EMC in I/O Cables

RONALD W. BRENNIAN, JR., JEFFREY L. SHOWERS, and ROBERT L. WILLIAMS, JR.
AMP Incorporated

INTRODUCTION

EMC would be easier to attain without interconnecting cables. Input/output (I/O) points can be major sources of EMI, forming a window for EMI to enter and exit an otherwise tightly shielded box. What's more, cables can act as antennas, radiating and receiving noise when the length of the cable approaches one-quarter wavelength. Interconnecting cables can often radiate more energy than the device itself.

The control of EMI falls into two complementary categories: signal transmission quality (STQ) and electromagnetic compatibility (EMC). STQ applies to maintaining high-quality signals that do not become distorted through ringing, jitter, differential delays, and other phenomena. EMC, on the other hand, relates to controlling conducted and radiated emissions. For example, STQ considers the effects of crosstalk; EMC considers the same energy as it radiates or is conducted from the cable. STQ also can help reduce EMI problems by mitigating the causes of EMI. Basic STQ issues such as choice of logic family, pulse rise times, and pc board layout can all affect EMI in both a positive and negative sense.

Traditionally, EMC focused on preventing a device from producing EMI. Recent European requirements also demand that a device not be susceptible to EMI. Emissions and susceptibility are related: efforts to control one are generally effective against the other. A shielded cable, for example, serves equally well at containing EMI generated by the system and preventing external EMI from entering the system via the I/O cable.

A shielded cable serves equally well for containing EMI generated by the system and preventing external EMI from entering the system via the I/O cable.

There are several approaches to controlling EMI in a cable:

- System design, done properly, can reduce the generation of EMI.
- Shielding is used to control susceptibility. Filtering is used to control conducted noise.
- Grounding is essential to achieving good shielding and filtering.
- Immune to EMI, fiber optics is an alternative to copper cables.

SYSTEM DESIGN: THE ESSENTIAL FIRST STEP

The importance of designing with EMC in mind from the beginning cannot be stressed enough. Good design practices are the essence of STQ and EMC. STQ/EMC efforts at the front end can often reduce system and design costs in the long run. Most importantly, they can eliminate last-minute corrections that become necessary when a device fails to pass regulatory requirements. Not only are last-minute fixes expensive to implement, they can also be costly in terms of redesign and delayed entry to market.

Basic issues like transmission modes and signal encoding can dramatically affect the signal integrity and the likelihood of EMI. Digital speeds are pushing to ever higher limits in everyday applications. Most high-speed designs are moving toward balanced transmission rather than single-ended transmission. From an EMC standpoint, a high-impedance single-ended transmission is the least efficient. Such systems, using ribbon cable or discrete-wire cables, are limited to low speeds and short distances. The high impedance allows energy to radiate more easily, while capacitative coupling allows crosstalk. The amount and severity of crosstalk depends on the relationship between signal conductors and ground. A single conductor used as a ground return places each conductor a different distance from ground, thus showing a different capacitance to ground. If the driven line is separated by several other conductors, energy capacitively coupled from the driven line to ground appears on one or more of the intervening conductors.

Transmission efficiency can be improved by lowering the apparent circuit impedance, shielding the cable, increasing the driver signals, and using balanced mode transmission. Circuit impedance can be lowered by using more grounds, preferably in a signal-ground-signal-ground arrangement (Figure 1). The drawback, of course, is that more and more conductors must be dedicated to ground. For rise times of over 10 ns, a limited number of grounds suffices. At 10 ns, a signal-to-ground

