

IEEE Standard for Backplane Electrical Performance

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of the
IEEE Computer Society**

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IEEE Standards Board

Abstract: The proper treatment of the electrical elements of the backplane that provides a physical and electrical connection between different modules in a computer system is covered. Techniques for measuring impedance, capacitance, and crosstalk are provided; and crosstalk, ground bounce, and decoupling are discussed. Relationships among the key elements controlling backplane performance, such as driver and receiver characteristics, the distance of the driver and receiver from the backplane, the impedance of the bus traces treated as transmission lines, lumped elements such as connectors and vias, and the termination are examined.

Keywords: backplane, backplane bus, bus, high-performance backplanes, low-performance backplanes, measurement techniques, medium-performance backplanes, transmission lines

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Foreword

(This Foreword is not a part of IEEE Std 1194-1991, IEEE Standard for Backplane Electrical Performance.)

This standard was prompted by the conflicting performance claims of various backplane implementations. The claims were made with differing conditions, making true comparisons of performance difficult. The definitions and techniques presented in this standard provide a guideline upon which these comparisons can be made. This standard is not a backplane benchmark, nor is it meant as a tutorial on transmission line theory. Rather, it is a practical guide to the problems associated with measuring backplane electrical performance.

Special thanks go to those who contributed the most toward making this standard possible. R. V. Balakrishnan served as chairman in the first few months and got the standard effort started. Jeff West served as the draft editor, writing most of it and helping review the ballot comments. Joel Martinez handled most of the administrative duties as the Working Group secretary, contributed to several sections of the standard, and helped review the ballot comments. Dan Yaklin helped review the ballot comments. Paul Borrill made technical contributions in several areas. Clyde Camp, Chair of the Microprocessor Standards Committee, helped tremendously, answering my “What needs to be done next?” questions.

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IEEE Standard for Backplane Electrical Performance

1. Scope

The backplane provides a physical and electrical connection between different modules in a computer system. Each module communicates with other modules by way of the backplane bus. The wires or traces on the bus and the traces on the modules are more than just a common connection point for electrical signals; they are electrical elements. Proper treatment of the electrical elements of the backplane (such as capacitance, inductance, impedance, delay constants, termination, connectors, driver, and receiver characteristics) is essential if the design of the backplane is to be successful.

This standard covers the proper treatment of the electrical elements of the backplane. It contains measurement techniques for impedance, capacitance, and crosstalk; a discussion of crosstalk, ground bounce, and decoupling; and a study of the relationships between the key elements that control backplane performance. Some of these key elements are driver and receiver characteristics, the distance of the driver and the receiver from the backplane, the impedance of the bus traces treated as transmission lines, lumped elements such as connectors and vias, and the termination. Each element contributes to the performance of the backplane.

The performance of a backplane can be categorized into three groups, as identified in Chapter 6 of [B3] :¹

- 1) Lumped model for low-performance backplane designs
- 2) Transmission line reflected wave switching for medium-performance backplanes
- 3) Transmission line incident wave switching for the highest-performance backplane designs

The lumped model treats the backplane as a capacitor equal to the total capacitance along the signal path, backplane, and plug-in modules. The lumped model can be used where the rise time of the signal is slow compared to the signal propagation time down the backplane, or where the bus performance is not critical and only a final state at some later time is needed. The lumped capacitance is charged or discharged by the driving device or the termination and is controlled by an RC time constant. The signal transition from a low to a high is of the form $1 - e^{-t/R_1 C}$, and a high-to-low signal transition is of the form $1 - e^{-t/R_2 C}$, where R_1 and R_2 are the equivalent resistance of the charging and discharging device.

¹The numbers in brackets correspond to those of the bibliography in Section 7.

As an example, Fig 1 shows the equivalent bus schematic of the open collector bus analyzed as a lumped model, where the open collector driver releases the bus and the voltage, $v(t)$, makes a transition from low to high.

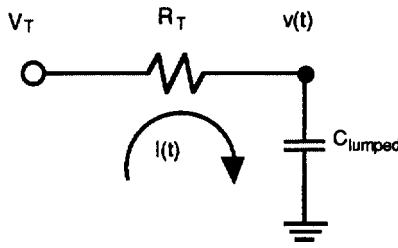


Figure 1— Low-to-High Lumped Model for Analysis

V_T is the termination voltage, C is the total lumped capacitance, and R_T is the termination resistance. Analysis of the circuit gives the following:

$$I(t) = C \frac{dv(t)}{dt} = \frac{V_T - v(t)}{R_T},$$

or

$$\frac{dv(t)}{dt} + \frac{v(t)}{R_T C} = \frac{V_T}{R_T C}.$$

This is a first-order differential equation and has a solution of the form

$$v(t) = V_T(1 - e^{-t/R_T C}).$$

When the driver asserts the line low, the equivalent diagram for analysis of the behavior of the backplane is shown in Fig 2. R_d is the series resistance of the driver when it is in the ON state.

