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Number
2.5.5.11

Subject
Propagation Delay of Lines on Printed Boards by TDR

Date
04/2009

Revision

Originating Task Group
Propagation Delay Test Methods Task Group (D-24a)

IPC-TM-650
TEST METHODS MANUAL

1 Scope This method specifies time domain reflectometry (TDR) methods for measuring and calculating the propagation delay of uniform, controlled impedance transmission lines fabricated in printed board (PB) technology. The method defines a propagation delay per unit length t_D by specifying how to measure the time it takes a signal to propagate a given length of transmission line.

This method describes methods that utilize TDR measurements of multiple, unterminated test lines that are designed to differ only in length. A TDR signal, usually a step waveform[1], is injected into a transmission line or lines and the reflection response is measured some time later. This method shows how t_D is determined as the difference between the time it takes a TDR pulse to reflect from the unterminated ends of two transmission lines divided by the length difference of the two lines.

1.1 Applicability Engineering development of high-speed and high-frequency electronic circuits and systems requires detailed information on the electrical performance of PBs to assure that transmission line designs yield the expected performance characteristics. Detailed analysis of the design and fabrication variations expected throughout manufacturing assures that a proposed design can be manufactured at a useful quality level. Measuring and characterizing propagation delay on transmission line test structures is a direct means of assessing the success of the PB transmission line model.

Since transmission line measurements are affected by impedance conditions at the transmission line boundaries, propagation measurements specified here may not return the actual delay observed for a given application. The procedures test whether uniform, impedance controlled PB transmission lines exhibit the expected propagation delay based on an electrical model or reference test structures.

This method is generally applicable to uniform transmission lines fabricated with commercial PB processes (see IPC-2141), and is also useful for various transmission lines and material systems studied at the research and development stages.

The method is applicable when:

- Electrical contacts (connectors or probes) are readily made to the transmission lines test structures
- Transmission line characteristic impedance is neither extremely high nor low compared to the instrument's test port impedance
- Transmission line propagation loss sets acceptable signal-to-noise ratios for the measured signals

The current version of this method specifies singled-ended TDR measurements of unbalanced transmission lines, though the method is sufficiently general to be extended to differential TDR measurements of balanced lines.

1.2 Measurement System Limitations Applying a specified test method helps assure accurate and consistent propagation delay results, however measurements of propagation delay can vary depending on equipment used. Known measurement system limitations include:

a. Electrical noise of the TDR receiver, limiting propagation delay accuracy and repeatability when signal levels are low
b. Trigger, source, and receiver jitter in the TDR instrument, limiting temporal resolution
c. Drift in the trigger point of the TDR sources limiting, temporal resolution
d. Slow TDR pulse rise times, limiting temporal resolution
e. Waveform distortion induced by the low-quality test set-up cables, connectors, and the signal launch points, inducing errors in the reported propagation delay

Further measurement system considerations and notes are provided in Section 6.

1.3 Sample Limitations The type of test sample used may also impact propagation delay accuracy. The sample-based limitations include:

a. Lines on a fabricated PB deviating significantly from design. For example, microstrip lines longer than 15.0 cm [5.91 in] on PBs with plated-through holes (PTH) often have variations in line width due to nonuniform plating and/or etching. This makes the uniform transmission line

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[1] The signals used in the TDR system are actually rectangular pulses; because the measured duration of the TDR waveform is much less than the actual pulse duration, the TDR waveform appears to be a step function.

assumption invalid and introduces errors in the reported delay

b. Short test lines reducing the t_D accuracy due to system temporal limits (see 4.1.2)

c. Short test lines reducing ability to identify intentional discontinuities from signal launch

d. Long test lines detrimentally reducing amplitude of reflection signal due to large skin effect and dielectric losses

2 Applicable Documents

IPC-2141 Design Guide for High-Speed Controlled Impedance Circuit Boards

IPC-TM-650 Test Methods Manual

1.9	Measurement Precision Estimation for Variables Data
2.5.5.7	Characteristic Impedance of Lines on Printed Boards by TDR

3 Test Specimens The test specimen can take one of several forms depending on the application, but it must contain at least one transmission line (or interconnect) test structure and be representative of the actual PB product. Four definite types of specimens are described in 3.1.1 through 3.1.4. The transmission lines to be measured may be of either stripline or microstrip construction.

3.1 Test Specimen Examples

3.1.1 Example 1 Test specimens are representative PBs selected out of a lot of fabricated product. In some cases, this sample set may contain all PBs in the lot. Agreed upon functional and nonfunctional transmission lines on the PB are used as the test set for this specimen. The selection of lines that form the test set must be based on these criteria (nonexclusive):

a. Inclusion of the PB's critical features

b. Accessible line terminations for measurements

c. Absence of line branching

d. Absence of impedance changes within the transmission line under test

e. Representation of controlled characteristic impedance Z_O signal layers

3.1.2 Example 2 Test specimens are representative fabricated PB samples or entire lots as in 3.1.1. The test lines used in these specimens are nonfunctional lines designed into the PB for easy termination and connection to TDR equipment. Such test lines should be designed to include critical features typical of functional lines and should lie in the controlled Z_O signal layers of the application.

3.1.3 Example 3 Test specimens are test coupons cut from representative fabricated PB samples or entire lots. The test coupons are cut from the master PB at the time the individual PBs are separated. Such test coupons will have one or more nonfunctional transmission lines with termination suited for TDR testing. Such test lines should include critical features typical of functional lines and will be fabricated in the same configuration and structure as the master PB on the same controlled Z_O signal layers as the application.

3.1.4 Example 4 Test specimens are a sample of the substrate laminate to be characterized before PB manufacturing and fabrication. The test line fabrication on these specimens may involve laminating several PB layers together in the same manner anticipated for PB manufacture.

3.2 Identification of Test Specimen For specimens of types called out in 3.1.1, 3.1.2, or 3.1.3, each specimen **shall** be identified with no less than a PB part number, PB serial number, and date code. Specimens of the type called for in 3.1.4 must include the lot or panel identification for the substrate laminate being evaluated.

3.3 Conditioning Environmental conditioning prior to test may be called for as part of the test. When conditioning is required, test specimens **shall** be stored before testing at 23 +1/-5 °C and 50 ± 5% RH for no less than 16 hours. If a different conditioning procedure is required, it must be specified and documented in test reports.

3.4 Test Interconnect Placement The ability to correlate propagation delay values derived from measurements of nonfunctional test lines to propagation delay values of functional lines is directly related to the proximity of the nonfunctional test structure to the functional lines. The closer the test and functional lines, the more likely the nominal material properties will be the same. The placement of test structures on the PB or panel should be analyzed for each PB design and be based on the propagation delay tolerance and practicality of the layout. When deciding on the best test interconnect placement, consider the following placement priorities:

1) Inside the functional area of the PB;

2) At the edge of the PB but outside the functional circuit area; or

3) Outside of the PB area and at the center or edge of the panel.

If coupons are placed in all the locations listed above, a comparison between a statistically significant sample set taken from each location over time can yield data that will relax placement requirements without reducing confidence in test results.

3.5 Test Interconnect Geometry The test structures should use the same line width and conductor thickness, and be located in the same dielectric environment (permittivity, thickness, and layering) as the target functional interconnects. Spacing between conductors should also match that of the functional interconnects. If edge coupons are used, and previous studies have shown that conductors at the edge of the panel experience different lamination from those in functional panel areas, then a compensation factor may be needed to adjust the propagation delay measurement for this difference.

3.6 Lengths for Two-Line Test Structure When using two nonfunctional transmission lines as the test structures, thenominal physical lengths of the transmission line pair should be 76.2 mm [3.0 in] and 152.4 mm [6.0 in]. Variations in test structure lengths **shall** be documented.

