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IPC-TM-650 TEST METHODS MANUAL

1 Scope This document describes time domain reflectometry (TDR) methods for measuring and calculating the characteristic impedance, Z_0 , of a transmission line on a printed circuit board (PCB). In TDR, a signal, usually a step pulse, is injected onto a transmission line and the Z_0 of the transmission line is determined from the amplitude of the pulse reflected at the TDR/transmission line interface. The incident step and the time delayed reflected step are superimposed at the point of measurement to produce a voltage versus time waveform. This waveform is the TDR waveform and contains information on the Z_0 of the transmission line connected to the TDR unit.

Note: The signals used in the TDR system are actually rectangular pulses but, because the duration of the TDR waveform is much less than pulse duration, the TDR pulse appears to be a step.

1.1 Applicability The observed voltage or reflection coefficient change in the TDR waveform is related to the difference between Z_0 of the transmission line and the impedance of the TDR. If the impedance of the TDR unit is known via proper calibration, then the Z_0 of the transmission line attached to the TDR unit may be determined. Thus, the TDR method is useful for measuring Z_0 and changes in Z_0 of a transmission line. These impedance values thus determined can be used to verify transmission line design (engineering development), measure production repeatability, and qualify manufacturers via transfer or artifact standards.

Engineering development requires detailed information on the electrical performance of prototype units to assure the transmission line design yields the expected performance characteristics. Detailed laboratory analysis of the effect of variations in design features expected in actual manufacture can be done to assure the proposed design can be manufactured at a useful quality level.

1.2 Measurement System Limitations Measurements of Z_0 often vary greatly, depending on equipment used and how the tests were performed. Following a specified method helps assure accurate and consistent results. Both single-ended and differential line measurements have limitations in common, including the following:

- The Z_0 measured units are derived and not directly measured.

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- The value of characteristic impedance obtained from TDR measurements is traceable to a national metrology institute, such as the National Institute of Standards and Technology (NIST), through coaxial air line standards. The characteristic impedance of these transmission line standards is calculated from their measured dimensional and material parameters.
- A variety of methods for TDR measurements each have different accuracies and repeatabilities.
- If the nominal impedance of the line(s) being measured is significantly different from the nominal impedance of the measurement system (typically 50 Ω), the accuracy and repeatability of the measured numerical value will be degraded. The greater the difference between the nominal impedance of the line being measured and 50 Ω , the less reliable the numerical value of the measured impedance will be.
- Measurement variation (repeatability, reproducibility) may only be a small component of the total uncertainty in the value of the characteristic impedance. For example, if the uncertainty in the characteristic impedance of the reference air line is $\pm 0.5 \Omega$ (for a 95 % confidence interval), then the uncertainty in the measured characteristic impedance of the test line can be no better than $\pm 0.5 \Omega$ even if measurement variation is much less.
- The particular TDR methods described herein are not suited for measuring the characteristic impedance as a function of position along the transmission line (impedance profiling) because signal reflections within the transmission line under test and between the TDR unit and transmission line under test may adversely affect measurement results.
- The requirements for the length of the transmission line under test given in Section 3 of this test method as well the IPC-2141 must be met.

Further measurement considerations and notes are provided in Section 6.

1.3 Sample Limitations The type of test sample used may also impact Z_0 values (see IPC-2141). The sample-based limitations include:

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- a. The transmission line under test varies along its length whereas the value of Z_0 obtained assumes a uniform transmission line. Therefore, the measured Z_0 only approximates the characteristic impedance of an ideal line that is representative of the line under test.
- b. Lines on a printed circuit board may deviate significantly from design. For example, microstrip lines longer than 15 cm [5.91 in] on boards with plated-through holes often have variations in line width; this variation is due to plating and/or etching variations.
- c. If the transmission line is too short, the accuracy of the calculated impedance value may be degraded (see 4.1.2). If the transmission line is too long, skin effect and dielectric loss may cause a bias in the impedance measurement.
- d. Depending on where the measurements are made, the value of Z_0 obtained may be affected by dielectric and conductor loss and other effects. The farther away from the interface between the probe and the transmission line under test, the worse these effects will be.
- e. Duration of the measurement window (waveform epoch) may need to be adjusted for sample length and location of midpoint vias along the transmission line.
- b. Accessibility of terminations for the line.
- c. Absence of branching.
- d. Absence of impedance changes within the transmission line under test.
- e. Representation of controlled Z_0 signal layers in a multi-layer board.

