EMI Design of Shielded Cable Assemblies

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***Abstract*— Most discussions on shielding for EMC address the shielding of enclosures and give rules of thumb regarding the size of slots and holes. These recommendations are not applicable in general to the design of shielded cable assemblies. Because there exists a gap in published information on the unique shielding requirements for cable assemblies, this document was generated. The scope of this document is that it will apply to low cost shielded multiconductor cable assemblies. While some of this information will be applicable to coaxial RF cable assemblies, this is not the main focus of this document.**

Keywords-shielded connectors, transfer impedance, shield termination

I. DEFINITIONS

Shielding Effectiveness (SE) has a classical definition of the ratio of the radiated power density in the source space to radiated power density in the quiet or shielded space. For cables and connectors it is important to understand that SE is better characterized as the ratio of current on the inside of the shield to current on the outside of the shield. Due to skin effect the current on the inside of a shielded connector is usually much higher (roughly 40 decibels (dB)) than the current on the outside of the shield. Current on the outside of the shield is what causes electromagnetic radiation. In the frequency range of interest (30 MHz to 1 GHz) connectors are inefficient radiators by themselves. When connected to cables or PCB's the entire system is large enough to be an efficient radiator and the connector can be the noise source which drives this radiating system.

The term "shielding" is broadly used in this paper and is specific to a fairly narrow bandwidth of the electromagnetic spectrum. In the frequency range of interest (30 MHz to 1 GHz) the wavelength varies from 10 meters to 0.3 meters. This is a much longer wavelength compared to x-rays (wavelength of 10^{-9} m) or gamma rays (wavelength of 10^{-14} m), consequently the shielding issues discussed herein differ greatly from shielding discussions for the much shorter wavelengths.

The term Transfer Impedance will be used throughout this document. Transfer impedance is measurable (although the measurement can be rather complex) and relates to specific components of a shielded system. The shielded connector will have one transfer impedance while the associated shielded cable will have a different transfer impedance. In addition to being applicable to components, transfer impedance is independent of the measurement system and is a function of only the shield. Transfer impedance is the ratio of series (or longitudinal) voltage to current in shielded systems. A coaxial system is the easiest geometry to describe. The current is simply the current on the inside of the shield, or the current on the inside surface of the shield closest to the center conductor. The series voltage is that voltage which is generated due to perturbations in the current flow on the shield. These perturbations are usually due to gaps or holes (referred to as apertures). The series voltage sources in a shielded system are the primary mechanism by which current on the inner surface transforms into current on the outer surface. Figure 1 shows the current path and resulting series voltage due to an aperture.

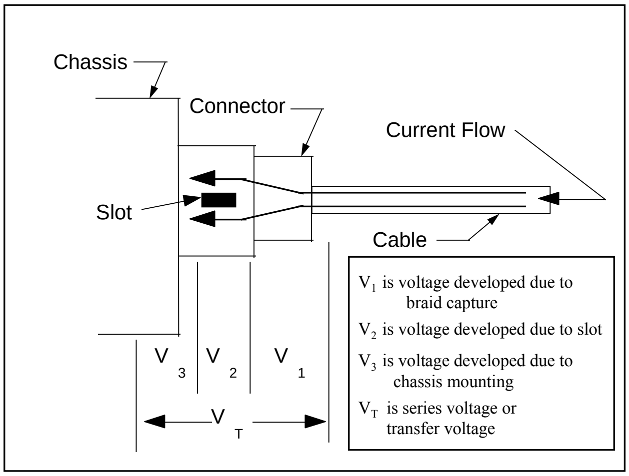


Figure 1. Current Flow and Resulting Transfer Voltage

II. MATERIAL SELECTION

A. Bulk Material

The shielding of a connector is more a function of the gaps, apertures and contact resistance than of the actual material itself. This does not mean that the material does not matter, only that the material choice is of less concern than the physical design of the shield. Requirements of the shield is that it should be a good conductor having conductivity of $\sigma > 10^6$ S/m The material should be capable of providing a series DC resistance of less than 0.1 milliohms for a finished product when measured from cable capture to connector termination assuming no contact resistance.

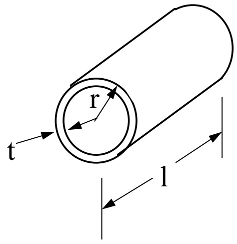
Contact physics becomes an important material parameter at the separable interface, the braid capture region and at the connection to ground. It is critical that these connection points have a low resistance, high durability connection.

