Grounding Bonding and Shielding

Joint Spectrum Center
E3 & Spectrum Engineering Division, OS35

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Who Are We

Defense Information System Agency (DISA) Mission

- To conduct DODIN operations for the joint warfighter to enable lethality across all warfighting domains in defense of our Nation.

Defense Spectrum Organization (DSO) Mission

- Deliver tools, capabilities, and expertise to empower DOD to solve tomorrow's electromagnetic spectrum challenges today.

Joint Spectrum Center (JSC) Mission

- Provides direct support to the JCS, CCMDs, and MILDEPs to enable trusted, efficient and effective use of the Electromagnetic Spectrum Enterprise (operations, services, data, tools/capabilities), Applied Engineering, Acquisition and Analysis, and the mitigation of Electromagnetic Environmental Effects (E3) in support of national security and military objectives.

Welcome to "Grounding Bonding and Shielding

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Over 35 years of E3 engineering experience from a wide variety of organizational aspects, including defense contractor system developer, DoD support contractor, commercial product developer…

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Topics

- **Background**

- **Basic EMI Theory**

- **Enclosure Shielding**

- **Cable Shielding**

- **Grounding**

- **Bonding**

Training Objectives

- **Provide some basic EMI design principles**

- **Show how grounding and bonding ties in to overall E3 design**

- **Provide some examples of real-world grounding/bonding applications**

- **EMI requires three elements:**
  - Source of electromagnetic (EM) energy, having a specific magnitude and spectral content
  - A medium for transferring the EM energy
  - A victim or susceptible circuit that responds to the transferred EM energy.

- **EMI is controlled by modifying one or more of these elements.**

Basic EMI Problem

Sources

- RF Transmitters (Comms, EW, Radar)
- Computer/Digital Processing Equipment
- Motors/Motor Drives
- Power Supplies
- Lightning/ESD
- "Rusty Bolt" Phenomena

Coupling Paths

- Antenna to Antenna
- Cable to Cable
- Antenna to Cable
- Cable to Antenna
- Antenna to Box
- Box to Antenna
- Cable to Box
- Box to Cable
- Common Impedance
- Power line Conduction

Victims

- Receivers
- Amplifiers
- Weapon system EIDs
- Video and analog circuits
- Digital circuits

SOURCE   **Coupling Path**   **VICTIM**

What Are We Trying To Solve?
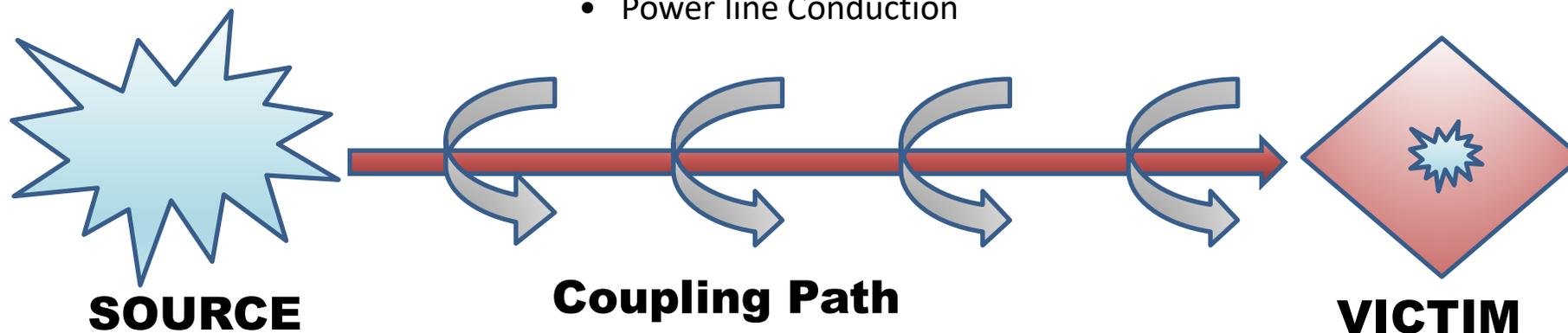
- **Minimize the noise generated by the system**

  − Conducted and radiated emissions

- **Maximize the noise immunity of the system**

  − Increase susceptibility margins of components

- **Minimize coupling of external fields to cables and equipment**

  − Filter or shield unwanted signals

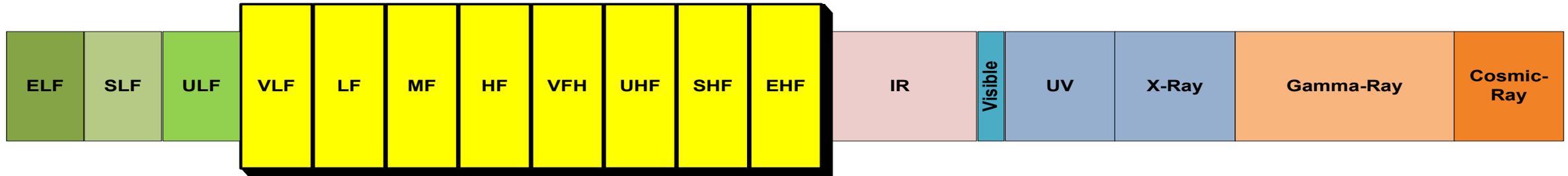**Provide a system that works in its intended electromagnetic environment**

Specifications for EMI Design

- **For DoD systems, MIL-STD-464 is the usual top-level spec.**

- **MIL-STD-461 is normally applied to equipment and subsystems**
    - Provides well-defined design/test objectives via standardized emissions and immunity limits
    - Degree of difficulty varies based on the given platform or installation.

- **Other EMI standards and handbooks provide lower-level requirements and "how-to" bonding, grounding and shielding design information.**

MIL-STD-1310H	SHIPBOARD BONDING, GROUNDING, AND OTHER TECHNIQUES FOR ELECTROMAGNETIC COMPATIBILITY, ELECTROMAGNETIC PULSE (EMP) MITIGATION, AND SAFETY
MIL-B-5087B	Bonding, Electrical, and Lightning Protection, for Aerospace Systems
MIL-HDBK-419A	GROUNDING, BONDING, AND SHIELDING FOR ELECTRONIC EQUIPMENTS AND FACILITIES
MIL-STD-188-124B	Grounding, Bonding and Shielding for Common Long Haul/Tactical Communication Systems Including Ground Based Communications- Electronics Facilities and Equipment
NASA-STD-4003	ELECTRICAL BONDING FOR NASA LAUNCH VEHICLES, SPACECRAFT, PAYLOADS, AND FLIGHT EQUIPMENT
NASA-HDBK-4001	ELECTRICAL GROUNDING ARCHITECTURE FOR UNMANNED SPACECRAFT
CECOM TR-98-6	A Guide to Proper Earth Grounding and Bonding Methods for Use with Tactical Systems
SAE ARP1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety

DoD EMI Solutions

- **Often differ significantly from commercial product solutions**

- **Increased design focus on:**
  - Grounding
  - Bonding
  - Shielding
  - Add-on Filtering

- **Software**
  - Software sometimes used to "process-out" undesired responses.

- **CONOPS**
  - EMI risk assessment based on specific CONOPS.
 - Out-of-spec conditions often acceptable.

EMI Basics

Electromagnetic Spectrum

Radio Spectrum

| ELF | SLF | ULF | VLF | LF | MF | HF | VFH | UHF | SHF | EHF | IR | Visible | UV | X-Ray | Gamma-Ray | Cosmic-Ray |

Frequency →

ELF	Extremely Low Frequency	3 Hz – 30 Hz
SLF	Super Low Frequency	30 Hz – 300 Hz
ULF	Ultra Low Frequency	300 – 3 kHz
VLF	Very Low Frequency	3 kHz – 30 kHz
LF	Low Frequency	30 kHz – 300 kHz
MF	Medium Frequency	300 kHz – 3 MHz
HF	High Frequency	3 MHz – 30 MHz
VHF	Very High Frequency	30 MHz – 300 MHz
UHF	Ultra High Frequency	300 MHz – 3 GHz
SHF	Super High Frequency	3 GHz – 30 GHz
EHF	Extremely High Frequency	30 GHz – 300 GHz
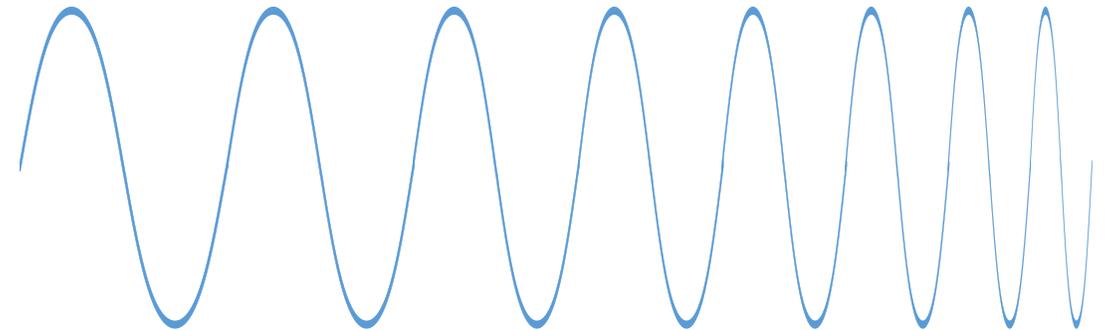
As frequency increases, the wavelengths decrease. Higher frequency means shorter wavelength, lower frequency means longer wavelengths.

Frequency and Wavelength

- Wavelength = λ = speed of propagation divided by frequency.

- In air:
$$\lambda = \frac{c}{f}$$ c = speed of light (3×10^8 m/s)

$$\lambda_{meters} = \frac{300}{f_{MHz}}$$

- Useful to compare wavelength to the physical length of the radiating or receiving element (i.e. cable or slot) in question.

- When a structural element or cable is "electrically short" (the element is small compared to a wavelength), simplifying approximations often apply when calculating coupling.

