetime will vary with equipment type between 50-300 psec.

Automation: The use of computer control to automate the measurement technique is preferred over manual methods and should be required for any manufacturing test implementation. Robotic or fixture based probing is also preferred to enhance the repeatability of the process.

Standard deviation values of four (4) picoseconds can be achieved in flight time measurements in a manufacturing environment through the use of such equipment.

Interconnect Attributes: In addition to equipment issues, the physical attributes of the interconnect being measured can adversely affect the ability to measure flight time. These issues include skin affect and dielectric loss affect and their adverse affect on the observed TDR risetime at the end of interconnect trace. Impedance discontinuities associated with launch via and termination vias can also affect the quality of measurements.

Differential structures will produce different results for propagation delay from comparable single-ended structures due to electrical coupling between the differential pair of interconnects and that affect on the dielectric property of the adjoining material.

Actual vs. Coupon Interconnects: Flight time measurements can be taken on both actual (image area) interconnect traces or on TDR coupon traces. The measurement method (as described below) often will determine which type of interconnect will be tested. Additional considerations include:

- Differences in laminate (or soldermask) properties surrounding the interconnects in TDR coupons verses in the image area which can cause significant variations in the measured values.

- Purpose of data collection: To understand the lot-to-lot variation of dielectric material properties, testing of coupon interconnect traces can be sufficient. To quantify material variations across a panel or to verify interconnect trace delay impacts on timing margins then image area traces would be tested.

Equipment
The following equipment is required to carry out production level testing (measurement) of interconnect propagation delay.

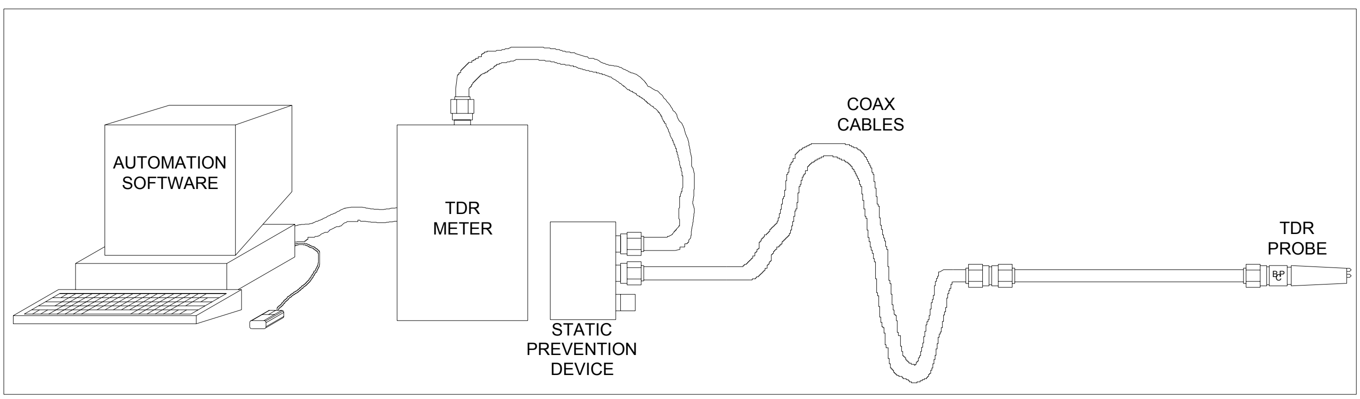

Figure 1 - TDR Equipment

Time Domain Reflectometry (TDR) meter: The meter's specifications should match the required measurement accuracy and repeatability.

High Frequency Coax Cable(s) to connect the meter to the TDR probes. The cables should be kept as short as possible and their specifications reviewed to ensure minimal degradation of the TDR signal risetime.

TDR Probe(s) to provide the interface between the measurement system and the interconnect under test. TDR probes should be passive, 1X attenuation, and ideally have a matched impedance of 50 ohms. The probe's specifications should be reviewed to ensure minimal degradation of the TDR signal risetime.

Automation Software is necessary to ensure repeatability of the measurement process and to simplify it to achieve production level test. Software can shorten and simplify calibration procedures, all probe and interconnect measurements and all necessary calculations. Software can also guide the operator through all hand probing operations to minimize probe error.

Automation Hardware (i.e., robotics, fixtures). Further automation including machine probing of the interconnect under test enhances the repeatability of the measurement system. This automation also allows practical probing of image area interconnects in addition to panel coupon test traces.

Precision Reference Airline. This device is utilized to calibrate the TDR measurement system.

Measurement Methods

Method One: Multiple Line Lengths

This method utilizes two or more interconnects of varying lengths on the same board layer in close physical proximity (typically on a TDR panel coupon). The objective is to eliminate the adverse affects of the launch via (its capacitive/inductive discontinuities and subsequent ringing when a TDR pulse is applied) on the ability to determine the electrical and physical start of trace

Advantage:

- •Eliminates launch via affects

Disadvantages:

- Need for more than one interconnect (takes up space and requires more measurement time)
- Assumption that via affects are consistent over the two or more interconnects
- Varying lengths produce varying adverse affects of skin and dielectric loss which will produce varying values of TDR signal risetime at the end of trace (These affects degrade the ability to determine accurately the end of traces and the variability increase the measurement uncertainty).