The requirements of low contact resistance and high bulk conductivity makes conductive polymers a poor choice for shielded cable connectors. Conductive polymers (either intrinsically conductive or polymers loaded with a conductive media) may have very good shielding properties when measured as a bulk material but are ineffective because of the high resistance developed across separable interfaces. In general, there bulk conductivities are several orders of magnitude lower than for metals which leads to the development of series voltages. If a technique is developed to make a low resistance (<0.5 milliohm) separable interface for conductive polymers, they may become a viable material selection provided their volume conductivity is on the order of 10^6 S/m. For applications which do not require the connection of shielded cable, carbon or silver loaded polymers are effective as a shielded housing material. An example of this type of shielded connector is a SCSI terminator. The shield in this case is acting primarily as a protection against ESD and a conductive polymer is considered adequate for this type of application.

B. Plating Aspects

Because the skin depth of good conductors at frequencies above 30 MHz is quite small (475 µinches for copper), the material does not need to be more than 3 times the skin depth (1425 µinches for Cu) to function well as a shield. This is true provided the shielded connector is only used as a deterrent for RF emissions/immunity. If the shielded connector is used as a safety ground for equipment, the potential exists for low frequency (60 Hz) fault current (>10 amperes) to flow through the shielded connector. While this application may not be intentional, it does happen in practice and customers need to be aware that a thinly plated connector is not a good choice if this scenario is a possibility.

What is the minimum plating thickness assuming that fault current will never flow through the connector? The answer depends on the application. Remember that the purpose of the shielded connector is to provide a low impedance path to ground for a shielded cable. Low impedance depends on application. For a circular military connector which terminates a highly screened cable, low impedance could be <0.5 milliohm. For an RJ-45 connector which terminates an aluminized mylar shield, low impedance could be <10 milliohms. To translate the low impedance termination requirement (0.5-10 milliohms) into a plating thickness requirement, the connector can be roughly modeled as a short fat hollow cylinder where the plating comprises the walls of the cylinder. Using this approach we end up with an equation for an absolute minimum plating thickness as follows:



R_{DC} is the DC resistance (Ω)
r = radius (m)
t = plating thickness (m)
l = length(m)
σ = conductivity (℧/m)

$$R_{DC} = \frac{l}{\pi[r^2-(r-t)^2]\sigma}$$

for t << r

$$\boxed{t \approx \frac{l}{2\cdot\pi\cdot r\cdot\sigma\cdot R_{DC}} \quad \text{(m)}}$$

There are other considerations which may cause the plating thickness to be specified as being thicker than the minimum obtained from the equation above. If the plating thickness is non uniform, the minimum thickness should be as from above. If an existing design is to be modified by decreasing the plating thickness, care needs to be taken to ensure that regions of incidental contact are not adversely affected. Incidental contact refers to those portions of the interface which are not guaranteed to make contact. As an example, consider a long flexible piece of metal secured to another piece of flexible metal only at two end points. Incidental contact will occur between the two contact points and may or may not form a gap.

III. MECHANICAL DESIGN

A. Detent Sapcing

It has been demonstrated [1] that adding detents to D-subminiature connectors at the separable interface can dramatically improve electrical performance. Figure 2 shows the separable interface and the detents. Detents are intended to guarantee contact at several locations around the periphery of the separable interface.

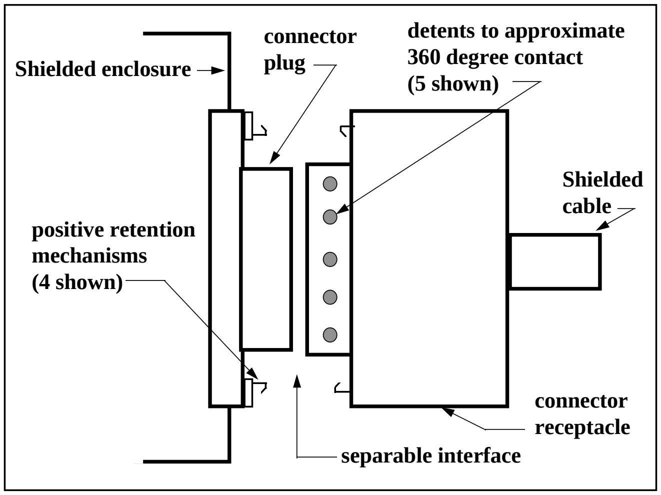


Figure 2. Detents to Approximate Circumferential Connection

B. Cable Braid Capture

The cable braid capture, like the detent height and spacing requirement is attempting to approximate circumferential connection of the shield to the connector shell. Figure 3 shows one type of cable braid capture employing a ferule and compression nut. There are other types available ranging from the staple and channel approach to crimps of various forms. Manufacturing processes will dictate the degree to which the braid is disturbed by the termination process. The key attribute here is to minimize the openings in the braid due to handling.

