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High-Performance Connectors—The Often-Underestimated Weak Link

In an era of increasing speed and complexity, designers must perform careful characterizations of available connector options.

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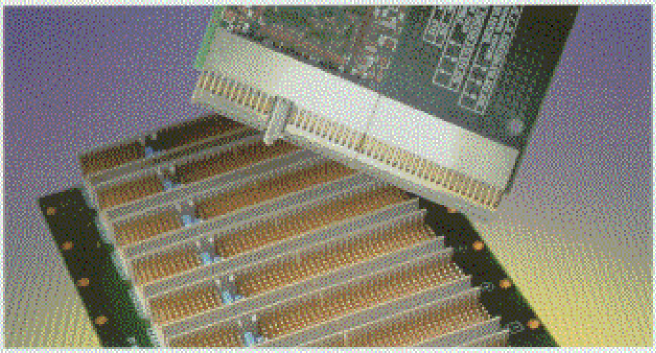
To answer the call for faster systems with ever-increasing I/O rates, manufacturers are revamping older bus structures such as the VMEbus, while developing new bus structures such as the CompactPCI. As a result of these faster data rates, it is more important than ever to hone the interconnect path by focusing on possibly its weakest link—the connector. Because connectors affect both the performance and characteristics of the interconnect path, it is essential for engineers to make more precise measurements to confirm the simulation model used in circuit design. It is important to review the measurement fundamentals, and how basic characteristics are derived from the relevant formulas. Armed with this information, the necessary measurements can then be taken to provide the basis for the verification of a connector SPICE simulation. For this purpose, two popular connector systems will be examined: the older, high-density (HD) 160-pin DIN connector and the 2-mm hard-metric (HM) connector that is used to handle larger numbers of signals and higher frequencies.



The engineer who understands how the connector will behave in the circuit will get products to market more quickly, and with fewer surprises.

Due to the stringent performance demands of higher signal frequencies and data rates, the short electrical length of connectors in the signal path can no longer be ignored. Good electromagnetic compatibility (EMC) and RF performance must be part of the design criteria of all components within the signal path. The key parameters affecting the RF performance of the connector system are: capacitance, inductance, characteristic impedance, signal propagation delay, differential time delay (skew), reflections, phase shift, crosstalk, and shielding efficiency.

Special test boards, made from standard FR-4, were built with pseudo-coaxial layouts *(Fig. 1)*. The signal traces were implemented using 50-Ω stripline construction. SMA connectors were installed for injecting signals and connecting test equipment. Various configurations of ground pins, unused pins, and driven pins were examined *(Fig. 2)*.

Two fundamentally different measurement methods—time domain and frequency domain—were used to measure the parameters. Variable analog frequencies were used for the measurements in the frequency domain. In addition, a network analyzer, a signal generator with a spectrum analyzer, and a Wheatstone bridge arrangement measured capacitance, inductance, reflections, and crosstalk.

In general, digital signals with very fast rise-times are used for time-domain measurements, with a time-domain reflectometer (TDR) as the measuring instrument. This method obtains the characteristic impedance curve and the signal propagation delay.

The digital signals change state very rapidly (in the region of picoseconds), and produce a frequency spectrum that extends up to 20 GHz (due to the edge-rate effect). As a result, the measuring setup must meet tight