Measurement Steps

1) Determine the electrical end of the TDR probe in reference to the TDR system's horizontal time axis. (Figure 2)

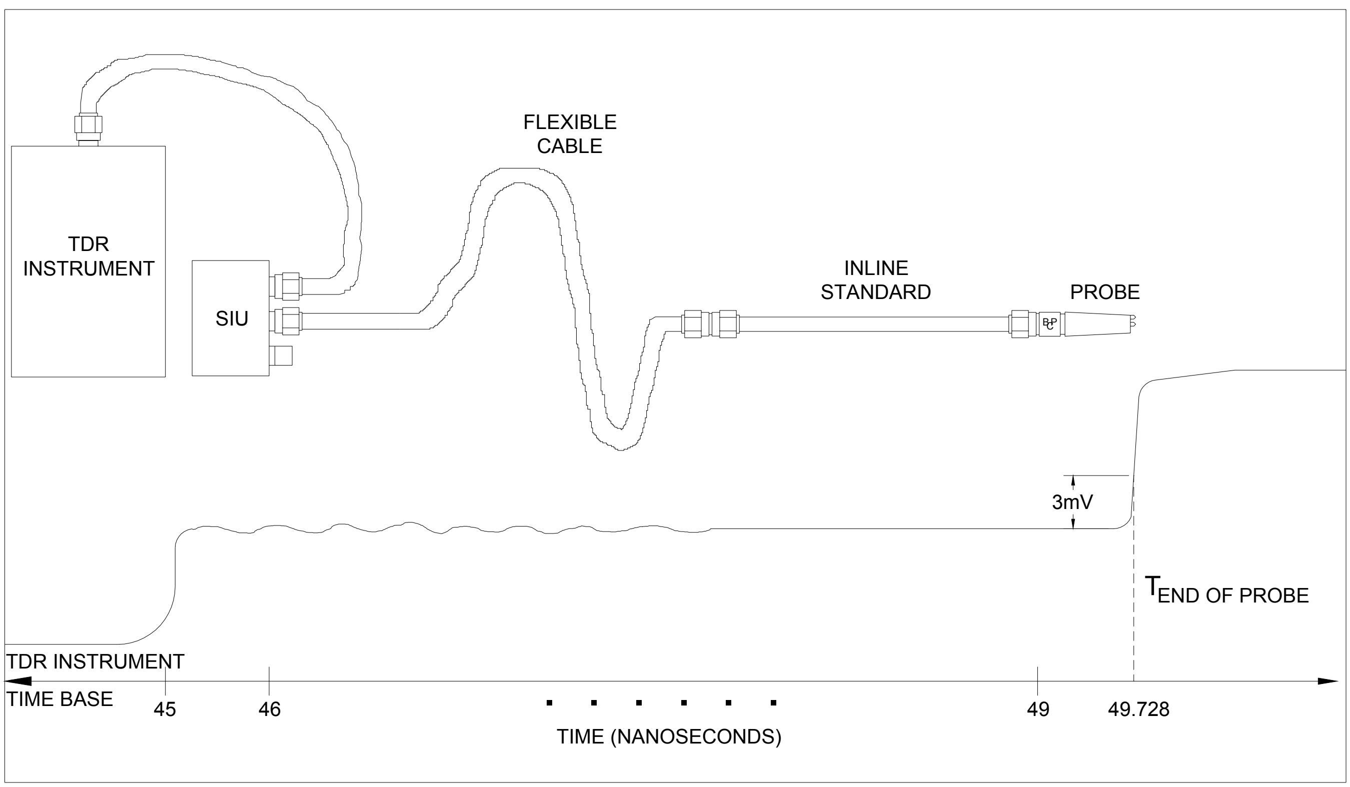

Figure 2 – Multiple: Find End of Probe

2) Apply the TDR probe to Trace #1 (shorter trace). Determine the time difference (in picoseconds) on the systems horizontal scale between the end of probe (start of trace) and the end of the trace. This value represents the roundtrip TDR signal time. (Figure 3)