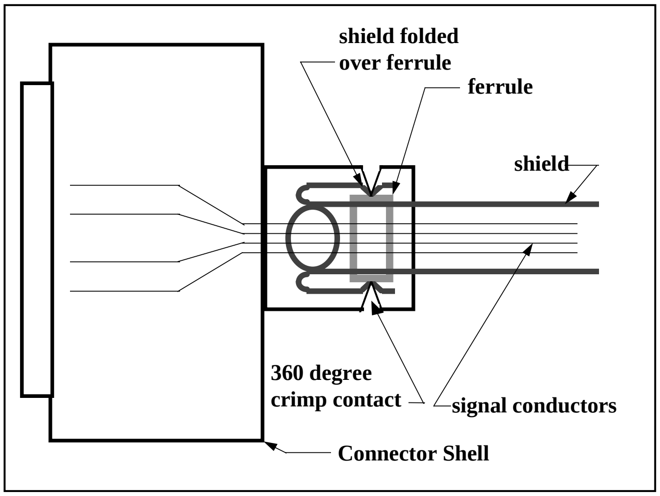


Figure 3. Cable Braid Capture

Aluminized mylar shields are typically terminated via a drain wire to a pin in the connector. These types of shields are capable of providing reasonable SE (20-30 dB) if the shield is terminated in a circumferential manner. Lab experiments have used a thin tube which has the aluminized mylar wrapped over the top and compressed with a hose clamp or other mechanical means. Commercial techniques to circumferentially terminate a mylar shield have not been widely adopted.

C. Cable to Chassis Connectors

A quality braid capture, such as a ferrule and compression nut, has a low impedance connection to the braid all around the periphery. At the separable interface, detents were used to guarantee contact at several points around the periphery. When a receptacle is mounted to a panel, the connection from the receptacle shield to the panel should likewise approximate a circumferential connection. Methods that can be used to achieve such a connection include a mounting nut plate that is in back of the receptacle and provide uniform pressure forcing the receptacle shell to contact the panel housing. A diagram of this approach is shown in Figure 4.

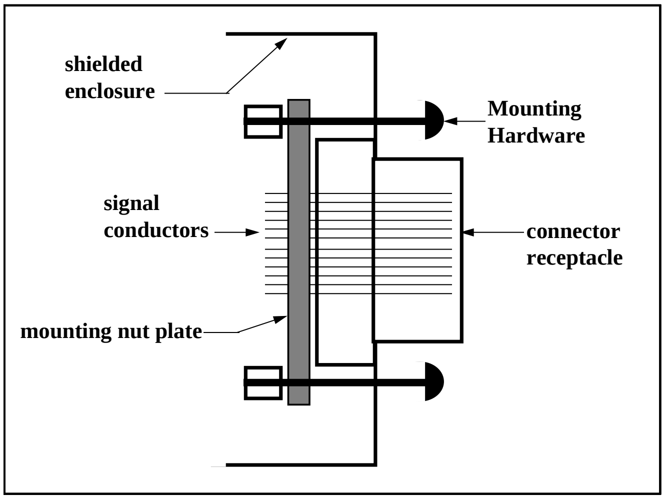


Figure 4. Diagram showing receptacle mounted to panel using a nutplate

Designers understand the importance of this connection and may opt to incorporate special panel cutout shapes which guarantee circumferential connection of the receptacle to the panel. This approach is shown in Figure 5.