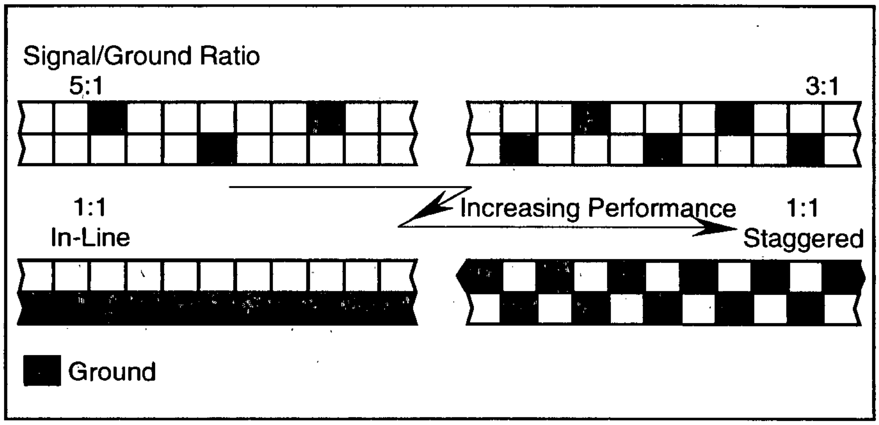

Figure 1. *A Generous Use of Grounds— Up to a 1:1 Signal-to-ground Ratio at Rise Times of 1 ns or Faster— Will Improve High-speed Performance.*

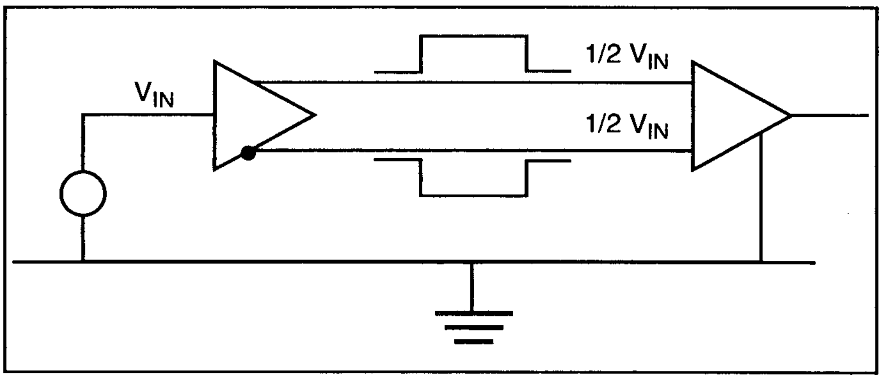

Figure 2. *Balanced-mode Transmission Offers Improved EMC Performance.*

ratio of 5:1 is recommended. By the time the signal rise time reaches 1 ns, the ratio should be 1:1.

A balanced circuit (Figure 2) offers improved performance, but is more complex. The balanced circuit uses two conductors to carry the signal. Ideally, the conductor and all circuits attached to them have the same impedance with respect to ground, which serves as a reference potential rather than signal return.

Each conductor carries a signal that is of equal potential but opposite polarity to the signal on the other conductor. A 5-V signal is carried at +2.5 V on one conductor and -2.5 V on the other conductor. A differential receiver detects only the difference in voltage between the two conductors. The balance cancels impinging noise. A perfectly balanced line rejects all common-mode noise voltages; real-world lines have some degree of imbalance so that not all noise is rejected by the receiver. Still, balanced-mode transmission offers much better EMI immunity. Twisted-pair cable is popular for balanced lines since the twisting forms small loops that cancel magnetically induced noise.

Line coding schemes also can play a role in EMC by allowing high digital rates within a low frequency envelope. Two methods growing in popularity are multilevel transmission (MLT) and carrierless amplitude and phase (CAP) modulation. MLT-3 is a three-level transmission scheme used in TP-PMD, the version of fiber distributed data interface (FDDI) for unshielded twisted-pair cable. The 125-Mbps transmission rate uses a cable bandwidth of only 31.25 MHz — a 4:1 bandwidth efficiency. CAP schemes use discrete combinations of amplitude and phase of a baseband frequency to encode several bits. For example, 16-CAP uses 16 different combinations of phase and amplitude differences to represent four bits each.

SHIELDING FOR RADIATED EMI

The purpose of shielding is to isolate conductors from the outside world. The shield provides a conductive path for noise, whether originating inside or outside the cable, to ground. While shielded cables come in many variations, the most popular types of shields are solid tube, woven braid, expanded mesh, and foil or foil/polymer laminate. Many cables contain multiple shields, such as a braid and foil combination.

