Hard Wire and Cable Considerations for TEMPEST Design

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INTRODUCTION

Selecting the proper electronic wire type, bundle configuration, routing scheme, shielding and connector are not simple tasks for the TEMPEST engineer. There are a multitude of circumstances and problems to investigate, not just from the TEMPEST perspective, but also from the perspectives of EMI, EMP, radar cross detection, and weight. In addition, with the increasing demands on cable performance in applications with higher and higher frequency digital information transfers, underwater service, and local area networking, previously successful approaches are often not sufficient to provide protection.

This article looks at solid metal wires and cables from several perspectives. Besides the usual electrical, frequency, and physical configuration requirements, shielding, coupling and routing will also be evaluated. Our primary interest will be the three fundamental concerns for non-fiber optic wires and cables in the EMI environment: radiated emission antennas, radiated susceptibility antennas and cable-to-cable crosstalk couplers. Since cables act as long wire antennas resonant at a wavelength four times their physical length, and since the majority of cable emission problems arise from common mode noise on the cable, concentration will focus on eliminating this noise through bypassing, shielding and filtering.

The fundamental concerns for non-fiber optic wires and cables in the EMI environment are radiated emission antennas, radiated susceptibility antennas and cable-to-cable crosstalk couplers.

Fiber optic cables are inherently secure and the cables themselves are EMI, EMP and lightning immune. However, the electronics and cable connectors for fiber optics must be treated like connectors of hard wires. While the suitability and affordability of fiber optics in the ruggedized military and airborne environment may be questionable at this time, their ultimate application to stringent environments represents a significant potential for secure and non-secure hardened communications.

ELECTRICAL REQUIREMENTS

The electrical requirements of a system generally dictate the configuration of the wire or cable used. Basic considerations include voltage, current, frequency, signal attenuation, velocity of propagation, inductance, capacitance, source and load impedance, and characteristic impedance. Depending on the engineer's background, selection of the proper wire or cable can be simple or immensely complex. TEMPEST engineers, due to the nature of the problems usually encountered, should consider wire selection one of the more serious issues they face.

The first consideration that should be evaluated by any engineer is the current carrying capability and voltage safety factor. The voltage safety factor (insulation breakdown voltage divided by operating voltage) for cables, due to their considerable flexing and moving, should be between 70 and 100 for each conductor. Hookup wire, which is normally used inside a chassis and is seldom flexed, has a voltage safety factor of 10 to 20. Test probe wire, with no voltage or current requirements, has a small voltage safety factor of 3 to 5 (Figure 1).

The next general consideration is the frequency requirement. Higher frequency signals require more care in the cable selection and connector terminations because of higher insulation losses and the need for broadband impedance matching. For

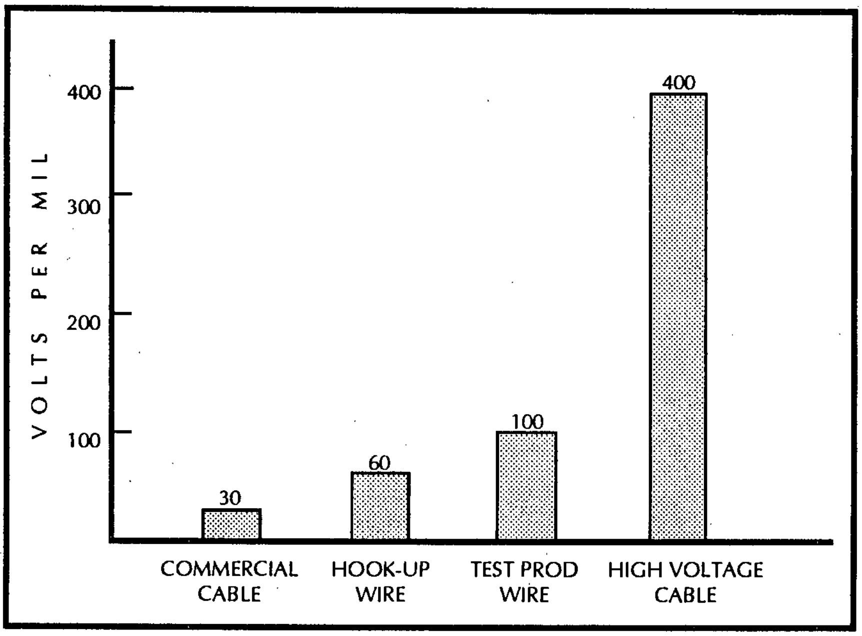

FIGURE 1. *Voltage Safety Factor.*

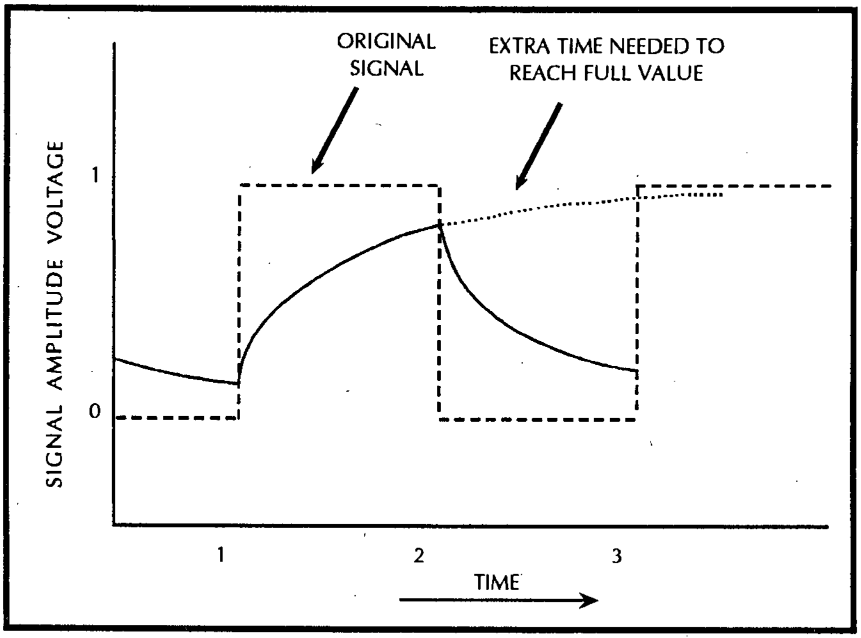

FIGURE 2. *Square Wave Pulse Distorted by Cable Capacitance.*

example, a long thin ground wire for a stepper motor casing of a printer may be adequate to eliminate the noises generated by the chopper pulse widths, which have frequencies in the kHz range. However, for the high frequencies of the signal edges, this thin ground wire will appear to be an inductor. With an AC or pulse signal, the cable capacitance must be charged before the load can receive full signal value from the source. If capacitance is too large, the load voltage at higher frequencies may never reach the full source value, and it may be greatly changed in shape because the cable is acting as a filter (Figure 2).

Normal engineering techniques may include driving the line "harder," i.e., with more current, using a wire insulation with a low dielectric constant, separating conductors and keeping the cables short. To minimize TEMPEST emissions from the wire, the line would be driven with the least amount of current necessary to achieve the performance; higher dielectric constant insulation should be used; and cables should be kept as short as possible. Also, routing wires adjacent to large conductors reduces signal radiation. Care must be taken in this technique, however, because it can degrade the susceptibility of the equipment to ESD or other spurious signals. In general, wires and cables should be designed to have just enough capacity to get a recognizable digital signal (the fundamental and first three harmonics) across the cable and no more.

Associated with the wire's capacitance are its attenuation characteristics. Attenuation is an indication of losses due to heat generated by the transmission of a signal through the wire. Part of the conductor loss is a result of resistance and part is proportional to the product of the dielectric constant and the dissipation factor value for the wire. The attenuation may thus be specified independently of the cable characteristic impedance. For example, two cables may have the same characteristic impedance or capacitance, but if one is physically larger than the other, it will have lower attenuation.

Higher dissipation factors are often used in TEMPEST applications where the signal strength of the driver cannot be reduced in the circuitry. While changing the wire dimensions may increase the loss, care must be taken because the ac attenuation may be decreased as the resistance is increased. Figure 3 shows the variation of attenuation with frequency.[1] The effects of the reactive components of cables are easily seen in the curve.

Series resistors are commonly

used to limit current and reduce emissions. For a long wire antenna with radiation resistance of 50 ohms, a series resistance of 500 ohms can yield up to 20 dB suppression.[2] For most applications, however, low impedance loads are being driven and series resistance cannot be used. In these cases a series inductor is often used, chosen to provide appropriate impedance for the frequency content of the signal. For example, an inductor of 10 microhenries will attenuate frequencies above a few hundred kHz.

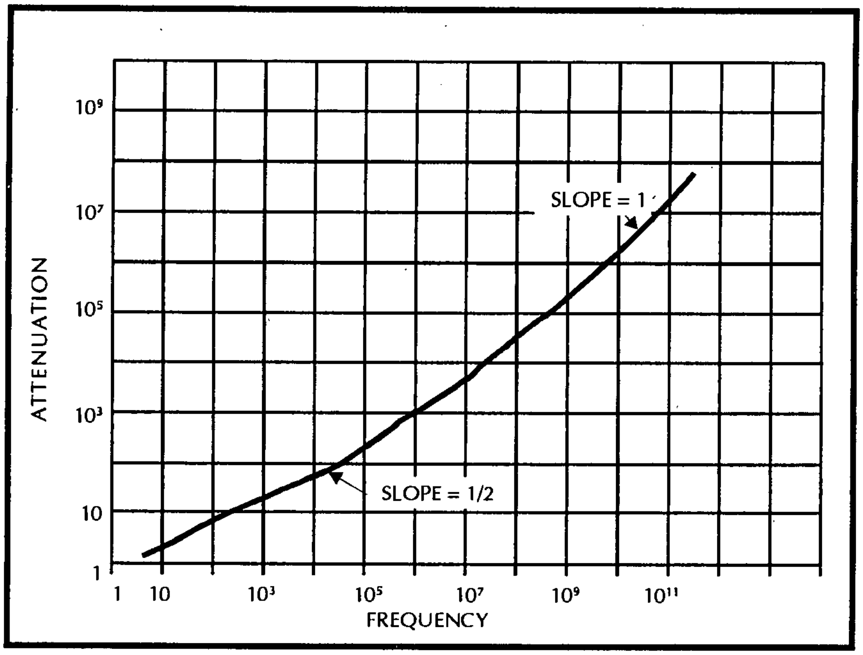

FIGURE 3. *Effects of Frequency on Cable Attenuation.*

Velocity of propagation for a cable, expressed as a percentage of the velocity of light in free space, is determined primarily by the dielectric constant of the insulating materials between the conductors. For similar cable configurations, this factor is inversely proportional to the dielectric constant of the wire insulation. In digital circuits and pulse circuits, waveform distortion can result when propagation velocities are low. This waveform distortion can cause data pulses to be miscounted, which results in increased bit error rate. On the other hand, a very fast rise time results in an increase in energy emission. As mentioned previously, the best approach is to create the slowest rise time that will allow correct information transfer.