3.1.2 Example 2 Representative samples should be as in 3.1.1, except that the test lines are nonfunctional lines designed into the board for easy termination for TDR measurements. Such test lines should be planned to include critical features typical of functional lines and should lie in controlled Z_0 signal layers.

3.1.3 Example 3 Representative samples should be as in 3.1.1, except test coupons are cut from the master board at the time the individual PCBs are separated. Such test coupons will have one or more sample transmission lines with termination suited for 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 board on the same controlled Z_0 layers.

3.1.4 Example 4 A sample of the substrate laminate to be characterized before use in manufacturing PCBs is fabricated with test transmission lines. The fabrication may involve laminating several board layers together in the same manner anticipated for PCB manufacture.

2 Reference/Applicable Documents

IPC-2141 Controlled Impedance Circuit Boards and High Speed Logic Design

IPC-TM-650 IPC Test Methods Manual

1.9 Measurement Precision Estimation for Variables Data

3 Test Specimens The test specimen can take one of several forms, depending on the application, but contains at least one transmission (or interconnect) test structure. As examples, four types are mentioned in 3.1.1 through 3.1.4. The transmission lines to be measured may be of either strip-line or microstrip construction and configured as either single-ended or differential. See IPC-2141 for a recommended test coupon design.

3.1 Test Specimen Examples

3.1.1 Example 1 Representative samples of the actual PCB being manufactured are selected. In some cases, this sample set may contain all of the boards. Agreed upon functional or nonfunctional transmission lines within the sample are used for the measurement. Criteria for selection of such lines includes:

- a. Inclusion of the PCB's critical features.

3.2 Identification of Test Specimen For specimens of types called out in 3.1.1, 3.1.2, or 3.1.3, a board serial number, part number, and date code should be adequate. Specimens from 3.1.4 should include whatever lot or panel identification is available for the substrate laminate being evaluated.

3.3 Conditioning If conditioning is required, test specimens shall be stored before testing at 23 °C (+1/-5) °C [73.4 °F (+ 1.8/-0 °F)] and 50 % RH ± 5 % RH for no less than 16 hours. If a different conditioning procedure is used, it must be specified by the user.

4 Equipment 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 device under test. IPC-2141 provides a short discussion of the TDR system architecture, system considerations, and the TDR measurement process.

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1.1 Measurement System Requirements

4.1.1 Measurement Accuracy The measurement accuracy of the TDR should be sufficient to provide the required accuracy in the value of characteristic impedance. The required measurement accuracy of the TDR unit will depend on the TDR measurement method. In general, the measurement accuracy of the TDR unit should be better than 1% of amplitude (either voltage or reflection coefficient). Noise in the measured values will affect the uncertainty in the calculated Z_0 values. The value of Z_0 may be affected by the length of the transmission line under test and the section of the transmission line from which Z_0 is calculated (see 3.1.1.d).

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. 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.

Per this definition, the resolution limit is:

- a. half the system risetime, t_{sys} , where t_{sys} is the 10 % to 90 % risetime or 90 % to 10 % falltime (depending on whether the TDR response is calibrated with a short or open circuit), or
- b. $0.5 t_{sys} \times v_p$, where v_p is the signal propagation velocity in the transmission line being measured.

These definitions are complementary.

For a given length of transmission line to be measured, the resolution should not exceed one fourth (0.25) of the available length, L_{TL} of the transmission line. Table 4-I provides examples of required resolution for typical surface microstrips in air, and on FR4 circuit board ($v_p \approx 2 \times 10^8$ m/s), for a given TDR system risetime.