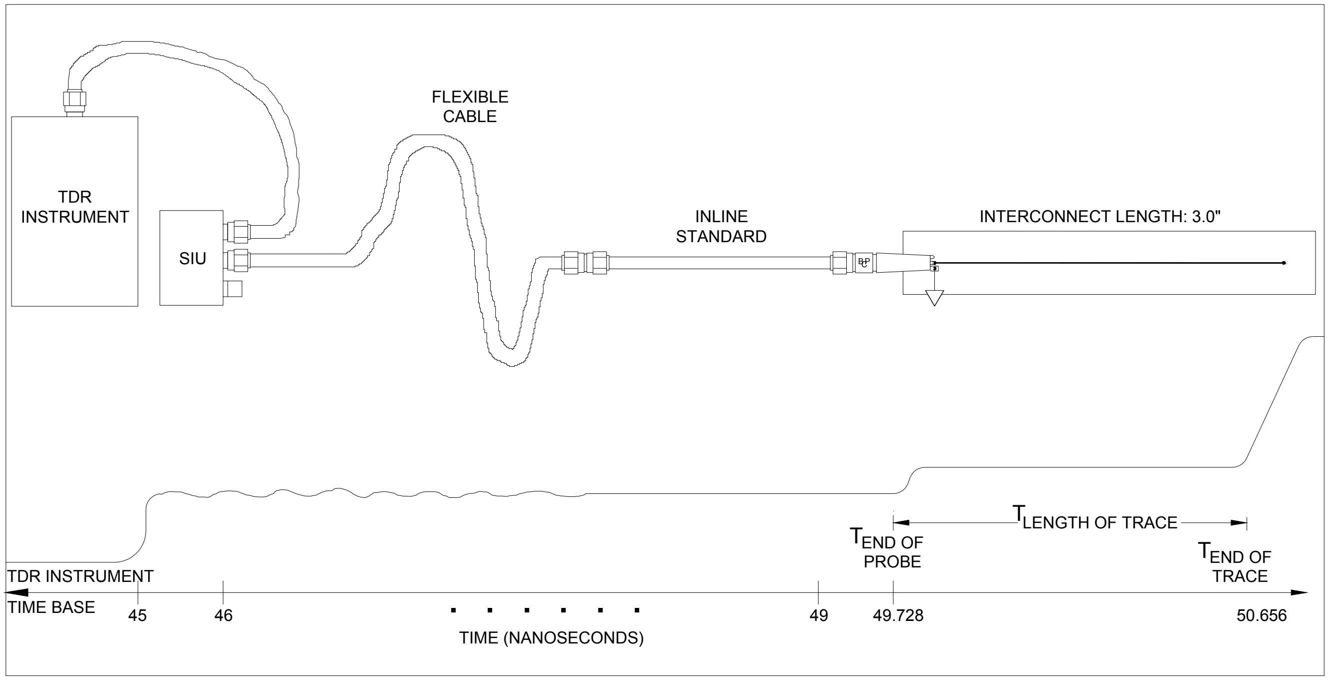

Figure 3 – Multiple: Find end of 3” Interconnect

3) Divide the value by two-(2) to determine the one way TDR signal flight time.

4) Apply a TDR probe to Trace #2 (longer trace). Determine the time difference (in picoseconds) on the systems horizontal scale between the end of probe (start of trace) and the end of the trace. Divide the value by two to determine the one way flight time. (Figure 4)

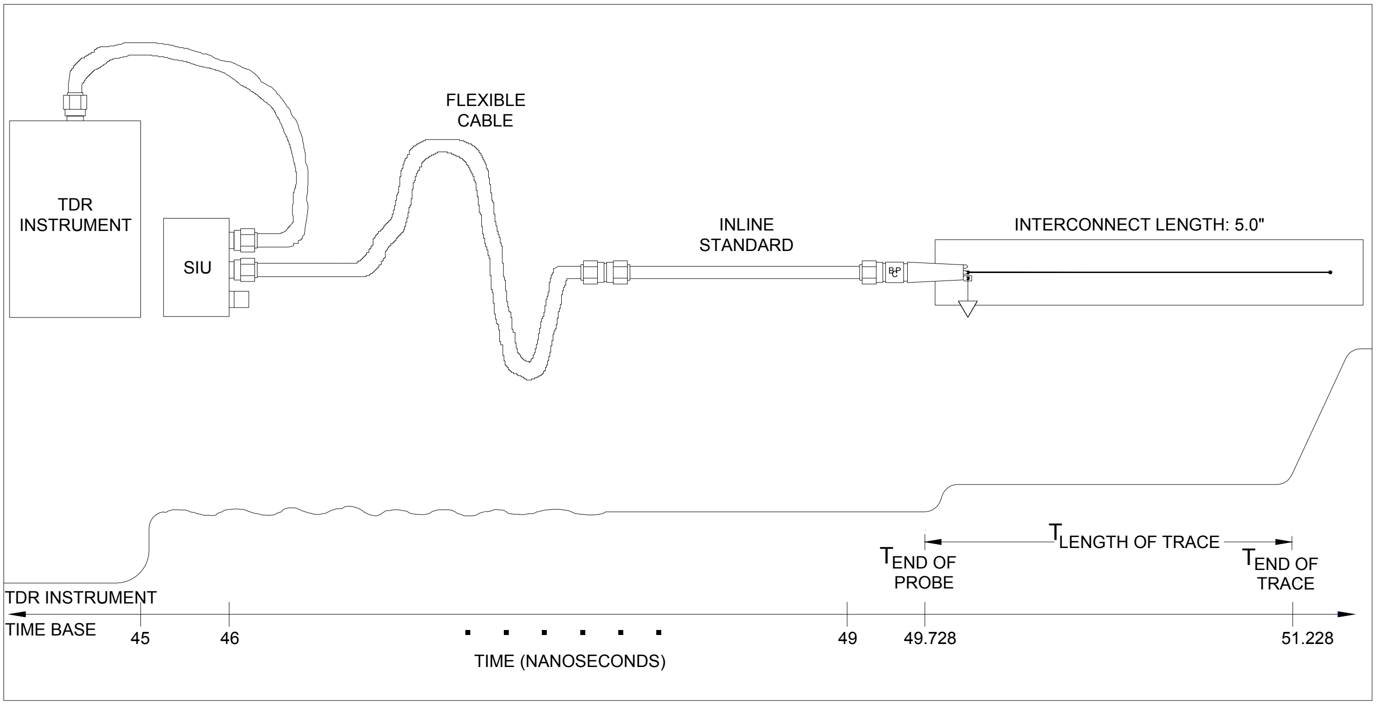

Figure 4 – Multiple: Find End of 5" Interconnect

5) Subtract the flight time value determined for Trace #1 from Trace #2.