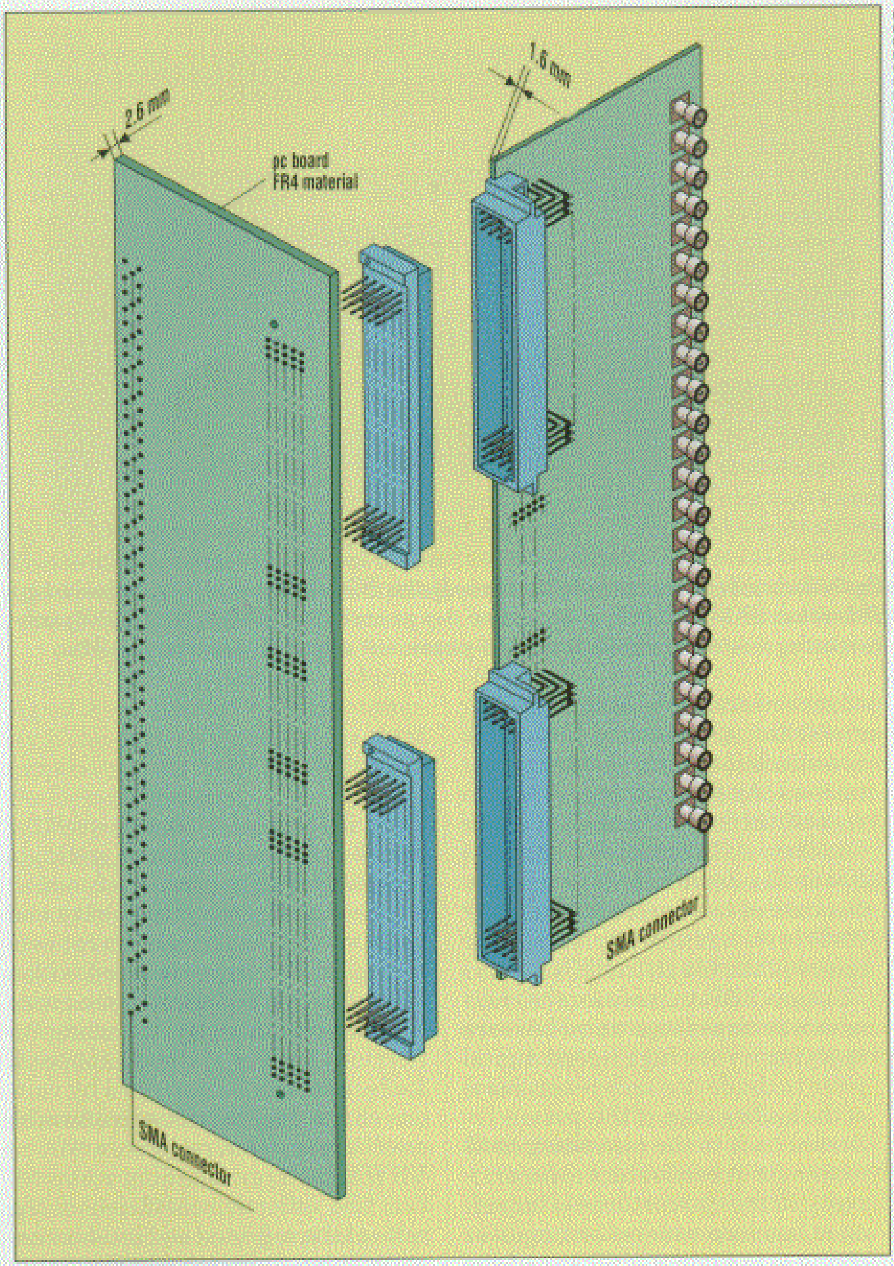


Fig. 1: RF measurements on connectors were made using a printed-circuit test board made from FR4 material. The signal traces were implemented using 50-Ω stripline construction and SMA connectors were installed for injecting signals and connecting test equipment.

specifications or spurious effects may substantially corrupt the results. In addition, the RF behavior of the connector also is a function of the signal's rise time. For sinusoidal signals, the frequency is easily determined. For digital signals, the equivalent analog frequency spectrum must be calculated. Fourier analysis can be used, and the following approximation is appropriate:

$$f_{An}(MHz) = 5 \times f_{Dig}(MBit/s)$$

or

$$f_{An}(MHz) = \frac{350}{T_r(ns)^*}$$

*Tr = rise time

Analyzing Parameters

Capacitance and inductance are the two key quantities which determine the characteristic impedance. The characteristic impedance is an important factor when considering the RF behavior of connectors.

The capacitance of a parallel-plate capacitor is given by the following formula:

$$C = \frac{A \times \varepsilon_r \times \varepsilon_0}{s}$$

Where A is the surface area, ε_r is the dielectric constant, ε0 is the electric constant (permitivity of free space), and s is the distance between the plates. Therefore, the smaller the distance between the plates and the greater the area of the plates, the larger the capacitance. Additionally, the capacitance is directly proportional to the dielectric constant (air = 1). Crosstalk in connectors is caused by, and directly proportional to, the coupling capacitance.