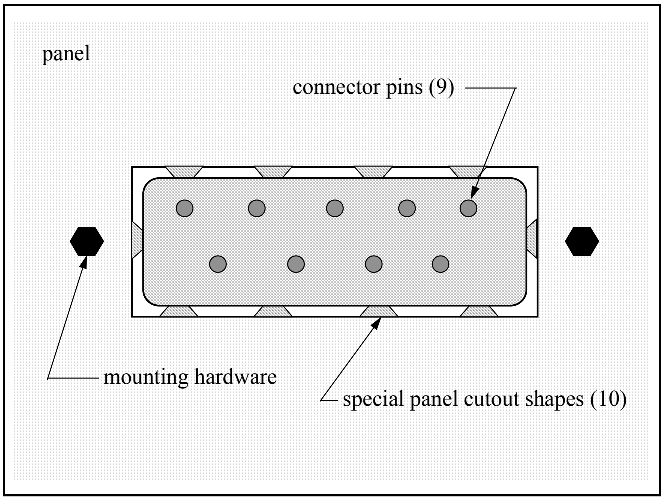


Figure 5. Diagram showing special panel cutout shape for receptacle mounting

Another approach which designers may opt to use is to incorporate a conductive gasket. Conductive gaskets can be quite effective but again represent an added cost to the product and are generally only used if an EMI problem is uncovered during system testing. A diagram of the conductive gasket panel termination approach is shown in Figure 6.

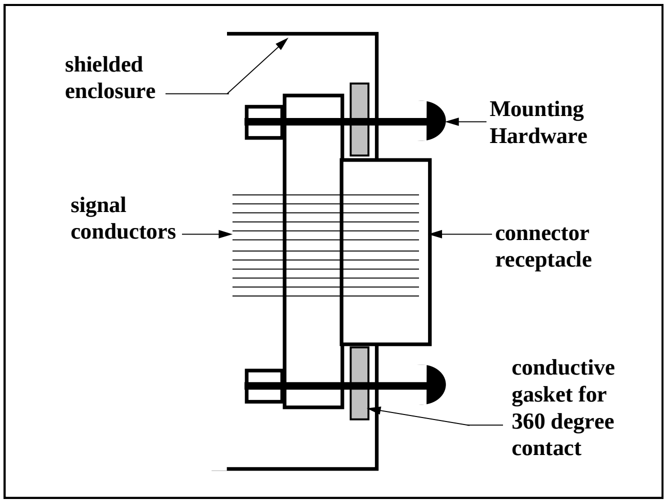


Figure 6. Diagram showing conductive gasket receptacle shield termination

An issue which sometimes arises is the very real problem of low frequency (<30 MHz) ground loops in shielded cable connector systems. The issue here is that a shielded cable may be quite long and connect to equipment chassis which are separated by a large physical distance. During a thunderstorm, lightning may strike the building causing large currents to flow through the facility ground grid. The result is a difference in reference potential at different points in the building. This can be due to lightning or exist as the norm in heavy industrial environments where heavy power usage is typical. If a shielded cable connects parts of the facility grid that are at different potentials, a low frequency current will flow on the shield. The magnitude of this current can be quite large (10-100 amperes) and for this reason shield isolation requirements are incorporated in some interface standards. To achieve shield isolation yet retain RF shielding performance, capacitive shield termination is required. The capacitor has a high impedance at low frequencies to provide the isolation and is low impedance at high frequencies for RF shield termination purposes. To maintain a quality shield termination will require multiple capacitors to approximate circumferential current flow.

D. Cable to Board Connectors

A popular approach toward shield termination is to utilize the ground plane(s) of a printed circuit board as the shield termination point. Products which do not have a traditional metallic enclosure are served well with this approach as the benefit of shielded cabling can still be achieved. The challenge is to design the printed circuit board such that the shielded connector contacts a quiet ground plane. The circuit board design approach should have the high speed logic and any noise generators physically separated from the region where the shielded connector is to be located as shown in Figure 7.

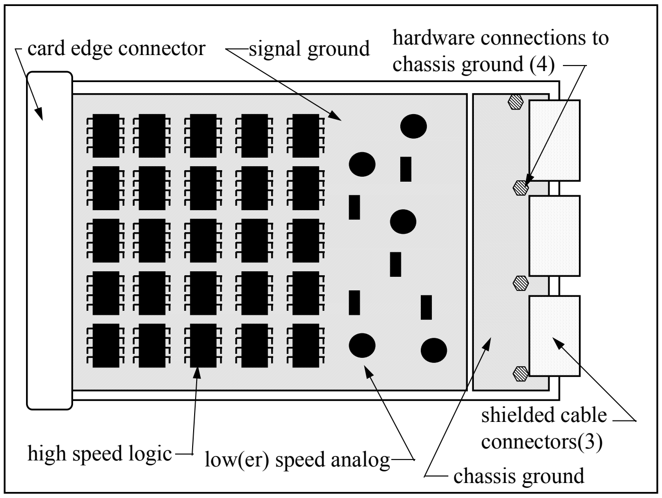


Figure 7. Typical PCB design for board mount shielded connector

From a connector design perspective the best design would have the shielded connector soldered directly to a surface ground plane. Electrically, this would provide the ideal circumferential shield termination. This approach would also free up routing channels in the PCB for traces which will interface to connector pins. There are manufacturability issues with this approach that may make it impractical. A more common alternative approach is to use ground pins which are integral to the connector shield design and are soldered into vias in the PCB. The vias should make contact to ground planes in the PCB with a minimum of thermal relief. This is depicted in Figure 8.