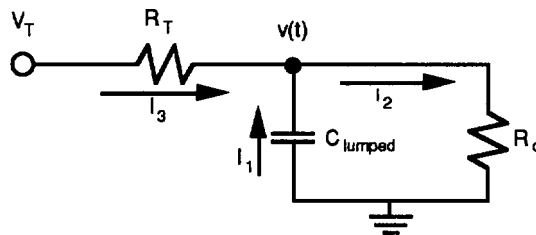


Figure 2— High-to-Low Lumped Model for Analysis

Analysis of this circuit gives the following:

$$I_2 = I_3 + I_1$$

$$\frac{1}{R_d} v(t) = \frac{V_T - v(t)}{R_T} - C \frac{dv(t)}{dt},$$

$$C \frac{dv(t)}{dt} + \frac{1}{R_d} v(t) = \frac{V_T - v(t)}{R_T},$$

or

$$\frac{dv(t)}{dt} + \left(\frac{1}{CR_d} + \frac{1}{CR_T} \right) v(t) = \frac{V_T}{CR_T},$$

and has a solution of the form

$$v(t) = V_T \left(\frac{R_d}{R_d + R_T} + \frac{R_T}{R_d + R_T} e^{-t/RC} \right)$$

where

$$R = \frac{R_T R_d}{R_d + R_T}.$$

By knowing the lumped capacitance of the backplane and the value for the resistances charging or discharging the backplane, the performance of the backplane can be analyzed for time and voltage.

If the signal transition times are short compared to the time a signal propagates down the bus, then it is better to analyze the backplane as a transmission line. That is,

$$\text{transmission line length} > \frac{T_R(\text{ns})}{2T_{PD}(\text{ns/ft})},$$

where T_R is the signal rise time at the source, and T_{PD} is the one-way propagation delay of the line per unit length.

General transmission line properties are found in texts on the subject (see, for example, [B12], p. 490), but for transmission line analysis of backplanes only a few key concepts need be well understood. A few of these include the characteristic impedance, Z_0 , in ohms; the characteristic delay, τ_0 , usually in nanoseconds per meter; and the reflection coefficient, ρ , which is defined as the amplitude of the reflected wave divided by the amplitude of the incident wave.

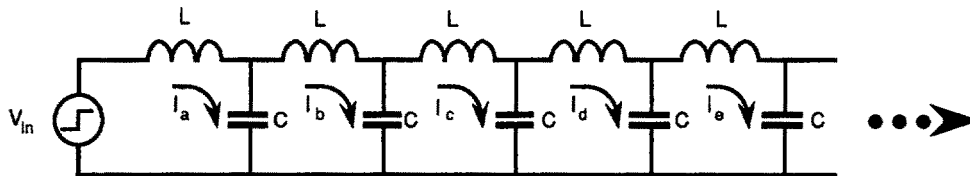


Figure 3— Simplified Discrete View of a Transmission Line

Figure 3 shows a simplified view of a transmission line as distributed inductance and capacitance. A voltage wave that is launched onto the transmission line at the left causes current to flow into the line. This current charges the distributed capacitance, but is delayed down the line by the distributed inductance. As long as the signal sees the same distributed L's and C's, the impedance of the line can be written as

$$Z_0 = \sqrt{\frac{L_0}{C_0}}, \quad (1)$$

where L_0 and C_0 are the distributed inductance (L) and capacitance (C) per unit length. The current flowing into the transmission line is

$$I = \frac{V_{in}}{Z_0}.$$

The time it takes for the signal to travel down the transmission line is calculated using the relationship, delay = distance * τ_0 , where

$$\tau_0 = \sqrt{L_0 C_0} . \quad (2)$$

On a backplane there are always connectors, which have capacitance and inductance, that connect the backplane to branch transmission lines called stubs. These branch transmission lines are on the plug-in modules and are the communication paths between the plug-in modules and the backplane.

