

EMC Design Guidelines: Design Rules for EMC-Compliant Product Design



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Topics

1. System Design
2. Cable and Connector Design
3. Grounding and Shielding
4. Circuit Design (and ESD protection)
5. Board Design (layout)

1. System Design

- Minimize the number of interconnects between subsystems
- Minimize clock speeds
- Minimize the speed (and drive strength) of IO lines
- For high-speed signals, use differential (LVDS) lines.
- Generate local power locally – from a single power bus (but watch carefully for IO devices that may not be powered)

System Design (cont.)

- A corollary of the requirement to minimize IO speeds is this: Design the system so that the data rates between subsystems is an absolute minimum.
- If possible, use well-defined (and industry standard) protocols (e.g., CANBus)
- Use serial, rather than parallel, bus structures to minimize the number of wires.

System Design (cont.)

- Don't depend on the metal parts (especially at moving joints) to provide ground continuity – add bonding straps.

2. Cables and Connectors

- Cable wiring for low EMI – two general approaches
 - Twisted pair (good bandwidth possible)
 - Coaxial cable (even higher bandwidth)
- Shielded twisted pairs (or shielded bundles)
 - Don't count on using the shield to carry the return signal – provide a separate wire for that purpose.
- High speed lines (which we are trying to avoid!)
 - Use off-the-shelf solutions (USB, Ethernet, etc.)

Cables and Connectors (cont.)

- **Shielding**

- The quality of the shield makes a difference.
- Tightly woven braided shield provide more protection than loosely woven shields.
- Double shielding – two layers of shielding, one inside the other – helps too.
- Good ground termination of the shield is essential.
 - The termination needs to be low inductance.
 - 360 degree connection from the shield directly to PCB ground.

Cables and Connectors (cont.)

- Shield effectiveness (at 30-50 MHz)

	Transfer impedance (mΩ/m)
Solid copper shield	0.01
Multilayer (braid + foil)	1
Optimized double-braid	8
Double-braid	15
Optimized braid	50
Braid	100+
Foil	300
Aluminized Mylar	10,000
Spiral serve (audio only)	» 10,000

Transfer impedance relates a current on the surface of a shield to the voltage drop generated by this current on the opposite surface of the shield.

Cables and Connectors (cont.)

