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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 waveform¹, 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:

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.

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

- 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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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_0 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_0 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_0 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 $23 \pm 1/-5^\circ\text{C}$ and $50 \pm 5\%$ 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

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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

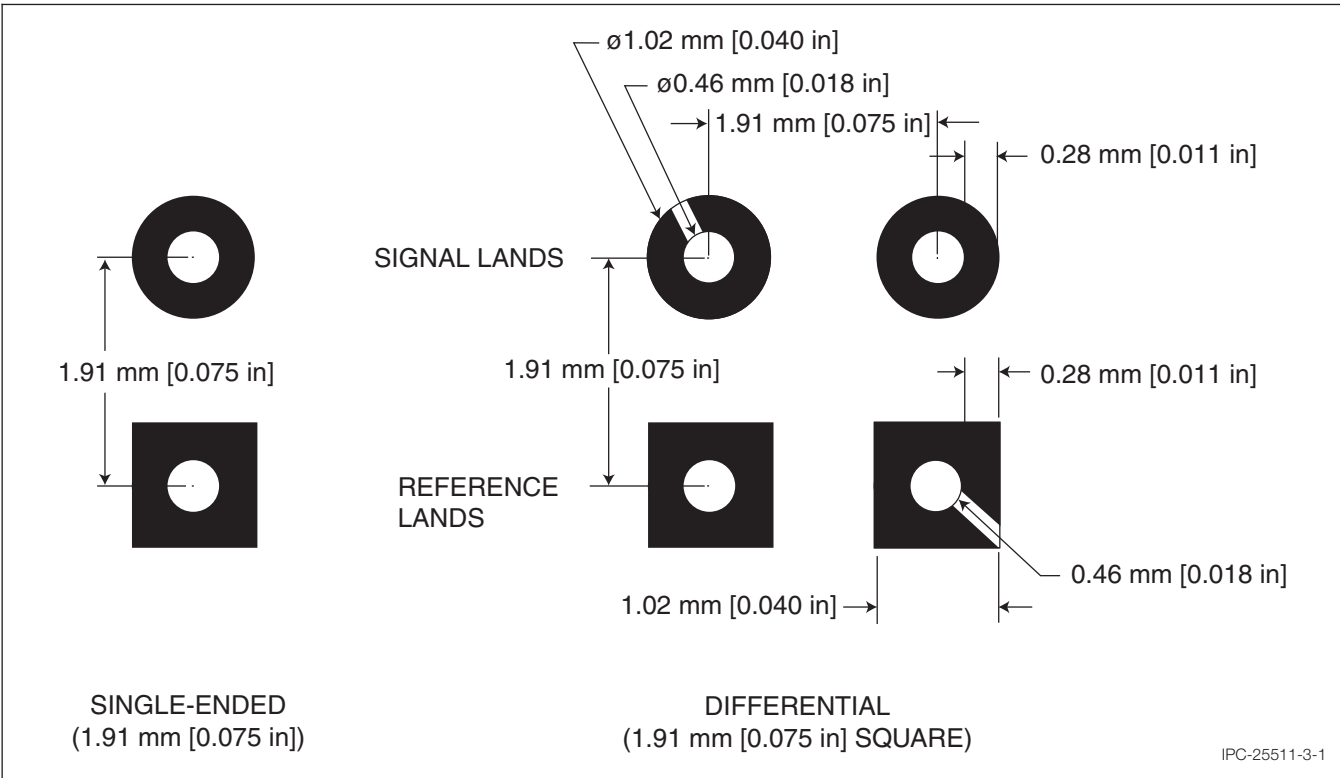


Figure 3-1 Contact Lands

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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.