The inductance (L) of a straight, round conductor is given by the following formula:

$$L = \frac{\mu}{2\pi} \times l \times \left(\ln\frac{2l}{r} - 3/4 \right)$$

One basic point is that the inductance increases as the length of the conductor increases, while it decreases with increasing conductor cross-section. An inductance of 8 to 10 nH/cm can be assumed to be as constant as possible over its entire length as it determines the characteristic impedance curve. Any abrupt impedance changes or discontinuities will cause reflections. Inductance in the ground path (ground bounce) plays an important role in signal transmission through connectors featuring a large number of contacts. The effect of this inductance can be reduced by increasing the number of connector pins that are used as a ground connections through on the connector. This lowers the total inductance in the connector's ground path, reducing interference at high data rates.

Characteristic Impedance

As mentioned previously, the characteristic impedance of a conductor is a function of its inductance and capacitance, and can be defined as the line impedance seen by a current that is varying with time (signal).

At high frequencies, this can be approximated as:

$$Z = \sqrt{\frac{L}{C}}$$

In other words, the lower the capacitance C, and the higher the inductance L, the greater the characteristic impedance, and vice versa. If substitutions for capacitance and inductance are made in the impedance formula, an important expression for discussing pseudo-coaxial arrangements can be obtained. The smaller the separation between the signal and the ground contacts, or the larger the surface area between the signal and the ground contacts (for example, higher capacitance), the lower the characteristic impedance. Conversely, the characteristic impedance increases as the conductor cross-section decreases (due to higher inductance).

These interrelationships are important when interpreting the impedance characteristic of connector assemblies, and must be taken into consideration when designing connectors. As far as crosstalk is concerned, the lower the characteristic impedance of neighboring lines, the lower the crosstalk. However, in the case of bus systems, the lower limit is determined by the driver power of the bus driver ICs.

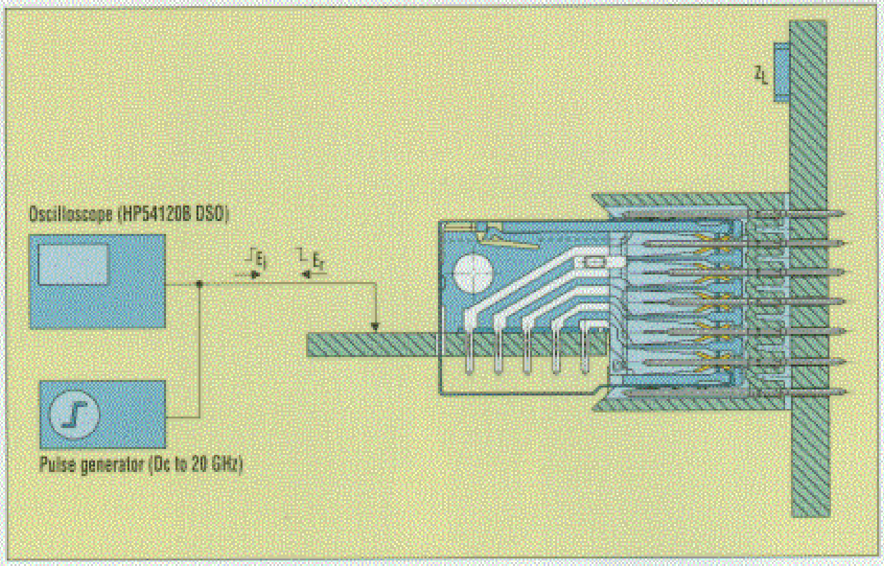


Fig. 3: The impedance characteristic, signal propagation delay, and skew were determined using TDR with an HP 54120B DSO, a four-channel step generator (dc to 20 GHz, HP 54121A), and terminating resistors, in addition to a special-purpose test adapter for connector assemblies.