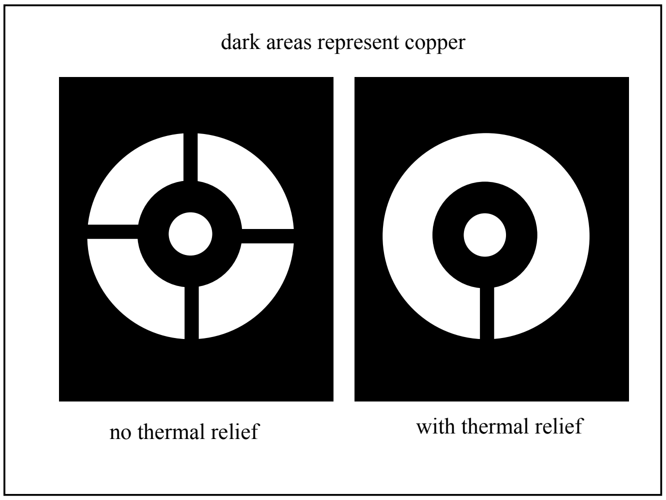


Figure 8. PCB via with and without thermal relief

There should be enough ground pins in the shielded connector design to approximate circumferential termination, roughly one ground pin every 30-45 degrees. Typically only 2 ground pins are provided and this explains the degradation in shielding performance associated with this approach. Adding numerous ground pins can eliminate many PCB trace routing channels making it difficult to route traces to the signal contacts in the connector.

A possible alternative would be to incorporate some type of spring contact mechanism on the PCB to simulate circumferential shield termination. Fingerstock or gasketting could be applied to the PCB to contact the surface ground plane and the connector shield as shown in Figure 9.

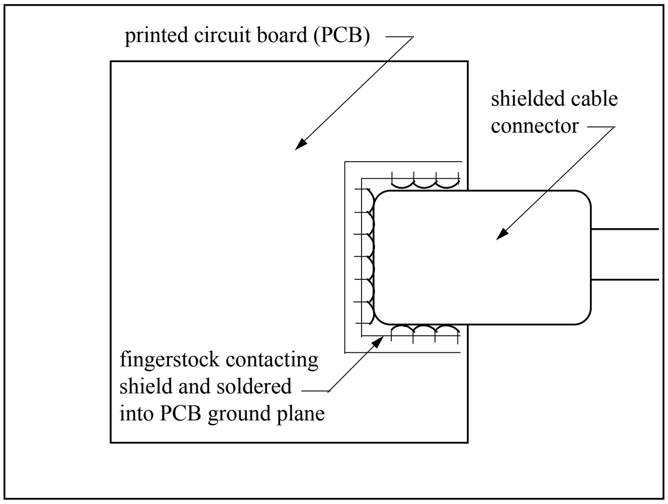


Figure 9. Fingerstock approach toward shield termination of a PCB mount connector

E. *Non-contacting Overlapping Shields*

Often in the design of shielded connectors the issue of non-contacting overlapping shields arises. The thought is to rely on the overlap in folded sheet metal designs and allow the capacitance formed by the overlap to act as an RF connection. In principal this technique would work but a problem exists with the relative magnitude of the capacitance formed. The magnitude of the capacitive reactance should be roughly 100 milliohms or less at 30 MHz or about 0.1 uF. A simple equation to approximate the amount of capacitance formed by the overlapping plates is as follows:

$$C = \frac{\varepsilon_o \varepsilon_r A}{d} \quad \text{(farads)}$$

ε_o = permitivity of free space

= 8.85×10^{-12} F/m

ε_r = relative permitivity

= 1 for air

A = the overlapping area (m^2)

d = plate separation (m)

example

A = 0 .5”x0.25” = 50.5×10^{-3} m^2

d = 0.001” = 25.6 $\times 10^{-6}$ m

ε_r = 1 (air dielectric)

$\underline{\underline{C = 17.5 \text{ nF}}}$

This example illustrates the limitations of this approach. For practical applications there is no benefit in having overlapping shields in a shielded connector design from a shield termination perspective.