These connectors and stubs change the impedance of the transmission line. Lumped capacitance along a transmission line, as in the case of regularly placed connectors on a backplane, changes the impedance and delay constant by the relationships

$$Z_L = \frac{Z_0}{\sqrt{1 + \frac{C_d}{C_0}}} ,$$

and

$$\tau_L = \tau_0 \sqrt{1 + \frac{C_d}{C_0}} ,$$

where C_d is the added capacitance per unit length, and C_0 is the intrinsic capacitance per unit length of the transmission line, Z_0 . These relationships can be derived by replacing C_0 by $C_0 + C_d$ in 1 and 2. (These equations do not take into account the effects at very high frequencies. In those cases, skin effects and other effects start to become significant. The assumption of frequency-independent values of Z_0 , L_0 , and C_0 are then no longer valid.)

A point along the transmission line where the impedance changes is called a discontinuity. An example of this occurs when the backplane is loaded with only one-half of the plug-in modules, and they are grouped to one end of the backplane. The impedance of the backplane has a discontinuity at the interface between the unloaded and loaded sections. At each point where a voltage wave traveling down a transmission line meets a discontinuity in the impedance, some of the signal is reflected and some is transmitted. The ratio of the reflected wave to the incident wave is called the reflection coefficient, ρ . The reflection coefficient has a major influence on the design and performance of a backplane. If the drivers or transceivers are placed too far from the backplane, or there is too great a mismatch of impedance on the backplane or to the termination, or there are improper driver and receiver characteristics, then reflections can cause serious noise problems. These problems include multiple switching and reduced noise margins. In this case, a unsettling time would be required before valid data could be presumed.

In high-performance backplane designs the bus impedance, termination resistance, termination voltage, stub length, and the driver and receiver characteristics are all carefully controlled so that valid data can be presumed on the incident wave of the signal.

The 1194 standard is intended to be used to design and evaluate high-performance backplanes. The standard has four sections. The first section covers measurement techniques for the impedance of a backplane and lumped capacitance placed along the backplane. These techniques are based on time-domain reflectometry. The next section deals with two types of noise that can be generated on a bus: ground bounce and crosstalk. The third section evaluates decoupling techniques, looking at both the current needed during switching and the capacitor's equivalent RLC network. The last section applies transmission line theory to worst-case bus loading configurations to derive backplane design constraints. These constraints relate the unloaded and loaded bus impedances, the termination resistance, and stub length. The purpose of this last section is to show that by knowing the desired noise margins and the characteristics of the drivers and receivers on the bus, derivations can be made that relate the key bus parameters, Z_U , Z_L , R_T , stub length, and lumped capacitance so that the desired bus performance can be achieved.

Although these derivations were based on the open collector type of bus and incident wave switching, the techniques can be applied to other bus structures. This is done by creating the Thevenin-equivalent termination and calculating the equivalent currents that charge and discharge the line. The process of creating a Thevenin-equivalent circuit for the termination, where an equivalent termination resistance and voltage are used instead of the actual circuit, is shown as

an example in Section 6., Fig 20. This shows how to convert a split-resistor termination from V_{CC} to ground, to a equivalent termination resistance and voltage.

The equivalent currents for charging and discharging the line are calculated from the termination, dc-quiescent currents, and the output driver. This usually requires solving simultaneous equations. With CMOS buses, full-logic swings are not usually accomplished on the incident wave because of low output drive and low termination currents. In both the low-to-high step and the high-to-low step, the driver current must be added to the bus current to determine the total current available to charge or discharge the line. The voltage step is calculated based upon the dc current flowing through the bus, plus the current the CMOS driver is supplying at that particular V_{OH} level, and the bus impedance. With TTL buses, the high-to-low transition is very similar to the open collector case where the current to discharge the line is the change in voltage divided by the transmission line impedance, assuming there is enough available current to make the full transition. If there is not enough current, then it must be analyzed like the CMOS case. The current to charge the line from low to high is current flowing through the line while in the low state, plus any current that the Darlington structure supplies at that voltage. Standard ECL buses operate almost exactly like open collector (or IEEE Std 1194.1-1991² based) buses except that current is sourced onto the bus from the driver instead of sinking current from the bus when the driver is ON.