CABLE DIELECTRIC	TIME DELAY(ns/ft)	VELOCITY (%c)
Solid Polyethylene	1.54	65.9
Foam Polyethylene	1.27	80.0
Foam Polystyrene	1.12	91.0
Air Sp. Polyethylene	1.15-1.21	84-88
Solid Teflon	1.46	69.4
Air Space Teflon	1.13-1.2	85-90

TABLE 1. *Propagation Characteristics for Dielectrics.*

Table 1 shows the velocity of propagation and time delay of cables insulated with the most commonly used dielectrics.[3]

Other factors are considered in the selection of the dielectric. For example, Teflon takes a charge and retains it very easily, thus making it very difficult to handle from an ESD standpoint.

Different cable configurations will have different attenuation properties. For example, Figure 4 describes the attenuation versus frequency for two different types of coaxial cable, while Figure 5 shows this data for twinaxial cables. Figure 6 compares the spectrum for a square pulse and capacitively loaded signal (see Figure 2). The greatly reduced spectral density of the harmonics (20 dB

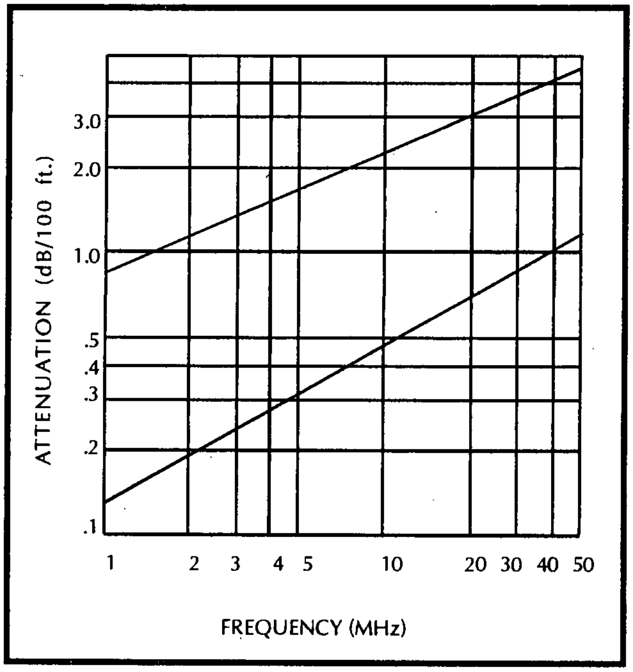

FIGURE 4. *Attenuation vs. Frequency, Selected Coaxial Cables.*

down by the 2nd harmonic) is clearly shown. The trade-off is in the switching time, as seen in Figure 2. Ideally, the signal should be attenuated enough to just allow switching when all noise buffers are considered.

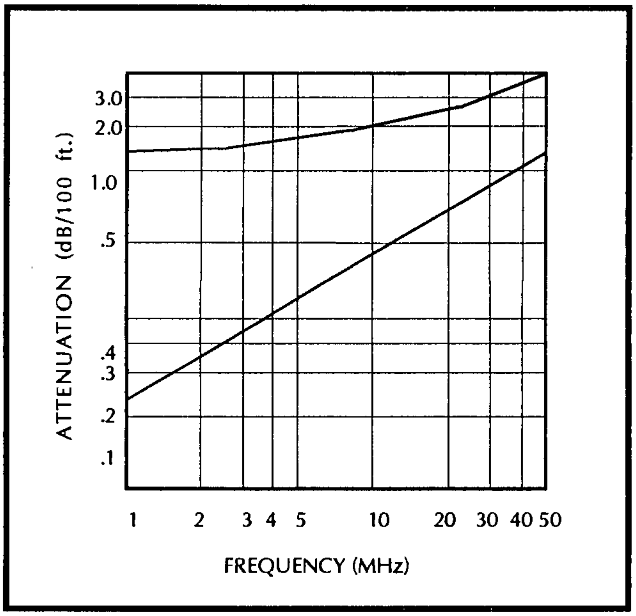

FIGURE 5. *Attenuation vs. Frequency, Selected Twinaxial Cables.*

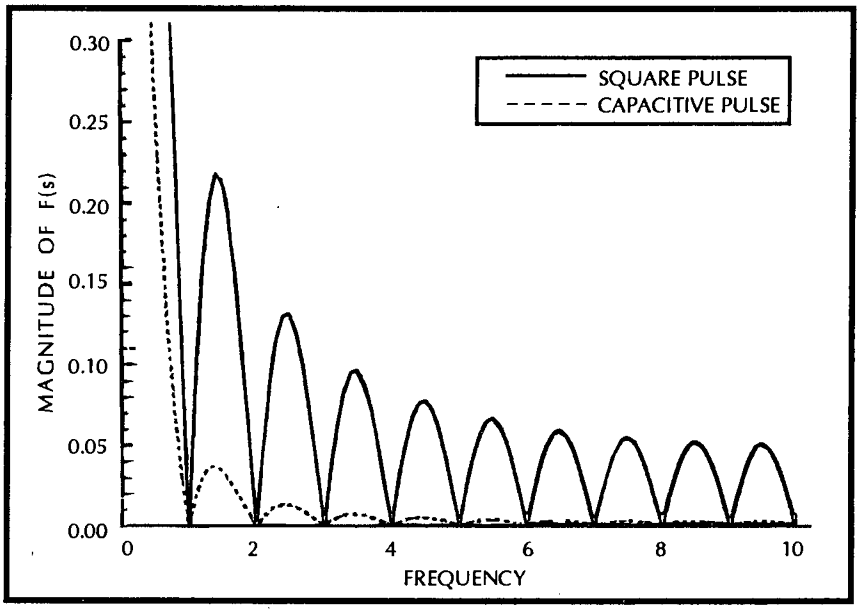

FIGURE 6. *Spectral Content for Signals of Figure 2.*

Associated with the propagation velocity is the characteristic impedance. Cable line drivers generally have much lower impedance than the cable they drive and require appropriate external matching or termination. Impedances must be matched at least for the principal Red data rate to prevent signal reflection and the standing waves associated with the reflections. Standing waves create significant TEMPEST problems because of the energy available for emission. In addition, large standing waves can overstress the voltage safety factor for wires with low safety factor.

CONDUCTOR PHYSICAL DESIGN

Copper is the most commonly used conductor in wire and cable design, although it is generally plated or coated with one of several other metals. Tin and silver are common plating materials. If added strength or long flex life is needed, copper alloys or copper covered steel conductors are usually specified. While copper covered steel has only 30 to 40% of the conductivity of an all-copper conductor at low frequencies, conductivity at high frequencies is nearly the same due to skin effect.

Nonmetallic conductors, textiles or compounds impregnated with conductive particles are an option in high voltage CRT applications, or where suppression of noise using high conductor resistance is practical. In general, these conductors are expensive and should be considered in TEMPEST applications when other techniques fail.

SPURIOUS SIGNALS

Understanding the electrical characteristics of a wire or cable is only half the battle. The TEMPEST engineer must also understand the electromagnetic characteristics of transmitted signals. Spurious coupling in cables and interface wiring occurs as a result of the sharing of a common conductor impedance, inductive coupling between conductors and/or capacitive coupling between conductors. It is also possible for the conductor to react to magnetic and electric fields in ways that produce coupling to objects other than adjacent conductors.

COMMON IMPEDANCE COUPLING

When a conductor or common impedance is shared by more than one circuit, as shown in Figure 7, the flow of current, I_1, from one circuit through the shared common impedance produces a voltage drop that may affect the operation of the other circuits sharing the reference. This effect can cause common mode susceptibility problems, spurious signals on all interfaces and radiated emissions in the TEMPEST environment. If the common impedance is shared by several chan-