The most effective shields provide total coverage of the entire cable. Any gaps or discontinuities present possible windows for EMI to enter or exit. Shield thickness is not usually an issue since currents induced by EMI are surface currents. The ideal shield is a conductive, discontinuity-free material that provides a uniform path to ground for current. Any discontinuities cause a constrictive resistance and a higher impedance. A braided shield, for example, typically offers from 60 percent to 90 percent coverage — less than 85 percent can degrade the shield's performance. Foil shields provide complete coverage, but tend to be harder to terminate and more fragile than braided shields. Laminating a polymer film to the foil increases its sturdiness.

The cable must be grounded at one or both ends. Drain wires to terminate the shield should be avoided. A pigtail or drain wire presents a high inductance and resistance to high-frequency noise, preventing proper termination and acting as an antenna. Such a poor connection can be a major form of EMI coupling, and can seriously compromise the effectiveness of the shield.

The best shield termination is a 360° one that maintains a low-impedance path to ground (Figure 3).

Continued on page 91

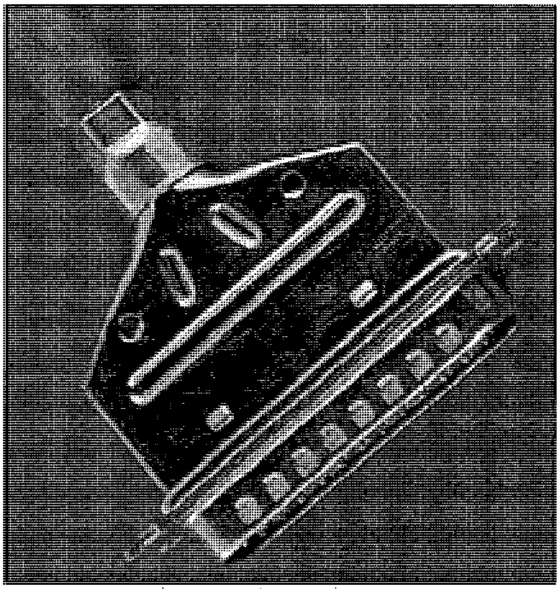

Figure 3. *Shielded Connectors Should Provide a 360° Termination of the Cable Shield and Maintain a Low-impedance Path to Ground.*

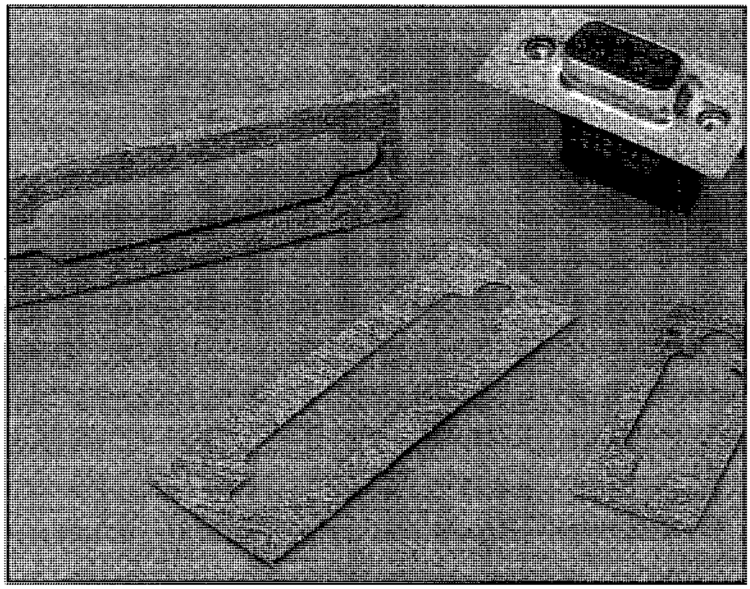

Figure 4. *EMI Gaskets can Eliminate Discontinuities at I/O Ports.*

Most shielded connectors today offer such an all-around shield termination. Equally important is to connect the shield to earth ground, such as a chassis or bulkhead. Using signal ground on a printed circuit board invites the addition of noise into the signal circuit through common-impedance coupling.

Choice of materials and shield thickness are not as important as maintaining a conductive path. However, electrolytically dissimilar materials, which can result in performance-degrading galvanic corrosion, should be avoided. A steel ferrule, for example, should not be used to terminate a copper shield. Many shielding mechanisms also form a strain relief/backshell, so they are quite sturdy. Both metal and metal-plated plastic backshells can be used. All-metal shields typically offer better performance, but metal-plated plastic is more than adequate in many applications.