3.7 Transmission Line Termination Transmission lines are to be terminated at both ends using PTHs to allow electrical connections to both ends of the line. Additionally, PTH terminations at both ends provide for DC and low frequency measurements of resistance, capacitance, conductance, and inductance as additional diagnostic tools in the event of an out-of-specification condition.

3.8 Contact Land The contact land should comprise PTHs and contact pads as shown in Figure 3-1. Reference contact lands should be square to aid in visual identification. The nominal hole diameter **shall** be 0.46 mm [0.018 in] and surface land **shall** be 1.02 mm [0.040 in]. However, the PTH should be of consistent dimensions to ensure repeatability and reliability of the tests for the given measurement equipment. Care must be used when specifying different hole sizes and land pitches since their electrical properties may affect the reported t_D in a secondary manner. Hole size should be larger only if required by plating/aspect ratio requirements. Ideally, hole and pad size should be the same as those of functional

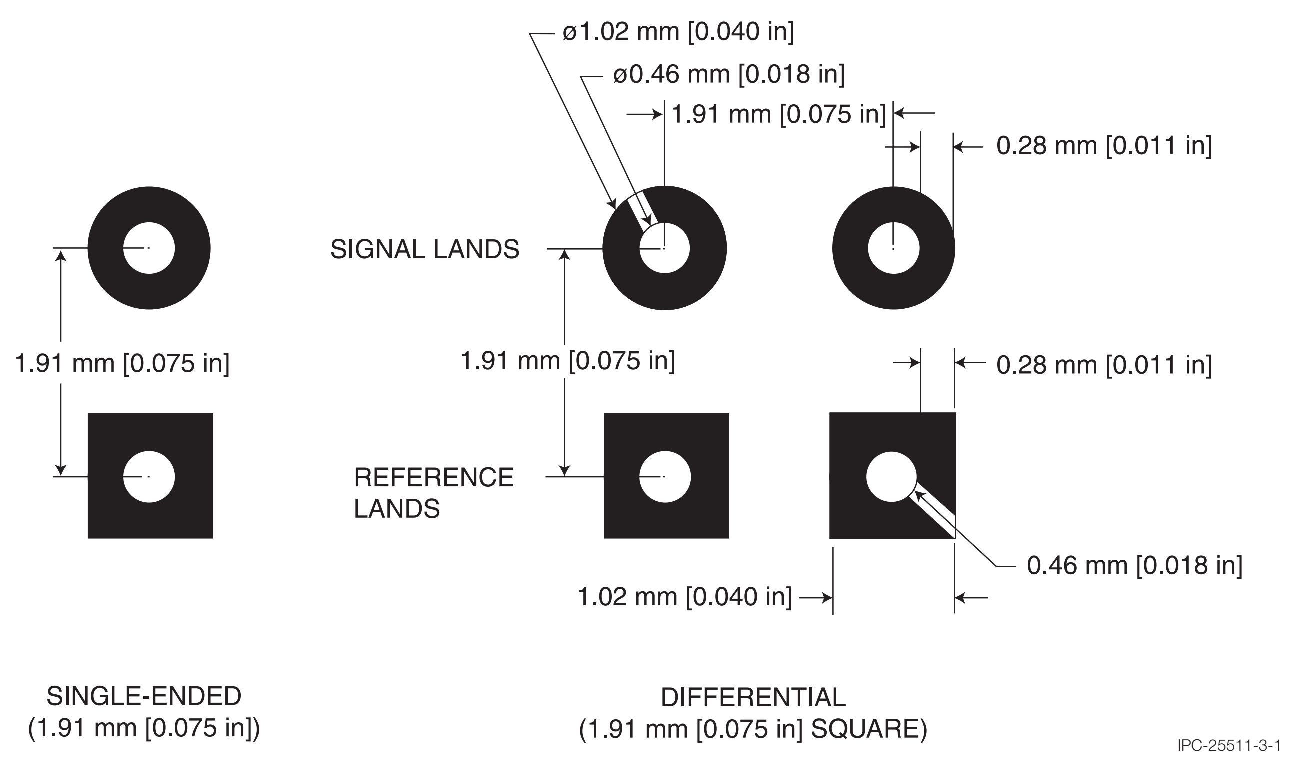

Figure 3-1 Contact Lands

interconnects, but a practical issue of operator ability to use hand-held probes may be considered. Test reports must report any deviation from the nominal contact land and PTH geometry.

3.9 Contact Land Pitch Whenever possible, the center-to-center distance between the signal and reference lands of the test interconnect should be consistent to simplify probing requirements and ensure measurement repeatability and reproducibility. Nominal center-to-center pitch **shall** be 1.91 mm [0.075 in]. The use of different contact and probe pitches must be specified and documented.

3.10 Single-Signal Conductor Transmission Line The single-signal conductor transmission line is also known as the single-ended, unbalanced, and asymmetrical structure. The probing area for these lines should consist of a contact land (see Figure 3-2) for each signal line. The contact land should provide connection to the reference, or ground, connection for the test structure. This method requires the use of one contact pitch to ensure measurement consistency between the test structures of the specimen.

3.11 Orientation The contact land orientation (placement and angle of the contact land of the signal line relative to the contact land of the reference plane) must be the same for all test interconnects of the specimen in order to ensure measurement consistency between test interconnects.

3.12 Test Interconnect Routing

a. The test interconnects **shall** only be routed over and under contiguous ground and voltage planes following controlled line impedance guidelines (see IPC-2141). The test interconnects must not extend into PTH clearance areas.

b. The test interconnects **shall** be kept at least six times the width of the signal conductor or 2.5 mm [0.0984 in], whichever is greater, from any PTHs and any other interconnect on the same plane. All conductive material (such as copper nomenclature, copper thieving, etc.) **shall** be kept at least 2.5 mm [0.0984 in] from each test interconnect.

c. Test interconnects **shall** be straight or contain gradual and rounded bends.

3.13 Nomenclature Labeling of all test interconnect contact lands on at least one surface layer is required for operator identification during manual probing operations. The label **shall** minimally contain information about which signal layer the test interconnect is modeling (for example, L1-3in, L1-6in, etc.). Nomenclature should be etched in copper and be spaced a minimum of at least six times the width of the signal conductor (of the test interconnect) or 2.5 mm [0.0984 in], whichever is greater, from the test interconnect area. Whenever practical, the terminations at both ends of test interconnect **shall** be marked.