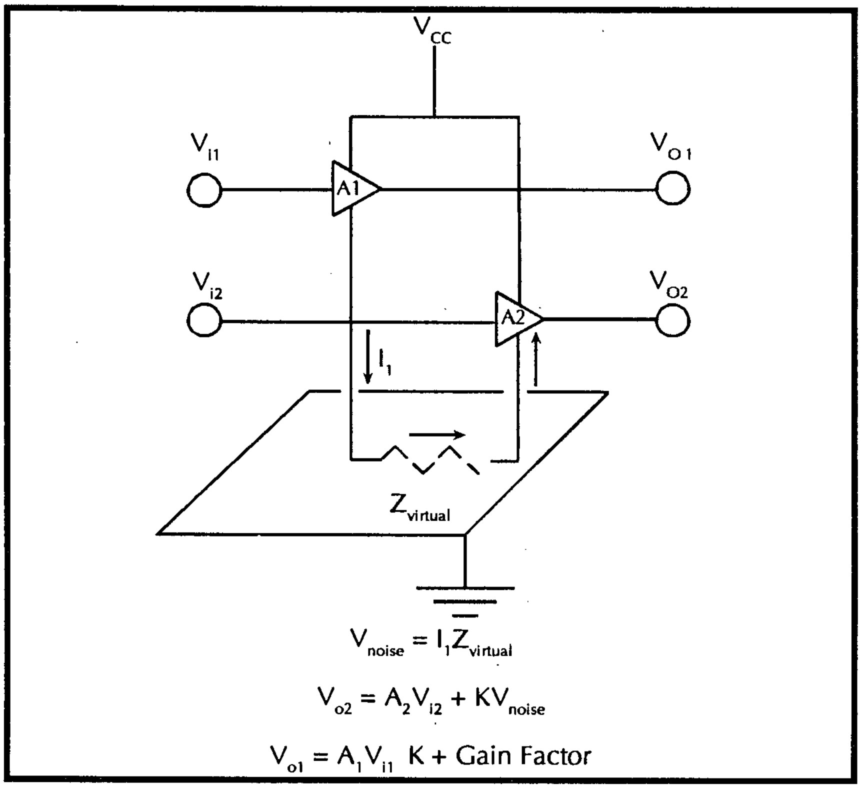

FIGURE 7. *Common Impedance Sharing.*

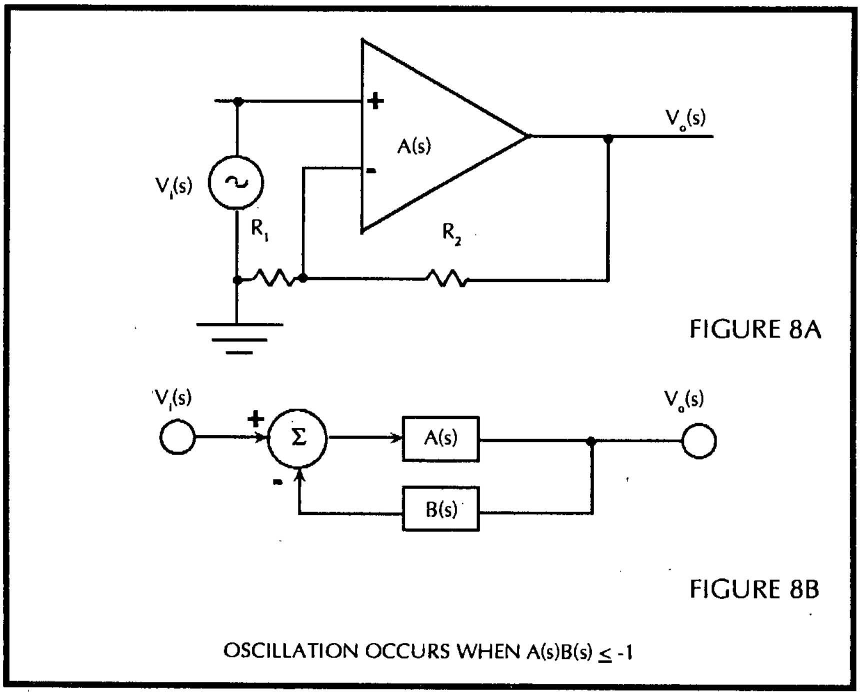

FIGURE 8. *Unplanned Feedback from Common Impedance.*

nels, interchannel crosstalk occurs.

If the common impedance is shared by both the input signal return and the output signal return of an amplifier, unplanned feedback will take place (Figure 8) in accordance with design equations shown below.

$$B(s) = \frac{R_2}{R_1 + R_2} \qquad [1]$$

$$\frac{V_o(s)}{V_i(s)} = \frac{A(s)}{1 + A(s)B(s)} \qquad [2]$$

Should the output, $V_o(s)$, be in phase with the input, $V_i(s)$, positive feedback will occur. If the gain of the amplifier is greater than the spurious coupling loss of the feedback path, the loop gain will exceed one, and the amplifier will oscillate ($A(s)B(s) \leq -1$). On the other hand, if the loss through the spurious coupling path exceeds the gain of the amplifier, the amplifier will not oscillate, but its operating characteristics will be altered drastically.

When, as a result of an increase in gain, an amplifier is operated nonlinearly, a corresponding increase in distortion and decrease in bandwidth will result. Thus, an unstable amplifier, or even an unstable transistor, can easily become not only the principal carrier source, but also the source of modulation in a TEMPEST environment.

When the amplifier's output is out of phase with its input, negative feedback takes place. This condition causes the gain and output impedance to decrease and the bandwidth to increase, resulting in a more stable amplifier. While some of these changes seem desirable, they often produce unplanned and relatively uncontrolled shifts in the component and system operating parameters.

Any spurious signals that appear on the common impedance line will also appear on signal wires or cables that share the impedance. In the worst case this may cause false switching of "quiet" lines. It may also cause additional delays in the switching of active lines. It is a very real source of concern to the TEMPEST engineer, particularly if the switching line is a Red signal and the quiet line is not. In this day of Very Large Scale Integrated (VLSI) circuitry, sufficient current may be switched in the drivers of a single chip to create havoc in the system.

There are a few approaches that help avoid the problems of these spurious signals, while not degrading system performance. First, signal returns should be isolated as much as possible. At the integrated circuit level, this means providing different reference lines for on-chip circuits versus off-chip drivers. At chip carrier level, it means providing enough interface points to distribute the energy. At the printed circuit wire level, it means tightly coupling the switching lines to a reference plane and isolating the switching lines from the quiet lines through physical separation and/or reference lines between signal lines. At the printed circuit board level, it means placing the I/O circuitry on a separate board. By doing so, common mode as well as differential mode coupling problems can be effectively eliminated. A solid reference plane should be employed and grounds to the frame or chassis can be controlled. Filtering can be employed directly between signal line and signal return. Bypass capacitors will shunt return currents directly to their source, as discussed below. At the cable level, it means physically separating shields and signal returns.

Second, capacitors may be placed between signal and reference lines, between positive and negative reference lines or between references lines themselves. These "decoupling" or bypass capacitors provide low pass filters which remove some of the spurious high frequency components that appear on quiet lines or are fed back to amplifier inputs. The value of the capacitor should be chosen according to the frequency requirements of the desired signals. Great care must be taken to avoid undesired inductance in decoupling capacitors. This inductance appears because of long (electrically) capacitor leads and the physical makeup of the capacitor itself. Any inductance in the capacitor will cause the capacitor to be a bandpass filter instead of a lowpass filter. For example, ceramic capacitors often have significantly better characteristics than others because they have wide leads and no pins. Also, some pin-in-hole capacitors are actually two capacitors in parallel, which cuts the series inductance of the pins in half. Manufacturers generally supply impedance curves or specifications of the equivalent series inductance (ESL) for their capacitors. All capacitors have some inductance, but if care is taken to keep it as low as possible, decoupling capacitors can be very effective at reducing the problems of common impedances.

CROSSTALK

A common problem in the TEMPEST design of cables and wiring is crosstalk. Crosstalk means the coupling of energy from one conductor to another due to close physical proximity. When coupling occurs in the secondary conductor, it may again couple or re-radiate to other conductors.

Some of the worst crosstalk offenders include cable connectors, printed circuit board connectors and chip carrier or DIP pins, primarily due to the close association of individual parallel wires within the packages.

CAPACITIVE

When two conductors are in close proximity, they form a small capacitor, as shown in Figure 9. The conductors act as capacitor plates with the wire insulation and other non-conductive materials forming the capacitor dielectric. Any varying voltage on one of the conductors is thus capacitively coupled to the other conductor(s). This spurious coupling path is different from the common impedance coupling, but similar principles apply. As described above, the

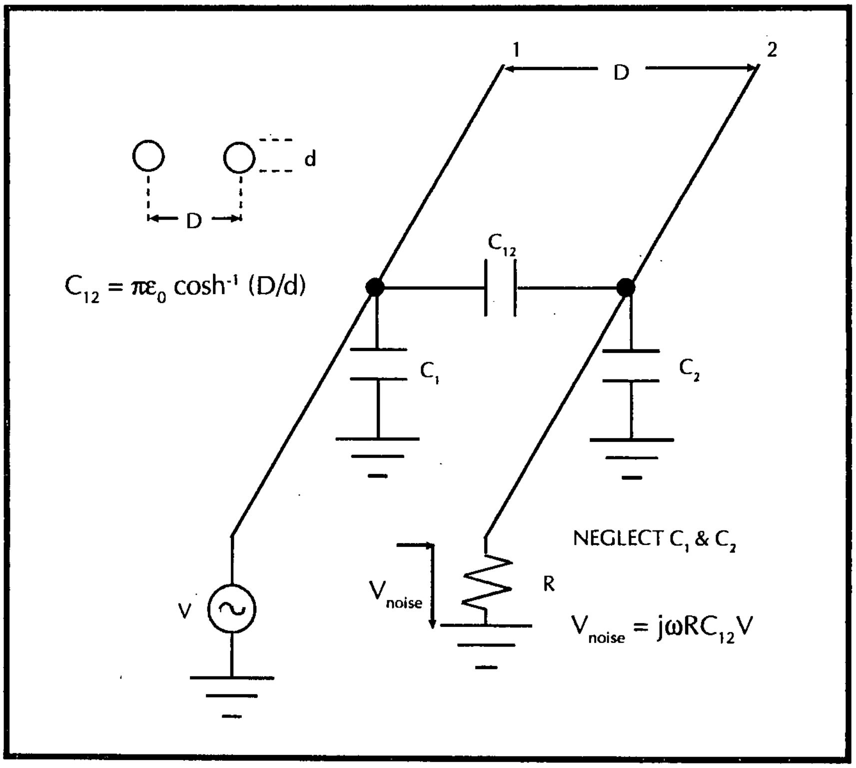

FIGURE 9. Capacitive Coupling.