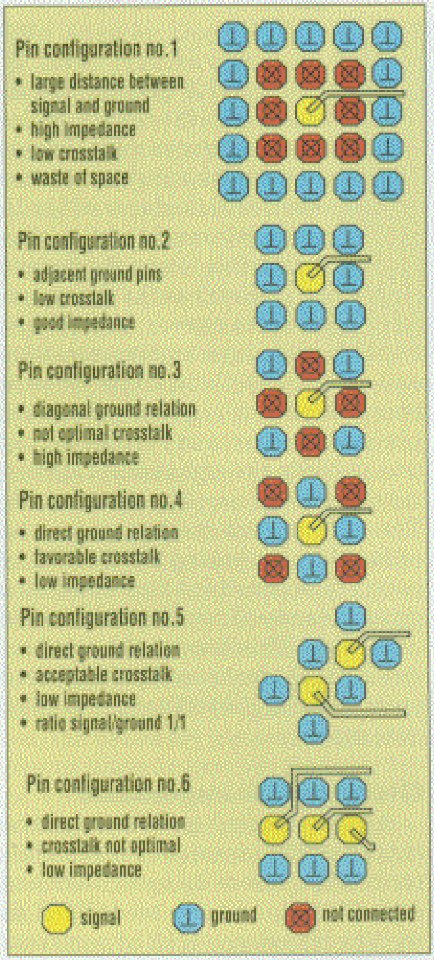


Fig. 2: Various configurations of ground pins, unused pins, and driven pins were examined to find the optimum layout.

Using a TDR to measure the characteristic impedance curve involves applying a very high-speed digital pulse to the device-under-test. Some of the leading edge of this pulse is reflected back to the measuring head whenever it encounters a discontinuity in the characteristic impedance, such as conductor bends or changes in diameter/ shape of the conductors within the connector. The characteristic impedance along the line is then calculated, with reference to an impedance (50 Ω), from the amplitude of the reflection of the injected signal. The measuring system's resolution is determined by the dielectric constant and, crucially, by the rise time of the pulse. The propagation speed of the measurement pulse is given by:

$$v_l = v_c / \sqrt{\varepsilon_r}$$

Consequently, the resolution, x, is given by:

$$X = v_l \times t_r / 2$$

or

$$X = (v_c \times t_r) / (2 \times \sqrt{\varepsilon_r})$$

A rise time of 35 ps was used for the above measurements, giving a resolution of approximately 3 mm.

The signal propagation delay and skew values for the various connector styles also were recorded with a TDR. The TDR plots indicate twice the propagation delay (including reflection) for any given signal path. Reflections can be described by various characteristic values: reflection coefficient, return loss, and the VSWR (voltage standing wave ratio). The reflection coefficient is the ratio of the reflected and incident energy at an unmatched transition point, and is equal to the ratio of the impedances (r = (Z-Z)/(Z+Z)). The return loss is the log of this ratio a= -20log r.

A standing wave is produced when the reflected and incident waves are superimposed, and the VSWR is the difference between the maximum and the minimum wave energy. The VSWR can be calculated from the reflection coefficient using the following formula:

$$VSWR = \frac{1+r}{1-r}$$

The reflection not only depends on changes in impedance, but also on the

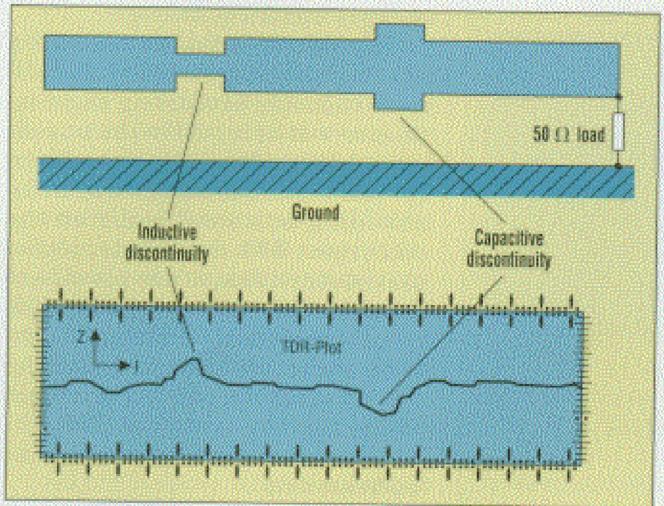


Fig. 4: A TDR profile of a microstrip line with abrupt changes in characteristic impedance clearly indicates the inductive and capacitive discontinuities and their effect on the TDR plot. The trace of the reflected voltage is shown on the DSO.

