Suppressing EMI Without Affecting Signal Integrity

Today's ever increasing operating speeds require the use of advanced RF design techniques to preserve signal integrity.

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Consumers have always been enamored with speed. In the 1960s and 1970s, we demonstrated this love by running the 400-plus cubic-inch displacement engines in our sporty cars. Now we have turned to the computers that we drive. Today's computer systems are being pushed to their thermal limits in the interest of speed! In order to achieve today's high operating speeds, PCB designers are required to incorporate advanced RF design techniques into both the devices and the PCB designs. These techniques, which include the use of microstrip and stripline transmission lines, impedance matching, and matched timing to assure coincident monotonic signaling, are essential to preserve signal fidelity. EMC engineers call this intra-systems EMC. Digital designers call this signal integrity. Whatever is done to the system in order to meet the EMC requirements must not effect signal integrity.

Besides reducing systems reliability, this push to go faster and faster results in dramatically increased radiated emissions, making it nearly impossible to meet the obligatory regulatory requirements. To put this into perspective, when computer circuits were operating at about 1 MHz, we were just squeaking by. Now we are operating at speeds in excess of 1000 MHz! That we can achieve a speed increase of 1000 times is in itself remarkable, but consider that the radiated emissions from a simple circuit current loop can be described by Equation 1:

$$E(\mu V/m) = 1.316 * A * I * F^2/D * S \quad (1)$$

where
E = Electric Field (μV/m)
A = Loop Area (cm^2)
I = Loop Current (amps)
F = Frequency (MHz)
D = Separation Distance (m)
S = Shielding Ratio

From this relationship, we see that the radiated electric field strength (E) increases as a function of the square of the frequency. Radiated emissions have therefore not increased by 1000 times, they have increased by 1000^2, *i.e.*, 1,000,000 times. Expressing the increase in field strength in dB, the increase is 20 log 1 * 106 = 120 dB. The development and adoption of lower current logic devices has reduced the emission levels by about 12 to 20 dB. Good multilayer PCB design can reduce the levels by another 50 dB. This reduction still leaves high speed circuits about 50 dB over the FCC/EU emissions limits at their fundamental frequency, thus more has to be done in order to meet the EMC requirements.

Circuit loops fall into two classes, differential-mode (in a high speed system, typically a differential pair over a ground plane), and common-mode (where some synchronous current from both the signal and its associated return lead returns via a common reference surface). Figure 1 shows both loop classes. High level differential-mode currents are our intended signals, and they travel from the source to the load over prescribed signal traces. Differential mode (DM) is called normal mode by telecommunications designers, a description which provides for better visualiza-

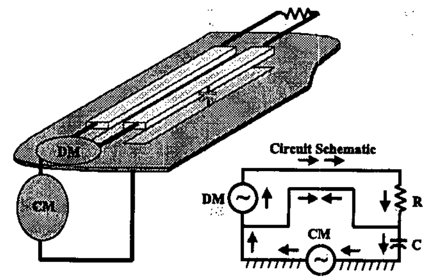

Figure 1. Common and differential modes.

tion. Unfortunately, all traces have series inductance (L) and are coupled to the underlying ground plane or other closely coupled conductors via shunt parasitic capacitance (C). For short traces, the LC transmission line characteristics can be approximated by a lumped pi filter network. Pi filters are low-pass networks with 60 dB per decade high frequency attenuation above their cutoff, along with substantial propagation delay. The propagation time through an LC circuit is given by Equation 2:

$$P_t = (LC)^{1/2} = [(L_0 + L)(C_0 + C)]^{1/2} \quad (2)$$

Common-mode (CM) currents (called longitudinal mode by telecommunications designers) arise from the unbalanced LC characteristics of the signal and return traces with respect to any closely coupled return path, usually the grounding system. It is these unbalanced conditions that result in differential signal skew. In addition, any LC circuit will ring (oscillate at its natural resonate frequencies) when shock excited by a transient or other signal with a very fast risetime that contains sufficient energy at its resonant frequency. These circuit resonances increase the amplitude of any radiated emissions that fall within the passband of these resonances. Since there is no way to eliminate the LC and resonance characteristics of these traces, in order for the PCB to function properly, the design must compensate for the variations by adding intentional delays to faster circuits in order to assure uniform signal arrival. Depending on distance, these faster circuits must be terminated in their characteristic impedance in order to minimize waveform distortion.

Returning to Equation 1, note that the separation distance (D) where the unit must comply with the appropriate EMC requirement is dictated by applicable government specification. Also keep in mind that various logic families have unique operating characteristics determined largely by their manufacturing process that determine both drive current (I) and operating frequency (F). In this quest for speed, every manufacturer is trying to switch as fast as possible, even if it's not necessary. It is this "let's go faster" mentality combined with manufacturing related characteristics that sometimes dramatically changes the system's RF signature when a change is made from one manufacturer's device to another.

Since the PCB designer has almost no control over the characteristics of logic devices, its easy to see that all high frequency loops should (in fact, must) be kept as small as possible. This imperative is especially important with regard to signal integrity. The higher the frequency, the shorter the transmission line must be in order to minimize unwanted delay and to prevent waveform distortion from impedance mismatches. Incidentally, most autorouters aren't smart enough to handle both signal integrity and EMC.

Unfortunately, there is a limit on how small the radiating loop can be because of physical constraints imposed by the size of the components being mounted on the PCB. The loop cannot be smaller than the area required by the components. Figure 2 shows the relationship between loop area, drive current and the FCC Part 15B specification limit. This figure shows that the maximum high-speed loop areas must be kept so small that the necessary area is often unattainable. Some compaction can be done by creating ASICs specifically for an application, but that is often prohibitively expensive. Even then this may not result in a loop area small enough to meet the requirements. Consequently, PCB layout cannot be expected to completely solve the emissions or susceptibility/immunity problem completely. Thus, other suppression techniques must be used to meet these EMC requirements. Care must be taken to prevent these techniques from degrading signal integrity.