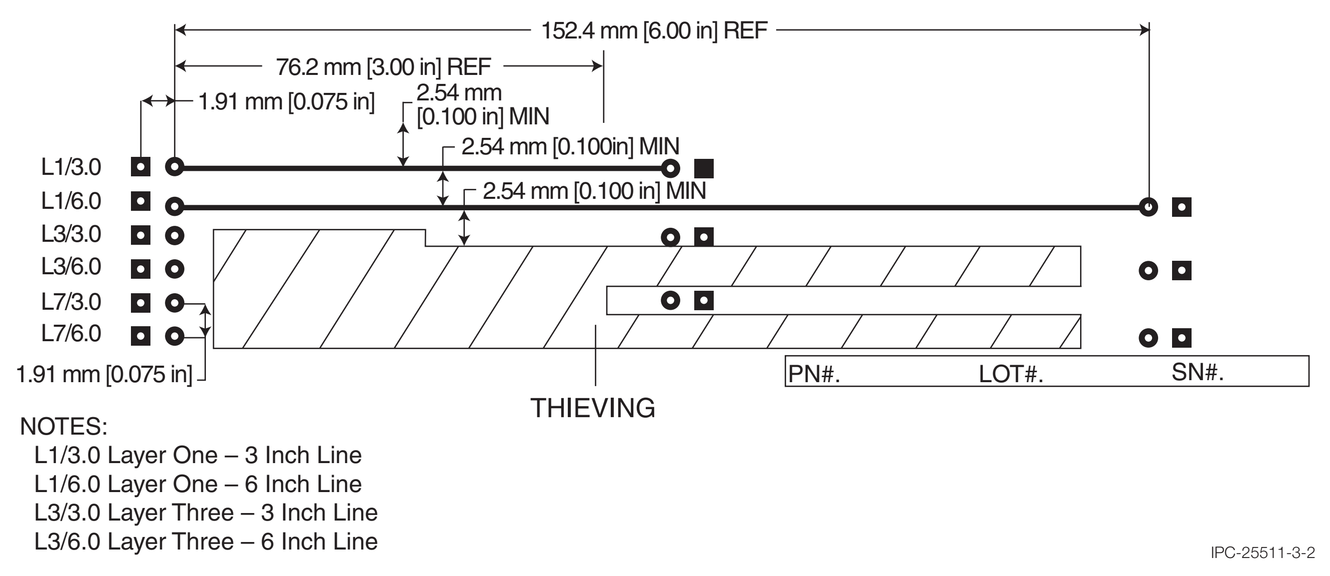

Figure 3-2 Transmission Line Structures

3.14 Additional Guidelines for Testing Panel Coupons Test interconnects may be contained within one or more panel coupons. It is recommended that there be at least one coupon per PB on the panel as long as it does not adversely affect panel utilization. With this configuration, the following additional design guidelines apply. More than one coupon may be necessary on a PB to ensure uniformity. Also, more test interconnects may be required than can fit inside one test coupon. In that case, more than one test coupon is necessary.

3.14.1 Reference and Ground Planes All reference planes existing in the coupon are to be connected together within the coupon area and be electrically independent of conductor planes in the functional circuit area.

3.14.2 Surface Condition The panel test coupons **shall** have the same surface plating and use the same solder mask requirements as the functional PB.

3.14.3 Thieving Differences in circuit density between the inside of a panel coupon and the functional area may produce surface plating and etching differences. In order to compensate for these differences, thieving (the use of nonterminated copper structures, such as planes, pads, and/or traces adjacent to test lines) may be used. All thieving structures **shall** be kept at least six times the width of the signal conductor (of the test interconnect) or 2.5 mm [0.0984 in], whichever is greater, from each test interconnect.

4 Apparatus and Instrumentation The TDR measurement system contains a step generator, a high-speed sampling oscilloscope, and all the necessary accessories for connecting the TDR unit to the test structures under test. IPC-2141 provides a discussion of the TDR system architecture, system considerations, and the TDR measurement processes used herein.

4.1 Measurement System Requirements

4.1.1 Voltage Measurement Accuracy The voltage measurement accuracy and linearity of the TDR sampling oscilloscope **shall** be sufficient to provide the required accuracy in the value of propagation delay. Nominally, the voltage measurement accuracy should be better than ± 1%.

4.1.2 Temporal/Spatial Resolution The resolution limit of a given TDR unit is defined as that particular time or distance wherein two discontinuities or changes on the transmission line being measured, that would normally be individually discernable, begin to merge together because of limited TDR system bandwidth, timing jitter, or a reduced signal-to-noise ratio. The resolution limit is specified in either time or distance, and is always related to the one-way propagation time between the two discontinuities t_P (see Figure 4-1), and not the round trip propagation time 2 t_P.

Per this definition, the temporal resolution limit is:

a. one half of the system risetime, that is 0.5 t_{sys}, where t_{sys} is the 10 to 90% risetime or 90% to 10% falltime depending on the propagating edge of the TDR signal;

and the spatial resolution limit is:

b. 0.5 $t_{sys} \times v_p$, where v_p is the signal propagation velocity in the transmission line being measured.

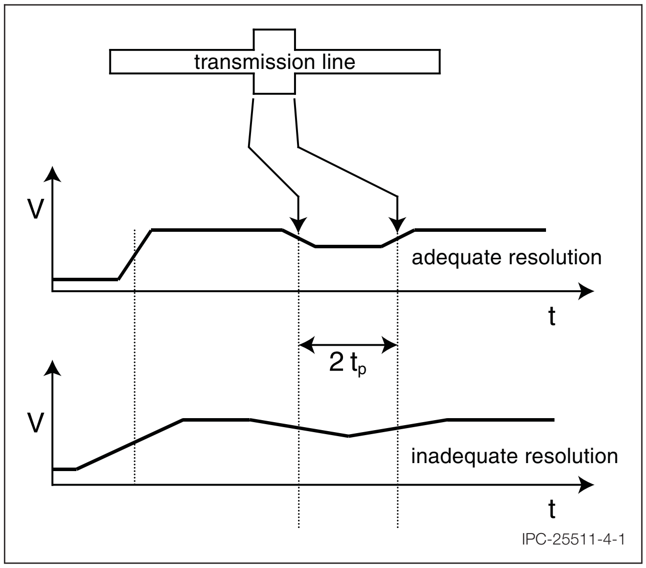

Figure 4-1 Resolution and Electrical Length of Transmission Line

For a given length of transmission line to be measured, the resulting spatial resolution of the TDR measurement set-up should not exceed one fourth (0.25) of the available length of the transmission line L_{TL}. In other words, L_{TL} should be at least four times the spatial resolution of the measurement system.

Table 4-I relates TDR system risetime values to minimum L_{TL} for typical surface microstrip lines in air on FR4 PB material ($v_p \approx 2\times10^8$ m/s).

Table 4-1 Resolution of TDR Systems

TDR System Risetime	Resolution	**Minimum** L_{TL} 4x Resolution
10 ps	5 ps / 1.0 mm [0.04 in]	4.0 mm [0.16 in]
20 ps	10 ps / 2.0 mm [0.08 in]	8.0 mm [0.31 in]
30 ps	15 ps / 3.0 mm [0.12 in]	12.0 mm [0.47 in]
100 ps	50 ps / 10.0 mm [0.39 in]	40.0 mm [1.57 in]
200 ps	100 ps / 20.0 mm [0.79 in]	80.0 mm [3.15 in]
500 ps	250 ps / 50.0 mm [1.97 in]	200.0 mm [7.87 in]

Intermediate values can be linearly interpolated from Table 4-1 or using:

$$t_{sys} \le \frac{L_{TL}}{2}\frac{1}{v_p}\ .$$

For example, if the test structure was a 32.0 mm [1.26 in] long transmission line, then a TDR system with $t_{sys} \le 80$ ps must be used. Note that, if the probe launch and test set-up cables cause excessive ringing in the TDR waveform, or if the variance in connection delay is significant, then t_{sys} must be made sufficiently small to clearly observe the desired discontinuities in the TDR waveforms.

4.2 TDR Requirements

4.2.1 Impedance The TDR source and measurement ports **shall** be electrically terminated with precision 50 Ω loads. This is normally the case with high-quality TDR instrumentation maintained on the manufacturer's maintenance and calibration schedules.

4.2.2 Voltage Step Repeatability For all passive electrical terminations, the TDR source **shall** repeat its voltage waveform to within 0.5% of the TDR pulse amplitude V_{step}.

4.2.3 Timebase Accuracy When oscilloscopes are used in the TDR measurement system, errors in the reported time of the samples may arise due to imperfections in the counters and clock sources used to establish the timebase. These are systematic errors and may depend on the exact time/div and delay settings of the scope. When applying this method, the TDR system's timebase accuracy must be better than 8 ps + 0.01% of the measured interval.

4.2.4 Timebase Repeatability (Jitter) The RMS value of random timing uncertainty in measured voltage samples **shall** be less than 10% of t_{sys}.

4.2.5 Waveform Averaging The TDR equipment **shall** perform waveform or sample averaging to reduce jitter and electrical noise effects in the recorded waveform measurements.