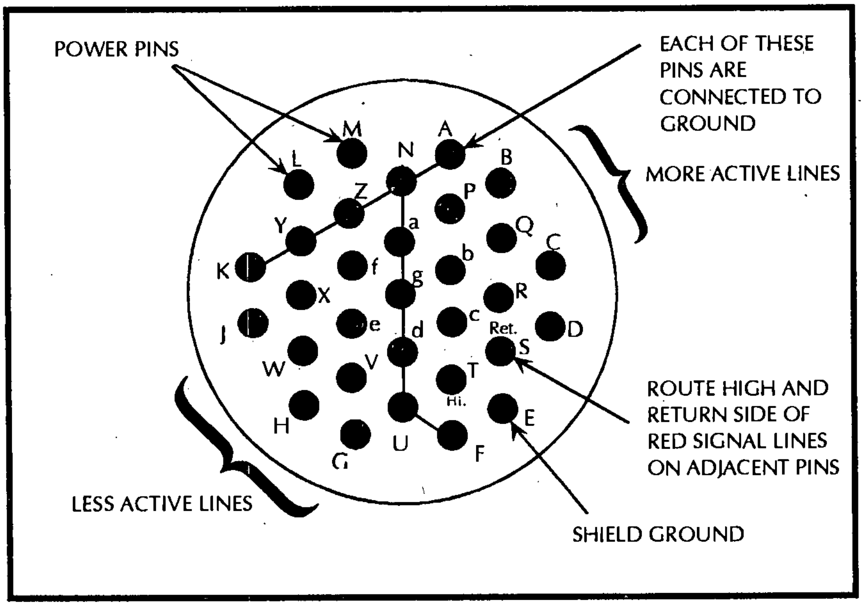

FIGURE 10. *Connector Pin Isolation.*

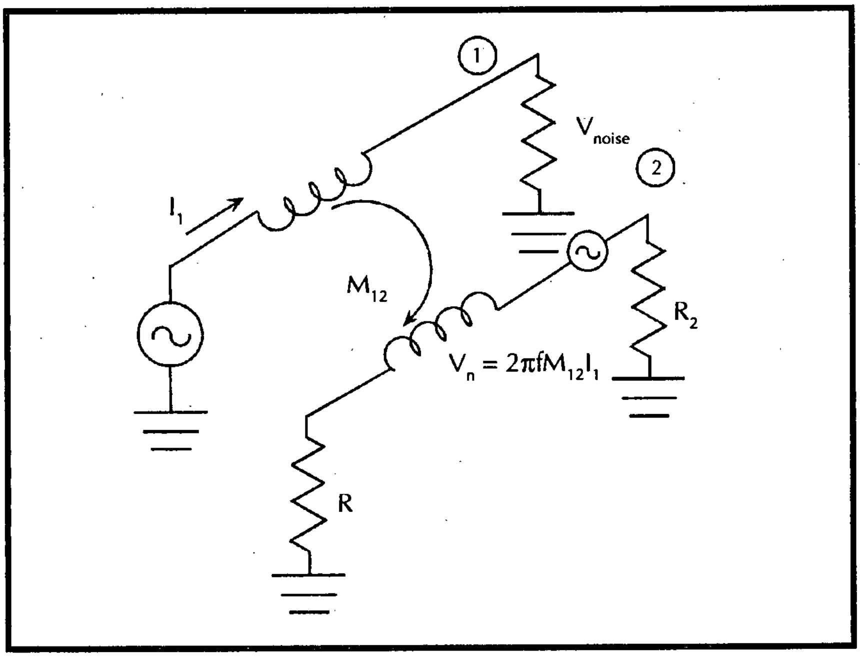

FIGURE 11. *Inductive Coupling.*

isolation of signal lines through physical separation, tight coupling to the return line and the use of reference lines between signals applies equally to the problem of capacitive coupling. In addition, separating I/O printed circuit boards from other logic circuitry will significantly reduce the possibility for crosstalk coupling.

The engineer should pay close attention to the physical assignment of connector pins early in the design when it is easy to control the layout. Many problems can be avoided simply by choosing wise routing and isolating noisy switching circuits from quiet secondary lines. An example of isolation through connector pin assignment is shown in Figure 10.

INDUCTIVE

The mere existence of a longitudinal conductor creates a small inductor. When two conductors are in close proximity, they form a transformer as a result of their mutual inductance, M_{12}, as shown in Figure 11. Any varying current flow in one conductor induces a current flow in the adjacent conductor(s). Again, this coupling is different from the common impedance coupling, but similar principles apply.

If the critical circuit is a Black circuit forming a loop through a ground path, the maximum voltage that can be induced on this loop by a Red signal-carrying wire is found from

$$E \simeq (3.19 \times 10^{-8}) fLI \ \ln\left(\frac{r_2}{r_1}\right) \quad [3]$$

where f is the frequency in Hz; L is the loop length in inches; I is the current in the Red line; E is the induced voltage; r_1 is the closest distance of the loop to the wire, in inches; and r_2 is the furthest distance of the loop to the wire, also in inches.

The above equation is nearly exact for a square loop, becoming less exact as orientation and geometry vary. This means that should a ground loop be identified within a cabling system, its orientation with respect to Red signal-carrying wires could be optimized.

As in common impedance sharing, separation of the signals and decoupling capacitors between positive and negative (or neutral) reference lines or planes are very effective for reducing inductively coupled spurious signals.

A video recording amplifier for a low level multiplexed instrumentation tape recorder serves as an example. The amplifier circuit is packaged as a potted welded module with a single connector for power, signal input, test points and recording head output. The cable consists of wires bundled together for 2' before fanning out

Continued on page 96

to the power supply, input connector, test connector and recording head. All conductors are unshielded, untwisted single conductor wires. The amplifier has a bandwidth of 100 kHz, a sensitivity of 1 mV, and an output of 10 mA into the recording head.

The output current flowing through 2' of wire (10 mA at 100 kHz) will induce 2.25 mV on the adjacent input line. The input impedance of the amplifier is 100 kΩ; therefore, the 2.25 mV does not decrease due to loading. This 2.25 mV exceeds the sensitivity of the amplifier and causes oscillation if it is in phase with the input signal because the gain through the amplifier exceeds the loss through the coupling path. If the spurious signal is out of phase with the input signal, negative feedback occurs which significantly changes the amplifier operating characteristics.

If the wire carrying the output signal is physically separated from the wire carrying the input signal, or if each signal wire is part of a twisted pair with its own return, the spurious coupling can be reduced to an acceptable level. Figure 12 shows such a condition and the associated grounding for a differential amplifier. Separating the cables within 4" of the amplifier connector would reduce the spurious signal at the amplifier input to 375 µV, providing a stability margin of 8.5 dB for the amplifier. However, this may still be too much spurious energy for the TEMPEST requirements.

Using the twisted pair wiring for the input and output signals to within 1" of the connector reduces the spurious signal to 94 µV, providing a stability margin of 20.5 dB. Shielded cables produce a similar result.

The decision of how to isolate signals on cables involves many trade-offs, including cost, system performance, TEMPEST requirements and EMC requirements. Some comparisons are given below.

SHIELDING & TWISTING

SHIELDING

The magnetic shielding effectiveness of ordinary non-ferrous shielding materials is considerably lower than that of ferrous materials at frequencies below approximately 100 kHz. Even ferrous materials have a relatively low magnetic shielding effectiveness at 60 Hz and 400 Hz when applied in reasonable thicknesses. Twisted wiring, even without a shield, provides the most effective isolation from low frequency magnetic fields.

Examples of various shielded cables are shown in Figure 13.[4] Comparisons are shown in Table 2.

TWISTED PAIRS

When a conductor is surrounded by a changing field, current is induced in the conductor, causing a voltage potential to appear at each conductor end. The amplitude of this induced voltage is proportional to the intensity of the field. Every circuit has two conductors: a "hot" or signal lead and a return lead, bus or structural path to provide cir-

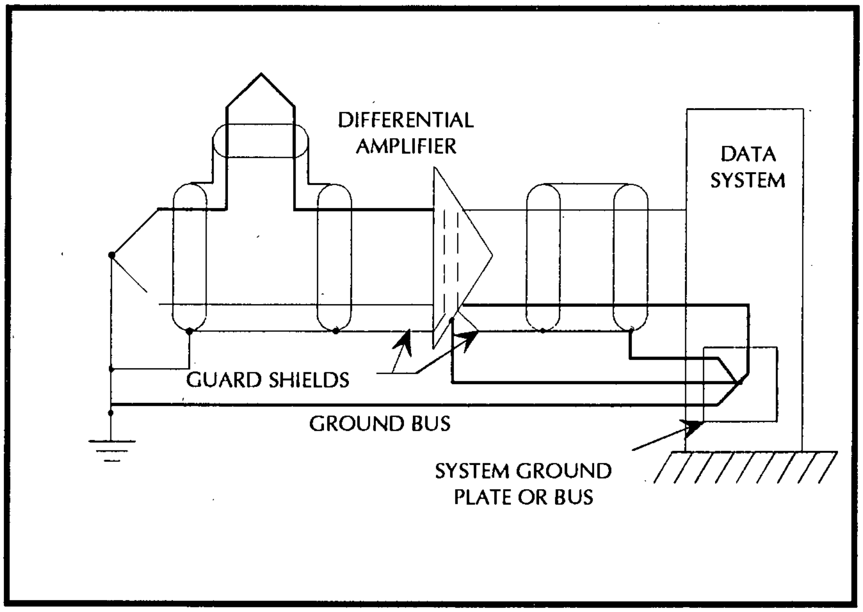

FIGURE 12. Cable Branch Separation for Differential Amplifier.

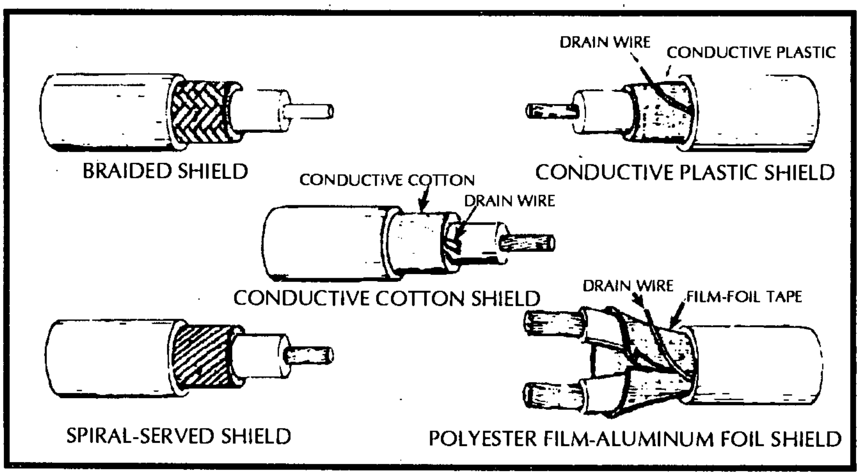

FIGURE 13. Shielded Cable Types.

SHIELD TYPE	SHIELDING AUDIO FREQUENCIES	SHIELDING RADIO FREQUENCIES	PERCENT COVERAGE	TERMINATION METHOD
Copper Braid	Good-Excellent	Good-Excellent	60-95%	360°
Copper Wrap	Good	Fair	90-97%	360°
Conductive Textile	Fair	Poor	100%	Drain Wire
Aluminum Mylar	Good	Fair	100%	Drain Wire
Conductive Plastic	Fair	Poor	100%	Drain Wire

TABLE 2. *Cable Shield Comparisons.*

cuit continuity. The problem voltage impressed across the functional circuit is the instantaneous difference between the voltage on the signal lead, and the voltage appearing on the return path conductor at the functional circuit.

Since the current induced in each conductor is proportional to the field intensity at the conductor, it is possible to create identical voltages in two conductors if they can be made to occupy points of identical intensity within the field. If identical voltages are created in both conductors, no differential voltage exists between the conductors. The functional circuit, therefore, has no interference voltage across it.

The easiest way to cause conductors to occupy points of identical intensity within a changing electromagnetic field is to twist them symmetrically. Since the conductors rotate about a common axis, they occupy points of maximum and minimum field intensity sequentially as the twist proceeds down the conductors. Induced voltages resulting from the field intensities on each conductor differ at any given point in the twist, but the sums of the induced voltages averaged over the lengths of the conductors will be almost identical.