From Equation 1, it can be determined that suppression techniques must rely on reducing signal current, limiting bandwidth, and/or limiting amplitude. This goal can be accomplished by adding series resistors, series inductors (ferrite beads, etc.), shunt capacitors, filters (which are combinations of inductors and capacitors), diode clamps, and/or shielding. Unfortunately, as indicated in Equation 2, anytime an additional component is introduced into a high-speed circuit, it generally effects the operation of the circuit by changing either L or C, thus adding delay. Only a very small change in delay can be tolerated before a high-speed PCB design is compromised. Even if there is no added delay, adding an additional component always reduces the reliability of the circuit and its associated mean time between failure (MTBF). Shielding is an exception. Because it is not placed in the circuit, it does not have these effects on the system. The next several paragraphs will examine these various suppression components.

In a high speed system, the propagation time through logic devices is small compared with the delay introduced by the trace, inductance and capacitance. Any component used to meet radiated emissions requirements must not add inductance or capacitance to the trace or it will effect signal integrity. Non-inductive series resistors are very good broadband suppression devices because (even though they are inserted in series with the circuit), the delay they introduce

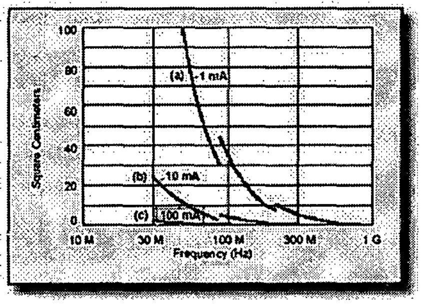

Figure 2. Correlation between maximum loop area (cm^2) and FCC Part 15B(B) limit for radiated RF at 1 mA (a), 10 mA (b), and 100 mA (c) of current. Measurement distance = 3 m.

from their parasitic capacitance is generally minimal, and they usually do not affect a system's functional operation. Unfortunately, their capability to reduce radiated coupling is limited to approximately 6 to 12 dB. Sometimes this reduction is enough to allow the device to meet emission requirements, but often we need a lot more attenuation than can be provided by a simple series resistor. As a general rule, a resistor will not provide adequate attenuation of externally coupled fields to permit the system to meet its radiated susceptibility/immunity requirements.

Series inductors, especially ferrites with their broad bandwidth high frequency characteristics, work especially well as low-pass frequency filters in low impedance circuits to reduce emissions. If the EMC problem is associated with systems power or power distribution, adding ferrites with their 200 to 400 ohms RF impedance is the preferred approach to solving emissions or susceptibility/immunity problems. In a low impedance power distribution circuit, for frequencies over 50 to 100 MHz, a 200-ohm ferrite can be expected to provide as much as 40 to 45 dB attenuation. Plus, delay isn't a problem. Of course care must be taken to assure that magnetic flux levels do not saturate the ferrite material. Signal leads are an entirely different matter. Most high-speed systems use microstrip or stripline transmission line impedances that range from 50 to 80 ohms. The signal transmission line impedance is largely determined by trace density and crosstalk considerations. Unfortunately, series inductors do not work well in high impedance circuits. The 200-ohm ferrite that works so well for the power distribution problems could only be expected to provide 6 to 8 dB (which is probably not enough), when used in a signal line. It will introduce significant delay which must be compensated for in the design. When used in signal circuits, the inductor works better to control emission than susceptibility/immunity problems.

Shunt capacitors and diodes are used for different EMC suppression purposes; the first as a low-pass frequency filter because of its decreasing impedance with frequency; the second as an amplitude limiter because of its ability to clamp high level transients to some more reasonable lower value. In a signal line, both components have the same effect of adding excessive delay to their associated circuits because of their capacitance. This effect does not mean that capacitive components can not be used.

Capacitors will provide upwards of 40 to 50 dB attenuation, depending on frequency, and they will often work in those applications were inductors will not. In fact, if a series inductor does not work, it generally means that the circuit RF impedance is high, and that is the circumstance where a shunt capacitor works best. Capacitors also work better for solving susceptibility/immunity problems. But like the inductors used in signal traces, their use must be considered and designed into the circuit from the beginning. They should not simply be added later when a problem has been discovered because of their effect on signal integrity. The EMC problem may be solved, but the system may not work. When added later, the effect on the design should be analyzed, because timing delays may have to be adjusted to prevent logic race, skew, and glitches.

Shielding is a very unique suppression technique. The shield behaves as a high-pass electric field filter and reduces radiated coupling for both emission and immunity without being placed directly in the signal or power distribution path. As long the shield placement does not tightly capacitively couple it to the circuit, it will not affect signal integrity.

For digital systems electric fields (EF), shielding is generally all that is required. The key element of good EF shielding is a reasonably good conductive material enclosure with no apertures (or at least a minimum number of small apertures) that completely surrounds the circuit that needs protection and/or suppression. The size of any apertures is limited by the size of the enclosure, *i.e.*, the largest aperture dimension cannot exceed the largest dimension of the enclosure. Since the high frequency cutoff is determined by aperture size, smaller enclosures generally have better high frequency performance. It is easier to control their mechanical tolerances. PCBs mounted in separate enclosures are very effective, with attenuation levels of 60 to 80 dB achievable. They can be used to minimize board-to-board crosstalk, another major signal integrity problem.

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