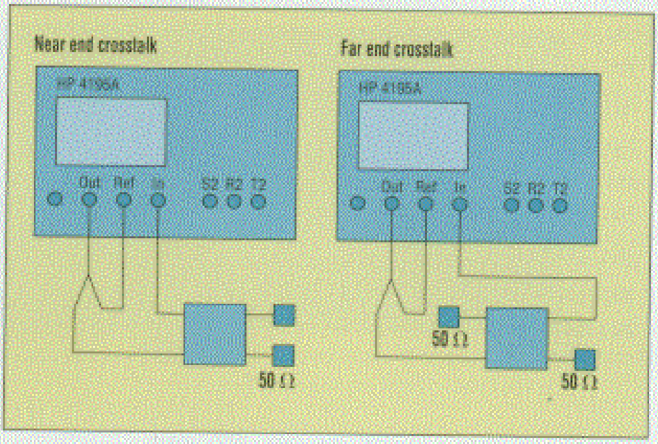


Fig. 5: Both near- and far-end crosstalk were determined with slightly differing measurement setups. In both cases, the test signal was applied to the pc board. In the case of near-end crosstalk the signal was measured on the pc board. The near-end crosstalk is the sum of capacitive and inductive coupling, while far-end crosstalk is the difference between capacitive and inductive coupling.

length of the discontinuity. A digital signal is not affected by a discontinuity if the edge's transit time is short (approximately <1/25) in relation to the signal's rise time.

The parameters of crosstalk and shielding are discussed in greater detail in the description that follows, however, inductance and capacitance also produce a phase shift between current and voltage. In addition, in the case of connectors, the capacitive effects are much greater than the inductive effects.

Measurement Setup

All measurements were conducted with the test pc boards described earlier for the various pseudo-coaxial configurations. For measuring capacitance and inductance, a network/impedance analyzer, an impedance adapter, and a special-purpose test adapter were used. Capacitance and inductance were measured from 50 to 500 MHz. The measured values for f = 100 MHz are compared in the following evaluations. The characteristic impedance was calculated from the formula $Z = \sqrt{L/C}$. The impedance characteristic, signal propagation delay and skew were determined using the TDR. The TDR was an HP 54120B digital storage oscilloscope (DSO), a 4-channel step generator (dc to 20 GHz, HP 54121A) and terminating resistors, in addition to a special-purpose test adapter for connector assemblies *(Fig. 3)*.

A TDR profile of a microstrip line with abrupt changes in characteristic impedance clearly indicates the inductive and capacitive discontinuities and their effect on the TDR plot *(Fig. 4)*. The trace of the reflected voltage is shown on the DSO. The TDR profile makes it possible to determine not only the impedance characteristic, but also the propagation delay as well as the skew. The specified propagation delays relate to the signal's forward and return journey.

Crosstalk

Crosstalk is defined as the ratio of the measured voltage to the signal voltage, and can be expressed in percentage or in dB (the log of this ratio). To measure crosstalk, a pulse generator (HP 8657B), a spectrum analyzer (HP 8562A) or network/impedance analyzer (HP 4195), power divider, and terminating resistors (50 Ω), in addition to a special-purpose test adapter were used. Both near-end and far-end crosstalk were determined with slightly differing measurement setups *(Fig. 5)*.

In both cases, the test signal was applied to the pc board. In the case of near-end crosstalk, the signal was measured on the pc board. In the case of far-end crosstalk, the signal was measured on the backplane. The near-end crosstalk was the sum of the capacitive and inductive coupling, while the far-end crosstalk was the difference between capacitive and inductive coupling.

Results And Evaluation

The measurement results for a specific pseudo-coaxial pin configuration for the 2.54-mm HD 160-pin DIN connectors and the 2-mm HM connectors are shown in Figures 6(a) and (b), respectively. The signal pin is surrounded by ground pins in a pseudo-coaxial array. This design provides a direct ground reference.