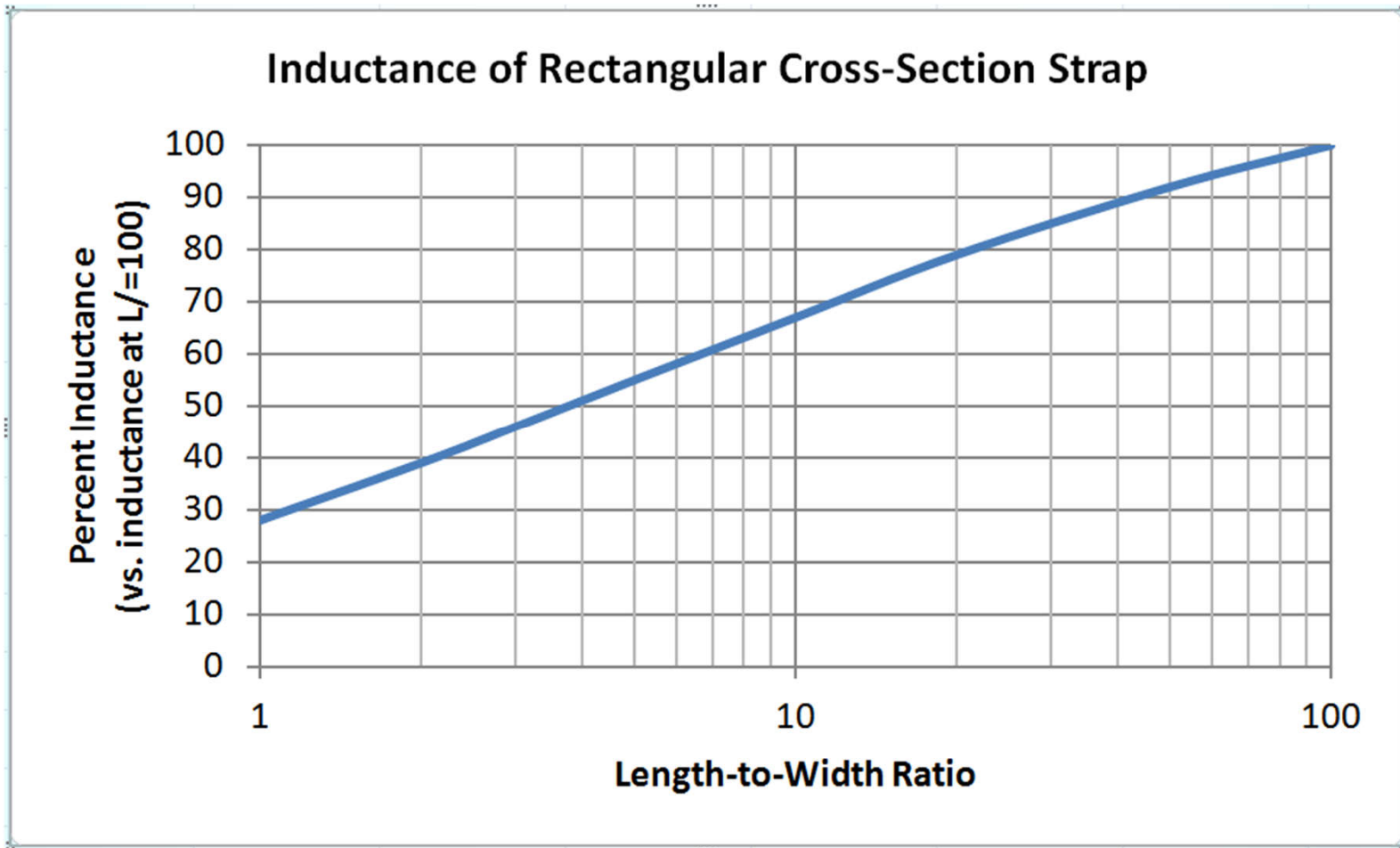
$$R_{dc}, R_{ac}, \text{ and } X=2\pi fL$$

For 2 inch-long conductors at 100 MHz:

Type	R_{dc} (m Ω)	R_{ac} (m Ω)	L (nH)	$Z = R_{ac} + jX $ (Ω)
26 AWG Cu	6.6	10.5	55	35
19 AWG Cu	1.3	4.6	47	30
16 AWG Cu	0.65	3.2	44	28
0.5in x 2mil Cu	1.3	5.2	27	18