The length of the twist must be a small fraction of a wavelength at the problem frequency to obtain satisfactory cancellation of the interference voltages. At frequencies where the length of the twist becomes a significant fraction of the wavelength, the instantaneous intensity of the wavefront impinging on the conductors at all points along the twist may not be uniform enough, and satisfactory cancellation of the fields will not occur.

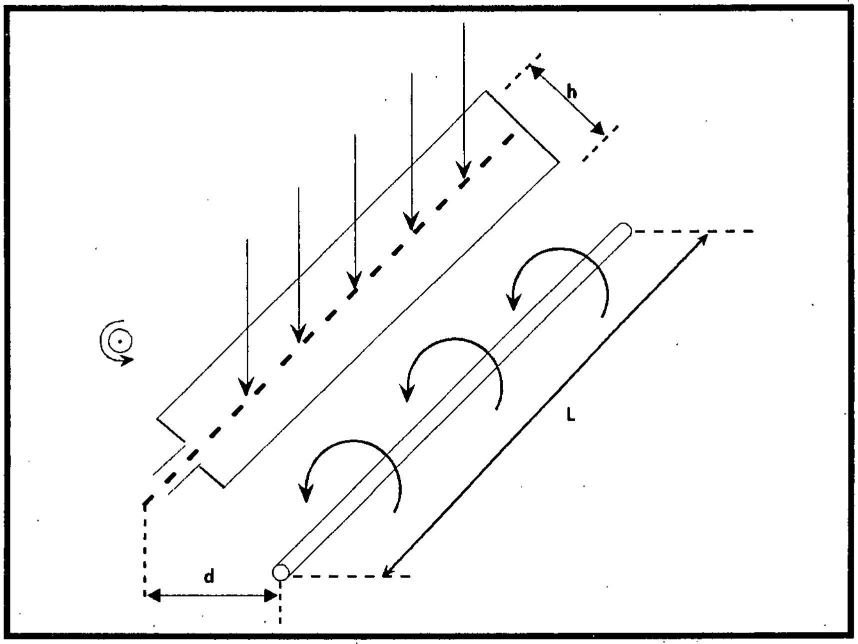

FIGURE 14. *Pick-up Loop Coupling.*

From Equations 3 or 4, the induced voltage in the pick-up loop of Figure 14 is seen to be proportional to the area of the loop.

$$V = -\frac{\omega\mu L I}{2\pi} \ln\left(1 + \frac{h}{d}\right) \quad [4]$$

Reducing the loop area through twisting or increasing the distance between the loop and source will create a significant reduction in the induced voltage level.

Twisted conductors are the only effective means of preventing power and audio frequency magnetic fields from introducing interference on the functional circuit end of interconnection wiring in situations where conductors are balanced to ground and the shield is not a current-carrying part of the system. Conventional non-ferrous shielding braids are not effective magnetic shields at low frequencies. Specialized magnetic shielding foils are also relatively ineffective magnetic shields at low frequencies when used in practical thicknesses.

Coaxial cables are most suitable for unbalanced circuits with the shield grounded and serving as one conductor. Coaxial cables are more broadband in their shielding effectiveness than are twisted pairs, but when the shield is attached to the logic or signal ground it can carry spurious signals into the circuitry. Sometimes it is necessary to use a combination, i.e., a twisted pair of signal and return cables with a gross shield. Coaxial cables have lower capacitance per length and lower attenuation than twisted cables.

SHIELDED WIRING

Shielded conductors have greater attenuation than unshielded conductors because the conductor-to-conductor capacitance is decreased and the conductor-to-ground plane capacitance is increased. Capacitance between shielded conductors is negligible except where the center conductors may be exposed, such as the connector entry area or within the connector itself. Besides the braid and foil mentioned above, conduit is sometimes used as a cable shield. Shields may be an integral part of the wire, or can be added, as in the case of zippertube.

Shielding is usually dependent on the percentage of cable coverage provided by the braid and/or the thickness of the shielding material. The shield braid angle and percent braid coverage are determined in accordance with MIL-C-7078C, with a minimum coverage of 94% indicated for GSE flight deck applications. Figure 15 shows a braided shield cable with 85% coverage under flexing.

The following guidelines are good rules for designing and specifying shielded wires or cables:

- Minimize the length of unshielded conductor.
- Ground the shield well for good electric field shielding.
- Use a shielded line with the shield grounded at both ends to prevent magnetic field radiation from a conductor forming a ground return between both ends.
- Do not use a signal conductor for a low frequency shield.
- Isolate one end of the shield from ground for a low frequency shield.
- Terminate braided shields uniformly (360°) around the braid at the connector.
- A shield surrounding a conductor and grounded at one end has no effect on the induced voltage in the conductor.

LIMITATIONS AND ADVANTAGES OF TWISTED AND SHIELDED CONDUCTORS

For low frequency isolation, shields must be connected to the structural or frame ground at only one end to prevent ground loops. This is a conflict with high frequency requirements, whereby shields must be connected to the structural ground directly or through extremely short jumpers at distances no further apart than 1/10 wavelength of the highest frequency of interest. An inadequately grounded shield has a considerable impedance to the frame ground. Any potential appearing on the shield as a result of spurious signals will be both radiated and coupled to the center conductor of the shielded cable.

The conflicting requirements for high and low frequency shield grounding techniques prevent the application of a simple panacea to solve all grounding problems. Each case must be considered individually. In cases where both low and high frequency isolation are required, a hybrid approach may be required, with a well-grounded outer shield and an inner shield grounded at one end.

Conventional non-ferrous shielding braids are not effective magnetic shields, but work well as electrostatic shields at low frequencies. Most metallic materials are satisfactory shields against both electrostatic and magnetic fields at higher frequencies.

Shielded conductors permit the transmission of low level signals at high impedance levels through areas where excessive interference voltages would be induced into low impedance conductors by low frequency magnetic fields, or where sensitive information must be sent. Shields on wires are like shields on rooms, the continuous enclosure acting as a barrier to radiation. Fields near the surface will set up currents in the conductor which tend to cancel the incident fields. However, the shield is only as good as its

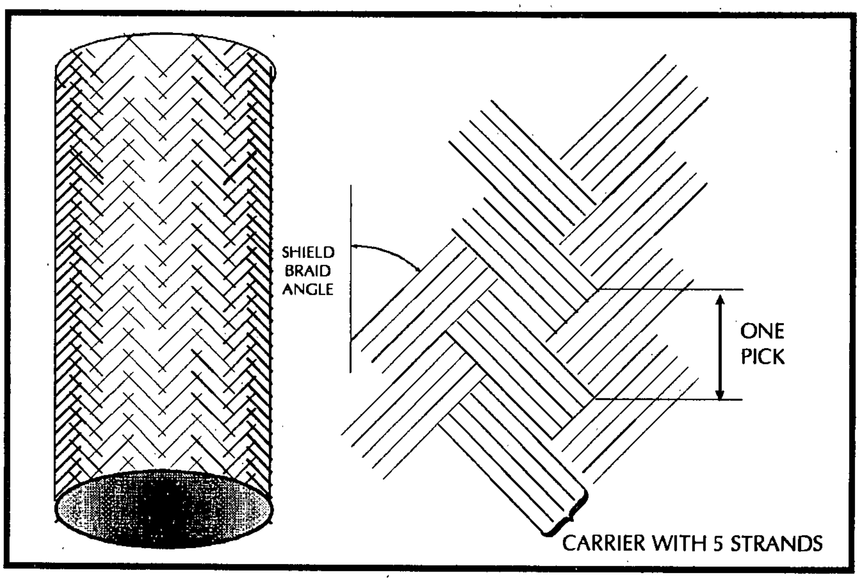

FIGURE 15. *Braid Shield on a Shielded Cable.*

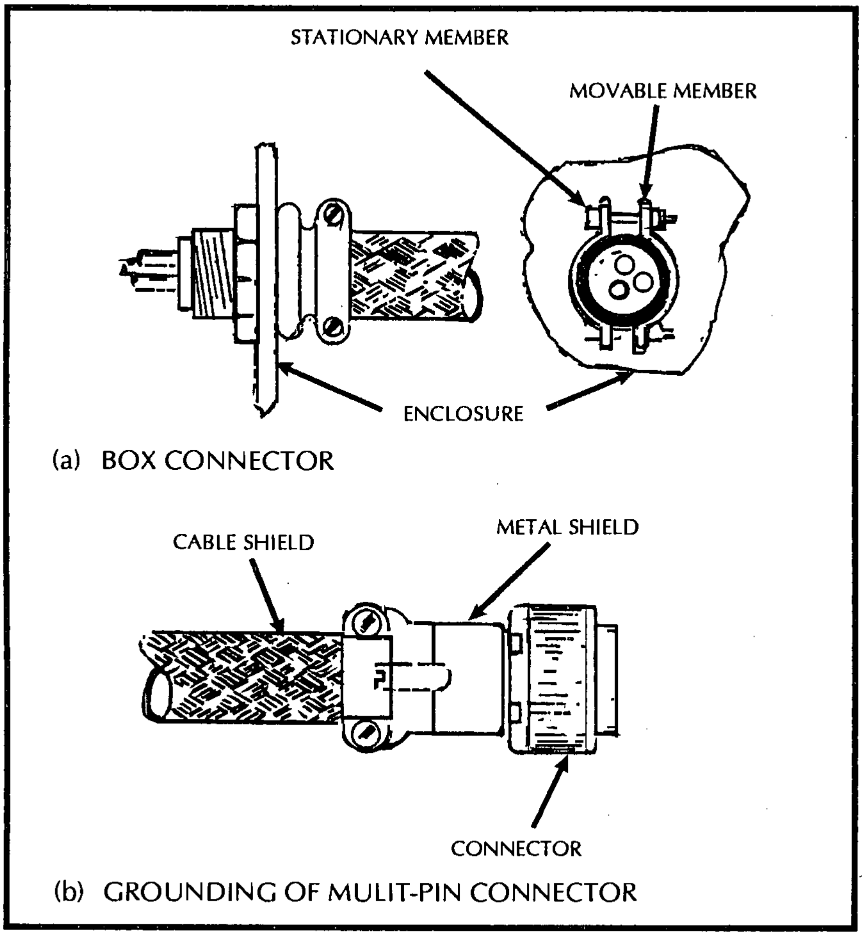

***FIGURE 16.** Proper Grounding of Connectors/Cables to Structure.*[5]

ground reference since shields radiate like any other conductor. For some applications it is necessary to provide a shield around the signal line and a gross shield around the cable. These shields are terminated to different references. Shielded wire is normally used in high frequency, high impedance circuits associated with electric field problems. Twisted wire is used in all other cases of signal transmission where coupled noise, either capacitive or inductive, is a problem.