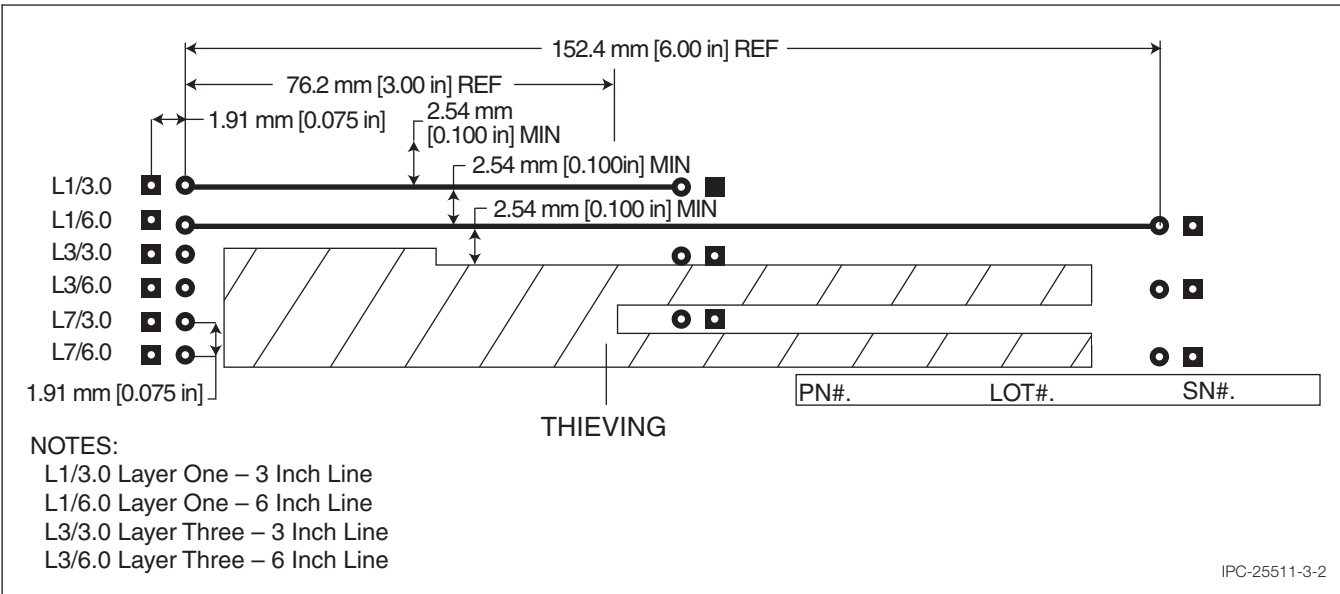


Figure 3-2 Transmission Line Structures

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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 $\pm 1\%$.

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 $2t_p$.

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.

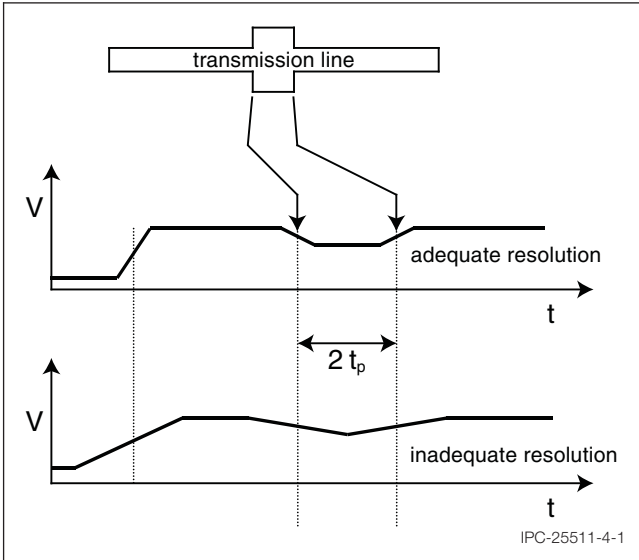


Figure 4-1 Resolution and Electrical Length of Transmission Line

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 4-1 relates TDR system risetime values to minimum L_{TL} for typical surface microstrip lines in air on FR4 PB material ($v_p \approx 2 \times 10^8$ m/s).