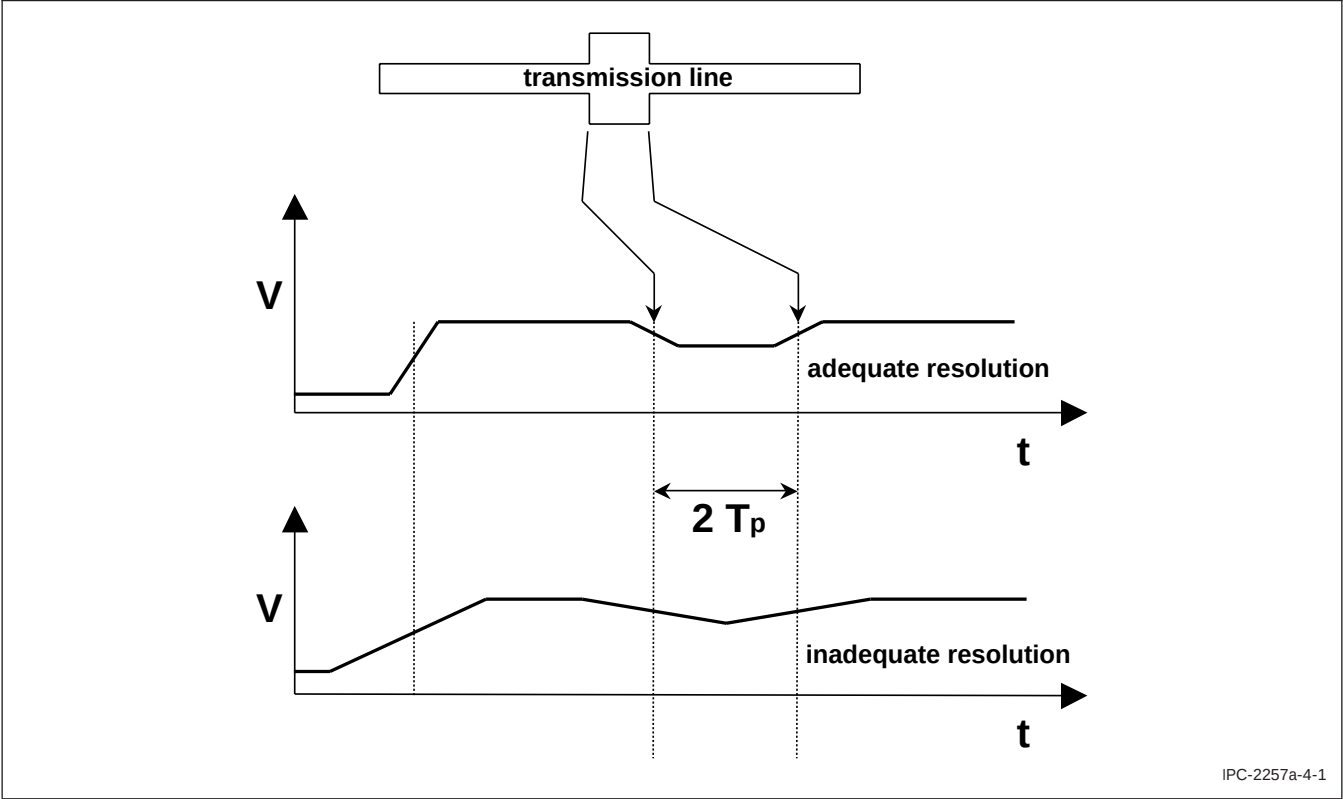


Figure 4-1 Resolution and Electrical Length of Transmission Line

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Table 4-1 Resolution of TDR Systems

TDR System Risetime	Resolution	4X Resolution
10 ps	5 ps / 1 mm [0.04 in]	4 mm [0.16 in]
20 ps	10 ps / 2 mm [0.08 in]	8 mm [0.31 in]
30 ps	15 ps / 3 mm [0.12 in]	12 mm [0.47 in]
100 ps	50 ps / 10 mm [0.39 in]	40 mm [1.57 in]
200 ps	100 ps / 20 mm [0.79 in]	80 mm [3.15 in]
500 ps	250 ps / 50 mm [1.97 in]	200 mm [7.87 in]

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

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

For example, if a 32 mm [1.26 in] long transmission line was being measured, a TDR system with $t_{sys} \leq 80$ ps should be used. Note that, if the probe launch caused excessive ringing in the TDR waveform, or if the launch does not repeatably replicate the connection to the standard, then the 0.25 factor may need to be smaller.