4.2.6 Step Aberrations The TDR source waveform aberrations **shall** be less than 1% of the total step amplitude V_{step}. The ability of the TDR instrument to measure transmission line discontinuities is related to how well the instrument can minimize aberrations (ringing, overshoot, undershoot, settling, etc.). These aberrations (see Figure 4-2) can cause significant errors in determining the instant that the waveform crosses a user-defined voltage value. Additionally, low frequency step aberrations may produce a ramp in measurement zone and this can cause a significant bias in the computed propagation delay value.

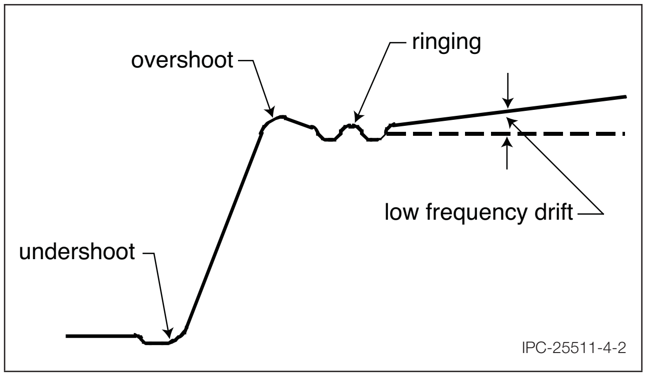

Figure 4-2 Potential TDR Step Aberrations

4.3 Other Equipment Requirements

4.3.1 Connectors Propagation delay test set-ups **shall** use precision coaxial connectors whenever possible. TDR systems typically come with SMA, 3.5 mm [0.138 in], 2.92 mm [0.115 in], or 2.4 mm [0.094 in] connectors at their measurement ports. These connectors are all 50 Ω connectors. They are precision connectors (they have a low impedance uncertainty due to their mechanical precision) whose bandwidth must be great enough so that the connectors do not limit the accuracy of the TDR measurement. The useable bandwidth of these connectors are approximately 33 GHz, 40 GHz, and 50 GHz, respectively. The reflection and insertion losses of all connectors used in the test set up **shall** be less than 27 dB and 0.3 dB, respectively. Other connectors with comparable or better performance may be used, but must be specified and documented. All coaxial connections **shall** be tightened with a calibrated torque wrench to specification of the connector. Table 4-3 provides the typical connector torque specifications.

Table 4-3 Connector Torque Specifications
[The conversion factor is 0.1128 N-m/(lb-in)]

Connector Type	Required Torque
SMA	0.56 N-m (5 lb-in)
3.5, 2.92, and 2.4 mm	0.90 N-m (8 lb-in)

4.3.2 Cabling All test cables **shall** be high-quality, low-phase delay coax and with a nominal characteristic impedance of 50 Ω. Cables used in the measurement circuit of the transmission line under test **shall** have connectors that are compatible with the instrument and probes. The bandwidth of the cable must be great enough so that the cable does not limit the accuracy of the propagation delay measurement. The length of the cables should be kept to a minimum. The total insertion loss (including connector loss) of the cabling connecting the transmission line under test to the TDR should be kept to less than 3.3 dB/m (1db/foot) at 26.5 GHz. Table 4-4 contains suggested maximum cable lengths for the TDR test set up as depicted in Figure 5-1 and described in 5.2.

Table 4-4 Maximum Suggested Cable Lengths for TDR System (As Depicted in Figure 5-1)

TDR Cable Assembly	TDR Cable Length
Sampling Unit to Static Isolation Unit	30.0 cm [11.8 in]
Static Isolation Unit to In-Line Secondary Standard	91.0 cm [35.83 in]
Transfer Standard (such as semi-rigid coaxial cable)	10.0 cm [3.94 in]

4.3.3 Probes The probe assembly characteristic impedance **shall** either be 50 Ω or the same value as the characteristic impedance of the transmission line under test, with an uncertainty of ± 1.0 Ω or less. The probe tips should be of sufficient diameter and pitch (spacing between signal and ground tips) to provide accurate and repeatable connections to the desired probe contact pad geometry (see IPC-2141 for additional recommendations on probe landing layouts for TDR coupons). Single-ended probes should contain two electrode tips, one each for the signal and ground lines. The probe tips should have moderately sharp edges to cut through any oxides. The probe bandwidth should be sufficient for the desired temporal/spatial resolution (see 4.1.2). The probe response time should be sufficiently short so as not to increase the duration of the measurement period. The overall performance of the probe can be incorporated into the TDR system response for computing TDR system temporal/spatial resolution (see 4.1.2). Inconsistent probe force and placement is common and can cause a significant yet unknown error in t_d. Probe connections to the measurement system cables should be tightened with a torque wrench following the connector specifications. For hand held probe assemblies, the probe handle should be ergonomically shaped.

4.3.4 Terminations TDR sources are not perfect voltage source generators; they may perform differently under different electrical load conditions. Therefore, the termination conditions of any verification experiments should match those of the interconnection test structures, and all test structures in a given specimen should be of the same design. For example, if the propagation delay test is to be performed on lines that are electrically open at their far end, all lines should be terminated in electrically open circuits, and any TDR field verification tests (see 5.2.1.2) should be made using open circuit terminations.

4.3.5 ESD Protection Static build up on specimens and test cables prior to test can damage the signal samplers in the TDR equipment; ESD protection and transmission line discharging procedures must be used. ESD protection can be supplied internally to the TDR system or externally using a Static Isolation Unit (SIU). If supplied externally using a coaxial switch (as shown in Figure 5-1), the switch should be placed between the transmission line under test and the TDR instrumentation. The SIU should have a return loss and insertion loss less than 16 dB and 0.3 dB, respectively, at 18 GHz. A maximum of 30.0 cm [11.8 in] of high quality, high frequency cable may be used to connect the TDR instrument to the SIU protection switch. Test interconnections should be first grounded with the SIU and/or passed through some type of deionization device prior to testing to remove any residual static electrical charge. Use of proper ESD control methods, control components and humidity control will help reduce electrostatic discharge damage to the measurement system. Automation software can be used to enhance the effectiveness of the static isolation unit by switching the static isolation unit on/off as required to minimize the amount of time that the TDR sampling unit is exposed to potential ESD.

4.3.6 Transfer Standard The TDR measurement system (see Figure 5-1) specified for measuring propagation delay requires a precision coaxial transmission line to set the reference impedance of the reflectometer measurements. This standard **shall** be a rigid, or semi-rigid, cable not more than 10 cm long with a uniform impedance profile along its length.

The transfer standard **shall** have precision coax connectors that match the test cables and probes. The uncertainty in the nominal characteristic impedance of the transfer standards **shall** be less than or equal to ± 0.015 Z_{ref}, where Z_{ref} is the characteristic impedance of the transfer standard (nominally 50 Ω.)

4.3.7 Check Standards The method makes use of two precision coaxial air lines of two different lengths to verify the operation of a test set-up (see 5.2.1.2). The air lines are precision coaxial lines where the center conductors are held in place with an isolation bead or the center pins of the end connectors, and are not filled with any other dielectric material. The coaxial air lines serve as a precise delay standard that can be measured during field checks (see 5.2.1.2) to verify the measurement set-up. The coaxial air line standards are available commercially with any of the precision coaxial connectors. Probe contact to coaxial transitions must be fabricated to use with a given probe tip configuration.

5 Procedures In TDR, the observed voltage waveform is the sum of incident and reflected signals. The reflections are related to the difference between the characteristic impedance Z_0 of a transmission line and any impedance discontinuities along the transmission line or at its end.

The method procedures establish the means of determining a time delay per unit length t_d from TDR measurements of two transmission lines that differ in length. The transmission lines are the interconnect test structures fabricated in PB materials as specified. The far end of the transmission line is either electrically open- or short-circuited in order to create a clearly observable reflection feature in the measured TDR waveform.