The configuration is characterized by a signal-to-ground ratio of 1:1, a low characteristic impedance, and acceptable crosstalk values.

In comparing the measured values for the HD 160-pin DIN connectors and the 2-mm HM connectors, the differences are already very clear at a frequency of 100 MHz *(Fig. 7)*. The characteristic impedances show the various TDR plots for the same pin configuration for two different connectors. The impedance fluctuations in the area of connectors differ greatly. For example, while the impedance of the HD 160-pin DIN connector fluctuates between approximately 53 and 100 Ω, the 2-mm HM connector features a very smooth characteristic impedance curve.

The 2-mm HM connector also showed very good results for propagation delay and skew. The plots clearly indicate the influence of vias which cause abrupt impedance

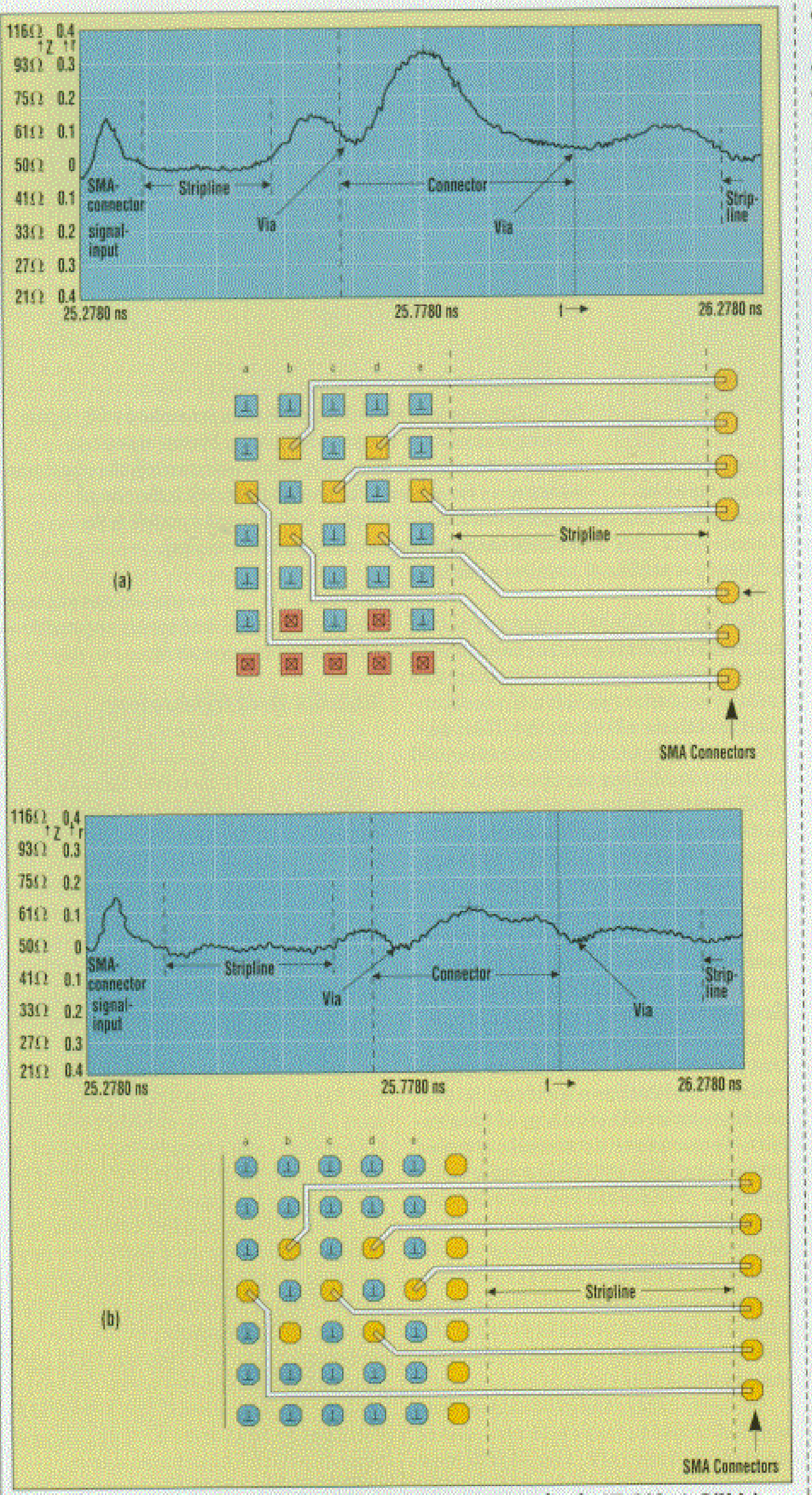


Fig. 6: The TDR plots for the same pin configuration (at 100MHz) for the HD 160-pin DIN (a) and the 2-mm HM (b) connectors show that the impedance fluctuations in the area of connectors differ greatly. The plots also clearly indicate the influence of vias which cause abrupt impedance changes that are quite large.

changes that are quite large.

The measurements assessing the effect of shielding on crosstalk indicated that only a relatively slight influence was detected in the impedance-matched signal lines (pseudo-coaxial structure). The shielding acts specifically on the outer rows. With the various pseudo-coaxial structures, it was possible to decrease the crosstalk by 20 to 30% by using shielding. For signal contacts without impedance matching (i.e. no ground pins), the crosstalk was reduced by as much as 120%.

Conclusions

These results allow for some general requirements applicable to all connectors and pc boards for RF signal transmission:

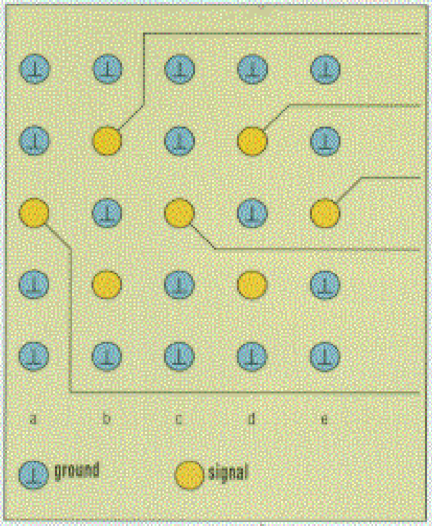
- The connectors should have an impedance as close to 50 Ω as possible (*Fig 6b*), and as low a capacitance as possible at the terminals. It can be seen that the impedance is up around 93 Ω, then down to 61 Ω *(Fig. 6a)*.