If wires with a tight twist and tight shield braid weave are selected for use, the achievable improvement is controlled by the installation configuration. Breaks in the cable at connectors and other terminations violate the integrity of both the conductor twist and the shield braid.

If the twisted or shielded connectors have a theoretical improvement of 1000 to 1 over untwisted unshielded conductors, then the achievable improvement factor is controlled primarily by the total length of perturbations in the twist or shield, unless the total cable length exceeds 1000 times the total length of the perturbations. The achievable improvement factor is total cable length divided by the perturbation or discontinuity length. For example, if a 5' shielded cable has 6" of shield removed where it attaches to the connector, the achievable improvement factor is 5/.5 or 10 to 1 at best, instead of the theoretical improvement of 1000 to 1. The actual improvement factor may be even worse, depending on the frequency of the signal.

For any cable of reasonable length, the only way to improve the achievable improvement factor is to reduce the shield perturbations or discontinuities. Reactive cable terminations may have a significant effect on the actual improvement factor, so the cable and circuit designers must work together.

SIGNAL RADIATION

Probably the most commonly treated concern in TEMPEST cable design is the electromagnetic radiation of information. In this section, a few areas that may normally be overlooked will be considered. Usually energy radiation from a properly shielded cable is a result of common mode current flowing in the shield or a leak in the cable/connector assembly. There are many potential sources of leakage problems: the cable and connector may be poorly bonded, the cable shield may be improperly terminated, the reference lines may not be carried through the connector properly, and so forth.

Figure 16 shows the proper way to connect a clamped shielded cable and connector assembly to the chassis ground. As seen in Table 2, there are many types of shields. The added impedance of drain wires degrades shielding effectiveness, which is also frequency dependent. Connector selection may greatly impact the shielding effectiveness. For example, filtered connectors may remove undesired and unnecessary high frequency components from a signal before they can propagate down the cable. In addition, miniature packages are now available that contain ferrite beads for common mode and differential mode applications. If the package is intended for common mode applications, it usually consists of many leads wound on a small

Continued on page 112

common core. Since the parts are printed circuit mountable, they can be placed near the line drivers to reduce common mode coupling before reaching the connector and cable assembly.

The shielded connector must be considered an integral part of the cable assembly. Poor connectors or connector/wire shield terminations will significantly degrade the shielding effectiveness of cables. Often, the attachment between wire and connector is initially solid, but breaks down with age, flexing or vibration. In general, cable shields should be attached a full 360° to the connector, and not tied through a pigtail, as shown in the computer connector assembly of Figure 17. Pigtails have little application in the TEMPEST environment since they negate the low impedance connection required between the shield and the ground reference.

REDUCING CABLE TERMINATION PERTURBATIONS

In the connection between cable shields, connectors and grounds, it is important to stress the fact that a low DC impedance is not the same as a low RF impedance. An inductor looks like a very low impedance to an ohm meter, but it is far from a short circuit at its resonant frequency. A length of conductor is an inductor.

Sometimes an ohm meter measurement will give an indication of the quality of the connector/cable/ground connection where lengths are already minimized. For example, some cable connections are required to have a DC resistance less than 0.1 ohm. In this case, the DC resistance is a good indicator of the ground continuity for radio frequency signals.

It is impossible to achieve worthwhile signal radiation improvement factors unless the twisted or shielded portion of the cable is properly carried through the cable assembly. Once the signal is inside the equipment it is usually not necessary to carry the shield through. Care must be taken in the termination of the shield to the connector. The use of standard connectors and normal manufacturing processes produce cable assemblies with untwisted or unshielded conductors extending back from the cable ends for distances as great as 6", with typical lengths of 3". An example of a standard shielded cable and connector assembly is shown in Figure 18. Figure 19 shows a shield connector employing a crimp approach to connect the shield to the backshell assembly.

The unshielded conductor distances can be minimized with a reasonable manufacturing effort, but the expenses involved are often excessive. One inexpensive approach with shielded cables is to use a disk type connector termination, as shown in Figure 20. Individual shields are circumferentially terminated on the disk, which is mounted within the connector shell. Perturbations in the shield braid can also be eliminated by specifying connectors with conduc-

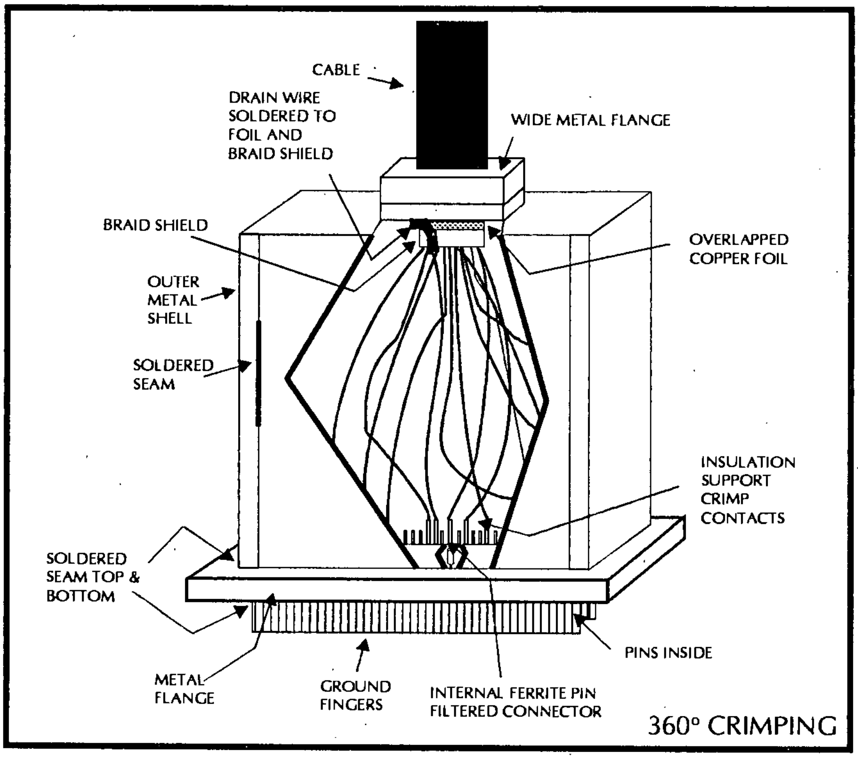

FIGURE 17. *Standard Shielded Computer Cable and Connector.*

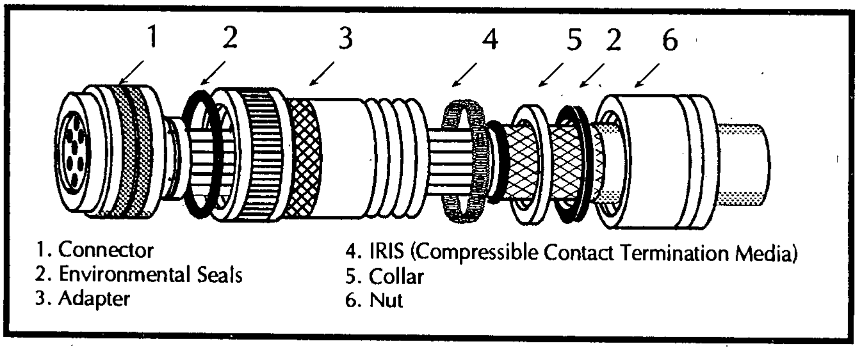

FIGURE 18. *Standard Shielded Connector and Cable Pin.*

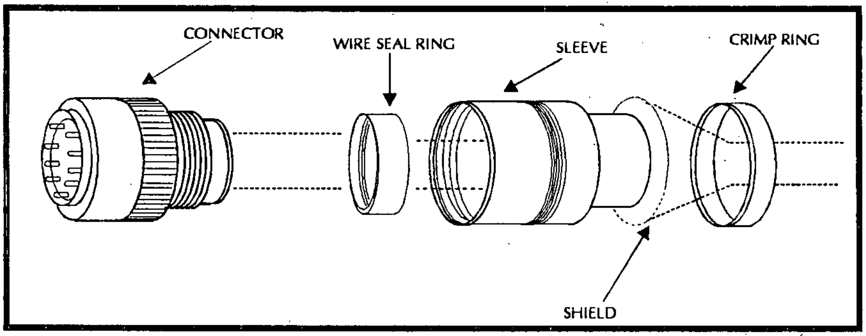

FIGURE 19. *Shield Termination Using Crimping.*

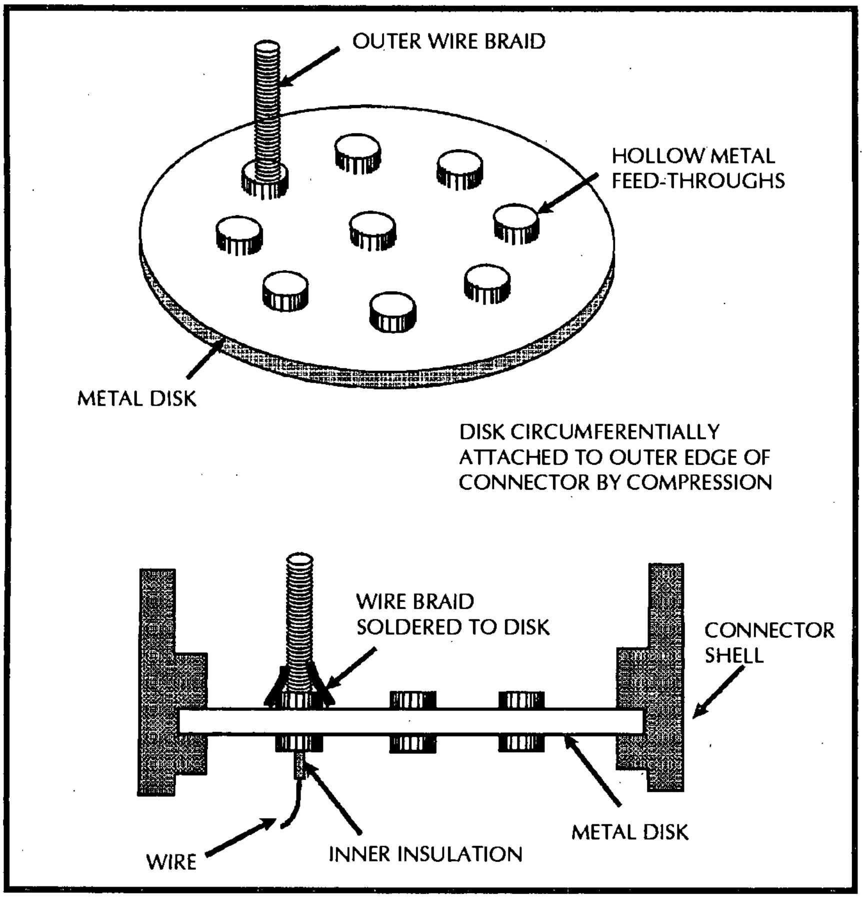

FIGURE 20. *Disk-type Shield Termination.*

tive finishes, and by incorporating provisions for attaching the shield braid to the connector shell in a manner similar to that used with coaxial connectors. Twisted pair perturbations are completely avoidable except for the actual lengths of the connector pins. The use of appropriate connector shell materials also provides additional shielding.