Resonant Frequency

- **When the length L of a radiating element (slot or cable) is equal or nearly equal to half a wavelength, it will radiate most efficiently.**

- **The half-wave resonant frequency is calculated by:**

$$L = \frac{\lambda}{2} = \frac{c}{2f}$$

$$f_{MHz} = \frac{150}{L_{meters}}$$

Electromagnetic Field Concepts

- **All circuits in which current is flowing or voltage is present generate electromagnetic fields.**

- **Fields are present <u>all</u> the time around <u>all</u> voltage and current-carrying conductors.**

- **Not just confined to intentional capacitors and inductors.**

Magnetic field encircles the conductor carrying the current, always perpendicular to it.

Electric field lines emanate outward from the source and terminate on nearby conductors.
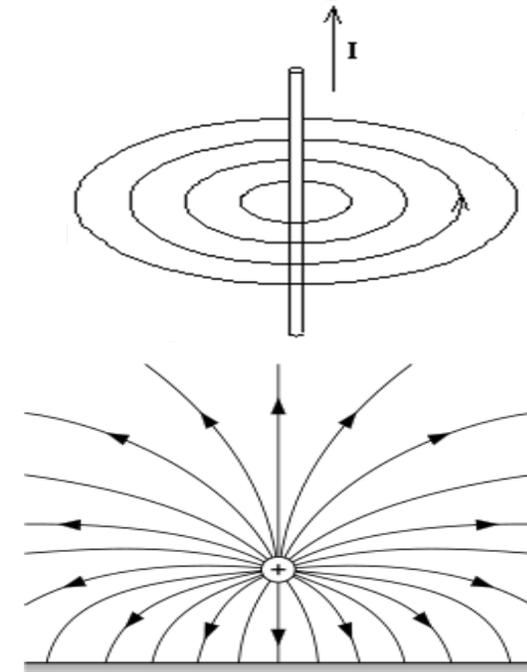
- **EM fields are the primary mechanism by which energy is transferred from one conductor to another.**

- **Any time-varying field induces current/voltage into an adjacent conductor.**

- **Fields tend to "diffuse" high frequency energy away from their intended conductors onto other conductors and spaces inside an enclosure/PCB.**

- **Very difficult to model the whole space inside the equipment or on/around the PCB (easier to measure).**

- **Not necessary to fully solve Maxwell's equations (we can simplify!)**

Electromagnetic Radiation (EMR) can be described as a wave of energy composed of oscillating electric and magnetic fields that travel through space at the speed of light.
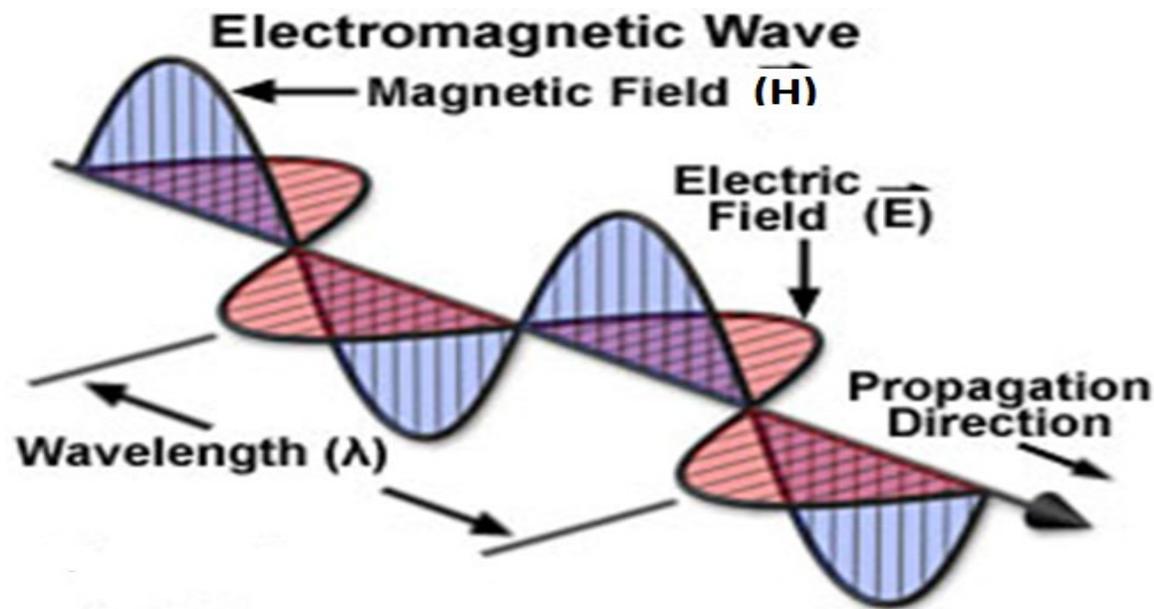
An electromagnetic wave is characterized by:

- **Field strength (amplitude)**
  - E or H (or both)

- **Frequency (wavelength)**

- **Polarization**
  - Orientation of E

Near-Field and Far-Field Regions
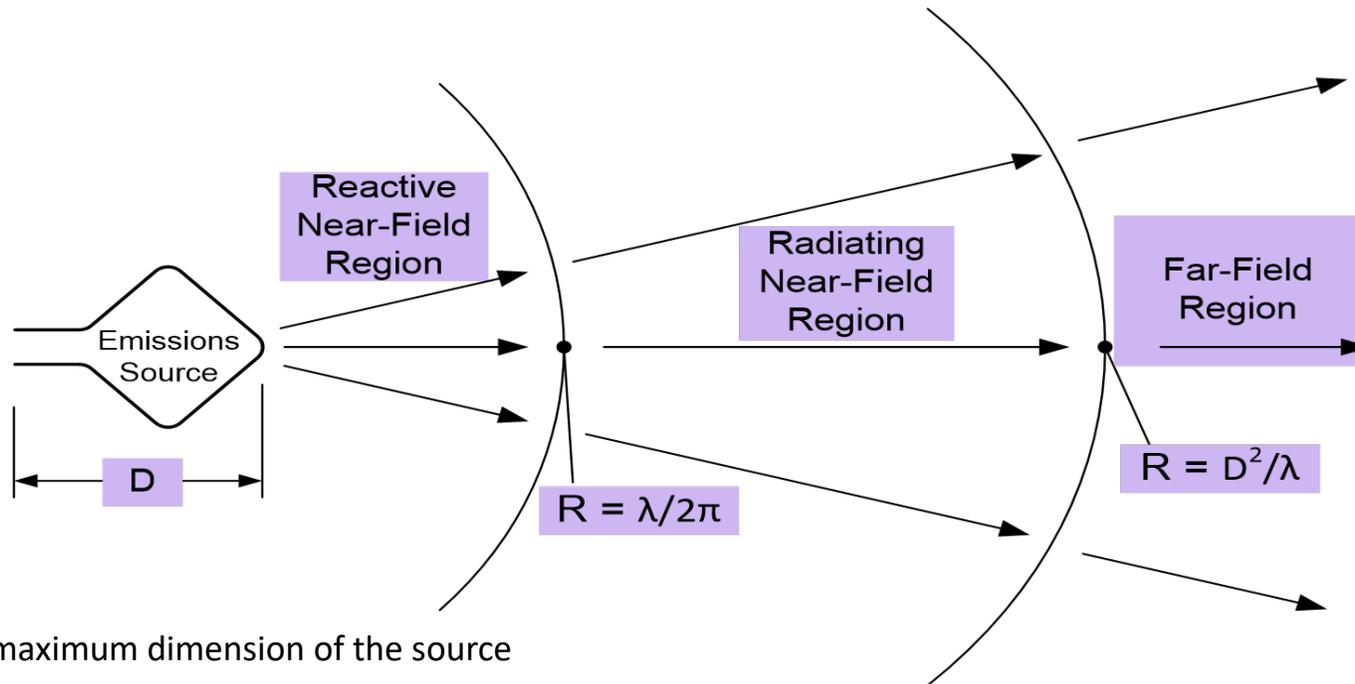
D = maximum dimension of the source

Far Field Region

- E and H fields are transverse to the propagation direction and to each other (plane wave).
- E and H fields fall off proportional to 1/r.
- Ratio of E/H is 377Ω.
- Boundary typically starts at R = D^2/λ

Reactive Near-Field Region

- Fields fall off proportional to $1/r^2$ or $1/r^3$ (depending on source type)
- Outer boundary is R = $\lambda/2\pi$

Radiating Near-Field Region

- Fields oscillate out to a distance r = $D^2/4\lambda$
- Cannot accurately predict amplitude variation in this region.
- May not exist if D << λ

Wave Impedance

is a function of distance from the source

E

S (direction of propagation)

H

$$Z_0 = \frac{E_\theta}{H_\phi}$$
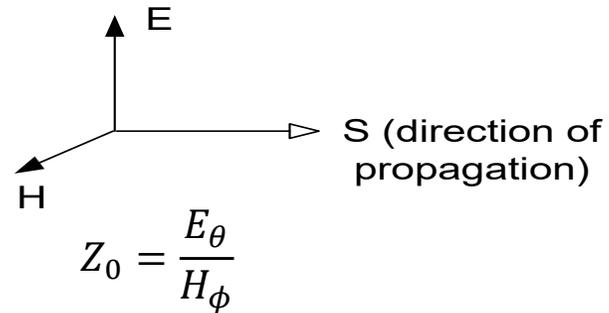
Far field → $Z_0 = 377$

Near field → $Z_0 < 377$ (loop source)

Near field → $Z_0 > 377$ (dipole source)

Predominantly E-Field

Predominantly H-Field

3770

DIPOLE

WAVE IMPEDANCE (Ω)

1000

377

100

LOOP

37

10
0.1   1   10   R/(λ/2π)

DISTANCE FROM SOURCE
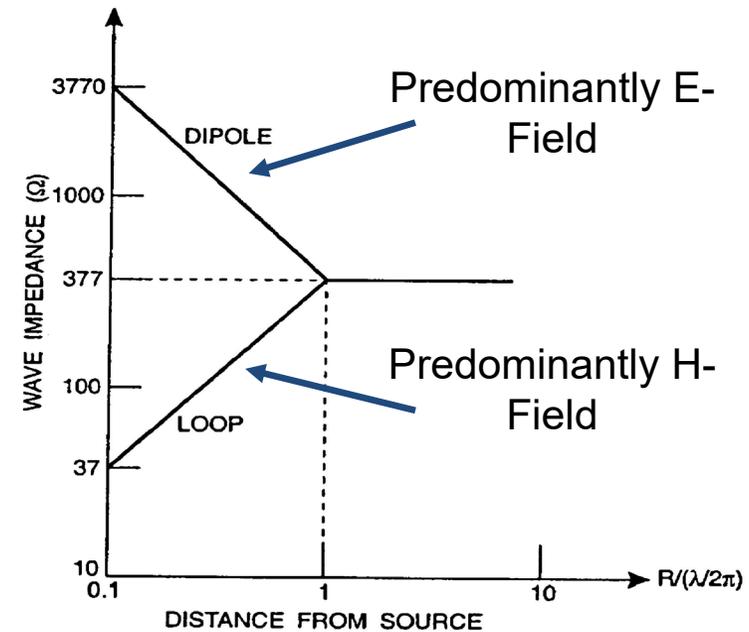
Why is this important?