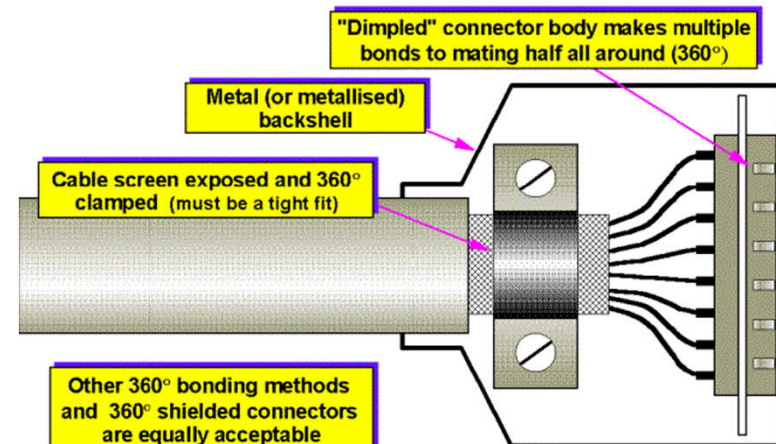
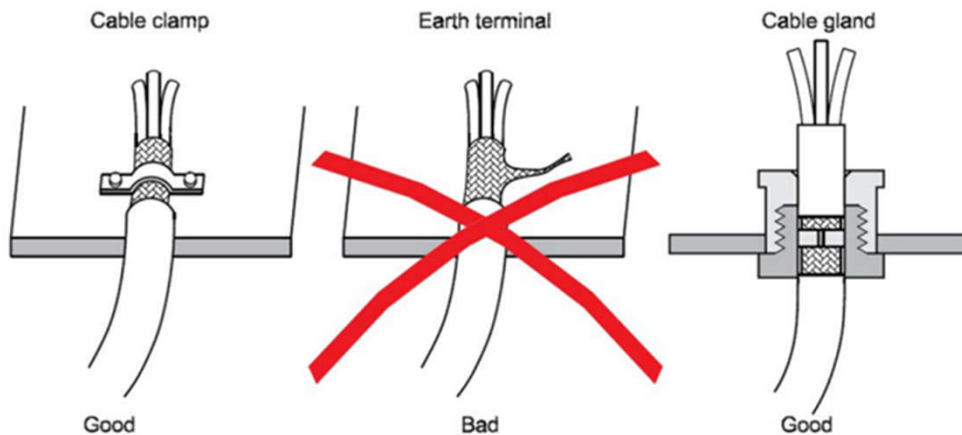
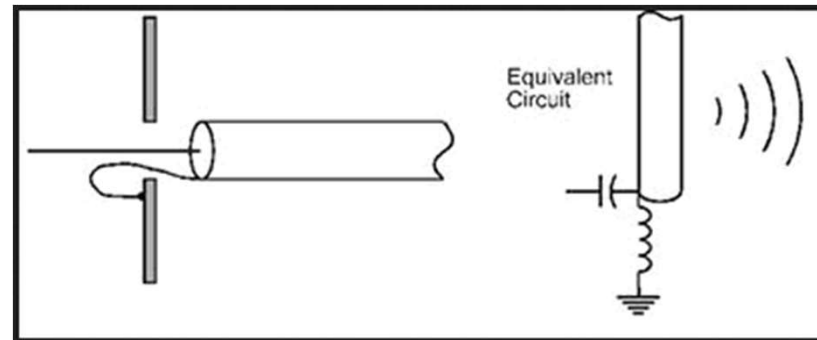
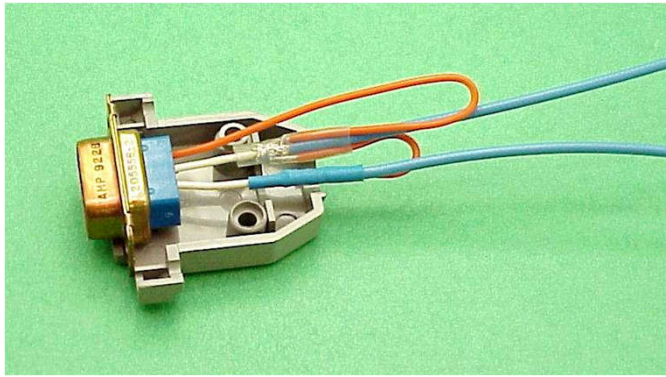
Even though a wide strap is better than a wire, we need to do better. Even 10 Ohms in a “ground” connection is too much.

Cables and Connectors (cont.)



Cables and Connectors (cont.)

Terminating the shield



Cables and Connectors (cont.)

- Cable ground termination
 - Low inductance connection to PCB ground is essential.
 - If the PCB is in a shielded enclosure, you need a low inductance connection to PCB ground and the enclosure both.
 - An EMI gasket between the PCB connector and the enclosure is the best way to do this.

Cables and Connectors (cont.)