The procedures in this section establish the propagation delay per unit length as the differential propagation time obtained using the TDR measurements of two interconnect test lines divided by the length of the same interconnects:

$$t_d = t_p / 2L_p$$

Here, t_p is the measured propagation time difference given by

$$t_p = \left| \mathrm{t}_{\mathrm{T1}} - t_{T2} \right|,$$

where t_{T1} is the round-trip propagation time for the first transmission line and t_{T2} is the round-trip propagation time of the second transmission line.

L_p is the propagation length difference of the transmission line pair given by

$$L_p = \left| \mathrm{L}_{\mathrm{T1}} - L_{T2} \right|,$$

where L_{T1} is the length of the first transmission line and L_{T2} is the length of the second transmission line.

5.1 Measurement Preliminaries This section provides common considerations for the calibration and initial configuration of the TDR measurement system, and the method to establish the waveform epoch (time window) used in the delay measurements (see 5.2 and 5.3).

5.1.1 System Calibrations

5.1.1.1 Manufacturer Calibrations The TDR oscilloscope or other TDR equipment used **shall** be calibrated and serviced following the recommended schedule of the instrument manufacturers.

5.1.1.2 Field Calibrations Manufacturer ecommended field calibrations **shall** be performed in addition to scheduled factory calibrations. TDR system field calibrations **shall** be performed at the frequency recommended by the instrument manufacturers and after a change of any system component, such as a sampler of TDR source unit. The user must ensure adequate system warm-up time before performing field calibrations, as specified by the instrument manufacturers.

Users-accessible field calibrations for TDR oscilloscopes may include the application of an internal voltage calibration for each sampler and TDR source. Though not required for this method, TDR field calibrations may also include a reflection coefficient or impedance normalization/calibration procedure where standards are connected to the instrument's test port following a menu-driven procedure. Field calibrations are required for the following reasons:

a. TDR instrument specifications vary with temperature

b. TDR instrument specifications vary with time (drift)

c. TDR instrument specifications vary due to minor ESD damage

d. TDR instrument factory calibration usually does not include user supplied auxiliary components (i.e., cables, probes, etc.)

5.1.2 Pre-Measurement Checks

5.1.2.1 Instrument Warm-Up and Stability Before performing delay measurements, the user **shall** ensure adequate instrument warm-up time as specified by the instrument manufacturers, and ensure that the TDR waveform is not drifting in amplitude or time.

5.1.2.2 Environmental Conditions The user **shall** ensure that the temperature and humidity of the test environment is within TDR instrument specifications and that the conditions will be stable for the duration of the measurements. If the test environment is substantially different than that used for specimen conditioning (see 3.3), the user **shall** document this in the test reports.

5.1.2.3 Test Structure Isolation The user **shall** ensure that the signal line and reference planes of the test structures are located an adequate distance from objects and surfaces (such as the work surface of a test bench) that could electrically couple or interact with the test structure and probes. If surface layer microstrip lines are used, the recommendation is to keep extraneous objects and surfaces at least 6 *w* from the test coupon or PB, were *w* is the width of the signal line. If the tests are being conducted with hand probes, care must be taken to ensure that the hands and arms of the operator do not come in close proximity to the coupon or PB being tested.

Any fixtures used to ensure electrical isolation of the test fixtures must also be sufficiently strong to accommodate the probing force required for repeatable electrical connections.

5.1.3 Suitable Waveform Epochs The waveform epoch is the measurement interval over which the propagation time for a given discontinuity will be computed. The time epoch may be described in terms of the TDR instrument parameters *delay* and *time per division*. The user **shall** ensure that the instrument settings can be adjusted so the waveform epochs can contain the arrival of the far end reflection signals of both the shorter line and the longer line in the test structure; the user must ensure an epoch includes the reflection signal and sufficient pre- and post-waveform data to establish the required reference amplitude levels; and the user **shall** ensure that the delay and time/div settings can re-adjusted to repeat the desired epochs. This requires probing both test structures using the TDR measurement set-up (similar to that depicted in Figure 5-1). As shown in Figure 5-1, the user may first find the arrival point of the reflection signal for the open-circuit probe to help locate the subsequent reflection signal of the interconnection test structure.

5.1.4 Suitable Amplitude Resolution In order to compute propagation delay, this method requires the recording of the instants when the TDR waveform crosses a specified voltage reference level. The reference level, V_{REF}, is given generally by:

$$V_{REF} = xV_{refl} + V_{off,refl}$$

where V_{refi} is the amplitude of the reflected pulse (measured when it is superimposed on an incident step pulse), x is the fraction of V_{refl} used to determine the transition instant (for example, $x = 0.5$ corresponds to the 50% reflection amplitude value), and $V_{off,\,refl}$ is the amplitude of an incident TDR step pulse.

This method specifies two possible values for x:

$$x_{5\%} = 0.05$$
$$x_{50\%} = 0.50$$

The method also allows the user to specify their own x as long as the same value of x is used in all delay measurements and verification field tests. The user must document which value of x is used in the test reports.

The user **shall** ensure that the TDR equipment amplitude settings can be adjusted to capture the reference level V_{REF} with sufficient resolution to minimize errors in recording time of the crossing instant.

5.2 Propagation Delay TDR Measurement Procedures This section contains the methods for measuring the propagation delay of single-ended transmission lines. The following steps should be used when the interconnect test structures under test are unbalanced (single-ended) transmission lines. This process can be followed or automated (recommended). Additionally, the use of quality fixtures based or robotic probing systems may reduce probe placement uncertainty compared to hand probe techniques of certain users.

5.2.1 Multiple Line Method To mitigate the effects of imperfect measurement system cables, probes, and contact pad discontinuities, the propagation delay measurements are defined using the ratio of differences of two measurements made on separate lines that are very similar except for their physical length. Therefore, the procedure requires careful and repeatable connections and measurements of TDR waveform from two lines of the interconnection test structure.

5.2.1.1 Establishing the Electrical Length of the Measurement System To assist in tracking the repeatability and suitability of the measurement system, the method includes the following procedure to determine the electrical length of the TDR measurement system from the TDR sampler to the end of the probe tip. The user may record this time value for a given set-up over subsequent measurement sessions in order to verify consistency in system performance over long time periods.

Step 1 – Turn on the TDR source and enable triggering.

Step 2 – Hold the probe in the air away from other objects and surfaces and set the waveform epoch to include both the incident signal from the TDR source and the superimposed reflection signal from the probe tip (see Figure 5-1).

Step 3 – For this epoch, adjust the number of sample points to achieve a sample density of no less than 2 S/ps. For example, this is achieved with a time record of 4,000 sample points and a waveform epoch that is 2,000 ps long (10 division x 200 ps/div).

Step 4 – Identify the arrival time t_{inc} of the incident pulse edge as 50% of the incident amplitude. For step signals, use the difference of average pre- and post-step voltage levels to establish the incident amplitude.

Step 5 – Identify the arrival time t_{refl} of the reflection pulse edge as 50% of the reflection amplitude. For step signals, use the difference of average pre- and post-step voltage levels to establish the reflection amplitude (this is often near the region of maximum dV/dt.)

Step 6 – Record the system's electrical length as one half of the round-trip time: $t_{syslen} = (t_{ref} - t_{inc})/2$.