- Importance must be attached to consistent mechanical geometries and consistent conductor cross-sections. Impedance is constant and the curve is smooth (*Fig 6b*). These conditions are due to the uniform mechanical dimensions of the contact cross section within the connector path.
- All signal paths within the connector should have approximately the same length to avoid signal propagation skew, hence the serpentine contact path for the 2-mm HM connector *(Fig. 3)*.
- All blades, beams, and tails should be as short as possible.
- For right-angle connectors, the contacts should be embedded in plastic with no variation in the dielectric. Typically, HD 160-pin DIN connectors have contacts in open air, while the 2-mm HM connector has the right-angle leads within the plastic. This arrangement is responsible for the bottom end of the curve dropping down as it approaches the via *(Fig. 6a)*.
- Any abrupt discontinuities in the signal path must be eliminated. The design and geometry of the contacts themselves can have a substantial influence on performance.

Of course, certain features of the pc board itself affect the RF characteristics. These include, the trace geometry, the pc board's dielectric layer construction, capacitance of the via design, and power and ground plane spacings. Ground leads and grounding surfaces also should have a low impedance. Other requirements include proper termination design, trace isolation, and minimum stub lengths. Besides selecting a suitable pc-board laminate, it also is necessary to ensure compliance to the design tolerances during lamination, etching, and plating.

All of the above factors contribute to the electrical characteristics of the interconnect path, but it is important to realize that they all are within the control of the designer—with the exception of the signal path within the connector itself. This path has a fixed geometry, and its effect can either complement or degrade the interconnect system. For this reason, it is essential that the connector be fully characterized and chosen carefully for its intended application. The engineer who understands how the connector will behave in the circuit will get products to market more quickly, and with fewer surprises.