- EM shielding effectiveness depends in part on the wave impedance.

- Strong fields close to source do not always result in significant far fields.

- In the near field, E and H contributions must be considered separately.

Shielding Theory

- **Shielding is achieved by a metal barrier that reflects or absorbs impinging fields.**

- **The magnitude of shielding depends on:**
  - Material conductivity, permeability, frequency
  - Impedance of the incident field (low/magnetic, high/electric, or plane wave)

- **Reflection**
  - Typically high for E-fields and plane wave, lower for low Z (magnetic) fields
  - Increases with material conductivity

- **Absorption**
  - Primary component of magnetic field attenuation
  - Increases with shield thickness, permeability, conductivity

Shielding Effectiveness (Solid Sheet)

$$SE = 20Log\left(\frac{E_0}{E_i}\right)$$

$$SE = 20Log\left(\frac{H_0}{H_i}\right)$$

E_o, H_o = transmitted field
E_i, H_i = incident field

Incident Field E_i

H_i

Shield cross section

E_0

H_{refl}

Reflected Field

E_{refl}

H_0

Transmitted Field
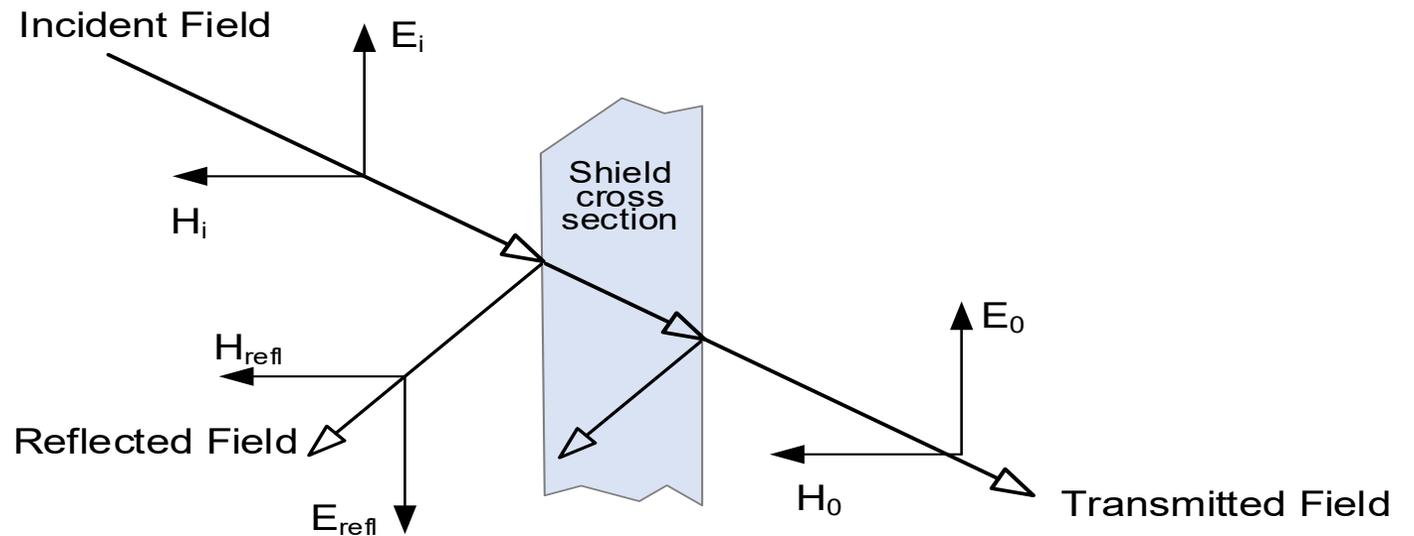
Shielding effectiveness is a combination of effects from the material

- **Reflections from the first surface**
- **Absorption within the material**
- **Reflections from the second surface**

$$SE = R_1 + A + R_2$$

Skin Effect and Skin Depth

- **Skin Effect** - the tendency of a high-frequency alternating current to flow through only the outer layer of a conductor

- **Skin Depth** - distance required for a wave/current to be attenuated to 37% of its original value

$$\delta = \frac{2.6}{\sqrt{f \mu_r \sigma_r}} \ in$$

$\mu_r = permeability \ (rel \ to \ copper)$

$\sigma_r = conductivity \ (rel \ to \ copper)$

$f = frequency, Hz$

Skin Depth of Various Materials - Inches

Frequency	Copper	Aluminum	Steel
60 Hz	0.335	0.429	0.034
100 Hz	0.260	0.333	0.026
1 kHz	0.082	0.105	0.008
10 kHz	0.026	0.033	0.003
100 kHz	0.008	0.011	0.0008
1 MHz	0.003	0.003	0.0003
10 MHz	0.0008	0.001	0.0001
100 MHz	0.00026	0.0003	0.00008
1 GHz	0.00008	0.0001	0.00004
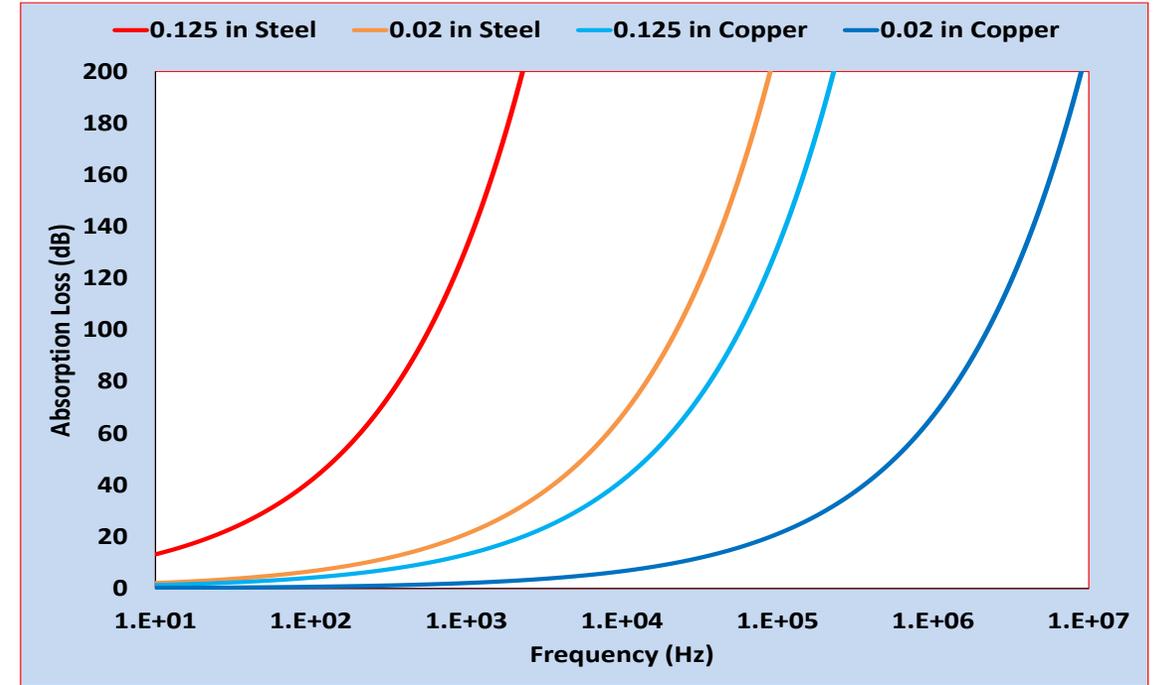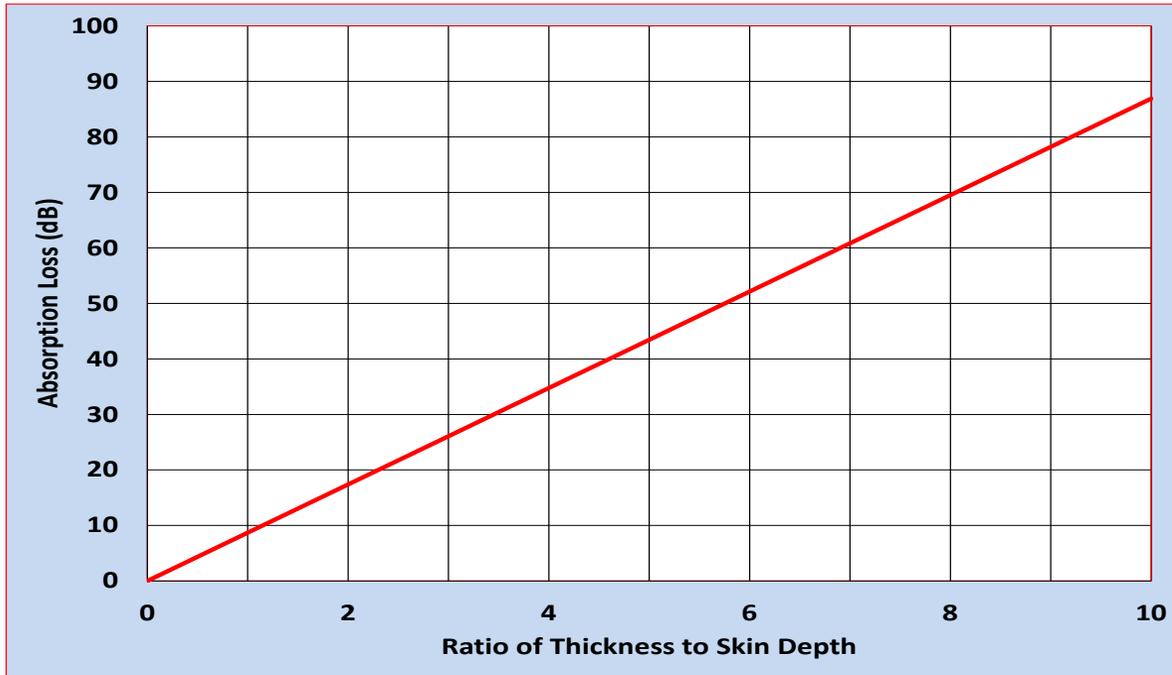
Absorption Loss

$$A = 8.69 \left(\frac{t}{\delta}\right) dB$$

$$\delta = \frac{2.6}{\sqrt{f \mu_r \sigma_r}} \ in$$

$$A = 3.34 t \sqrt{f \mu_r \sigma_r} \ dB$$

Absorption Loss Increases with Frequency, Permeability and Shield Thickness

Skin Depth and Absorption

Some observations:

- At RF, fields and currents are confined to the very outer surfaces of the shield.
- At RF, very small shield thickness is required for good absorption.
- At RF, separate independent current profiles can exist on either side of a thick shield.
- Low frequency shielding requires significantly greater shield thickness.
- Higher permeability materials (steel) offer more absorption loss for a given thickness

Reflection Loss

Reflection loss equations are dependent on shield material properties and source-to-shield distance

| Reflection loss for an electric field | Reflection loss for a magnetic field | Reflection loss for a plane wave |

$$R_E = 322 + 10Log\left(\frac{\sigma_r}{\mu_r r^2 f^3}\right)$$

$$R_H = 14.6 + 10Log\left(\frac{\sigma_r r^2 f}{\mu_r}\right)$$

$$R_p = 168 + 10Log\left(\frac{\sigma_r}{\mu_r f}\right)$$

$f =$ Frequency in Hertz $\qquad$ $r =$ Distance from the source in meters

Typical Reflection Losses - Infinite Sheets of Common Materials

Frequency	Electric Field (dB)		Magnetic Field (dB)		Plane Wave (dB)	
	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel
60 Hz	280	240	20	0	150	115
1 kHz	240	200	30	10	140	100
150 kHz	180	130	50	20	115	80
15 MHz	115	80	75	40	95	70
100 MHz	90	60	80	60	85	60

SE Plot for Solid Aluminum Shield

At RF, typical materials and thicknesses provide more than enough shielding for practical applications

0.020" thick aluminum

Noise and Interference Sources
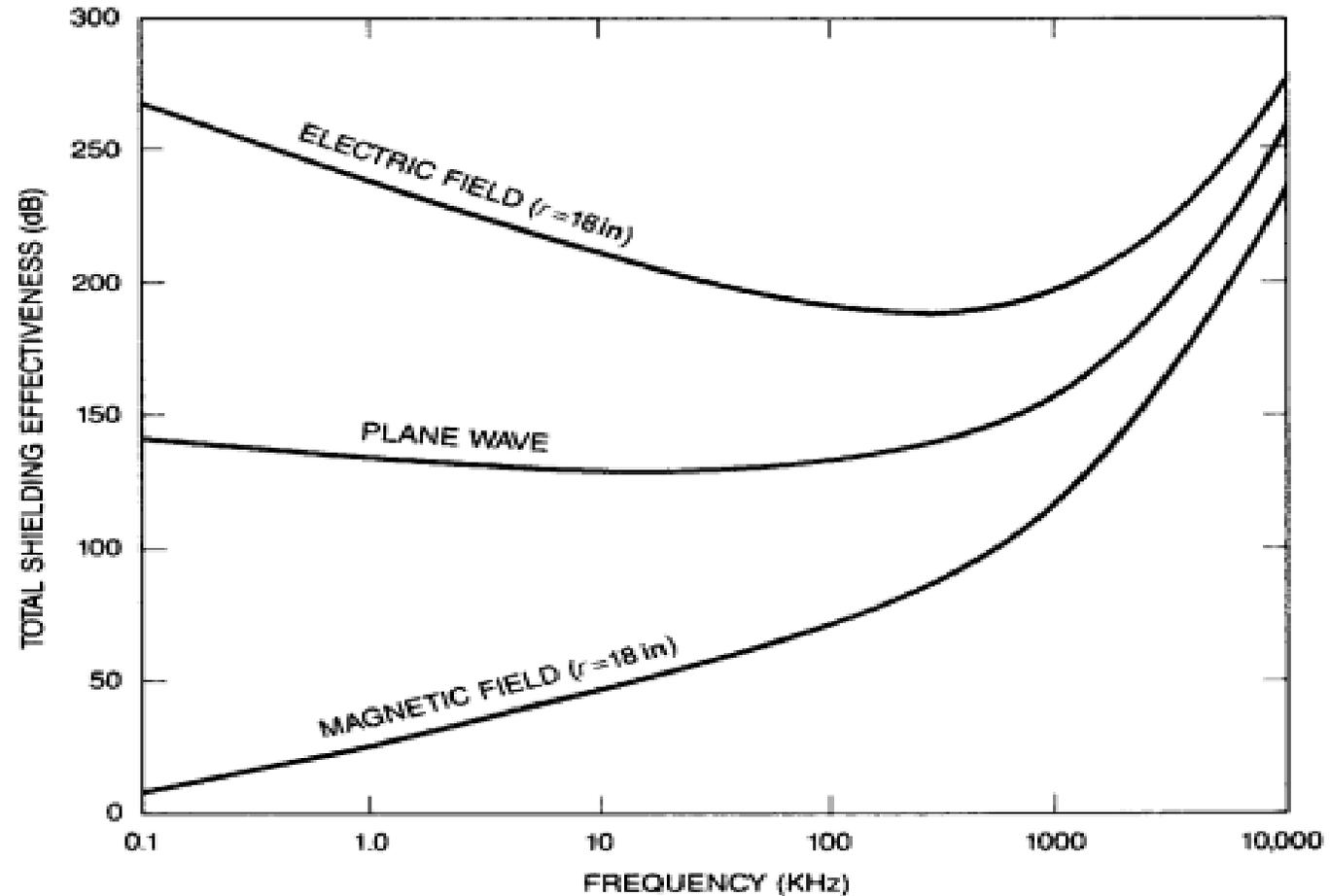
- **Intrinsic**
  - Thermal Noise
  - Shot Noise
  - Contact Noise

- **Man-made**
  - Transmitters
  - Welders
  - Motors
  - Digital

- **Natural**
  - Atmospheric noise
  - Lightning
  - ESD

Noise: an unwanted disturbance superposed on a useful signal that tends to obscure its information content.

Interference: is anything which modifies or disrupts a signal as it travels along a channel between a source and a receiver.

Coupling Methods

- **Capacitive Coupling**
  - Also known as "Electric"
  - Results from the interaction of electric fields between two closely spaced conductors
- **Inductive Coupling**
  - Also known as "Magnetic"
  - Results from the interaction of magnetic fields between two closely spaced conductors
- **Radiated Coupling**
  - Also known as "Electromagnetic Radiation"
  - Propagates well over large distances
  - Dominant mechanism at large distances
- **Common Impedance Coupling**
  - Source and victim share a common path

Common Impedance Coupling
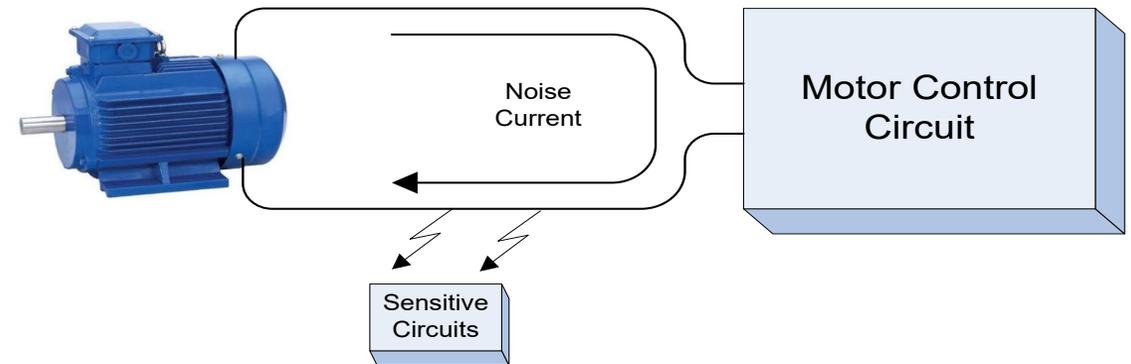
- **Change in Load 1 impedance results in time-varying current flow through the common impedance.**

- **Voltage across the common impedance is reflected across each load.**

- **The effect is equivalent to a noise voltage source in series with the desired signal source.**

- **This effect is often seen in power buses, but will occur in any type of circuit having common current paths.**