At the mating point between the bulkhead and cable connectors, it is again important to avoid discontinuities that will raise the impedance and degrade shielding performance. Connectors mate the shields through a friction fit that may only provide a minimum of actual intimate contact between the mated metals. This creates high impedance across the junction. Consequently, most connectors are designed with spring members, bumps, or other features that maintain intimate electrical contact between the shielding members.

The best coverage at the mating interface is through EMI gaskets, which serve two purposes: they maintain a low-impedance path to ground for shield currents, and they close up any remaining gaps at the port to prevent EMI from radiating into or out of the system. A popular type of gasket for this application uses a metallized fabric wrapped around an elastomer core. Nickel over copper on a polyester fabric offers excellent conductivity without the galvanic corrosion concerns associated with a silver-plated fabric. Shielding effectiveness exceeds 80 dB. A good gasket requires compression on the order of 30 to 50 percent. A neoprene core provides good compression and memory, so that compression set (a loss after extended deflection of the complete springback when the deflection force is removed) is minimal. An additional convenience of gaskets is the ease with which they are custom fabricated to fit the port cutout of the system (Figure 4).

While it is desirable to ground the shield at both ends, this can create ground loops if the chassis grounds at each end are at different potentials. These differences in potential between boxes can result in high low-frequency currents, which can also occur between signal-reference grounds. While the shield can be uncoupled at one end, if the cable is longer than 1/6 wavelength, it will act as an excellent RF antenna that will significantly degrade the shielding effectiveness of the system. Adding a capacitance in the form of a dielectric gasket between connector and bulkhead can produce a high-impedance path to ground noise and a low-impedance path to high-frequency EMI.

The common method of expressing the performance of a shielded cable, connector, or cable assembly is shielding effectiveness. A shielding effectiveness test compares the emissions from shielded and unshielded samples in a shielded room. Unfortunately, this method tells more about the shield's performance under the specific conditions of the test than about the intrinsic quality of the shield. Small changes in the test setup can significantly change the measured shielding effectiveness.

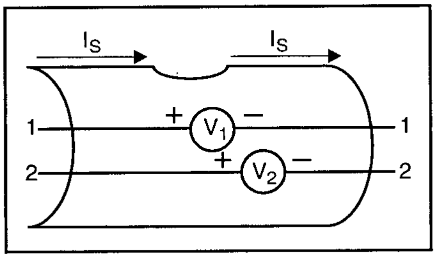

Figure 5. *Transfer Impedance Provides a Useful Measure of Shielding Performance.*

A more useful concept to describe the performance of a shield is transfer impedance (Figure 5). Consider surface currents on the outside of the shield. Through some mechanism, energy will couple to the conductors within. This energy can be represented as a voltage source inserted in series with the internal conductors. The ratio of this voltage to the outside surface current is the transfer impedance.

A lower transfer impedance means better shielding, fewer emissions from the cable and less induced external noise on the conductors. One advantage of using transfer impedance is that it only requires a current to exist on the shields. There is no need to consider the electromagnetic problem that put it there.

The mechanisms that allow the surface currents to couple energy onto the conductor include diffusions, aperture coupling, and junction effects. Diffusion is the natural propagation of electromagnetic energy through a material and is affected by the shield's conductivity and thickness. Lower conductivity and thinner shields mean higher diffusion. Reducing diffusion requires a high conductivity shield of sufficient thickness. A thickness of three skin depths is usually sufficient. Skin depth is a frequency-dependent quantity that can be expressed as an amplitude reduction as the wave passes through the material — about 37 percent for each skin depth. For most metals at high frequencies, this requires only a few thousandths of an inch.

Apertures allow coupling by capacitive and inductive coupling. Openings in the braid and seams in connectors can offer apertures.

Junction effects are the discontinuities formed by joining different components in the shielded cable assembly — cable shields-to-connector shields, cable connector-to-bulkhead connector, and bulkhead connector-to-ground. Each junction will contribute a voltage drop whose magnitude depends on the quality of contact between the materials.