Prior to joining ERNI Elektroparate GmbH as an engineer in 1991, Roland Modinger was with ERNI's sister company, Regletron (Adelberg, Germany). At Regletron, Mr. Modinger was involved in software and hardware design. Before joining the ERNI Group, he was an engineer with Bosch Telecommunications in Germany.

Michael Munroe joined ERNI USA in 1995 as product manager for the ERmet 2-mm HM connector line. Currently, Mr. Munroe is responsible for evaluating new products for the VME and CompactPCI industry. Prior to joining ERNI, Mr. Munroe was Strategic Marketing Manager at Hybricon Corp.

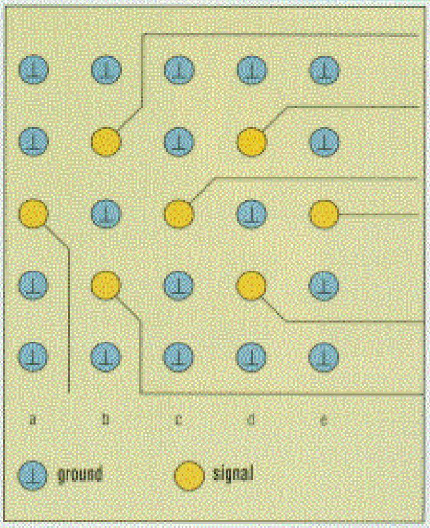


The measurement values in the table below are based on this pin configuration

Parameter	Connector pin row				
	a	b	c	d	e
Capacitance C (f = 100 MHz)	2.5 pF	2.8 pF	2.9 pF	3.1 pF	3.2 pF
Inductance L (f = 100 MHz)	6.8 nH	7.6 nH	8.3 nH	8.7 nH	10.5 nH
Characteristic impedance	52 Ω	52 Ω	53 Ω	53 Ω	57 Ω
Propagation delay*	111 ps (86) ps	119 ps (94) ps	126 ps (101) ps	141 ps (116) ps	157 ps (132) ps
Signal skew	8 ps	9 ps	14 ps	15 ps	
	maximum 46 ps				
Crosstalk (f = 100 MHz)	← 57 dB →				
			← 53 dB →		
Reflection factor (50 Ω and f = 100 MHz)	0.02	0.02	0.03	0.03	0.065
VSWR (f = 100 MHz)	1.04	1.04	1.06	1.06	1.14
Reflection loss (f = 100 MHz)	34 dB	34 dB	30.5 dB	30.5 dB	24 dB

* The higher value of the propagation delay is measured from solder-side to solder-side. The value in parenthesis is calculated from component-side to component-side.

5 row 2mm HM connector



The measurement values in the table below are based on this pin configuration

Parameter	Connector pin row				
	a	b	c	d	e
Capacitance C (f = 100 MHz)	2.8 pF	3.05 pF	3.2 pF	3.3 pF	3.4 pF
Inductance L (f = 100 MHz)	8.8 nH	9.8 nH	12.7 nH	14.0 nH	17.0 nH
Characteristic impedance	56 Ω	57 Ω	63 Ω	65 Ω	70 Ω
Propagation delay*	126 ps (101) ps	145 ps (120) ps	161 ps (136) ps	176 ps (151) ps	193 ps (168) ps
Signal skew	19 ps	16 ps	15 ps	17 ps	
	maximum 67 ps (row a to row e)				
Crosstalk (f = 100 MHz)	← 48 dB →				
Reflection factor (50 Ω and f = 100 MHz)	0.056	0.065	0.115	0.13	0.166
VSWR (f = 100 MHz)	1.12	1.14	1.26	1.3	1.4
Reflection loss (f = 100 MHz)	25 dB	24 dB	19 dB	18 dB	15.5 dB

* The higher value of the propagation delay is measured from solder-side to solder-side. The value in parenthesis is calculated from component-side to component-side.

5 row DIN 41612 connector

Fig. 7: Measured values for a frequency of f = 100 MHz.