6) Divide this value by difference in physical length of Trace#1 and Trace#2. This value is the Propagation Delay (picoseconds/in) for these two trace structures

Measurement accuracy can be improved by utilizing three (3) interconnects of various lengths.

<u>Method Two: Time Domain Transmission (TDT)</u>
This method utilizes a single interconnect to measure flight time. In this method, only the one way transmission time is measured (not the roundtrip time). The advantage in this method is the reduction in TDR system risetime degradation because the TDR signal propagates only one way down the interconnect trace thus reducing the losses which cause the degradation.

Advantages:

- Reduces the risetime degradation
- Requires only one interconnect

Disadvantages:

- Requires two (2) TDR probes
- Requires more probing (more complex measurement system setup)
- Requires estimate of where the beginning and end of traces are on the TDR risetime curve

Measurement Steps

1) Connect a TDR probe to one channel of the TDR instrument. This probe will launch a TDR pulse into the interconnect.
2) Connect a second TDR probe to the second channel of the TDR instrument. This probe will capture the TDR pulse at both the end of the probe and the end of the interconnect.
3) Connect both probes together (signal pin to signal pin and ground to ground).
4) Measure the time at the end of the first probe. (Figure 5)

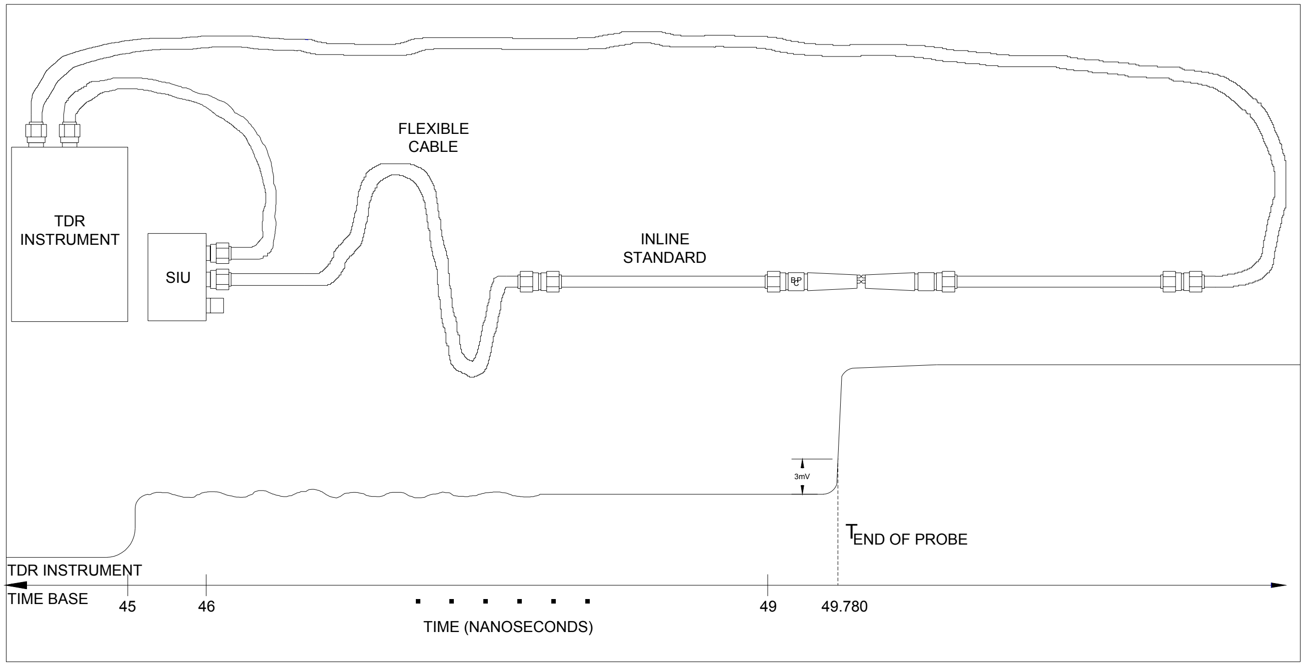

Figure 5 – TDT: Find End of #1 Probe

5) Connect the first probe to the start of the interconnect and the second probe to the end of the interconnect.
6) Measure the time at the end of the interconnect. (Figure 6)