2. Conventions Used in This Standard

C_0	= The capacitance per unit length of Z_0 .
C_d	= The lumped capacitance per unit length added to Z_0 , caused by the vias and connectors that are added to the backplane.
C_{stub}	= The capacitance per unit length added to the backplane impedance by the effects of the stub or plug-in board. This includes lumped capacitance such as drivers and receivers.
L_0	= The inductance per unit length of Z_0 .
ρ	= The reflection coefficient. It is the ratio of the reflected wave amplitude divided by the incident wave amplitude.
R_T	= The value of the termination resistor.
V_+	= The incident voltage wave traveling on the transmission line, also labeled V_1 .
V_-	= The reflected voltage wave traveling on the transmission line, also labeled V_R .
V_{IH}	= The high-level threshold voltage for the receiver.
V_{IL}	= The low-level threshold voltage for the receiver.
V_{OH}	= The actual high-level voltage produced by the driver on the bus.
V_{OL}	= The actual low-level voltage produced by the driver on the bus.
V_T	= The termination voltage.
Z_0	= The intrinsic characteristic impedance of the backplane trace. No capacitive effects of vias or connectors are included.
Z_L	= The fully loaded backplane impedance. This includes the backplane trace impedance, and the capacitive effects of the vias and connectors, as well as all of the plug-in modules inserted with their vias, connectors, traces, transceiver, etc.
Z_S	= The characteristic impedance of the stub between the driver and the backplane.
Z_U	= The unloaded impedance of the backplane. This includes the backplane trace impedance and the capacitive effects of vias, connectors, and everything on the backplane without the plug-in modules.

incident wave switching. Describes a voltage transition that is large enough in magnitude to change the state of a input to a receiver just once on the first edge of the wave. This assumes that subsequent reflections will not cause the receiver to switch back to a previous state.

noise margin. The difference between the actual voltage on the bus and the receiver threshold voltage, V_{IH} or V_{IL} .

²As this standard goes to press, IEEE Std 1194.1-1991 is not yet published. It is, however, available in manuscript form from the IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, 1-800-678-4333.

stub. The signal path on the plug-in board between the transceiver and the backplane. This includes the printed circuit board trace, connector, and all lumped capacitance such as drivers and receivers.

3. Measurement Techniques

3.1 Impedance Measurement Techniques

There are several methods of determining the impedance of a transmission line (backplane). The most direct method is to use time-domain reflectometry (TDR). TDR systems can measure exact impedance values and are easy to use. The user of TDR systems is referred to the TDR manufacturer's documentation and application notes (see [B11]). However, if a TDR system is not available, the backplane impedance can be derived using TDR techniques with common laboratory instruments.

The instruments needed are a high-bandwidth oscilloscope and pulse generator. The bandwidth needed should be greater than or equal to the reciprocal of 3.5 times the rise time of interest. The rise time of interest should be at least as fast as the transition times of devices used on the backplane. The procedure is to measure the incident and reflected waves caused by impedance mismatch between the unknown backplane impedance and a known impedance, and then calculate the impedance using the equations given. The known impedance is the $50\ \Omega$ test environment ($50\ \Omega$ input cabling and $50\ \Omega$ input to scope).

This method should be easy to use and is very accurate. This is because the measurement system is maintained in a $50\ \Omega$ environment and thus any loading caused by the use of probes is eliminated. Also, this method most closely replicates a TDR system.

Figure 4 shows the setup for the impedance measurement. The $50\ \Omega$ input to the scope is connected to the input cable by a T-connector.