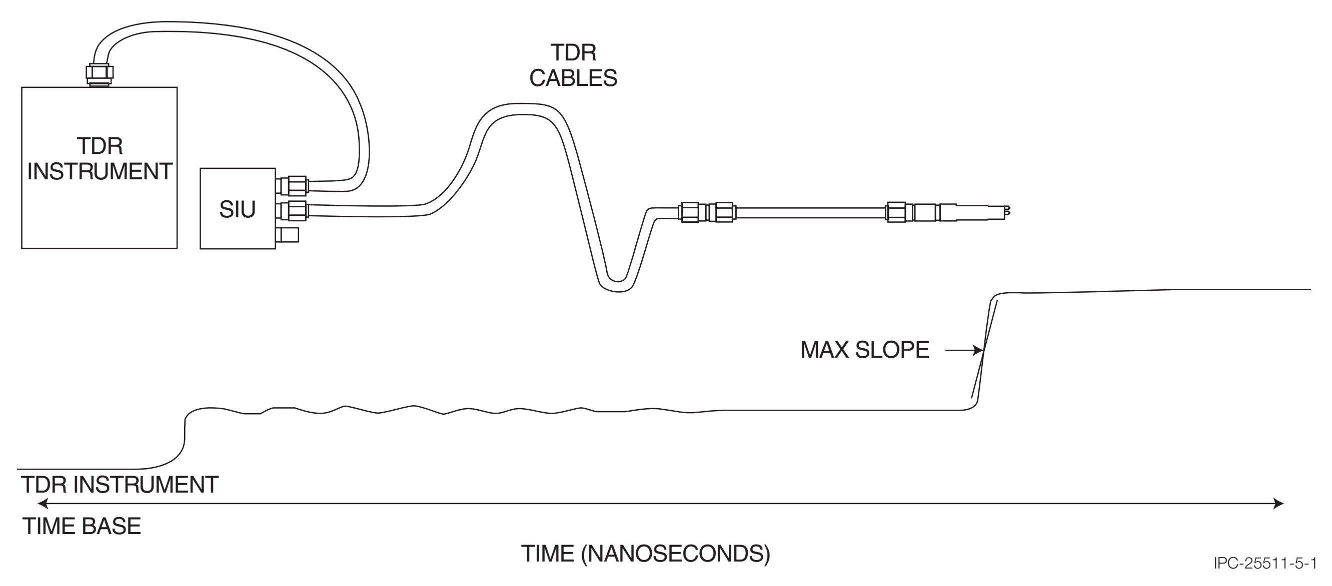

Figure 5-1 Measurement of Electrical Length of Test System up to the Open End of Probe

(Note: The optional static isolation unit (SIU) is a protection device designed to eliminate static discharge damage to the TDR sampling head.)

5.2.1.2 Verification Field Check The method includes a verification procedure to test the success of the measurement set-up in determining propagation delay. The verification procedure follows the same steps used when characterizing test specimens, but uses known and precise delay verification elements (as described in 4.3.7.) The user **shall** perform this field check prior to reporting delay results from the test specimens.

The user must fabricate their own transition cards that allow electrical connection to the end of the coaxial air lines using the probes of the measurement set-up. Figure 5-2 shows the probe contacting a transition to coaxial adapter.

Step 1 – Turn on the TDR source and enable triggering.

Step 2 – Connect the probe-to-coax adapter to one end of the longer air line check standard, leaving the opposite end open circuit. For beadless air lines, this requires the addition of an open circuit coax adapter at the far end in order to hold the center conductor in place. As with all coax connections, use the appropriate connection torque (see 4.3.1).

Step 3 – Connect the probe to the contact pads of the transition adapter.

Step 4 – Adjust the waveform epoch to capture the reflection signal from the far end of the longer open circuit air line.

Step 5 – Measure the arrival time of the reflection signal from the open circuit by testing when the reflection signal crosses V_{REF} as defined above for the user-selected value of x. Record the arrival time value as t_{T1}.

Step 6 – Connect the same probe-to-coax adapter used above in Step 2 to one end of the shorter air line check standard, leaving the opposite end open circuit. For beadless air lines, this requires the addition of an open circuit coax adapter at the far end in order to hold the center conductor in place. Use the same open circuit coax adapter used in Step 2. As with all coax connections, use the appropriate connection torque (see 4.3.1).

Step 7 – Connect the probe to the contact pads of the transition adapter.

Step 8 – Adjust the waveform epoch to capture the reflection signal from the far end of the shorter open circuit air line.

Step 9 – Measure the arrival time of the reflection signal from the open circuit by testing when the reflection signal crosses V_{REF} as defined above for the user-selected value of x. Record the arrival time value as t_{T2}.

Step 10 – Calculate the propagation time $t_p = t_{T1} - t_{T2}$.

Step 11 – Compare t_p to the difference in delay values provided by the air line manufacturer or calibration lab, and test whether or not the measurement system t_p agrees with the standards to within the uncertainty target of the measurement system or desired uncertainty required by the test specimens. The propagation time will not be known to contain a better resolution than that established in 4.1.2.

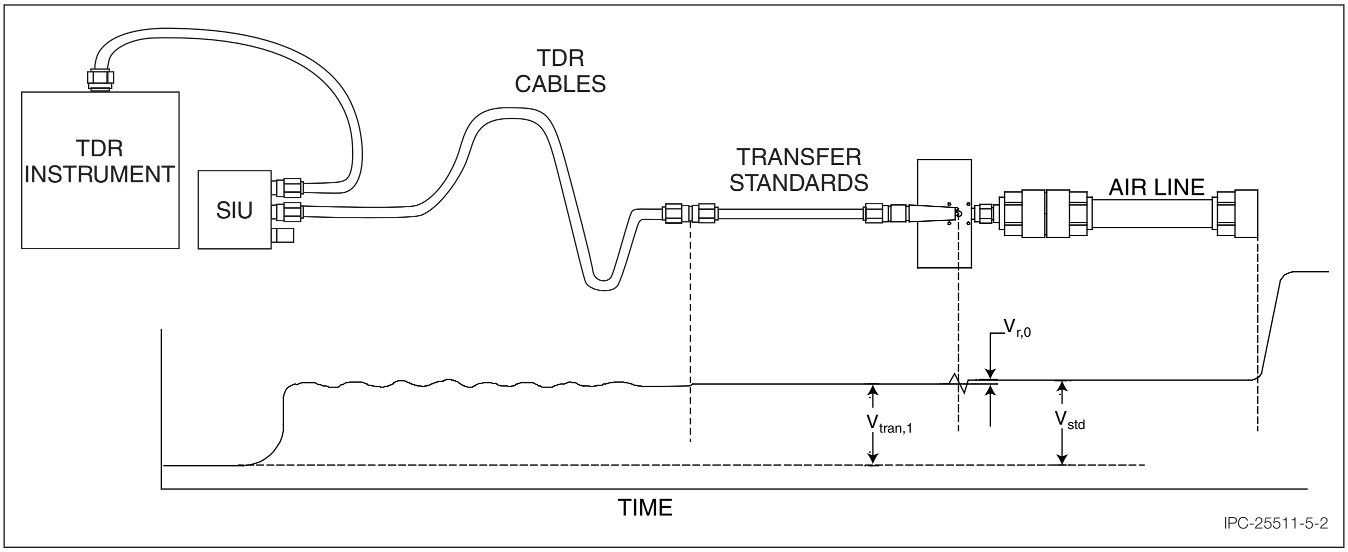

Figure 5-2 Measurement of Air Line Check Standard

5.2.1.3 Test Specimen Measurement Process This procedure will measure two interconnection test structures of different lengths. The propagation delay is calculated from the measurements of the difference in TDR reflections from the two test structures that differ in physical and electrical length.

Step 1 – Turn on the TDR source and enable triggering.

Step 2 – Connect the probe to the contact pads of the longer interconnection test structure.

Step 3 – Adjust the waveform epoch to capture the reflection signal from the far end of the longer test line. Figure 5-3 shows the case for an open circuit test structure.

Step 4 – Measure the arrival time of the reflection signal by testing when the reflection signal crosses V_{REF} as defined above for the user-selected value of x. Record the arrival time value as t_{T1}.

Step 5 – Connect the probe to the contact pads of the shorter interconnection test structure.