- Plan for ferrite beads that may be needed
- Consider a coaxial cable
 - Skin effect → differential currents are on the inside of the shield but common mode currents flow on the outside (and they radiate from there)
 - Ferrite bead introduces common-mode impedance that restricts the flow of unwanted current
- Make sure no intentional common mode currents are flowing in the cable

3. Grounding and Shielding

- Think “return path” – there is no “ground”
- Always think about the current loop area. The radiation from a current loop scales with the loop area. So if the signal current and ground return are close together, the loop area is small and radiation is small. If a break in the ground causes the loop area to increase, radiation goes up.
- The grounding and shielding system should not be carrying “functional” current
- Consider not just DC resistance, but skin effect and inductance
- Make all bonding without “pigtailed” (avoid wires altogether)

Grounding and Shielding (cont.)

- Putting your circuit in a conductive box is a very good way to reduce PCB EMI; it's a Faraday cage.
- Two types of conductive boxes:
 - Metal box
 - Best EMI performance
 - Plastic box with internal conductive coating
 - Less effective than metal but cheaper and easier to form
 - The coatings can be very thin, on the order of microinches, which limits their effectiveness. You want the coating thickness to be at least 2 skin depth (preferably several times that) at the frequency of interest.

Grounding and Shielding (cont.)

- Metal enclosure comments

- Seams are a major problem of folded sheet metal enclosures. Open seams are slot antennas and can radiate a lot when the seam length is large relative to a wavelength.
- When using sheet metal enclosures, keep any open seams short. Consider welding the seams.
- Machined or cast enclosures work best, but they are expensive.
- Aluminum is usually the best choice. With low frequency (< 10 kHz) magnetic fields, steel works better due to high permeability. But because of the high weight and high machining cost, aluminum is usually a better choice.
- For very low frequency (60 Hz) shielding of magnetic fields, there are very-high-permeability alloys such as mu-metal and conetic that work well. But their high mu performance can be ruined by folding, heat treating; you need to get your part formed by someone who knows how to work with these materials.
- The key to material selection is skin depth; each skin-depth of thickness gives 8.6 dB of attenuation. Ten skin depths is a lot of attenuation!
- Skin depth = $\sqrt{\frac{2}{\sigma\omega\mu}}$
- Metal coating is important. Aluminum enclosures should have a clear chromate conversion treatment or alodyne treatment so the surface remains conductive, allowing current to flow across part-to-part boundaries. Don't use anodizing, it's non-conductive.

Grounding and Shielding (cont.)

- Plastic enclosure comments
 - Inexpensive
 - There are different types of coatings with different levels of performance. Carbon coatings have relatively high resistance and as a result less effective shielding. Metal coatings are higher conductivity.
 - Coatings can be very thin. Remember that you want a thickness of at least one skin depth, preferably 10.

Grounding and Shielding (cont.)