FILTERING FOR CONDUCTED EMI

Filtering is used to combat conducted EMI. Since conducted interference can also radiate, filters can aid control of radiated emissions by eliminating them before they enter an I/O cable. Among the most important characteristics of the filter are the cut-off frequency and the insertion loss as a function of frequency. The cut-off frequency is that frequency at which the energy is attenuated 3 dB. Insertion loss is the amount of filtering at a given frequency and depends on the type of filter used. Typical values range from under 20 dB to over 90 dB at 100 MHz.

Filtering can be done with inductive, capacitive, or inductive-capacitive networks in both tubular and planar configurations built directly into connectors. The type of filtering selected depends on the amount of filtering required and the frequencies to be filtered.

Inductive filtering presents a high series impedance at high frequencies. At low frequencies, the inductor presents an impedance essentially the same as that of the conductor. At high frequencies, the inductor — typically a ferrite in filtered connectors — is lossy to increase the impedance.

Capacitive filtering between the signal conductor and ground presents a low-impedance to high-frequency noise and a high-impedance path to low-frequency noise. Consequently, noise is shunted to ground while signals are passed.

Inductive-capacitive filters combine ferrite and chip or film capacitors to form L- or pi-filter networks, combining the effects of both capacitance and inductance in decoupling noise and passing signals. While tubular filters provide flexibility in achieving different inductive and capacitive values and can offer high insertion losses, their relatively large form factors run against the trend toward miniaturized connectors. Ferrite blocks and chip and film capacitors are more conveniently applied in high-density connectors, especially if compatibility with unfiltered counterpart is important. Figure 6 shows typical insertion loss curves for filtered connectors using various filtering techniques.

Most filters operate reflectively; they present an impedance mismatch to EMI, reflecting the noise back toward the source. One important thing to note about filter specifications is that insertion loss is typically tested according to the requirements of MIL-STD-220, which specifies a 50-ohm system. Thus, mismatches are measured against 50-ohm sources and loads. If a system uses significantly different impedances, the degree of mismatch, and hence filtering, will change.

As mentioned, filters can be built directly into a connector. Most standard I/O connectors — subminiature-Ds, circular DINs, modular jacks, and miniature ribbon telecom connectors — are available in filtered versions (Figure 7). Most popular are drop-in replacement types having a footprint and pinout identical to the unfiltered connector they replace. A change from a filtered to an unfiltered interface with no or minimum redesign of the board or system can usually be made. Like the shielded cable, however, the filtered connector must be well grounded to chassis ground for the same reason: to provide a