4.2 TDR Requirements

4.2.1 Impedance The impedance of the TDR unit should be 50 Ω with an impedance uncertainty less than or equal to $\pm 0.5 \Omega$. This TDR impedance value is selected because it is the impedance used by most high-speed/high-frequency test

instrumentation and compatibility with this instrumentation is necessary for characterizing the dynamic TDR properties, such as its impulse response (or transfer function). The impedance of the TDR unit should be calibrated using an artifact standard, such as an air line (see 4.3.6). However, the TDR impedance is a function of frequency and calibration using a fixed region of the TDR waveform (the measurement zone) will only yield an average impedance value for the TDR unit for the corresponding frequency range.

4.2.2 Timebase Accuracy The horizontal timebase accuracy defines how well the TDR instrument's horizontal time scale can display the correct length of the trace. This affects both the accuracy of the measurement zone calculations and any propagation delay values. The timebase accuracy should be less than 0.25 t_{sys} (see also 4.1.2).

4.2.3 Step Aberrations The ability of the TDR instrument to measure the impedance of a transmission line is related to how well the instrument can generate a step-pulse with a minimum of aberrations (ringing, overshoot, undershoot, settling, etc.). Any ringing, overshoots, or undershoots will cause corresponding aberrations in the TDR waveform (see Figure 4-2). These aberrations can cause significant errors in the impedance value computed from the TDR waveform. Additionally, low frequency step aberrations may produce a ramp in measurement zone. This ramp can cause a significant bias in the computed impedance value. The TDR instruments step aberrations should be less than 1% of the total step amplitude. For example, the impedance error shown in Table 4-2 is for a 1 mV error of a 250 mV step. Poor settling and large

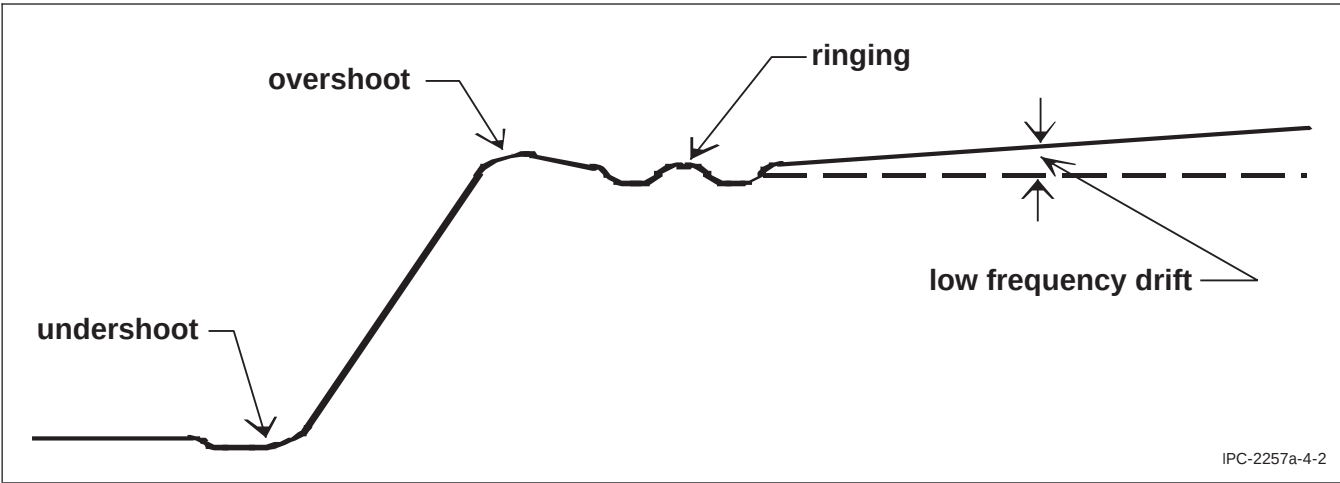


Figure 4-2 Potential TDR Step Aberrations

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aberrations will increase the variation in the average voltage or reflection coefficient value from which Z_0 is computed, thereby increasing the variation in the compute value of Z_0 .