Capacitive (Electric) Coupling
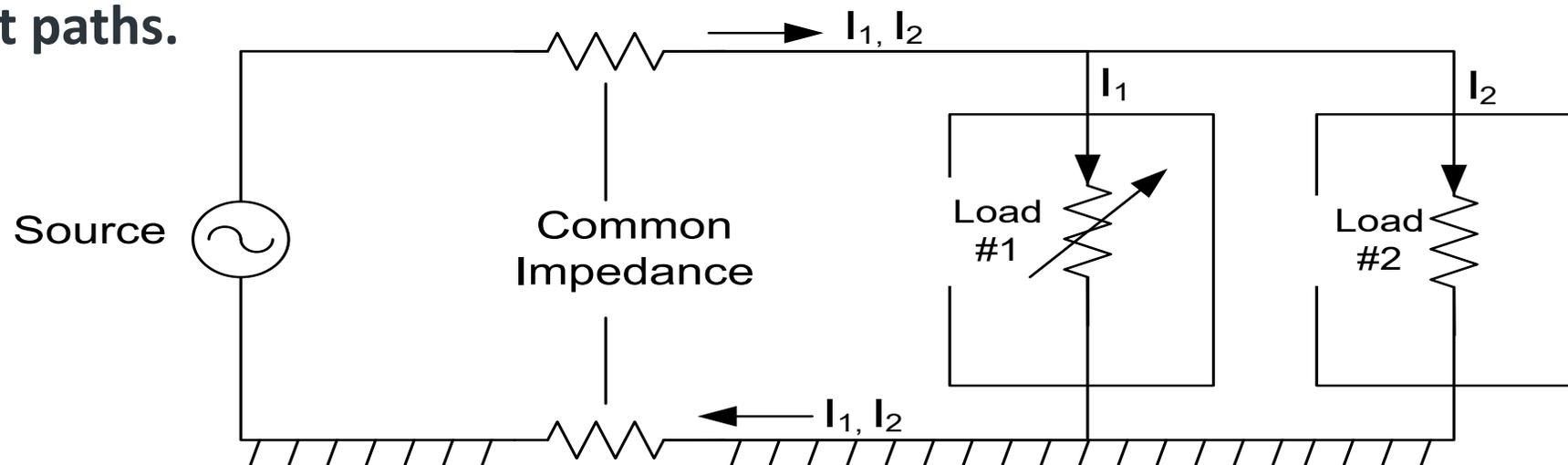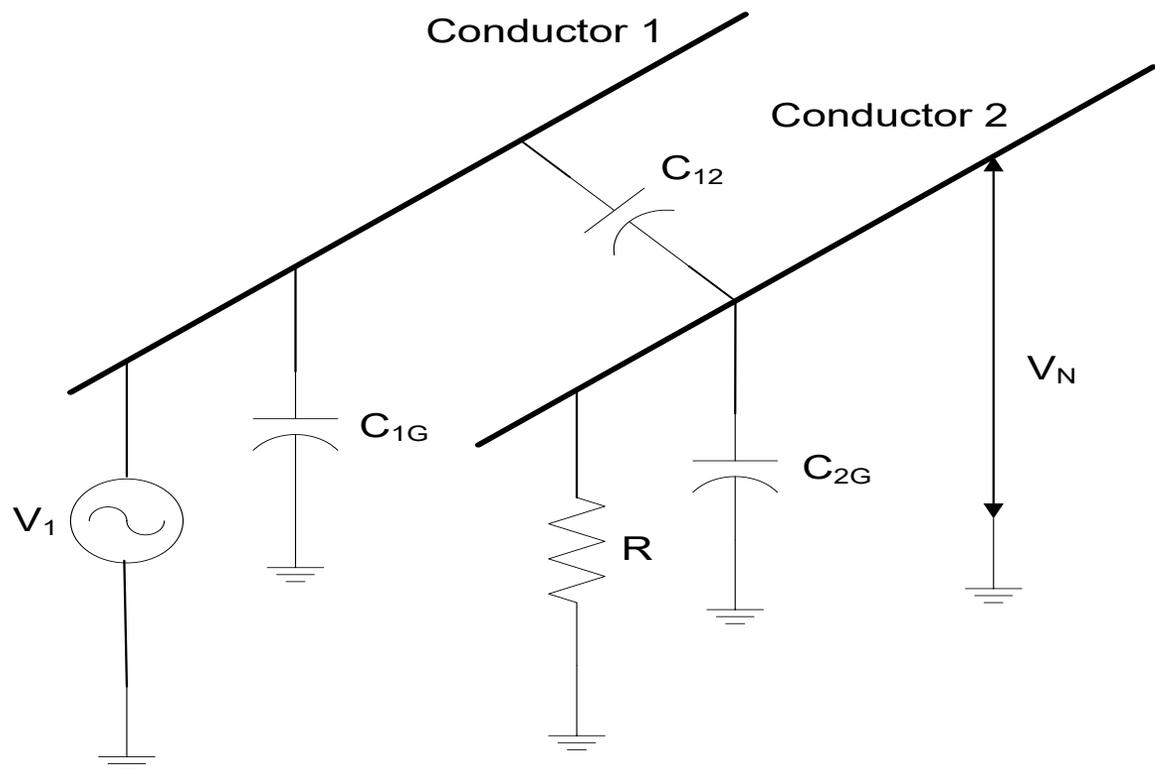
V_1 is the source voltage
V_N is the victim voltage
C_{12} = mutual capacitance

$$|V_N| = 2\pi f R C_{12} V_1$$

Capacitive coupling depends on the distance between conductors and the impedance to ground of the victim circuit.

Most Commonly Affects High Impedance, Sensitive Circuits

Inductive (Magnetic) Coupling
(mutual inductance)

Conductor 1
(Source)

Conductor 2
(Victim)

I_1

+

-

V_N

M
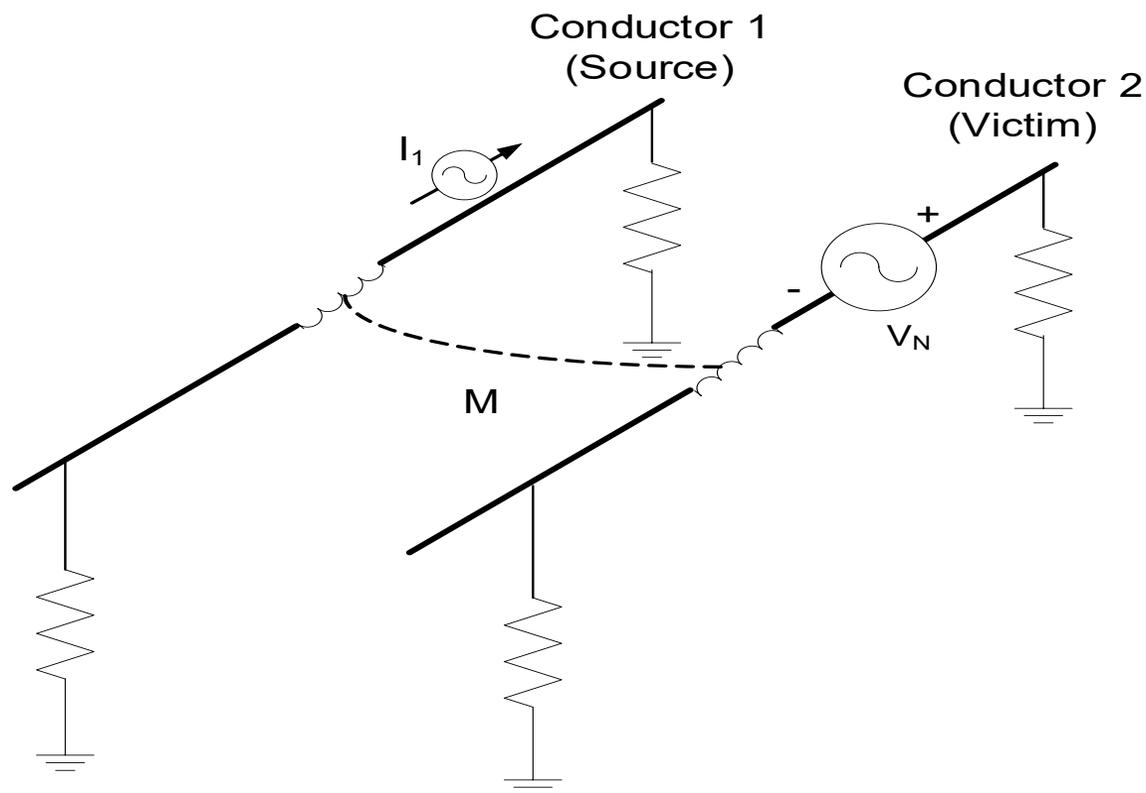
I_1 is the source current

Voltage V_N is induced in conductor #2, with polarity opposing the flow of source current.

M is mutual inductance (based on geometry)

$$V_N(t) = -M \frac{dI_1}{dt}$$
$$V_N(f) = j\omega M I_1(f)$$
$$|V_N(f)| = 2\pi f M I_1(f)$$

Inductive coupling depends on frequency, common length of source and victim, orientation, separation distance, and the heights of the circuits above ground.

Induced voltage does not depend on load impedances

Inductive (Magnetic) Coupling
(self-inductance)
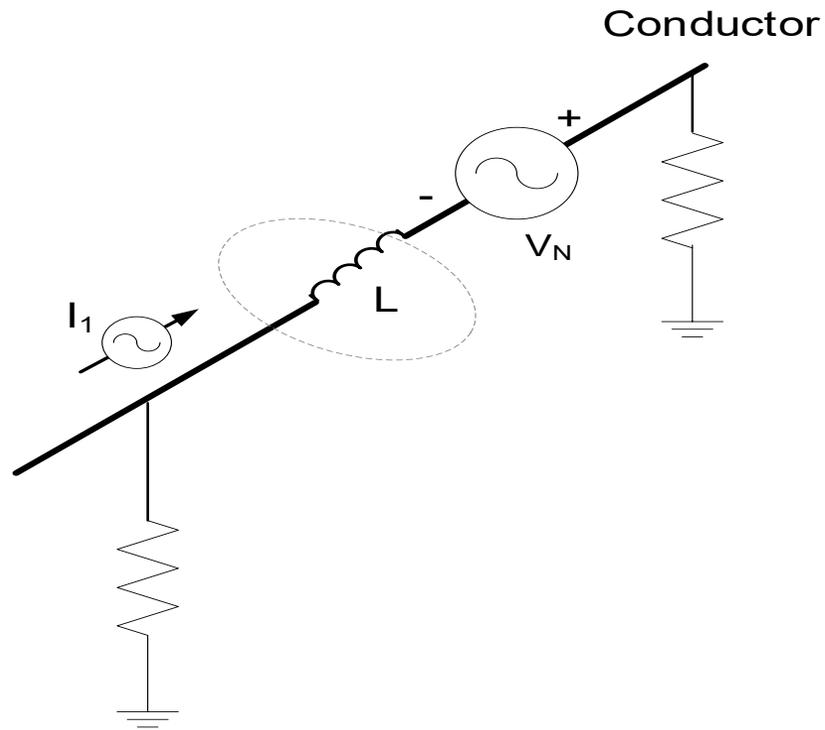
Conductor

I_1 is the source current (from the circuit itself, or an external source)

Voltage V_N is induced in the same conductor, with polarity opposing the flow of source current.