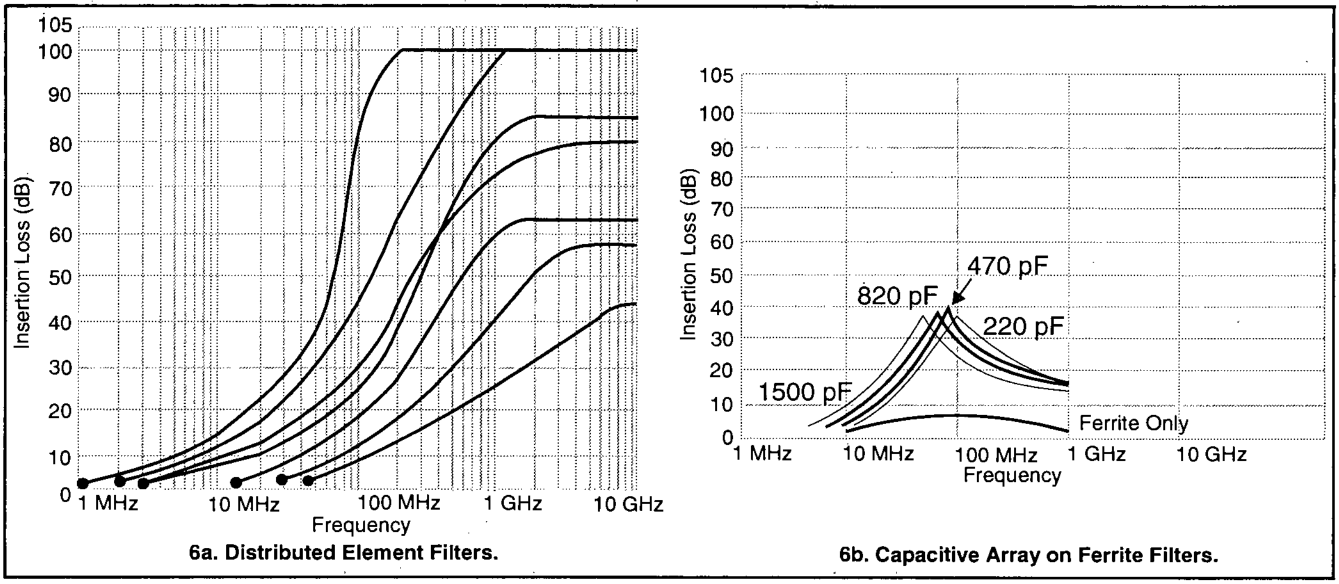

Figure 6. *Typical Insertion Loss Curves for Various Types of Filtered Connectors.*

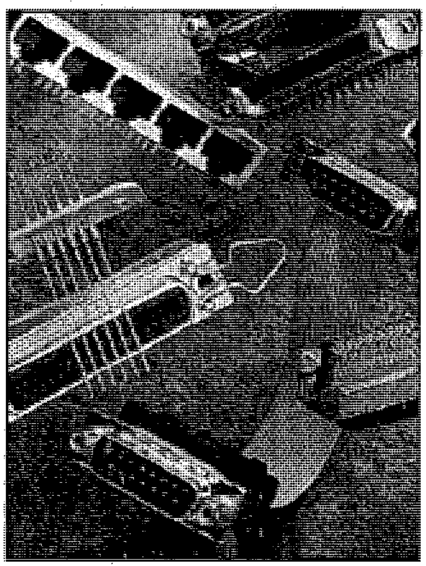

Figure 7. *Filtered Versions of I/O Connectors.*

low-impedance area for EMI to pass to and be dissipated. Failure to adequately ground the connector will degrade filtering performance.

Placing the filter in the connector has additional benefits in allowing flexible system configuration. For example, connectors may be stacked one above the other in a single unit, saving valuable space on the board and maintaining footprint compatibility with unfiltered versions. Filters can be built into each of the stacked connectors, something not practical if the filtering is done on the board. In fact, one concern with on-board filtering is the need to keep the filters as close to the output port as possible.

Printed circuit board design places discrete ferrite beads and capacitors directly behind the I/O connector, with traces for signal transmission between them. However, as little as 2 cm of circuitry contains enough inductance to create an antenna effect at frequencies over 100 MHz. This threatens the filtered signals before they leave the board and allows incoming signals to degrade system performance. Placing the filters in the connector puts the filtering directly at the I/O port and minimizes the effects of inductance. This can be especially helpful with a stacked connector since the circuit path is even longer to the upper connector.

Another type of filter is the distributed-element filter, which offers exceptionally high insertion loss at high frequencies. The filter consists of a sleeve of ferrite surrounded by a barium titanate ceramic. During manufacturing, the ceramic is sintered to the ferrite to form a one-piece sleeve that is plated inside and out. The one-piece construction distributes the inductance and capacitance along the length of the sleeve.

At high frequencies, the filter is modeled as a lossy coaxial transmission line. The capacitance passes high frequencies to the ferrite, which absorbs the energy. Most of the insertion loss is through this absorption and dissipation, rather than by reflection. Reflection accounts for only about 12 dB in a 50-ohm system. Insertion loss values can exceed 100 dB well into the gigahertz range; the filters also have a steep slope — 60 dB per decade — meaning that their insertion loss increases very quickly as frequencies increase. In contrast, a capacitive filter has a slope of about 20 dB/decade.

PRACTICAL FILTERING GUIDELINES

- Place the filter as close to the source of EMI as possible. Doing so eliminates the possibility of noise coupling to another line before encountering the filter.
- Place a reflective filter to achieve the greatest impedance mismatches. An inductor should face a low impedance and a capacitor should face a high impedance.
- Ensure that the filter is well grounded. A poor connection to ground presents a high-impedance path that degrades performance.