Table 4-2 Impedance Error

Impedance Error	Transmission Line Impedance
0.24 Ω	28 Ω
0.4 Ω	50 Ω
0.79 Ω	90 Ω
1.23 Ω	125 Ω

4.3 Other Equipment Requirements

4.3.1 Connectors TDR systems typically come with either "SMA," 3.5 mm, or 2.92 mm connectors at their measurement ports. SMA, 3.5 mm, and 2.92 mm connectors are all 50 Ω connectors and are electrically and geometrically compatible, therefore, they can be mated directly to each other. However, the 2.92 mm and 3.5 mm connectors are precision connectors (have a lower impedance uncertainty than the SMA) and are designed to provide a more repeatable connection than the SMA connector. Therefore, for accurate measurements, it is recommended that the 2.92 mm or 3.5 mm connector be used where possible. The bandwidth of the connectors must be great enough so that the connectors do not affect the accuracy of the TDR measurement. The typical -3 dB bandwidth of 3.5 mm connectors is approximately 34 GHz and of SMA connector is approximately 24 GHz. The reflection and insertion losses of the connector should be less than 27 dB and 0.3 dB respectively. Other connectors, comparable in performance to the 3.5 mm connector, may also be used. All cable connections using SMA, 3.5 mm, or 2.92 mm connectors should be tightened with a torque wrench to following specification, unless otherwise specified by the manufacturer of the connector or cable:

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

Connector Type	Required Torque
SMA	0.56 N-m [5 lb-in]
3.5 mm 2.92 mm, K	0.9 N-m [8 lb-in]

4.3.2 Cabling All test cables should be coaxial and have a characteristic impedance of 50 Ω with an impedance uncertainty of less than $\pm 1 \Omega$. Cables used in the measurement circuit of the transmission line under test should have connectors

that are compatible with the rest of the measurement system. The bandwidth of the cable must be great enough so that the cable does not affect the accuracy of the TDR 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 a minimum, for example, less than 0.033 dB/cm [1db/foot] at 26.5 GHz. Table 4-4 contains suggested maximum cable lengths. Faulty cables can contribute up to a 1 Ω error. Cable connections should be tightened with a torque wrench to ensure a good connection.

Table 4-4 Maximum Suggested Cable Lengths

TDR Cable Assembly	TDR Cable Length
Sampling Unit to Static Isolation Unit	30 cm [12 in]
Static Isolation Unit to In-Line Secondary Standard	91 cm [36 in]
In-Line Standard (such as, semi-rigid coaxial cable)	10 cm [4 in]

4.3.3 Probes The probe assembly should have a characteristic impedance of 50 Ω or of approximately the same value as that of the transmission line under test, with an uncertainty of $\pm 1.0 \Omega$ or less. The probe tips should be of sufficient diameter and pitch (spacing between signal and ground tips) to accurately and repeatably probe the desired probe contact pad geometry. (See IPC-2141 for recommended probe landing layouts for TDR coupons.) Single-ended probes should contain two tips, one each for the signal and ground lines. Differential probes should contain two tips for contacting the signal lines and one or two tips for contacting the reference plane or planes. The probe tips should have moderately sharp edges to cut through any oxides. For hand held probe assemblies, the probe handle should be ergonomically shaped. The probe bandwidth should be sufficient for the desired temporal/spatial resolution (see 4.1.2). The probe settling time should be short so as not to affect the duration of the measurement zone. 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 that can exceed 5 Ω . Probe connections should be tightened with a torque wrench to ensure a good connection.

4.3.3.1 Probes for Differential Structures The differential probe should be long enough to act as a transfer standard, similar to that described in 4.3.7 for testing single-ended

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transmission lines (see 5.2.1). This probe can be constructed using a printed circuit board differential transmission line that has a differential impedance similar to the traces being tested or by using short identical lengths of semi-rigid cable that connect the instrument cables to the differential probe. The probe or semi-rigid cable should be sufficiently long to provide an adequate duration for the measurement zone (see 4.1.2) used during calibration and measurement.

4.3.4 Terminations Many instruments perform differently under different electrical loads. If a test is performed with open circuited lines, the calibration of the reference should also be done using an open circuit termination.