L is self-inductance (based on geometry)

$$V_N(t) = -L\frac{dI_1}{dt}$$
$$V_N(f) = j\omega L I_1(f)$$
$$|V_N(f)| = 2\pi f L I_1(f)$$

Inductive coupling depends on frequency, length, height above ground, and conductor cross-section.

Induced voltage does not depend on load impedances

Inductance (key points)

- **A prime goal in EMI control is to minimize inductance in grounding and bonding paths.**

- **Inductance is a loop phenomenon. Loop area is the most important parameter.**

- **Inductance is primarily a function of conductor length, and (for mutual inductance) the spacing and geometry between conductors.**

- **Depends to a lesser extent on the conductor cross-section.**

- **At RF, inductance dominates the impedance of conductors (not resistance).**

Inductance Calculations

Self- and mutual-

Wire over ground plane

$$L_{wire-gnd} = 5.08 \ln\left(\frac{2h}{a}\right) \ [\text{nH/in}]$$
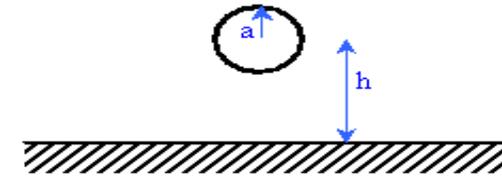
Isolated round wire

$$L_{wire} = 5.08\ell\left(\ln\frac{4\ell}{d} - \frac{3}{4}\right) \ [\text{nH}] \quad (\ell, \text{d in inches})$$
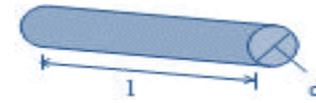
Flat conductor over ground

$$L_{trace-gnd} = 5 \ln\left(\frac{2\pi h}{w}\right) \ [\text{nH/in}]$$
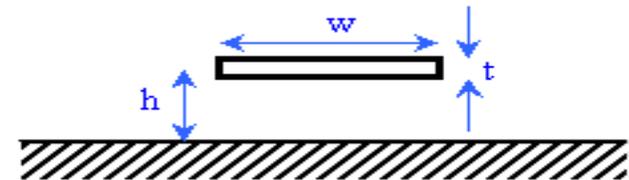
Two wire

$$M = 2.5 \ln\left(1 + \frac{4h_1 h_2}{s^2}\right) \ [\text{nH/in}]$$
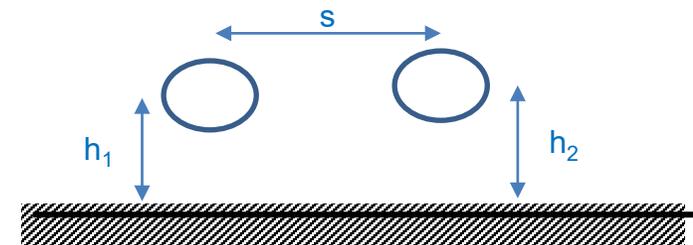
Impedance of Typical Conductors

Conductor Size (Copper)	Height Above Ground, inch	0-60 Hz Resistance, mΩ/in	Inductance, nH/in	Impedance 100 kHz, Ω/in	Impedance 10 MHz, Ω/in	Impedance 100 MHz, Ω/in
AWG #26	0.5	3.4	24.5	0.016	1.54	15.4
	2		31.6	0.02	1.98	19.8
AWG #20	0.5	0.8	21.0	0.013	1.32	13.2
	2		28.0	0.018	1.76	17.6
AWG #10	0.5	0.08	15.1	0.0095	0.95	9.5
	2		22.2	0.014	1.39	13.9
Flat (0.1" wide, 8 mil thick)	0.5	0.8	17.2	0.01	1.08	10.8
	2		24.2	0.015	1.52	15.2

- **Conducted noise that propagates via power or signal lines has two possible modes:**
  - Differential mode - flows through one wire and back through the other (same as the desired signal current)
  - Common-mode - flows through two or more wires in the same direction, and returns through a ground plane or system chassis/structure.

Common Mode vs Differential Mode
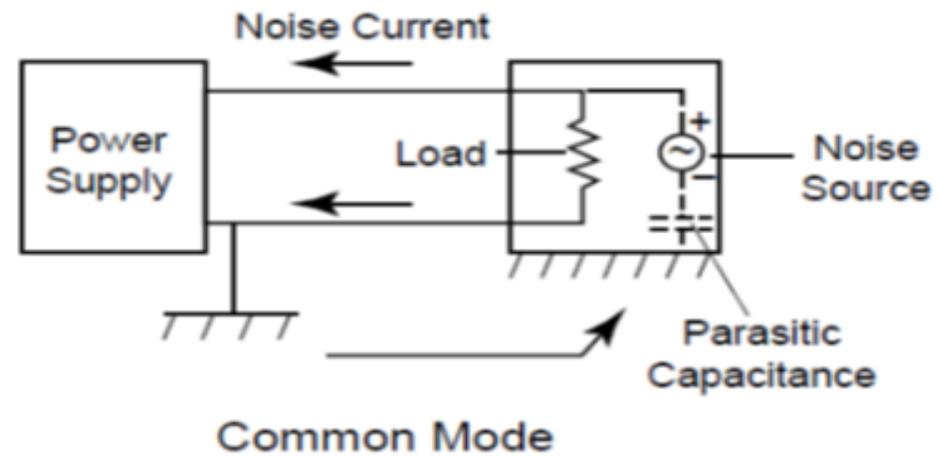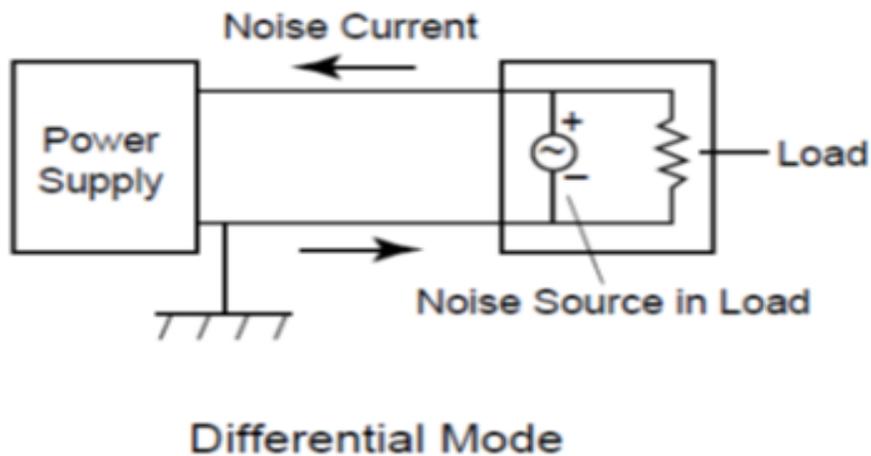
- **Differential Mode**
  - Typically associated with desired normal circuit operation
  - Currents flow in defined loops
  - Pathways are documented on schematics and wiring diagrams

- **Common Mode**
  - Does not relate to normal circuit operation.
  - Usually involves parasitic inductance or capacitance
  - More difficult to visualize and understand

- **Why is this important?**
  - Radiated emissions from cabling is almost always due to CM current (at RF).
  - Filtering architecture will vary depending on CM or DM source.
  - **Grounding fixes typically have effect only on CM noise (not DM).**

Shielding

DISA: TRUSTED TO CONNECT, PROTECT AND SERVE!

The Ideal Faraday Cage

- Faraday Cage - defined as an enclosure made of continuous, conductive materials that prevent the entry or escape of an electromagnetic field