Step 6 – Adjust the waveform epoch to capture the reflection signal from the far end of the shorter test line.

Step 7 – Measure the arrival time of the reflection signal by testing when the reflection signal crosses V_{REF} as defined above for the user-selected value of x. Record the arrival time value as t_{T2}.

Step 8 – Calculate and record the Propagation Delay for this test structure pair:

$$t_d = t_p / 2L_p$$

where the propagation time is $t_p = t_{T1} - t_{T2}$ and the propagation length is the difference in the physical lengths of the test structures, $L_p = L_1 - L_2$.

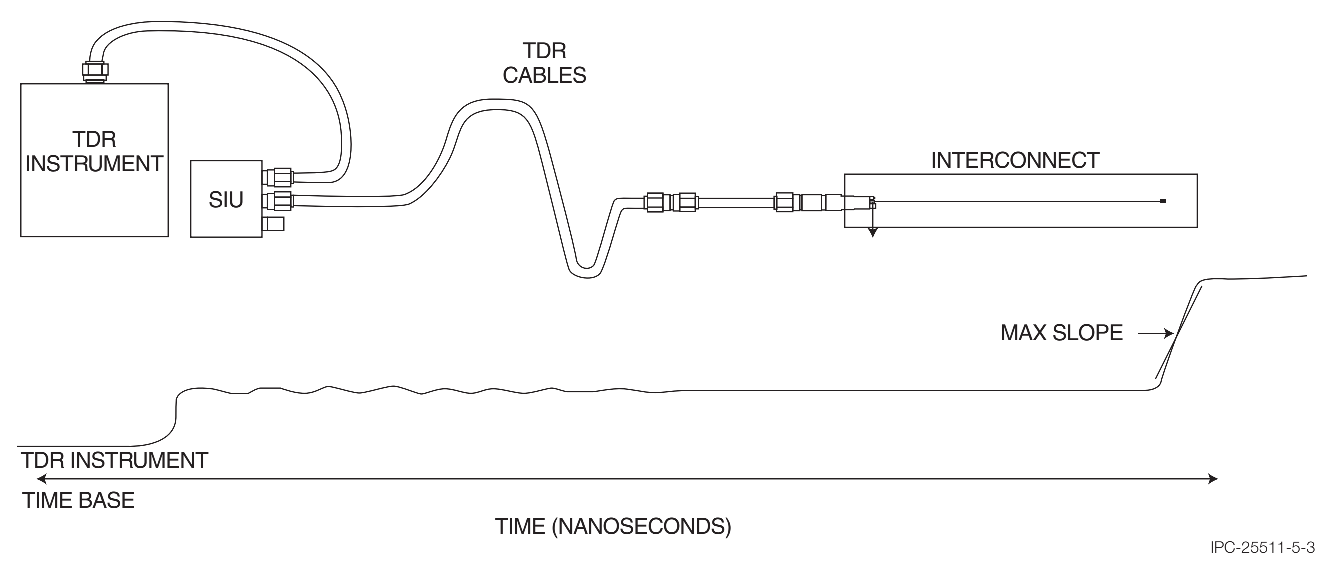

Figure 5-3 Measurement of Open-Circuit Interconnection Test Structure

6 Special Considerations and Notes

6.1 General

6.1.1 Quality Control Measurements for manufacturing control are performed to identify and correct process or materials problems occurring during a manufacturing run, as well as to assure that a product will perform electrically as designed. To facilitate the large number of measurements required in a production environment, and to maximize measurement repeatability and reproducibility between different operators and test systems, it is particularly useful to automate the TDR calibration and measurement by using computer control. This can be easily achieved using a computer and suitable automation equipment, resulting in access to sufficient repeated measurements to track the statistics of parameter variation.

The following list provides examples of parameter variations detectable by TDR, and that are evidence of process or materials problems:

a. Over/under-etching (line width problems)

b. Over/under-plating (line width and thickness problems)

c. Permittivity of the dielectric

d. Thickness of the dielectric

e. Degradation from excessive heating and humidity

f. Damage from excessive pressure during the multilayer process

g. Variations in the laminate glass-to-resin content

h. Variations in additional coatings applied to the PB surface, e.g., solder mask

Measurement repeatability is described in IPC-TM-650, Method 1.9, ''Measurement Precision Estimation for Variables Data.'' Method 1.9 also describes a process to evaluate the reproducibility of a measurement system for multiple operators, on different days, and when using different instruments. This evaluation process should be followed and a precision-to-tolerance ratio acceptable to the customer should be obtained.

6.1.2 Single-Ended and Differential Lines Increased performance requirements for computer and other electronic products often demand even greater signal fidelity, time precision, and noise immunity than can be obtained with a single-ended transmission line. A single-ended transmission line is a transmission line design consisting of a single signal conductor placed over one ground plane, as in a microstrip, or between two ground planes, as in a stripline. Single-ended lines may be called unbalanced transmission lines. Differential lines are used to increase signal fidelity with improved time precision and increased noise immunity to common-mode sources. Differential lines may also be called balanced or coupled transmission lines. The required TDR sources and samplers are different for differential lines, as are the probes used to make contact to the test structures, but this method is directly applicable to differential waveforms.

6.1.3 Environmental Factors Temperature and humidity should be monitored during the test. Long exposures to temperature and humidity other than standard laboratory conditions (temperature range of 20 to 23 °C and relative humidity range of 35 to 65%) can affect the dielectric properties of the materials in the test objects, and thus the propagation delay. Furthermore, the electrical characteristics of the TDR, such as sampler gain, are temperature dependent. Therefore, for the most repeatable measurements, the TDR instrumentation should be maintained within the manufacturer recommended temperature and humidity ranges. Low relative humidity may result in electrostatic discharge damage to the TDR unit.

6.1.4 Measurement Accuracy and Repeatability Accuracy and repeatability depend on the impedance of the line being measured, the type and condition of probes, cables, sampling head, and the experience of the test technician. Accuracy is the difference between the most likely measurement and the defined standard. The most likely measurement is also called the mode of all measurements within a sample set. Three times the standard deviation around each side of the mode is the repeatability.

The ability to resolve a measurement value is fundamental to the accuracy of any measurement process. The TDR instrument should have sufficient measurement resolution to facilitate the accuracy requirements of the measurement method described herein. The total risetime of the TDR system (including cables, probes, etc.) and step aberrations define the impedance resolution (see 4.1.2).

6.1.5 General Cautionary Statement TDR test systems and associated accessories are precision high frequency devices. Most TDRs include hardware to protect the static-sensitive sampling heads. However, operators and maintenance staff should take proper ESD precautions (see manufacturer's recommendations). High frequency cables, because they typically use solid center conductors, are not as flexible as typical coaxial cables. Consequently, care should be taken not to excessively bend and flex the high frequency cables.

The probes used in TDR systems typically use spring-loaded contacting mechanisms and these should be checked periodically to ensure proper operation. Statistical process control methods and control charts can provide useful information regarding the condition of the TDR system and its associated accessories.

6.1.6 Measured Values The units of the delay values computed using waveforms acquired by the TDR system are in seconds. Propagation delay, which is in units of time per unit distance (typically, s/m), is determined as described in Section 5.

6.2 Calibration

6.2.1 Verification Field Check – Check Standards The mechanical tolerances of air line check standards should be verified using mechanical gauges at each use. Damaged air lines should be repaired and recalibrated before use. They should always be handled with care. The air line should also be calibrated and documented periodically (not less than once every two years) by a qualified certification laboratory and kept in an environment safe from mechanical shocks, dust and dirt. Dust and dirt degrade the fine threads of the connection and damage the electrical mating surfaces. Also, some TDR equipment manufacturers have requirements for the minimum length of the air line artifacts. The user should check with the manufacturer regarding limits. For differential impedance of 100 Ω, each channel can be checked with a 50 Ω air line.