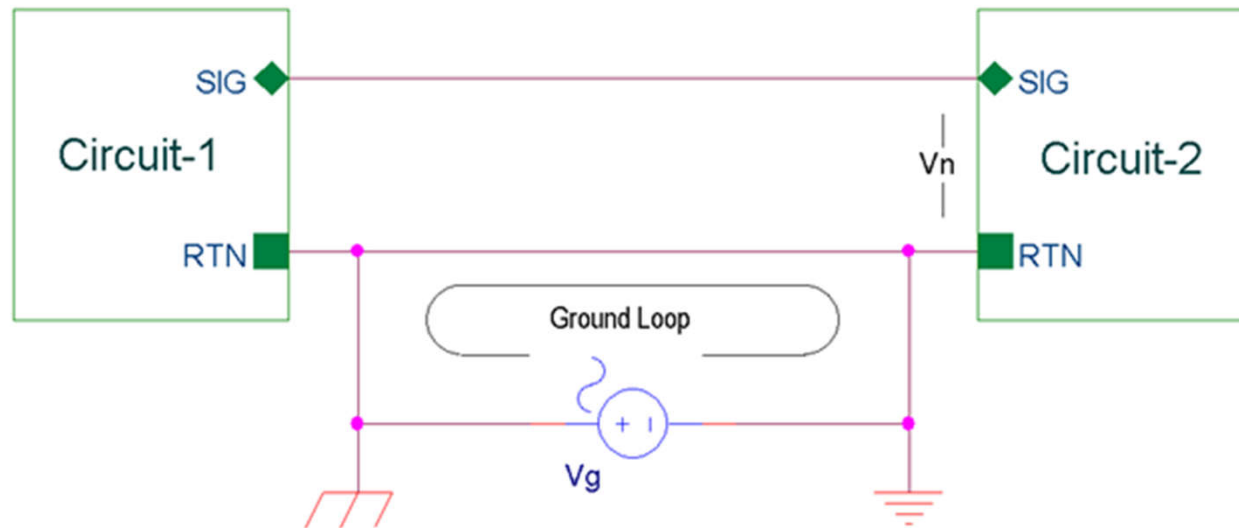
- Gaskets
 - If you screw two pieces of metal together, you won't have good electrical contact everywhere along the seam.
 - Gaps too small to be visible to the eye will prevent current from flowing across the gap.
 - You generally need a gasket between mating conductive surfaces.
 - Gasket types:
 - Metal fingers: beryllium-copper gasket strips. High conductivity.
 - Fabric-over-foam: These work well for shielding odd shapes like DB9 or DB25 connector holes.
 - Elastomeric gaskets. Silicone rubber impregnated with conductive material. Metal conductive filler is lower resistance than carbon and works better, but is more expensive.

Grounding and Shielding (cont.)

- Board level shielding
 - Solder metal cans over noisy circuits to limit radiation.
 - Doesn't work as well as an enclosure, but is helpful.
 - Leadertech (<https://leadertechinc.com/products/circuit-board-products/>) has a lot of stock parts, can do custom parts for now NRE.
 - Shields with removable lids allow rework.

Grounding and Shielding (cont.)

Ground Loops



The two grounds may be at different potential as a result of current flowing through the ground impedance. This will introduce a noise voltage into the circuit. The signal current has multiple return paths and may, especially at low frequencies, flow through the ground connection and not return on the signal return path. (Ott)

Grounding and Shielding (cont.)

Ground Loops

- Current return through the ground system (as opposed to the designated signal return path) is seldom a problem at high frequencies.
- The magnitude of the noise voltage may not be high enough to cause any problems.
- Most ground loops are benign. Most actual ground-loop problems occur at low frequency, under 100 kHz.
- Some ground loops are actually helpful. Consider the case of a cable shield being grounded at both ends in order to provide magnetic field shielding.
- Ground loops are a concern when dealing with low level analog signals.

4.Circuit Design

- Rule of thumb: If a net has an electrical length that is greater than about $1/6$ of the rise time then that net needs to be considered as a transmission line.^(a)
- Avoid multi-drop lines unless they are slow (use clock buffers as required)^(b)
- Series termination on all outputs
 - Usually 39 to 50 Ohms
 - Higher (much higher) for slower lines (e.g., 1100 Ohms \rightarrow 60 ns tr on 10" line, and line meets $1/6$ rule)

Circuit Design (cont.)

- Avoid using LC resonators – use crystal or RC oscillators
- Use shielded inductors, especially in switching power supplies
- Consider using spread-spectrum & multi-phase oscillators (e.g., for power supplies)

Circuit Design (cont.)

- Input and output conditioning
 - Add filtering to every IO line if possible.
 - Always need to consider the filter's effect on signal bandwidth.
 - Filter types:
 - Series resistor with optional shunt capacitor. Works well, but limits bandwidth. Not appropriate for power supply inputs.
 - Single-chip pi filters, like Murata NFL21SP106X1C3D. Provide a high level of filtering. Like all shunt filters, they need a low-inductance ground plane connection.
 - Ferrite beads, like Murata BLM15HG102SN1D. Good for power supplies due to low DC resistance. Choose appropriate part number based on DC current rating and impedance-vs-frequency curve.
 - Common mode chokes: Good for power supply lines and low speed IO.