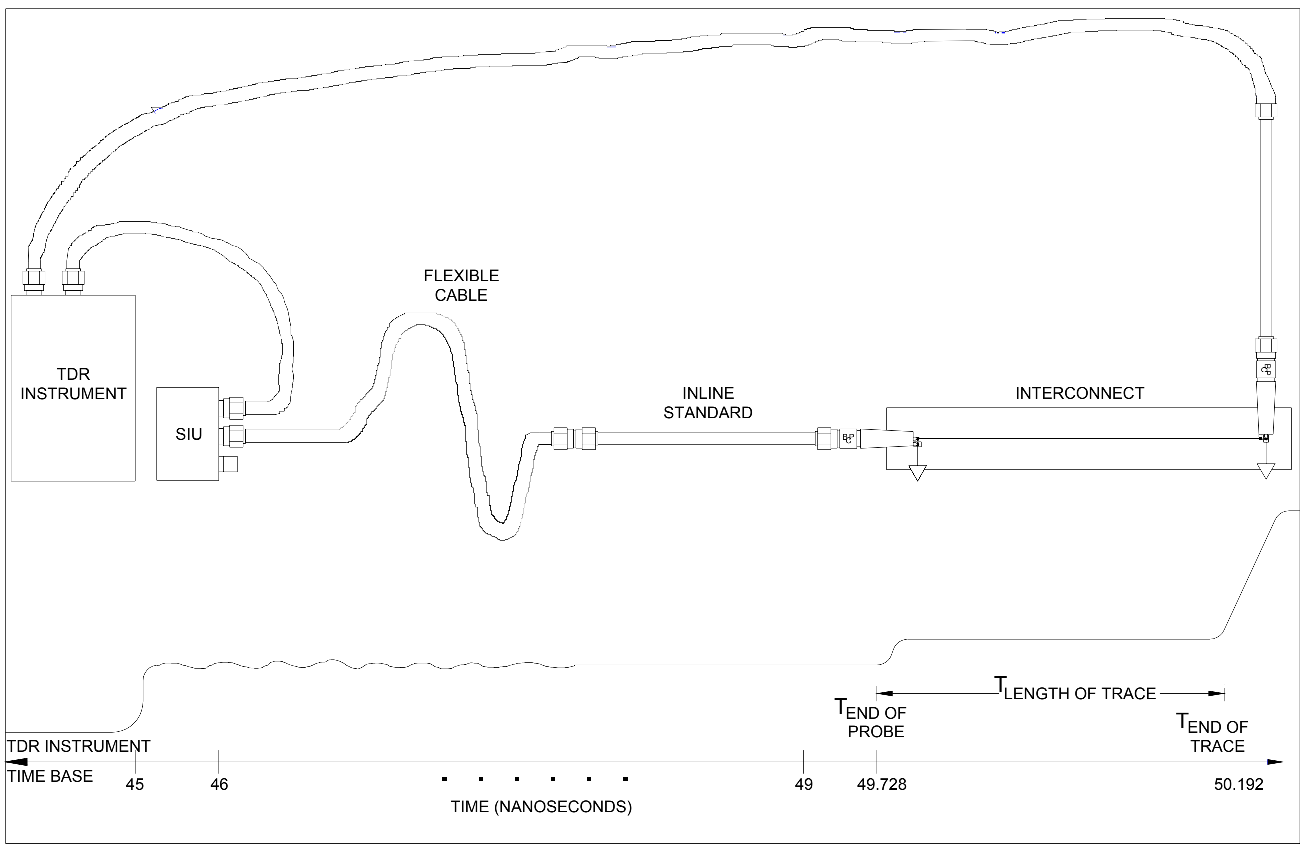

Figure 6 - TDT: Find end of Interconnect

7) Determine the time difference between the end of the probe and the end of the interconnect. This value is the flight time (Do not divide by two (2) as this value is the one way trip of the TDR pulse and fully represents the flight time of the pulse in that interconnect.)
8) Calculate the propagation delay by dividing the flight time by the length of trace.

Method Three: IPC TM-650 2.5.5.7 Characteristic Impedance and Time Delay of Lines of Printed Boards by TDR
This method utilizes a single interconnect to measure flight time. More than one measurement is made on the interconnect to determine the risetime degradation and to compensate for it.

Advantages:
- Reduces the risetime degradation
- Requires only one interconnect

Disadvantages:
- Requires additional measurements of the risetime of the measurement system and at the end of the interconnect
- Requires estimate of where the beginning and end of traces are on the TDR risetime curve
- Value represents estimate of risetime degradation and may not be linear across all interconnect structures.

Measurement Steps
1) Attach TDR probe to TDR instrument.
2) Measure the time on the waveform where the waveform reaches 40% of the voltage change from the base of the waveform to the top.
3) Measure the time difference on the waveform from 40% to 60%. (Figure 7)