6.3 Measurement System

6.3.1 Bandwidth/Risetime Resolution The frequency components of the TDR step are approximately related to the bandwidth by:

$$BW_{-3\text{dB}} \approx \frac{0.35}{t_d},$$

where

$BW_{-3\text{dB}}$ is the 3 dB attenuation bandwidth and
t_d is the 10 - 90% transition duration of the TDR step response.

Note that this relationship may not accurately represent the intended operational frequencies of the transmission line being tested. The bandwidth and risetime characteristics must be adequate to ensure the TDR can provide a waveform epoch appropriate to accurately determine t_d for a transmission line of a given length. This waveform epoch must provide sufficient resolution (see 4.1.2) to accurately determine the reference level instants (see 5.1.3) and be long enough to ensure the TDR waveform has settled to a nominal value (necessary for accurate computation of pulse amplitude.) Risetime considerations, however, are not the best method for determining TDR resolution. It is better to consider the temporal/spatial resolution of the TDR (see 4.1.2) than bandwidth/risetime resolution when determining the performance of the TDR measurement system.

6.3.2 Temporal/Spatial Resolution The TDR unit may not be the only limiting factor for temporal resolution. The probe connecting the TDR unit to the test specimen may also limit resolution and this needs to be considered. Because of the nature of TDR, it is easy to include the effects of the TDR unit and all of the probe devices collectively, by defining t_{sys} as the fall time of the TDR step that has reflected from a short circuit placed at the end of the probe and returned to the TDR head.

6.3.3 Amplitude Scale If a coarse vertical scale is used, quantization error can be significant in certain instruments. Many instruments change accuracy when their scales are changed, and this can result in significant but unknown errors in t_d .

6.3.4 Baseline and Amplitude Drift The ability of the TDR instrument to maintain a constant baseline voltage and constant amplitude step pulse are critical to the repeatability of the TDR measurement process. TDR step generators and sampling units are sensitive to time and temperature drifts. Drift should be minimized and have a value that corresponds to less than one-tenth the desired t_d uncertainty.

6.3.5 Electrostatic Discharge Damage ESD damage to TDR instrumentation is often not easily detected and may unknowingly affect measurement accuracy. Therefore, system calibration should be performed regularly to check for this (see 5.1.1). All cables should have a termination attached to one end when not in use and while they are being connected to the TDR instrumentation. The use of a static protection switch helps eliminate ESD damage to the TDR. Operators should have anti-static awareness training and should perform all measurements in anti-static work areas while wearing anti-static wrist straps.

6.3.6 Probes Hand-held probing solutions are sensitive to operator technique and may have a larger contribution to uncertainty due to repeatability of connections compared to mechanical probing methods. Operators and probing equipment should be tested in ability to repeat electrical probe contacts.

6.3.6.1 Probes for Single-Ended Transmission Line Measurements The probe assembly impedance is often chosen to be 50 Ω to match the impedance of the TDR system. Impedance matching minimizes reflections at the interface between the probe and the transmission line under test. These reflections, which appear at and around the transition region in the TDR pulse and can extend for some time after this transition, are perturbations in the TDR waveform and are undesirable because they may affect the computation of the reference level instant, thereby increasing measurement uncertainty. When the characteristic impedance of the transmission line under test is nominally 50 Ω, these perturbations will normally decay rapidly. If the impedance of the transmission line under test is significantly different from 50 Ω, the magnitude of the perturbations can be large and their duration long enough to affect the computation of the reference level instant. The effect of these perturbations must be taken into account when determining the appropriate waveform epoch (see 4.1.2). The design and quality of manufacture of the probe has a large effect on the magnitude and duration of reflections generated between the TDR system and the transmission line under test.

When probing non-50 Ω lines, it is possible to separate, in the TDR waveform, the large signal perturbations caused by the TDR/probe interface from those caused by the probe/transmission line interface. To do this, a specially designed probe is required that is impedance matched to the transmission line under test and that also has a long propagation delay between the TDR/probe connection and the probe tip. The long propagation delay can effectively move the large perturbations at the TDR/probe interface out of the waveform epoch.

6.3.6.2 Probes for Coupled-Signal-Line (Differential) Transmission Line Measurements The probe considerations described in 4.3.3 apply for probes used in differential transmission line measurements. However, the necessity to simultaneously probe two signal lines and one or two reference plane contacts makes differential probing more difficult than probing single signal line structures. In a PB manufacturing environment, the use of two probes that were previously used for single-ended measurements may not be possible. This is because the operator is required to use both hands for probing, which leaves them unable to operate the instrument. Contact your instrument manufacturer for their probing solutions and advice. Probes from one manufacturer can also be used with another manufacturer's TDR if the impedance values and connectors are compatible.

6.4 Adjustable Measurement Parameters

6.4.1 Sampling Interval (Point Spacing) The temporal resolution of the TDR unit is an issue only if it affects the duration of the transitions in the TDR waveforms (see 4.1.2) that are used to compute t_d. The temporal resolution of the TDR is affected by the transition duration of the TDR step response, the transition duration of the step response of all intervening electrical components (connectors, cables, adapters), measurement jitter, the interval between sampling instances, and timebase errors. For typical TDR measurements, timebase errors and sampling intervals should not be an issue (both are or can be made to be less than 10 ps). The effect of measurement jitter can be modeled by convolving the jitter distribution with the TDR step response to yield an effective TDR step response. The effect of jitter on the bandwidth of the TDR measurement can be assessed from the jitter spectrum, which can be described by:

$$J(f) = e^{-2(\pi\sigma f)^2},$$

where

J is the jitter spectrum,
f is frequency, and
σ is the rms jitter value.

If the effective jitter step response differentially impacts the duration of the two or more waveform transitions used to compute t_d, then jitter must be reduced. More than likely, jitter will be nearly identically distributed for each transition. But if the jitter is so great as to affect the accuracy of computing the transition instants, then the user must reduce the duration of the waveform period or reduce the system jitter. Reduction in the duration of the waveform period may introduce a bias in the voltage values and this may affect the computed value of t_d. If the rms jitter value is less than 20% of the transition duration of the TDR step response, then the jitter is small and can be ignored. For typical TDR systems, however, rms jitter is less than 10 ps and will not affect the t_d measurements. Similarly, the effect of cables, connectors, and adapters on the measurement can be modeled by convolving their step responses with that of the TDR unit. If the transition duration of this new step response meets the requirements of 4.1.2, then the performance of the cables, connectors, and adapters is adequate.

6.4.2 Waveform Averaging and Number of Samples in the Measurement Zone Waveform averaging reduces the effective noise level of the measurement by $M^{-1/2}$, where M is the number of acquired waveforms (typically, $8 \leq M \leq 256$). Consequently, averaging can reduce measurement noise. This reduction is limited by the number of bits of the analog-to-digital converter of the TDR system and the linearity of the timebase. However, if the TDR system exhibits drift in the timebase, averaging too many waveforms may result in a reduction of t_{sys} and a commensurate reduction in the temporal/spatial resolution of the TDR.

The number of samples (data points) in the waveform epoch will affect the accuracy and uncertainty of the computed value of t_d because this value is typically computed by interpolating between adjacent datum values. Therefore, the more samples in the waveform epoch, the smaller will be the error and standard deviation of the computed t_d value.

6.4.3 Selection of Waveform Period Inconsistency in defining the waveform epoch may cause a significant but unknown error than can exceed two sample intervals. Specifying the waveform period to be consistent for both long and short line measurements improves t_d repeatability, and this can improve assessment of design and fabrication quality and vendor capability. This waveform epoch should be long enough to accurately determine if the waveform has settled on both sides of the waveform transition but should be short enough, given the number of samples in the waveform, to accurately compute the transition instant. The waveform epoch is defined in 5.1.3.