F. *Effect of Gaskets*

As described earlier in section III. C., gaskets can be an effective method to provide circumferential shield termination in situations where only incidental contact would exist if gaskets were not used. Typically a conductive gasket would be used on a panel or board mount connector. Gaskets can take the form of a sheet of impregnated elastomer which is cut to fit around the connector and is compressed between the connector shell and the panel when installed. The purpose of the gasket is to provide a low impedance (<0.1 milliohm) connection over the operating frequency range (generally 30 MHz to 1 GHz). The gasket works by acting as a short circuit to shield currents. It is convenient (but incorrect) to think of the radiation as water leaking through holes in the chassis. The problem with this description is that erroneous conclusions can be reached such as the merit of overlapping shields discussed in section III. E.

IV. SHIELDING REQUIREMENTS

How much shielding is enough? There is no simple answer to this question. A conservative answer is that if a shielded cable is being used in the system design, additional cost has been incurred in an attempt to mitigate EMC problems. The function of the shielded connector is to connect the cable shield to chassis ground in such a manner that the performance of the cable connector system is not degraded. Levels have been established for coaxial cables, the SE of RG223 is on the order of 70 -80 dB, a very well shielded cable. RG58 has only a single braid and has a SE of only 40 dB. Many of the connectors in networking use an aluminized mylar shield with drain wire termination. If the drain wire is terminated to ground using a pin, a shielded connector is probably not required. For these types of systems the SE is only 5-15 dB.

A. *Emissions*

From an EMI design perspective, radiated emissions are the most demanding requirement for most telecom and computer applications. The regulation of the radiated and conducted emission levels by the FCC started in the late 1970's and the specific requirements have evolved over time. The European Union has adopted a Council Directive (89/336/EEC) requiring all electrical and electronic equipment to meet emissions and immunity requirements. The penalty for non-compliance is that a CE mark cannot legally be affixed to the product and the product cannot be traded with the EU.

Emissions are generally a result of common mode currents on the interconnecting cables and are usually the easiest feature to address. When radiated emission failures occur, the shielded connector design is very carefully studied and if a competing product is available which performs better, the new cable assembly will likely be designed in. The radiated field strength levels are on the order of 100-200 uV/m measured 3 meters from the product. This equates to a radiated power level of roughly 6 nW. These levels are extremely low, much lower than the local ambient.

There are several types of design approaches commonly used by designers to control emissions. Some of the more prominent EMI design areas are power system decoupling, signal referencing (grounding) and system partitioning. Attention is given to the power and ground distribution because power and ground are common to all circuitry and is the channel by which noise is conducted throughout the system. The noise can be thought of as an RF potential which acts as a source to drive unintentional radiators, often cables.

Shielding requirements are almost impossible for a system developer to define because of the number of variables which affect EMC design. Usually what has worked in the past defines a precedence which is the baseline approach. Most system developers take the approach of having provisions for additional EMI suppression features (which add cost) and rely on these features only if it is determined by test that they are needed.

B. Immunity

Immunity refers to the ability of a system to operate in the presence of electrical noise. The noise can be from intentional radiator like cellular phones or from environmental phenomena like ESD and lightning. Requirements for immunity for commercial equipment are part of the European Union Directives on EMC. Most major electronic providers have had immunity requirements as an internal design specification for many years. The reason is that if their product fails to operate during an ESD event (someone touching a CPU on a dry day) their reputation and sales will suffer.

Shielding requirements for immunity are less abstract then shielding for emissions requirements but are still vague. In principle the hardness level of interface circuitry can be defined and the external threat can also be defined. The difference between the two is the shielding requirement. As with emission requirements, cables and connectors are often the components scrutinized closely when an immunity failure occurs, primarily because it is one of the easier features to change. When a radiating field impinges on a conductor (a cable/connector system) a surface current develops on the outside of the shield. Apertures from slots in the connector design can act as voltage sources, which can cause electronic circuitry to malfunction. The same shielded connector design techniques which work well for emissions also work well for immunity.

V. CONCLUSION

The electrical design of shielded connectors is as much of an art as it is a science. The underlying principles are generally well understood but the lack of performance definition complicates the development process. A generally accepted practice is to develop a shielding approach in concert with an electrical design consultant and evaluate the performance via test techniques. It is anticipated that this approach will evolve in the next five years to include numerical simulation of electrical performance for a more exacting shielded connector development process.

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