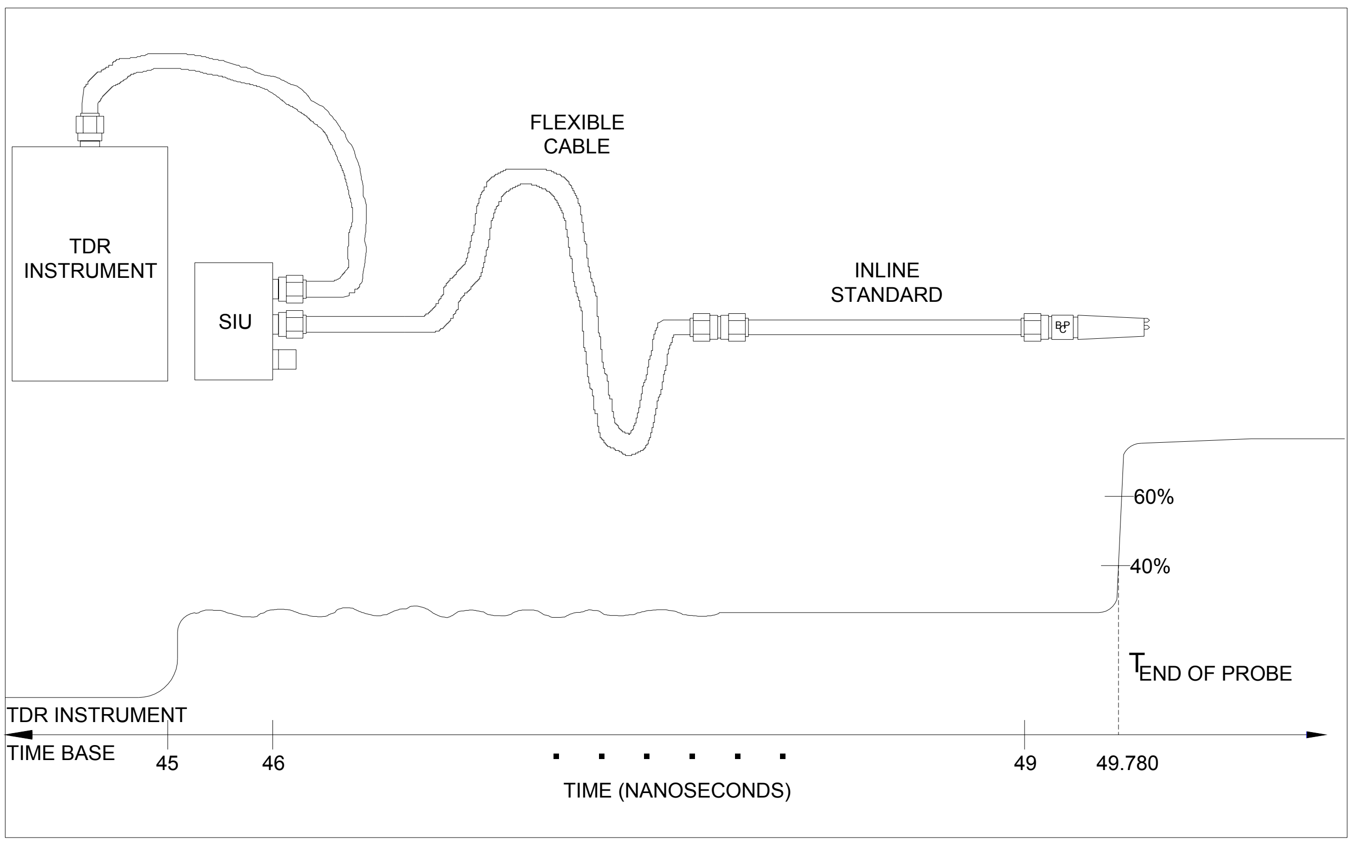

Figure 8 - TM-650: Find end of Probe

4) Probe interconnect
5) Measure the time on the waveform where the waveform reaches 40% of the voltage change from the base (defined as the voltage level of the TDR system coax cable just prior to the probe) to the top (open step voltage).
6) Measure the time difference on the waveform from 40% to 60%. (Figure 8)