- No leakage points

- Ideal Faraday cage is not possible for most systems

- Seams, apertures, ventilation holes, display ports

No EMI

Perfect 6-sided cube with no I/O, welded seams and no ventilation

What We Really Have
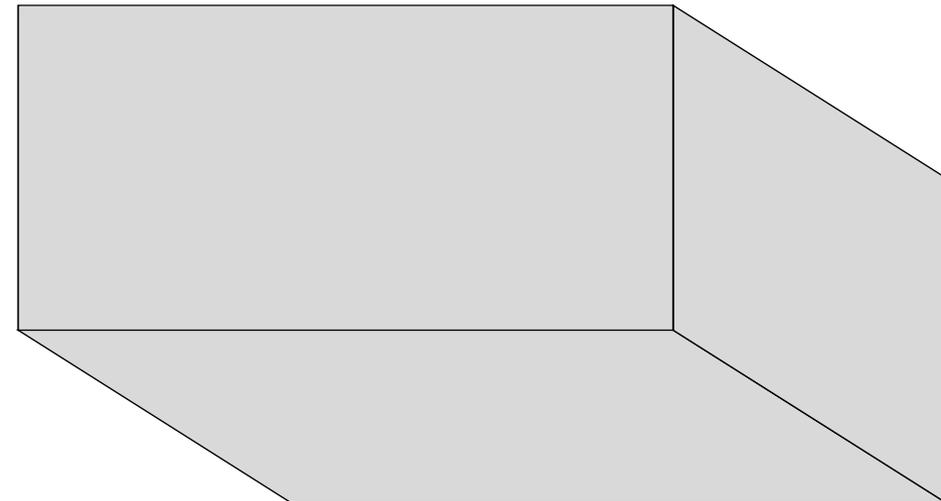
Displays

Ventilation

Seams/Apertures

Indicator Lights

Switches

Interfacing Cables
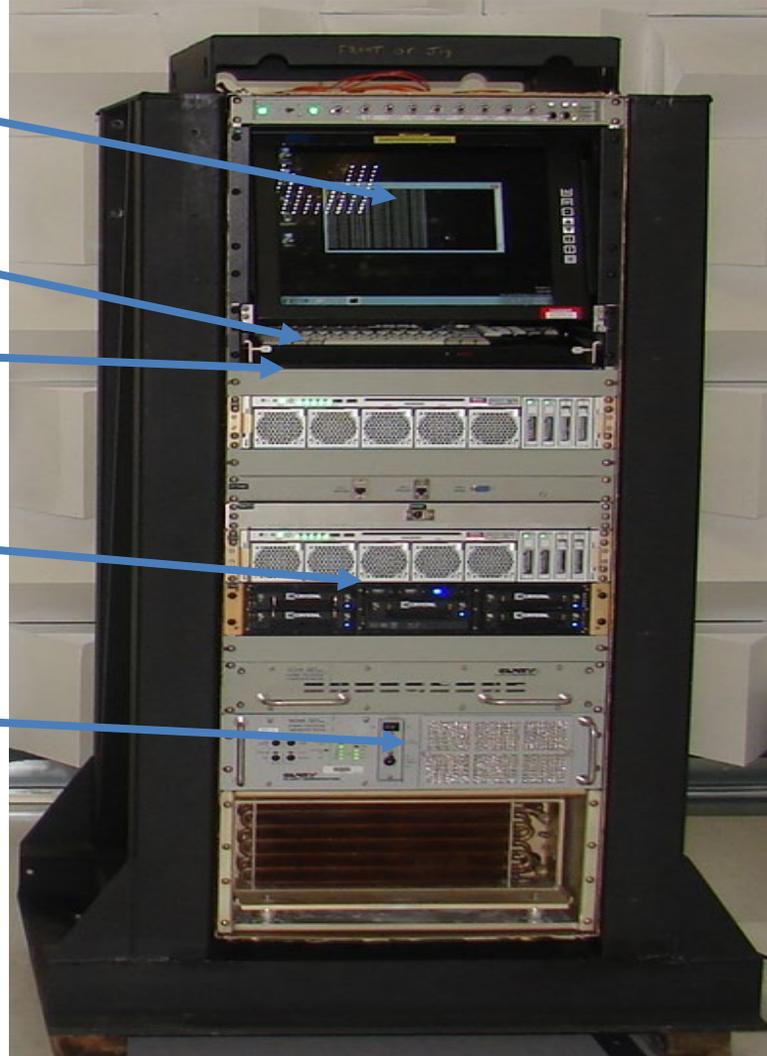
The Faraday Cage is just a fantasy!

Apertures

- **In practice, apertures, seams, and other breaks in the shield will govern overall shielding effectiveness (SE).**

- **At RF, the material itself provides ample SE in nearly all cases.**

- **Amount of leakage from a discontinuity depends on the maximum linear dimension of the opening and the frequency of the source.**

- **The maximum dimension is important, not the area.**

How Apertures Degrade Shielding

- Incident field induces currents on shield surface.
- Current generates an additional field that cancels the incident field.
- Presence of aperture forces current to be diverted, reducing the cancellation effect (inductance is increased).
- SE is decreased due to reduced field cancellation.
- Multiple small apertures have less diverting effect, thus less impact on shielding effectiveness.
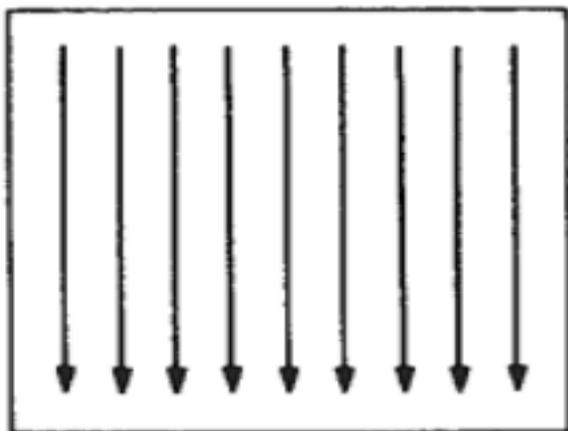
Induced shield current, no aperture
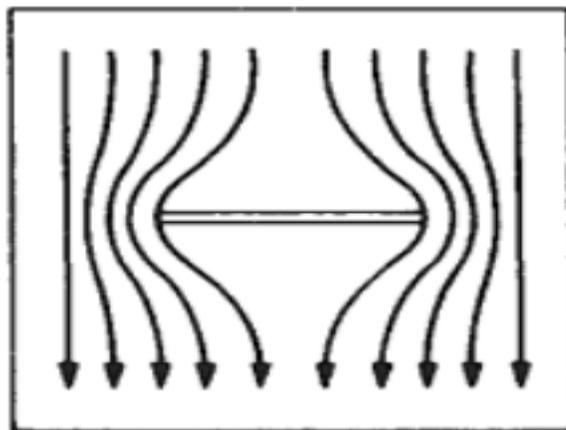
Induced shield current, slot aperture
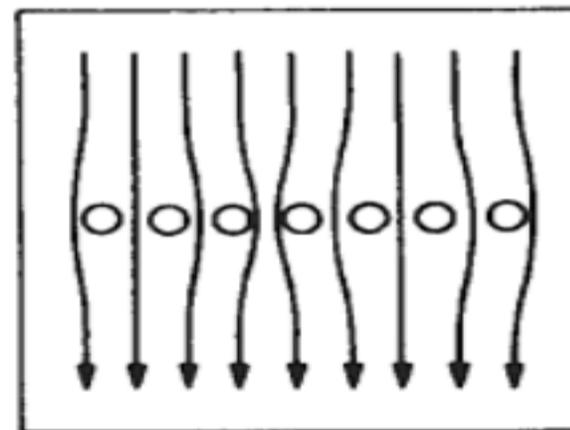
Induced shield current, multiple small apertures

Slot Aperture Shielding Effectiveness

- **Any aperture can be modeled as a slot antenna.**

- **A slot antenna is most efficient at resonant frequency (when its length equals half a wavelength)**

- **For practical purposes, SE = 0 dB at slot resonance**

- **SE increases linearly (20 dB/decade) as the aperture gets shorter**

- **The slot width is not a significant factor**

$$SE = 20\log\left(\frac{\lambda}{2L}\right)\ \mathrm{dB}, \qquad \text{for L} \le \frac{\lambda}{2}$$

$$SE = 20\log\left(\frac{150}{f_{MHz}L}\right)\ \mathrm{dB}$$

L = maximum aperture dimension, in meters

SE vs Frequency of Single Slot

Seams
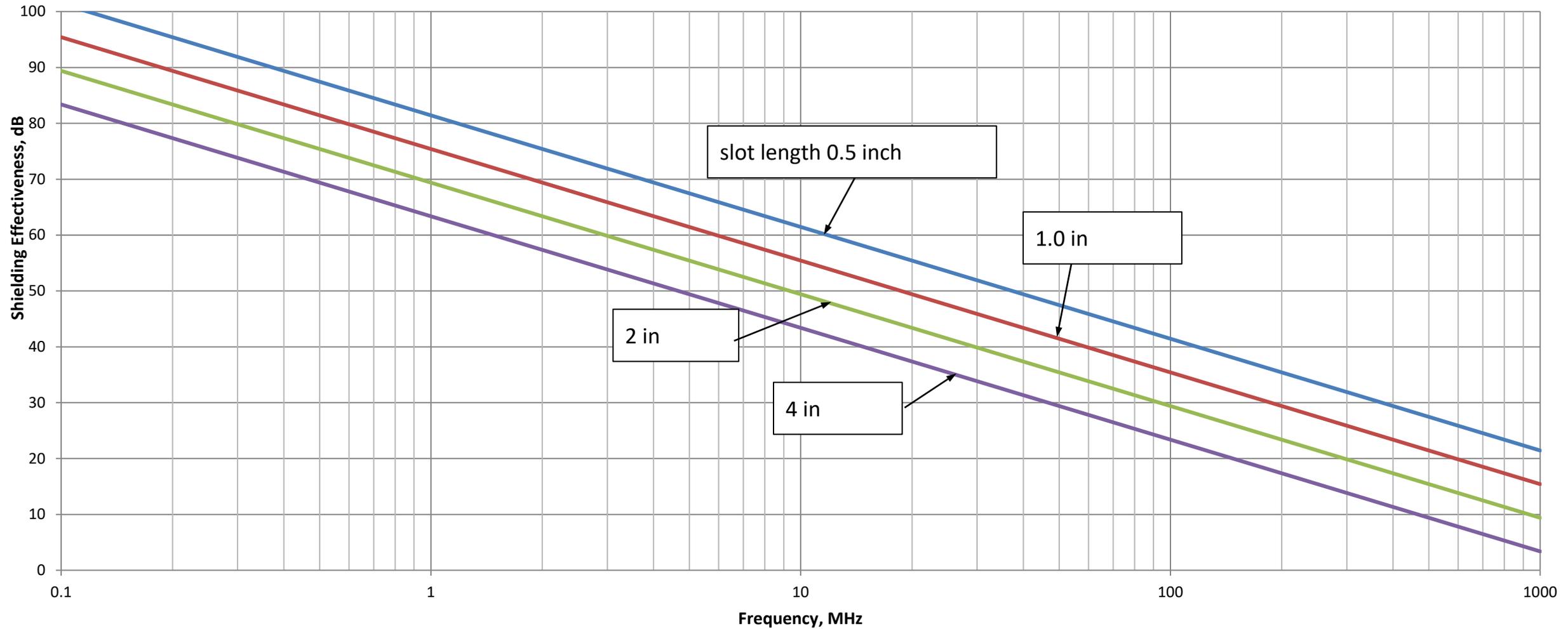
- **From a shielding perspective, a seam can be considered a slot that may or may not make good electrical contact at points along its length.**