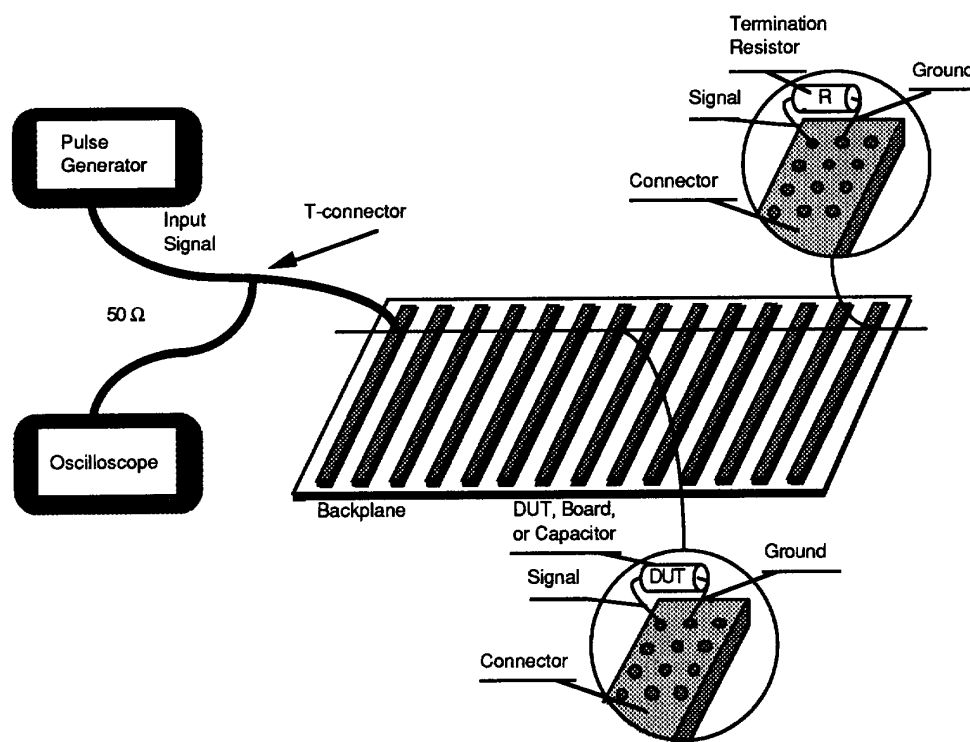


Figure 4— Test Setup for Backplane Impedance Measurement

The derivation for the impedance of the backplane being measured (Z_U) can be aided by the use of a lattice diagram (see Chapter 6 of [B3], pp. 231–235). Figure 5 shows the lattice diagram for measuring the backplane as set up in Fig 4.

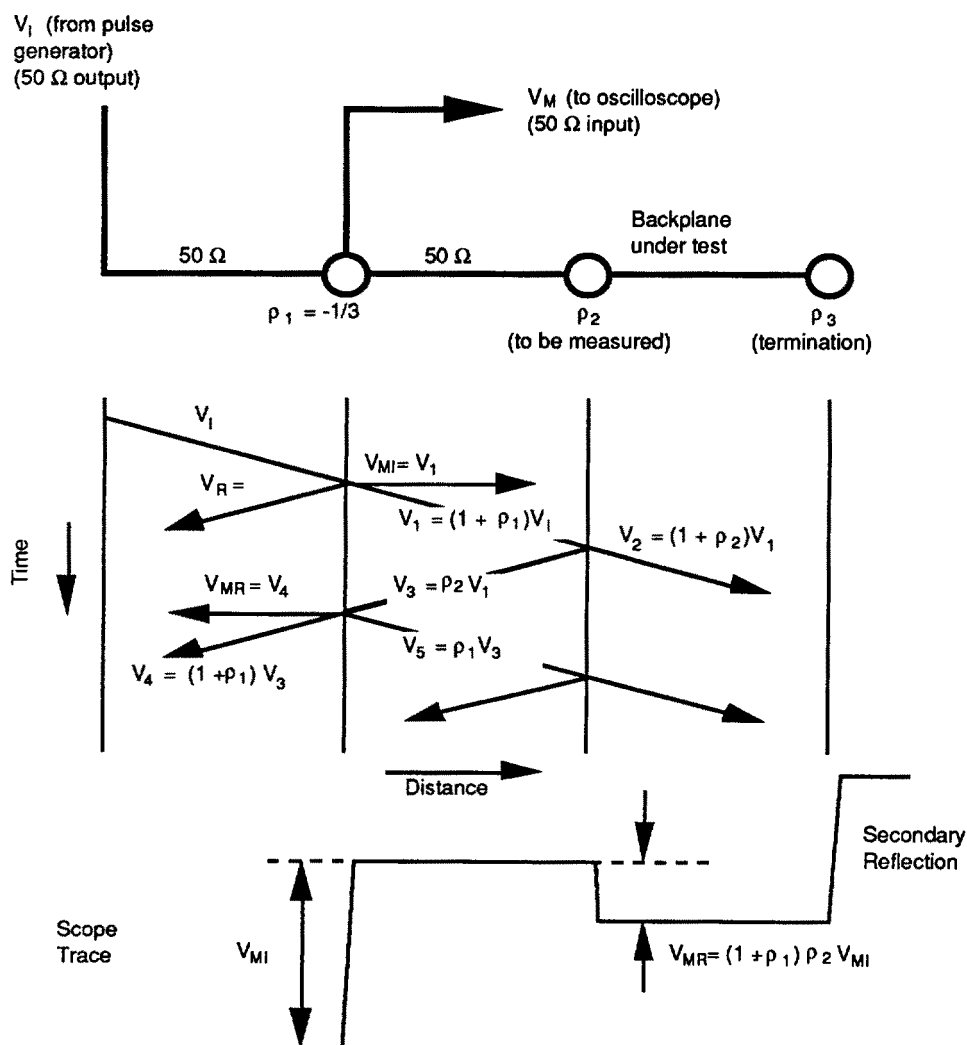


Figure 5— Lattice Impedance Measurement

From the lattice diagram in Fig 5, the reflection coefficient, ρ_2 , at the cable to backplane interface can now be derived, as follows:

$$\rho_2 = \frac{V_{MR}}{V_{MI}} \cdot \frac{1}{1 + \rho_1}$$

where V_{MR} and V_{MI} are measured reflected and incident voltages at the oscilloscope, respectively. Since

$$\rho_1 = \frac{25 - 50}{25 + 50} = -1/3,$$

and the reflection coefficient to be calculated, ρ_2 , equals

$$\rho_2 = \frac{Z_U - 50}{Z_U + 50},$$

the measured backplane impedance, Z_U , can now be written in terms of the measured voltages at the scope only, V_{M1} and V_{M2} , as

$$Z_U = 50 \frac{2V_{M1} + 3V_{MR}}{2V_{M1} - 3V_{MR}}.$$

If the measurement for the reflected wave is the incident plus the reflected wave, as shown in Fig 7, then the impedance of the backplane can be calculated as follows:

$$Z_U = 50 \frac{2V_{M1} + 3(V_{MR} - V_{M1})}{2V_{M1} - 3(V_{MR} - V_{M1})}.$$

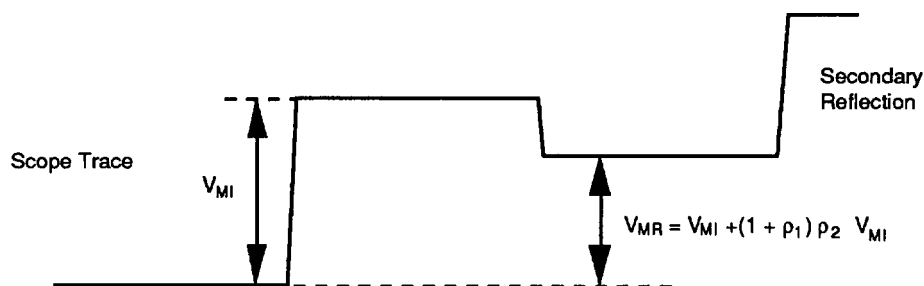


Figure 6— Measuring the Reflected as the Incident Plus the Reflected Wave

In TDR-type measurements, the input signal rise time has to be fast enough to separate the input wave (V_I) from the reflected wave (V_R) and any incidental reflections. The secondary reflection from the far end of the backplane to the termination resistor boundary would be an incidental reflection.

So that the desired reflections can be seen clearly, a rule of thumb is that the rise time must be less than 1/5 the time between reflections. The reflected wave of interest, that of the 50 Ω cable to backplane, will be seen in the round trip from the T-connector to the backplane and back. This distance is set by the cable length. The secondary reflection at the backplane to termination boundary will be seen in the round-trip delay over the entire backplane length. Typically the propagation delays are about 6.5 ns/ft on the backplane. A round-trip delay on a one-foot backplane is 2 times 6.5 ns or 13 ns. The rise time must then be 13 ns/5 or 2.6 ns or faster.

The minimum transition time on the input pulse should also be considered. In order to smooth out the reflections on the backplane created by the connectors for the plug-in cards and the distance between cards, a minimum pulse transition time of more than the two-way delay between connectors should be used. As an example, a typical τ_0 of the intrinsic backplane material might be 1.80 ns/ft. At a card spacing of 1 in, the round-trip delay between card connectors is about 305 ps. The rise time of the input pulse should then be slower than this.

3.2 Capacitance Measurement Techniques

The capacitive effect of a device or board that is to be plugged into a backplane can be determined by the method of reflection matching. This method compares the deflection on a TDR trace caused by the reflection in a wave traveling down the backplane from the device under test (DUT) with a known capacitive load. As in the case for measuring the impedance of the backplane, a TDR would be best suited for the job. However, a similar configuration for measuring lumped capacitance on a backplane can be made like that of backplane impedance measurement, again using common laboratory instruments; see Fig 7.

A voltage step, V_I , applied to the test transmission line, or backplane, shown in Fig 7, should produce a reflection of V_{RDUT} from the device under test (see Fig 8). This reflected voltage bump is equal to a voltage V_{RT} obtained from a test capacitor of equal capacitance to the device under test. The correct capacitive value is obtained by trying capacitors of different values until the same deflection is seen as with the device under test. The test capacitors should be a low-