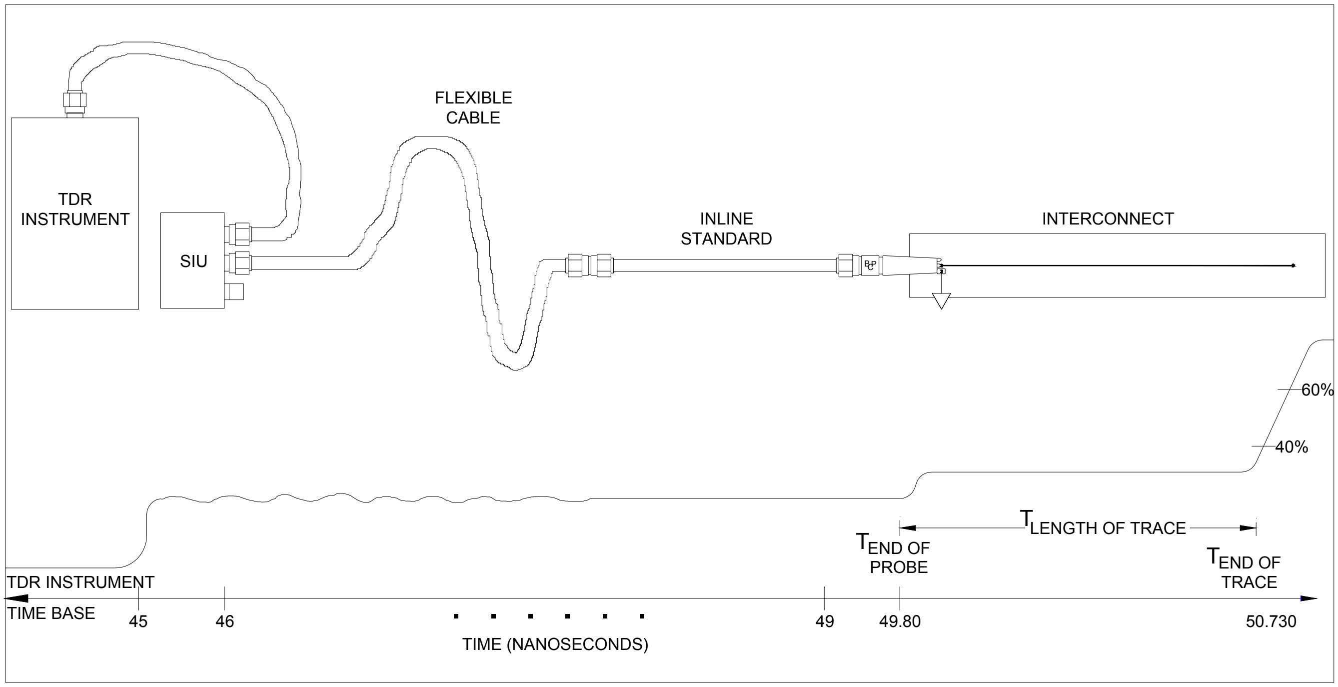

Figure 1 - TM-650: Find end of Interconnect

7) Flight time is defined by the following formula:

Flight Time= $\{T_{40\% \text{ of trace}} - (3.2 * \text{SQRT}[(T_{40\text{to}60\% \text{ of trace}})^{\wedge 2} - (T_{40\text{to}60\% \text{ of probe}})^{\wedge 2}]) - T_{40\% \text{ of probe}}\} / 2$

8) Calculate the propagation delay by dividing the flight time by the length of trace.

<u>Method Four: Coupon Method</u>

This method utilizes a specifically designed single interconnect structure typically located on a test coupon to measure flight time. The test structure incorporates small discontinuities at fixed locations in the interconnect to provide reference points as to the start and end points of TDR signal being measured.

Advantages:

- Eliminates the need to estimate the start and end points of the TDR measurement (eliminates the issue of risetime degradation)
- Requires only one interconnect
- Simple measurement process

Disadvantages:

- •Requires specialized test structure

Measurement Steps

1) Interconnect design: Test trace will be nominally six (6) inches long. At exactly one (1) inch for both ends of the trace there should be a small “pad” (approximately 3 times the linewidth and 0.050” in length). (Figure 9)

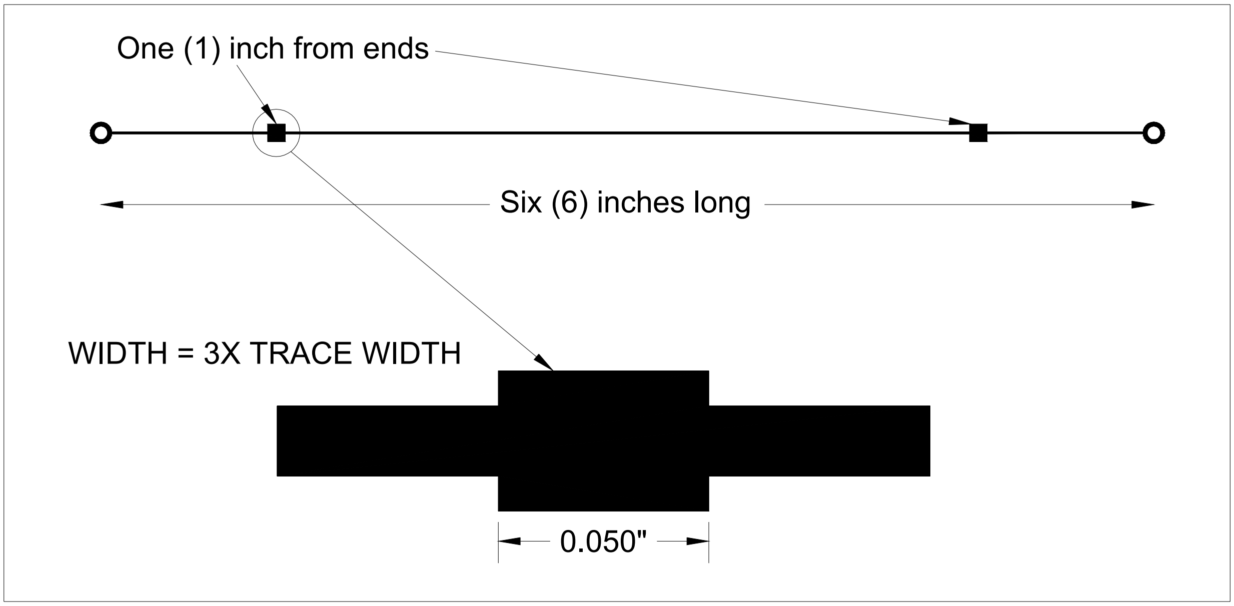

Figure 9 - Coupon Design

2) Probe the interconnect.
3) Measure the TDR signal waveform from the center of the "pad" (which is seen as a capacitive discontinuity) at one (1) inch from the start of the trace to the center of "pad" at the point one (1) inch from the end of the trace. The measured value when divided by two (2) is the flight time. (Figure 10)