4.3.5 ESD Protection Static build up on specimens prior to test can damage the sampling heads in the TDR equipment. Therefore, it is recommended that ESD protection be used. Such protection can be supplied internally to the TDR system or externally. If supplied externally, using a coaxial switch for example, then the switch should be placed between the transmission line under test and the TDR instrumentation. The switch, or static protection device (SPD), should have a return and insertion loss less than 16 dB and 0.3 dB at 18 GHz. A maximum of 31 cm [12.2 in] of high quality, high frequency cable may be used to connect the TDR instrument to the protection switch. Samples should be grounded to remove any residual static and/or passed through some type of deionization device prior to testing.

Keeping the relative humidity in the test area between 45 % and 55 % may minimize the buildup of static. 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 Calibration Artifacts (Reference or Reference Standard) A precision coaxial air line with calibration traceable to a national metrology institute (such as the National Institute of Standards and Technology), 3.5 mm or 2.92 mm connectors at both ends, and at least 10 cm [3.94 in] long should be used. The characteristic impedance of the air line is based on the geometry of a coaxial transmission line using air as the dielectric between the center conductor (signal line) and the ground shield. The center conductor may be held in place by glass beads located at both ends of the air line or by the external connectors that are attached to the connectors of the air line. The uncertainty in the nominal characteristic impedance of the air line should be less than or equal $\pm 0.015 Z_{ref}$ where Z_{ref} is the characteristic impedance of the reference air line.

4.3.7 In-Line (Transfer) Standard The transfer standard is placed between the probe and the TDR unit (see Figure 4-3). This standard could be an airline, a semi-rigid coax cable assembly with the same specifications as the flexible coax cable assemblies, or other. The transfer standard should be of

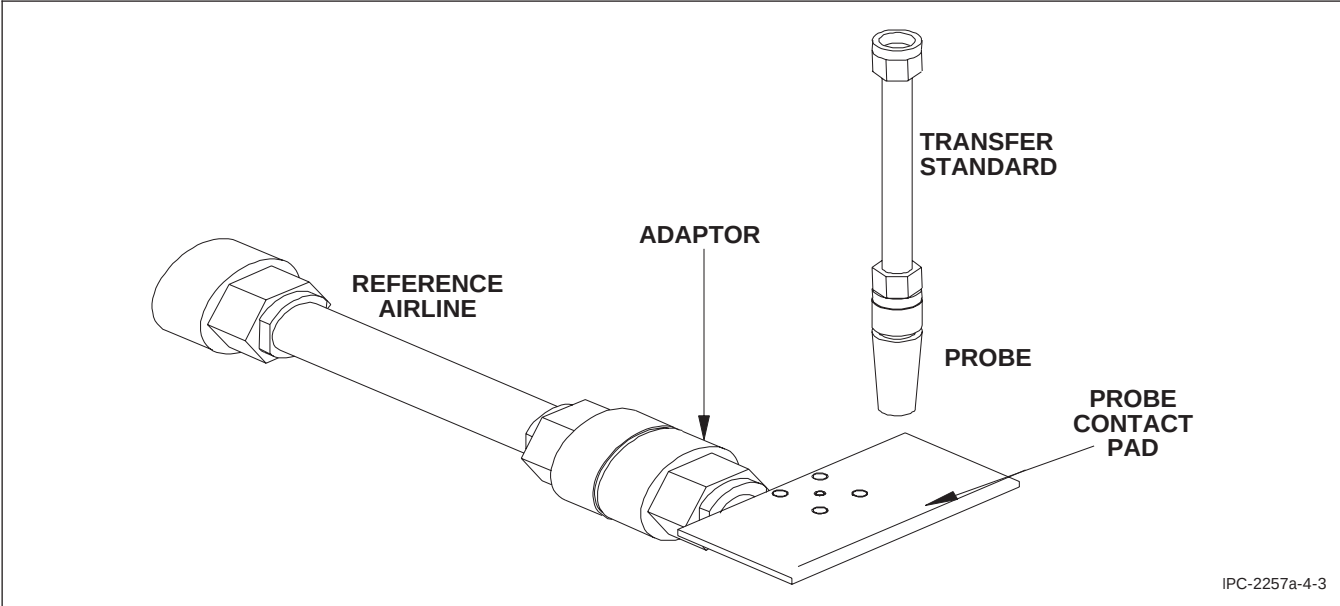


Figure 4-3 Reference Airline and Probe Contact Pad

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sufficient robustness so that its impedance remains constant between calibration cycles.