SHIELD BRAID GROUND CONDUCTOR LIMITATIONS

The shielding effectiveness of a shield braid is dependent on a low impedance path to an efficient ground. Long shield connections are inductive, with a corresponding increase in impedance as the frequency increases. Shield braids should be considered an extension of the shielding structure and must be connected directly to the nearest ground structure. This cannot be accomplished effectively with pigtails. Instead, the braid should be circumferentially connected to the connector backshell. The backshell bonds directly to the backshell of the other half of the connector, so it should be a good conductor, i.e., *not* plastic. The fixed backshell (not connected to the cable) should be directly attached to the grounded equipment frame. This is best done by a positive retention of flat metal surface of the backshell to flat (unpainted) conductive surface of the equipment. In cases where this is impossible, star washers must be used to break through the paint. However, the engineer should realize that this may not be an acceptable connection.

Any conductor will exhibit resonances based on its electrical length. The first mode, or fundamental, occurs when a signal is coupled to the conductor with a wavelength twice as long as the conductor. This coupling may be an input signal purposely placed on the conductor, or it may be a radiated signal picked up by the conductor. Harmonic resonances also occur at integer multiples of the fundamental. At resonance, relatively low input energy levels will produce high standing waves on cables that are not perfectly terminated. These standing waves tend to radiate. Since it is impossible to perfectly match cables, particularly over a very broad frequency range, it is important to keep cable lengths as short as possible. For external interface cables, which must often be long to be useful, it is sometimes necessary to run shielded cables through conduit to provide an extra measure of isolation. It is also beneficial to provide a filtered connector at wall or building interfaces to remove unnecessary frequencies.

GENERAL CABLE AND CONNECTOR GUIDELINES

The following design considerations are useful in external interface cables:

1. Cables penetrating the equipment frame should be shielded and the shield terminated in a 360° bond to the frame at the point of entry.
2. Cable shield ground should be separated from any signal grounds.
3. Connectors should be of the type that make shell ground before the pins mate in connecting and after the pins separate in disconnecting.
4. Pins of connectors leading to electronic circuitry should be female or recessed male pins.
5. Backshells should maintain the continuity of the shield.

In general, radiation can be minimized by tightly coupling a signal and its return, and by isolating the signal and return from other signals as much as possible. The termination of signal returns must also be done properly to avoid standing energy on the cable.

SIGNAL RETURNS & REFERENCES

High frequency circuit returns should be connected directly to the connector assembly, which is in turn connected directly to a reference plane. These reference levels are best kept isolated from the machine or frame ground except at one point, usually in the power supply. This will minimize ground loops, which can create very difficult radiation problems. If the equipment has multiple frame/circuit ground connections rather than a single point connection, it is better to tie frame and circuit grounds together everywhere to reduce the size of the ground loops. If twisted pair returns are bundled at the connector, rather than carried through separately, their effectiveness will be defeated because of the large switching currents appearing on the bundled connection. This bundled connection is an inductor at RF, and a voltage will therefore be induced. Ideally, the engineer would have the signal return closely coupled to the signal from the cable through the connector and right up to the circuit. In printed circuit boards this can be done by providing reference planes.

In many printed circuit applications, multiple reference planes are provided, e.g., 5 V and ground. In these cases, the reference planes should be decoupled with capacitors near the switching circuitry. For example, for a push-pull type line driver, the decoupling capacitors should be placed near the driver. For an open collector or open emitter line driver, the capacitors would be placed near the pull-up or pull-down resistors. These decoupling capacitors help to reduce the problems associated with shared impedances as discussed previously. Their value should be chosen according to the requirements of the switching signal, and inductances due to materials or leads should be minimized.

If signal returns are carried through properly, the return path impedance will be low and a true single-ended circuit will exist throughout the compromising frequency spectrum. In this case a return path filter is not required for differential mode signal reduction.

The return conductors of balanced circuits and floating circuits have the same lengths and inductive reactances as the signal conductors. If filters are required in the signal lines, they are also required in the return lines. Balanced line-to-line filters require a structural ground reference through a capacitive or inductive center-tap to eliminate common-mode interference. An ungrounded filter capable of eliminating line-to-line interference is not capable of eliminating line-to-ground interference due to the lack of continuity between the lines and ground at radio frequencies.

RIBBON CABLES

While ribbon cables are becoming the standard rather than the exception in most data processing equipment, manufacturers and engineers must be knowledgeable in their proper application. Ribbon cables are now available with shields, multiple internal ground traces and shielded connectors. In addition, installable shields and split ferrite cores are available to place over the internal ribbon cable. As with other cables, the ferrite sleeve acts as a choke for the common mode signal flowing in the cable, while allowing the differential signal to pass through unaffected. Typical ribbon cable designs are shown in Figure 21.

RIBBON CABLE CROSSTALK AND RADIATION

The two major problems with ribbon cables are crosstalk and radiated emissions. Since each wire in a single ribbon cable is exactly parallel to every other wire, distributed capacitance and mutual inductance create considerable opportunity for crosstalk. In addition, not only is direct crosstalk experienced, but, as previously explained, the coupled signal can be re-radiated at some other circuit connection point, causing even further contamination of the overall circuitry.

Several mechanical and layout techniques can reduce the radiated problems associated with ribbon cables. Some techniques also improve the internal crosstalk isolation. For simple

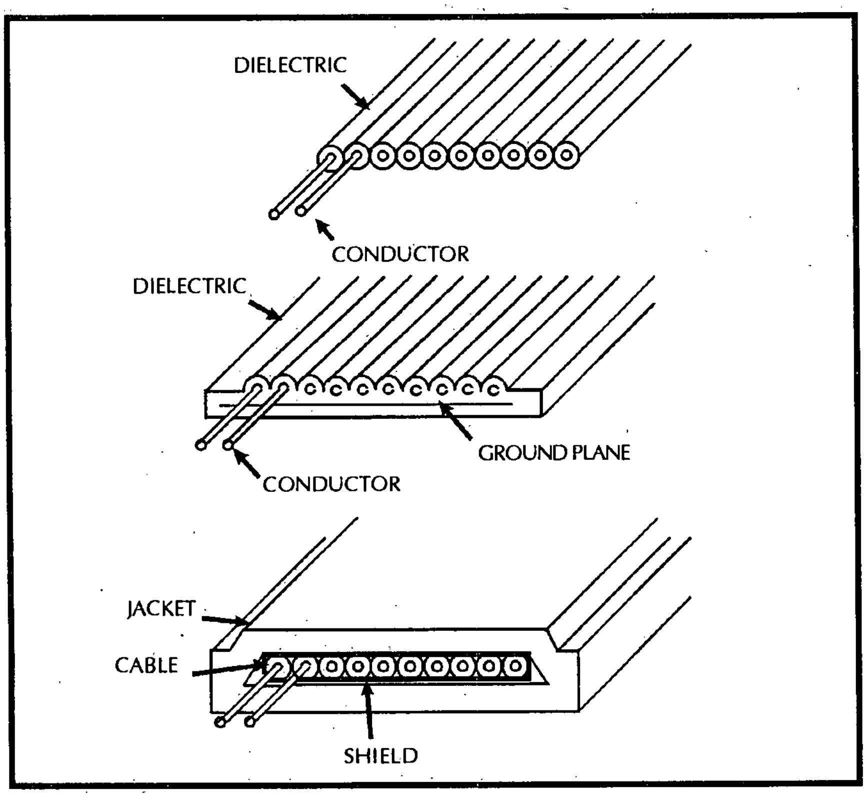

FIGURE 21. Typical Ribbon Cable Designs.

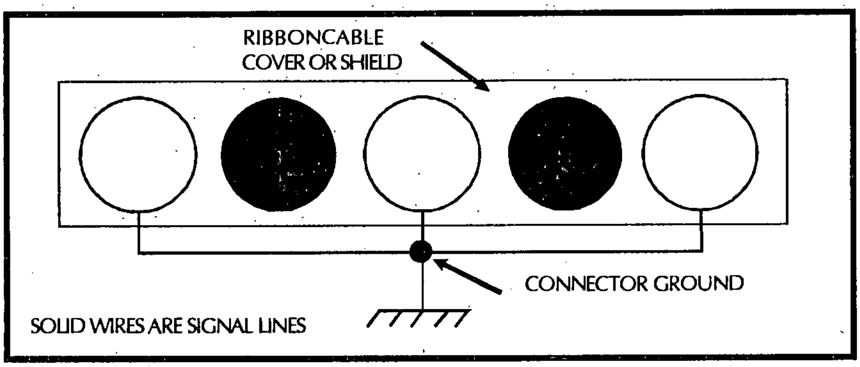

FIGURE 22. Alternate Grounding of Ribbon Cable Wires.

wire, both radiation and crosstalk are reduced by assigning grounded wires next to signal wires. In general, a 20 to 30 dB reduction in emission level is achievable by grounding the odd numbered wires in a ribbon cable.

Ribbon cables are also available with twisted pairs. The reduction in radiated emissions resulting from twisting pairs of wires in a ribbon cable is given by

$$R_{dB} = -20\log\left\{\frac{1}{2n\ell+1}\left[1 + 2n\ell \sin\left(\frac{\pi}{2n\lambda}\right)\right]\right\} \qquad [5]$$

where n is the number of twists per meter, l is the length of the cable in meters, and λ is the wavelength in meters.

