The most troublesome gaps that cause EMC problems are improperly grounded connector shells and poorly fitted seams between metal surfaces. Many connectors are available with metal bodies or metal shields around plastic bodies. If these metal surfaces are securely mounted to the metal chassis at multiple points such that openings are substantially smaller than $\lambda \div 4$, there should be no gap at the connector to allow excessive radiation. Seams between individual sheets of metal, either movable or fixed panels, must be designed to meet cleanly without the slightest buckling. Imperceptible buckling at seams opens gaps that radiate unwanted energy. A well designed sheet metal chassis should have all of its fixed panels adequately riveted or welded to ensure uniform contact across the seam. Movable panels almost always require additional assistance in the form of conductive gaskets and springs. A gasket or spring serves as a flexible conductor that closes any electrical gaps between two metal surfaces that move over time and that may expand and contract with temperature changes. Gasketing is directly akin to the rubber washer in a sink faucet—minute gaps must be closed to prevent leakage.

Plastic enclosures can also be shielded by applying conductive coatings, although this is usually more expensive than a sheet metal chassis, which is a reason why many products use metal rather than all-plastic enclosures. Many small electronic products can get away with less expensive, more attractive, and lighter uncoated plastic packaging, because their circuits do not radiate excessive energy. This may be because of their relatively slow signals, careful circuit design, or a combination of both.

Unwanted high-frequency noise that may be conducted onto exterior cables should be filtered between the active circuitry and the cable connector. Passive differential and common-mode filters are discussed earlier in this book. High-frequency data interfaces often have standard means of dealing with noise, including application-specific off-the-shelf transformers and common-mode chokes. Lower-frequency interfaces such as RS-232 may be effectively filtered with a second-order LC filter using either a choke or ferrite bead for the inductive element. If noise is still able to couple onto internal wiring harnesses that lead outside the enclosure, the weapon of last resort may be a ferrite core. Ferrite cores are available in clamshell types whereby the ferrite fits around a cable, and in ring forms whereby the cable is wrapped several turns around the core. The ferrite increases the inductance of the cable, which increases its attenuation of high frequencies. When you see a computer monitor cable or some other type of cable that has a noticeable round bulge near one end, a clamshell ferrite has been added, because the equipment was unable to pass emissions regulations without it.

Filters can also be employed to attenuate higher-order harmonics of digital signals as they are distributed on the circuit board to reduce the strength of ambient electromagnetic fields on the board and within the enclosure. Clock distribution can account for a substantial fraction of unwanted emissions, especially at higher-order harmonics that radiate through small metal gaps. One technique is to insert lowpass filters at clock buffer outputs to attenuate energy beyond the fifth harmonic. A square wave substantially retains its characteristics with only the first, third, and fifth harmonics present. Unfortunately, component variation, mainly in capacitors, across the individual filters on a low-skew clock tree can introduce unwanted skew at the loads. Instead of an LC or RC filter at the source, inserting just a ferrite bead may provide sufficient high-frequency attenuation to substantially quiet a system. If it is unclear whether such filtering is necessary, the design can include ferrite beads as an option. Ferrite bead PCB footprints can be placed at each output of a clock driver in very close proximity to any series termination resistors that might already be in the design. If the ferrites are not needed, they can be substituted with 0-Ω resistors. Introduction of an extra 0-Ω resistor very close to the clock driver should not cause problems in most systems. For truly conservative situations, these scenarios can be modeled ahead of time with field-solver software.

The method by which a system's many ground nodes are connected has a major impact on EMC in terms of noise radiating from cables leaving the chassis. Conceptually, there is a single ground node that all circuits use as their reference. This is easy to achieve at DC, because resistance is the dominant characteristic that causes voltage drops, and solid sheets of metal have very low sheet resistances. Additionally, there are no EMC problems at DC, because there is no AC signal to radiate. Inductance becomes the problem in maintaining equipotential across an entire system's ground structure at high frequencies. Small voltage differences appear across a circuit board's ground plane despite its low sheet inductance. These differences can cause EMC problems despite having little to no effect on signal integrity. The ideal situation is to ground everything to the same point to achieve an equipotential ground node, but finite physical dimensions make this impossible.

Any opportunity for a cable to have a high-frequency potential difference with respect to the chassis is an opportunity for unwanted electromagnetic radiation. The basic idea in many systems is to take advantage of a chassis' sheet metal surfaces as a clean ground reference because of low inductance and negligible current circulation. If a circuit board is grounded to one face of the chassis, and all cables are grounded to that same face, the ground potentials in that region will be nearly equal, with less opportunity for radiated emissions.

A complete discussion of chassis grounding techniques for EMC design is beyond the scope of this presentation. If you anticipate having to pass governmental electromagnetic emissions requirements, further reading is recommended. Electronic products are tested and certified for regulatory compliance at licensed test ranges where it is also common to find EMC consultants to advise you on solutions to emissions problems. Like most design tasks, it is better to seek help before building a product than to wait until a problem arises, at which point it is usually more expensive and time consuming to resolve.

18.6 ELECTROSTATIC DISCHARGE

Electrostatic discharge (ESD) is another phenomenon related to EMC and grounding. Static electric discharges are common occurrences and have been experienced by everyone. An insulated object accumulates a static electric charge and holds this charge until it comes into close proximity with a conductor. The human body can easily accumulate a 15,000-V charge while walking on carpet. If a person with a 15-kV charge comes into close proximity with a conductor at a substantially different potential (e.g., Earth ground), the charge may be able to arc across the air gap and discharge into that conductor. Higher potentials can jump across greater distances between the charged body and nearby conductors. The problems with ESD are twofold. First, ESD can disrupt a circuit's normal operation by inducing noise that causes errors in digital signals. Second, ESD can permanently damage components if the event is strong enough and the circuit is not protected. CMOS logic is particularly sensitive to ESD because of a FET's high gate impedance and the possibility of punching through the thin gate dielectric if a high potential is introduced.

When an ESD event occurs, it can couple onto a system's internal wires by inductive or capacitive means. A discharge is a brief, high-frequency, high-amplitude event with current peaking on the order of 10 A at 300 MHz. When ESD occurs, a very strong magnetic field is generated by the fast current spike. This field can be picked up by wires some distance away, and the coupling characteristics are governed by the same EMI concepts discussed earlier. Larger loops and thicker dielectrics make a more efficient antenna for ESD. A discharge to a chassis' metal panel not only establishes a strong magnetic field, it also creates a capacitor wherein the panel accepts the high-frequency signal and then may capacitively couple this energy to nodes within the enclosure. ESD occurs so rapidly that normal ground wires have too much inductance to drain the charge before it can do damage. A typical chassis is grounded to Earth through the AC power cord. This connection prevents gradual charge accumulation to dangerous potentials, but it cannot be expected to drain ESD before a circuit is disrupted.