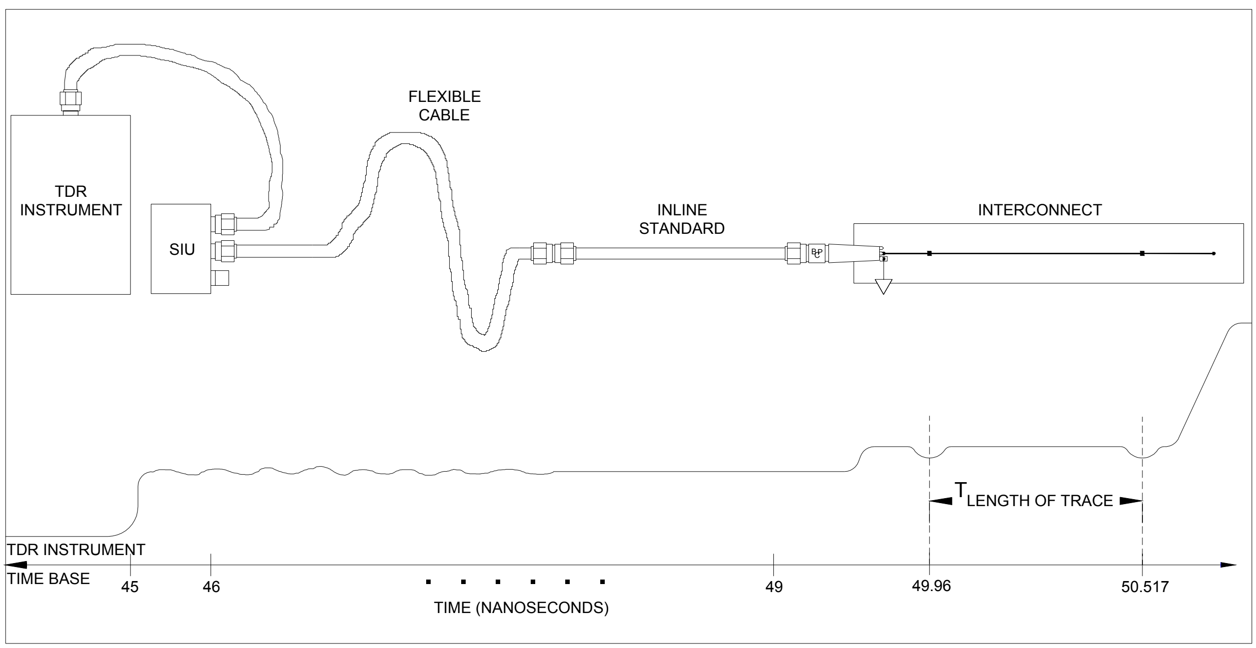

Figure 10 - Coupon: Measure start and end of interconnect segment

4) Calculate the propagation delay by dividing the flight time by the length of trace separating the two "pads".

Test Data

A comparison test was conducted utilizing each of the four (4) methods discussed. Two boards (4" x 4") were designed and fabricated, one with a 0.003" FR4 core and one with a 0.005" FR4 core. Both board designs contained surface microstrip structures with soldermask. Each board contained three (3) standard interconnects of varying lengths (2.5", 3.5", 4.5").

Each board also contained a coupon trace similar to that described in Method Four.

All interconnects were 7 mil wide and were fabricated from ½ oz copper foil.

The measurement equipment utilized was Tektronix Model 1180C TDR meter with Introbotics TDR probes. The measurement system's incident risetime was 25 picoseconds.

Tables 1 and 2 contains data on Propagation Delay collected utilizing the four- (4) different methods addressed in this paper. It is interesting to note that all methods yielded similar results for the specific interconnects utilized in this study. Further study is needed to understand the extent of the methods correlation.

Table 1 – FR4 5mil Propagation Delay (picoseconds/inch)

		FR4 5mil Dielectric (Microstrip)		
	Length	2.5"	3.5"	4.5"
TDT Method		151.2	153.8	150.7
TM-650		152.1	151.6	151.9
Multiple Line Lengths		N/A	151.7	149.1
Coupon Method		N/A	N/A	150.4

Table 2 – FR4 3mil Propagation Delay (picoseconds/inch)

		FR4 3mil Dielectric (Microstrip)		
	Length	2.5"	3.5"	4.5"
TDT Method		160.8	160.6	160
TM-650		159.9	161.1	161.6
Multiple Line Lengths		N/A	159.6	162.5
Coupon Method		N/A	N/A	160.2

Summary and Conclusion

In this paper the state-of-art in making flight time measurements on PWB interconnects was discussed. Four (4) methods were described and advantages/disadvantages were outlined. The equipment required and the need for automation (software and hardware-i.e., robotics) was identified including the ability to achieve measurement repeatability of four (4) picoseconds in high volume testing. Test data was also presented on each of the four (4) methods discussed. Similarity in the reported values leads to the conclusion that each of the methods could be utilized once consideration of the advantages/disadvantages was completed.

References

[1], [2] Howard Johnson, "High Speed Digital Design", Prentice Hall, 1993