Since twisting, adding a ground plane, and jacket shielding affect cost and signal transmission,[6] engineering trade-offs are necessary when selecting one method over another. Summarizing the techniques to reduce radiated emissions in ribbon cables:[7]

1. Provide grounded isolation wires between signals as shown in Figure 22.
2. Use twisted pair ribbon cables in balanced signals.
3. Replace unshielded ribbon cables with shielded ribbon cables.
4. Replace discrete ribbon cable with flexible printed circuit cables, as shown in Figure 23.
5. Reduce spacing between individual wires by increasing wire size and reducing insulation thickness. This approach is only feasible where crosstalk and safety factors are not problems.

INTERACTIVE PROBLEMS - ESD AND EMP

Primary source containment of TEMPEST signals is not the only concern relative to wire and cable design. Designers must also be concerned with energy coupling through paths created to protect against other susceptibility or hardening concerns. In this regard, both commercial and military systems require electrostatic discharge (ESD) protection, and military systems often incorporate electromagnetic pulse (EMP) protection also.

ESD and EMP may not be typical considerations for TEMPEST designers, but the effects of designs for ESD and EMP on TEMPEST behavior must be considered.

Often the design practices employed for reducing radiated or conducted emissions helps reduce the susceptibility to ESD or EMP. There are occasions, however, when the designs conflict. A couple of examples will illustrate this.

In testing a computer peripheral, a TEMPEST engineer finds information radiated from a

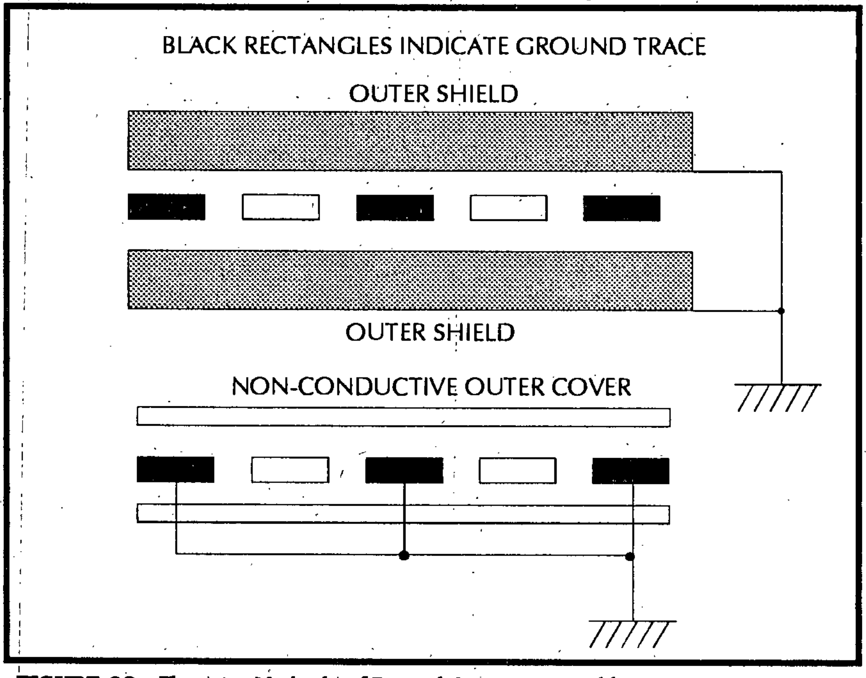

FIGURE 23. *Flexprint Methods of Printed Circuit Line Cables.*

coaxial interface. Upon investigation of the interface, the engineer notices that a varistor has been placed between the cable shield and frame ground for lightning protection, but the cable terminating hardware is referenced to the printed circuit card ground. The engineer ties the frame and logic grounds together and immediately finds an improvement in the radiated signal levels. Unfortunately, when the equipment is retested for ESD susceptibility, it fails because the ESD energy now has a direct path from the frame to the electronic circuitry.

In another case, a cost upgrade to a piece of equipment is made by replacing several integrated circuit modules with a single VLSI module. The equipment radiates too much energy. This problem is improved by bonding the equipment covers better, both to each other and to the frame ground. Again, the ESD performance is significantly reduced when this is done.

How does a TEMPEST engineer resolve this conflict? The common denominator for these examples is that the improved grounding has led to degraded ESD performance. This points to a problem in the grounding scheme. In the first example, the problem can be eliminated by connecting the frame ground and printed circuit board ground through a capacitor, rather than a direct connection.

In the second example, further scrutiny reveals that the ground to the cost-reduced printed circuit card is fed over a relatively long piece of wire directly to the new VLSI module. It had previously gone through a buffer. The problem in this case can be eliminated by isolating the ground through a buffer, or limiting the current with a resistor.

ESD is a real problem in the operating environment. In the first place, ESD is a major source of malfunction in machines.[8] In the second place, ESD generated within a machine will result in a radiating field,[9] which, if regular, can cause TEMPEST problems.

EMP is primarily a one-time nuclear event condition, with circuits generally hardened to survive an event in an operational state. When an EMP event occurs, a large electromagnetic pulse induces a severe current pulse into all conducting surfaces, wires and cables. Hardening is usually accomplished with protection devices, such as back-to-back zener diodes, or a terminal protection device (TPD) at the interface circuit. Using multiple shields (nested shields) greatly reduces the current coupled to the inner wires of the cable harness. The primary problem with adding protection devices is the same as with ESD - the creation of additional ground paths. One method of dealing with externally generated ESD is to control the environment creating the problem.

With regard to cables, the same general methods employed for shielding against radiation will be effective against ESD and EMP, as illustrated in Figure 24. Care must be taken, however, when attaching peripheral equipment to the central unit to avoid ground loops.[10] The technique of providing a bulk cable shield allows charge transmitted directly or indirectly to a cable to follow the path of the main power ground and not affect the signal or reference lines. If the ESD is generated internal to the equipment, as often occurs in printers, bulk cable shields may also protect against modulation of the ESD field by the signal-generated information.

In evaluating interface wiring with TPD's attached for EMP protection, the concern is that the device capacitance required to shunt large currents into the structure ground not create a path for TEMPEST problem currents. Since signal returns are also normally isolated and coupled tightly to the corresponding Red signal, the key is to locate the TPD close to the location of the central Red ground without necessarily being located on a circuit card.

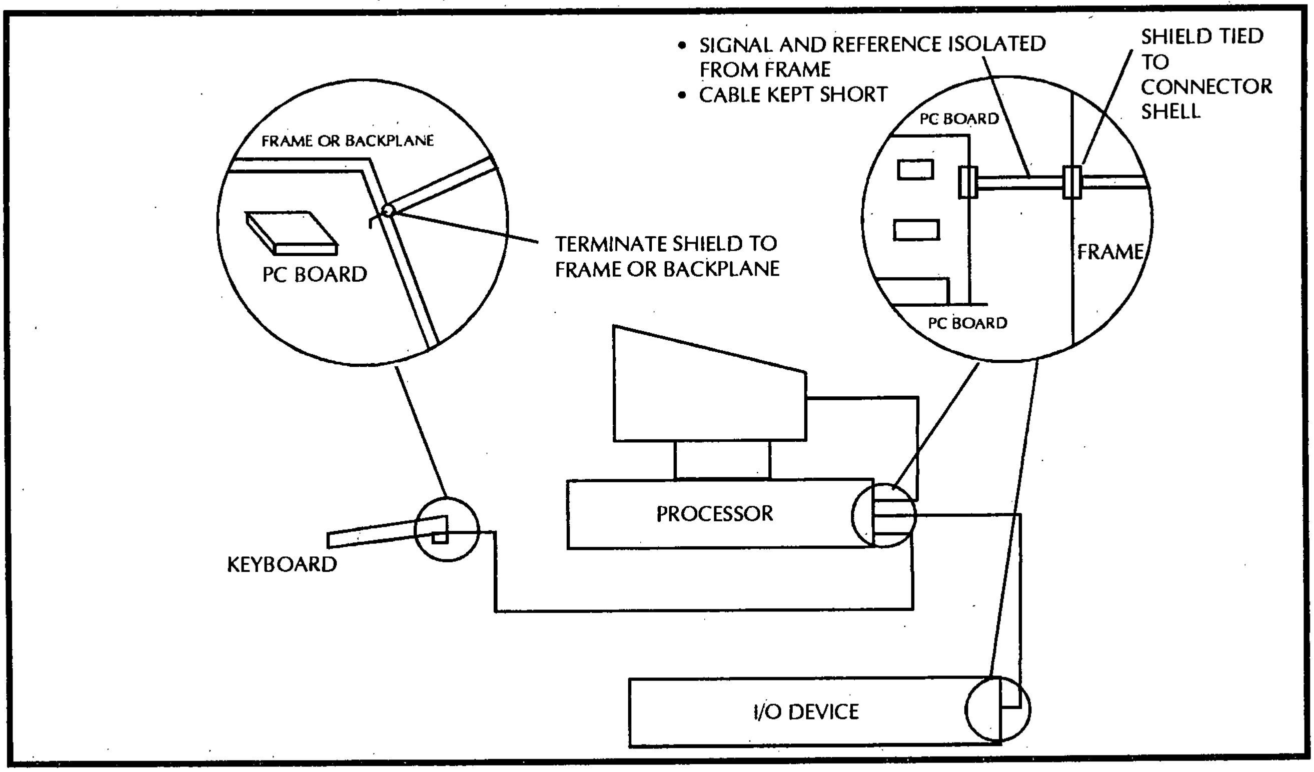

FIGURE 24. Examples of Good ESD Design.

EMP TPD's usually appear on an interface device just inside the hardened box. For critical TEMPEST signals it may be beneficial or necessary to provide a separate TPD.

Cable routing is particularly important in ESD and EMP, as is maintaining short cable lengths. Since these events create a large broadband field on the frame and ground structure of the equipment, it is imperative to route cables without a bulk shield away from external covers.

SUMMARY AND CONCLUSIONS

This article has attempted to indicate concerns in cable and wiring design for TEMPEST applications. Two items bear specific mention:

1. Concerns discussed here should be addressed as early in the design phase as possible. This consideration will nearly always save time and money.
2. Cabling and wiring is very much a platform related problem, highly dependent on other parts of the system design. The technology selection, for example, has a major bearing on the cables and wires employed.

TEMPEST design is a system level design problem, closely integrated with other hardening measures. Consideration of one problem without proper attention to its interrelated aspects can defeat whatever measures are employed.

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