Circuit Design (cont.)

ESD protection

- All IO lines should have ESD protection
- ESD protection lowers the failure rate in manufacturing and in the field.
- Some digital chips already have ESD protection BUT IT IS INSUFFICIENT (in most cases)
- ESD protection circuits degrade bandwidth; the appropriate protection technique depends on the bandwidth of the signal on the line.
- In general, inputs are more sensitive than outputs to ESD during normal operation, because outputs are low-impedance and inputs are high-impedance. But CMOS outputs are high impedance when power is turned off, so ESD protection is recommended for inputs and outputs.

Circuit Design (cont.)

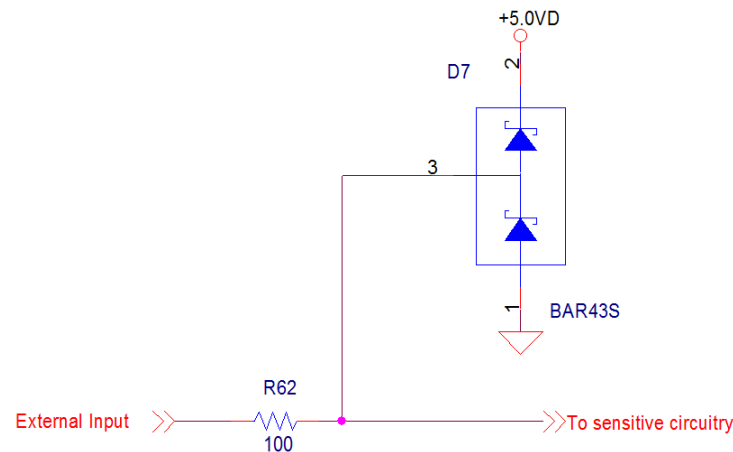
ESD protection

- Clamps
 - Clamping circuits prevent the signal on the line from going above V_{cc} or below ground.
 - Schottky diodes are the commonly used for this. They're frequently called TVS (transient voltage suppressor) diodes in this application.
 - Chips are available with arrays of clamps to protect several lines at once. Littelfuse SP724 is an array of four SCR/diode pairs in one SOT23-6 package.
 - Clamp capacitance will reduce bandwidth; you need to consider the effect of the clamp's capacitance (and leakage current) on your signal.
 - Use Schottky diodes, not signal diodes; they're faster. Also, the turn-on voltage is lower for Schottky diodes. So they will turn on and clip before the junction diodes in your IC.

Circuit Design (cont.)

ESD protection

- Series resistance
 - A series resistor makes clamps work better. It provides a means for dropping the large applied voltage in an ESD event..
 - The resistance value depends on the impedance of the line and the bandwidth. On a low impedance output driving a 50 ohm load, you can't go above 10 ohms or so.
 - On a slow high impedance circuit, the resistor can be 1 kOhm. With the diode clamp, this gives very good protection.



Circuit Design (cont.)

ESD protection

- Very high bandwidth lines (AVOID!!!)
 - Diode clamps have at least a few pF of capacitance, which is too much for gigahertz-bandwidth lines.
 - Littelfuse polymeric clamps have very low capacitance. PN PGB1010402 is only 0.04 pF! The downside of these parts is the high clamping voltage, 250V. These part provide some protection, but not complete protection. They're useful when the signal bandwidth is so high that nothing else has the required bandwidth.

5. Board Design

(more later)

- 6 layers absolute minimum for all but the most trivial (and slow) boards
- Avoid split power- and ground-planes
- Signals must never be routed across a split plane.
- Complex high-speed boards may require 10 layers or more.
- Controlled impedance routing is the norm

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