4.3.8 Adapter, Airline-to-Probe Contact Pad A preferred method of calibrating the TDR amplitude response is to connect a probe contact pad directly to the airline and to probe the airline through the contact pad (see Figure 4-3). The contact pad should have a nominal characteristic impedance of $50 \Omega \pm 1.0 \Omega$. An increase in measurement accuracy can be achieved by using a reference impedance standard that is closely matched to the impedance of the transmission line to be tested.

5 Procedures

5.1 Measurement Preliminaries In this section, common considerations for the calibration of the TDR measurement system and performing the TDR measurements are provided. 5.1.3 describes a method for establishing the measurement zone that can be applied to the measurement methods described in 5.2 and 5.3.

5.1.1 System Calibration Follow the TDR instrument manufacturer's recommendation for the frequency of factory calibration. TDR system "field" calibrations are to be performed at regular intervals in addition to the less regular factory calibrations. The field calibrations are required for the following reasons:

- TDR instrument specifications vary with temperature.
- TDR instrument specifications vary with time (drift).
- TDR instrument specifications vary due to minor ESD damage.
- TDR instrument factory calibration usually does not include user supplied auxiliary components (e.g., cables, probes, etc.).

TDR system field calibrations should also be performed after a change of any system component (such as, cable, probes, etc.). Ensure that the TDR instrument has been operating for at least 30 minutes prior to any calibration or test measurement procedure.

Use proper ESD control methods to avoid damage to the TDR instrument in all calibration and test measurement procedures. ESD control components can include static dissipative mats, deionizer systems, and operator gowning.

5.1.2 Premeasurement Checks The test measurement should be performed after the completion of the calibration

process. Ensure that plane of the signal line of a microstrip (or embedded microstrip) structure is at least a distance equal to six times the width of the microstrip signal line from any material (such as the testing table) that can affect the dielectric environment of the microstrip line. If the tests are being conducted with hand probe(s), care must be taken to ensure that the hands and/or arms of the operator do not contact any surface of the board over the transmission line being tested. Probes should be applied to the test points with sufficient force to ensure proper electrical contact between the trace and the probe assembly. Consistent application (that is, force, angle of placement, etc.) of the probes onto the test points is important to ensure repeatable measurement results.

Before recording any measurement results, ensure that the TDR waveform is stable (that is, not drifting in amplitude or time) otherwise measurement error will occur. To improve the accuracy of the impedance measurement, it is important to optimize the vertical gain setting (typically in V/div or p/div) and horizontal axis setting (typically in time/div) of the TDR unit so as to maximize the duration of the measurement zone within the TDR waveform and to increase amplitude resolution. Perform this TDR adjustment prior to acquiring any TDR waveforms from which Z_0 will be computed. Ensure that the temperature and humidity of the test environment is within TDR instrument specifications and is stable.

5.1.3 Establishing the Measurement Zone The value of the measurement zone is critical to the accuracy and repeatability of the TDR measurement process. Measurement zone differences are a large factor in correlation problems between measurements. The measurement zone should be set repeatability for each transmission line independent of the type of dielectric material surrounding the transmission line or its structure (surface microstrip, embedded microstrip, stripline, differential pair, etc.). The following process can be incorporated into the test measurement process. There are two measurement zones, one for the transmission line under test (see 5.1.3.1) and one for the reference (see 5.1.3.2), which may be either a transfer standard or a coaxial air line.

5.1.3.1 Procedure for the Transmission Line Under Test

Step 1 – Hold the probe in the air and locate the instant, $t_{1,TL}$, on the TDR waveform where the probe/open discontinuity occurs (see Figure 5-1). $t_{1,TL}$ is the instant in the TDR waveform when the reflection from the open circuit has reached 50 % of its amplitude (see Figure 5-1), unless otherwise specified by the user.