Continued on page 268

- Make sure that the bulkhead is sufficiently sized to prevent high-frequency EMI from jumping over the ground plane. A general rule is that the ground plane should have a dimension twice that of the lowest wavelength to be filtered.
- Avoid mixing filtered and unfiltered lines in a connector. Unfiltered lines present an EMI window that can defeat the effectiveness of filtered lines.
- Remember that most filter insertion-loss specifications are based on testing in a 50-ohm system. The more a system varies from this impedance, the greater the difference in filter performance, for better or worse.

GROUNDING REVISITED

The discussions of both shielding and filtering stressed the importance of good grounding. For EMC purposes, ground should be earth ground — or as close to earth ground as can be practically achieved in the design. Earth ground implies a ground whose potential does not change regardless of the current that passes through it. Thus the chassis ground of the system should serve as a local earth ground and should be sufficiently large enough to handle the RF currents without changes in potential. If the ground changes potential, it will drive the cable grounded to it. Thus bulkhead mounting is preferred to mounting on a printed circuit board. Since a bulkhead typically offers a more generous ground plane than a pc board, the bulkhead is the preferred mounting point for grounding a filtered or shielded connector. Pigtails or wires connecting the cable assembly to ground should be avoided because of the inductance. The system-side connector should not be mounted in an ungrounded bulkhead and then tied to a distant ground.

Intimate contact must be maintained between the connector and the ground plane. The connector should be firmly secured. Avoid mating dissimilar materials because of the chance of galvanic corrosion degrading the interface. Many systems have ended up with self-defeating I/O shielding and filtering because of poor connections to ground.

THE FIBER OPTICS ALTERNATIVE

Fiber optic technology offers an alternative to copper cables. From the EMC standpoint, fiber is an ideal transmission medium. As a dielectric, it neither radiates nor receives EMI; there is no capacitive or inductive coupling, no crosstalk, and no ground loops. In addition, fiber offers higher bandwidth over longer transmission distances than copper cable. For example, an industry-standard 62.5/125-micrometer multimode cable offers a bandwidth of either 160 MHz-km or 500 MHz-km (depending on the wavelength of the light used in the system).

Despite its clearly attractive features, fiber is only now becoming widely accepted in the networking and data communication markets. Use of fiber has been inhibited by the dominance of copper, the real and perceived higher prices of fiber components and subsystems, and by concerns over fiber's ability to withstand casual use and abuse in offices and similar environments. Component prices have dropped considerably, standards are in place on both the component and system level, experience shows fiber is quite rugged and robust, and emerging I/O channels are pushing performance upwards into areas where fiber looks even more attractive.

CONCLUSION

Effective EMC efforts begin with a system definition and proceed throughout the design. Doing so enables the design to control of all the variables that will affect EMI generation and its mitigation. From component selection and board layout through final system testing, negating the generation of EMI should be the first step in any EMC program. By reducing the amount of EMI generated, the need for filtering and shielding I/O cables can be reduced. Even so, the various options in shielding and filtering should be assessed to find the solution that is both technically sound and cost-effective.

Since a bulkhead typically offers a more generous ground plane than a pc board, the bulkhead is the preferred mounting point for grounding a filtered or shielded connector.

RONALD BRENNIAN, JR. *is a product marketing manager in the signal conditioning products division of AMP Incorporated. His product marketing responsibilities encompass EMI gaskets and filtered drop-in replacement connectors. Brennian received a BSME degree from West Virginia University. Since joining AMP in 1984, he has held various positions in product/manufacturing engineering and product management. (717) 564-0100.*

JEFFREY L. SHOWERS *is the product manager responsible for high performance distributed element filter products in the signal conditioning products division of AMP Incorporated. He received an EE degree from the Pennsylvania State University, and has over 13 years filter experience. Since joining AMP in 1983, he has held various engineering and product/business management positions. (717)564-0100.*

ROBERT L. WILLIAMS, JR. *is responsible for marketing communications in the signal conditioning products division of AMP Incorporated. He received BS and MBA degrees from the Pennsylvania State University. Since joining AMP in 1979, he has held various positions in marketing, planning, systems and product control functions. (717) 564-0100.*