- **To achieve good shielding, the seam length must be broken up into an array of shorter slots.**
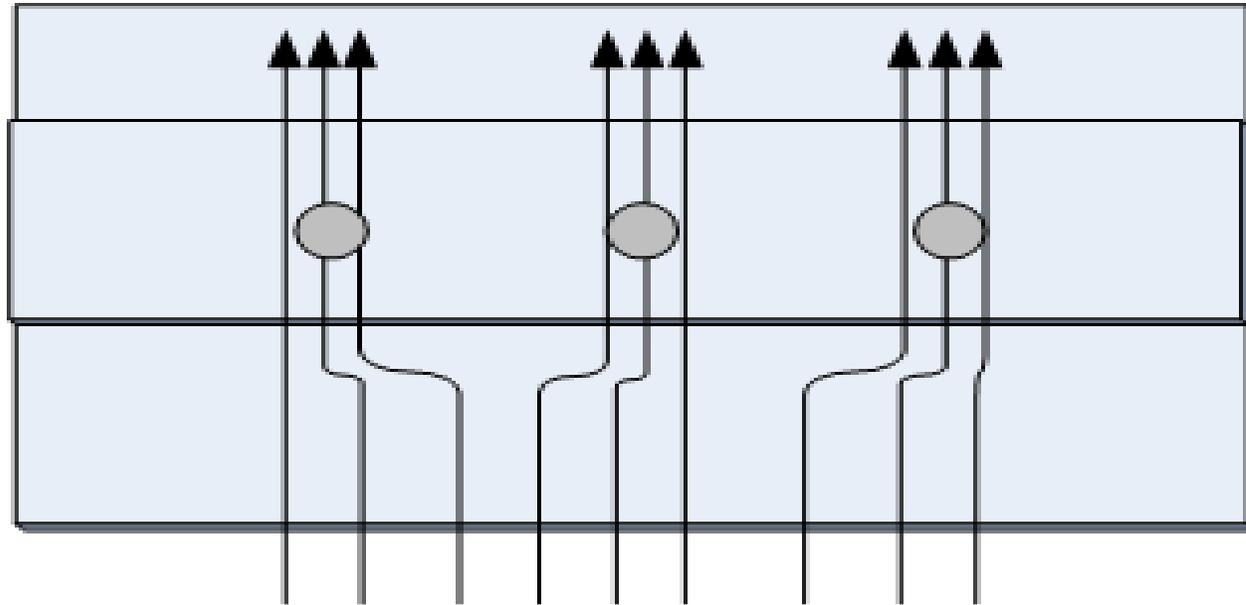
- **The goal for seams and joints is to maintain metal-to-metal contact at intervals small enough to maintain the desired SE.**
  - Continuous weld, spot-weld
  - Conductive gasket
  - Multiple fasteners, evenly spaced
- **All seams require high electrical conductivity (low contact impedance) between mating surfaces.**
- **Low contact impedance is achieved by:**
  - Conductive finish
  - Adequate pressure over seam length
  - Surface flatness

Fastener Spacing

- **Wide screw spacing + thin covers**

  - Usually results in radiated emissions failures

  - May be a problem even with an EMI gasket

- **2" screw spacing and panels ≤ 0.060" thick**

  - Often sufficient for radiated emissions compliance

- **EMI gaskets often not required**

- **Gaskets may be required for non-EMI requirements**

Approximate Effect of Fastener Spacing

EMI Gaskets
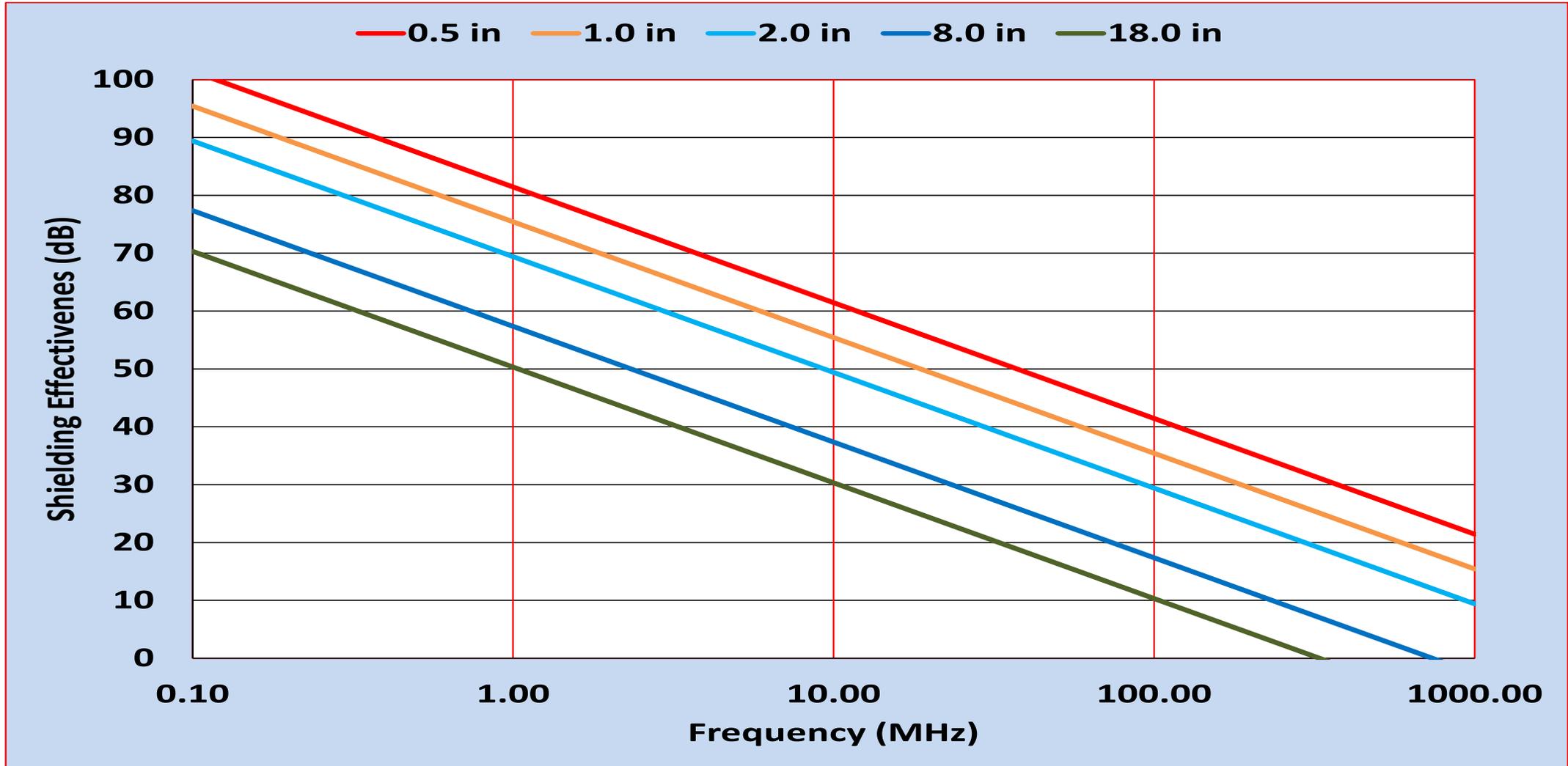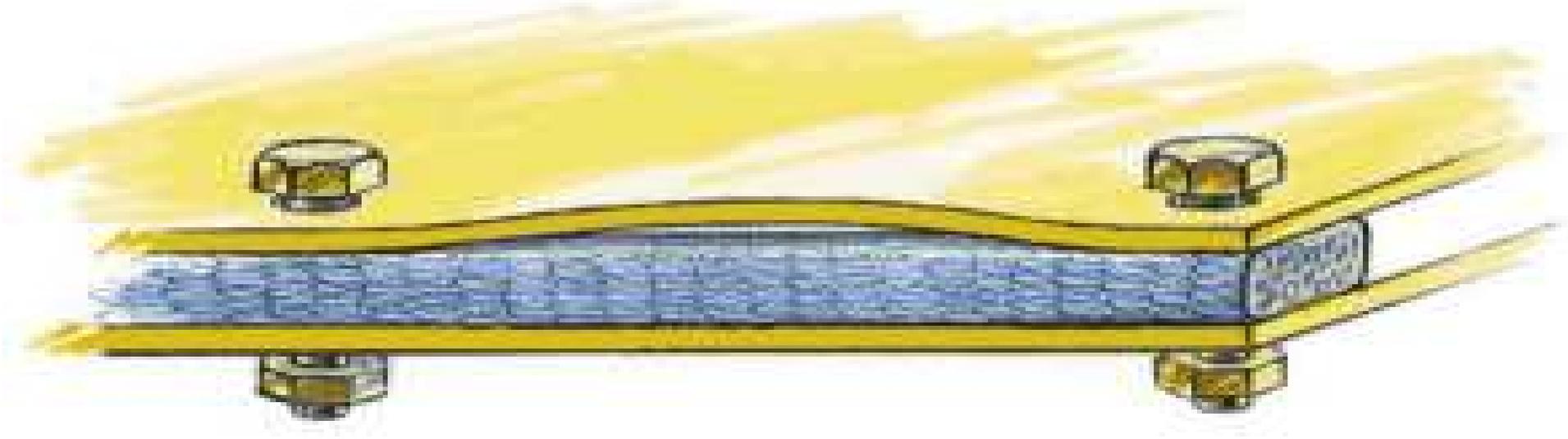
- **Preferred method for controlling seams and apertures is direct metal – metal contact**
- **Not always achievable due to other considerations**
- **Gaskets provide an option for minimizing the slot length**

- **Purpose:**
  - Provide a continuous conductive path across the two mating parts of a seam.
  - Typically used in situations where the required fastener spacing is too small to be practical.

- **Required Features - the gasket design should:**
  - Conform to joint mismatch under the applied force.
  - Have sufficient contact pressure to provide low contact resistance
  - But not so much that the gasket over-compresses at fastener locations.
  - Use a compression stop.
  - Utilize compatible materials/finishes.

Gasket Design Considerations

- **Shielding characteristics/contact impedance**

- **Mechanical compliance (joint cross-section)**

- **Compressibility and compression set**

- **Screw spacing**

- **Environmental requirements**

- **Shape and preparation of mounting surface**

- **Ease of assembly and disassembly**

- **Resistance to corrosion**

Gasket Supplier Applications Engineers Should Be Consulted for Best Results

DISA

Gasket Examples

Metal/elastomer combo

Fingerstock
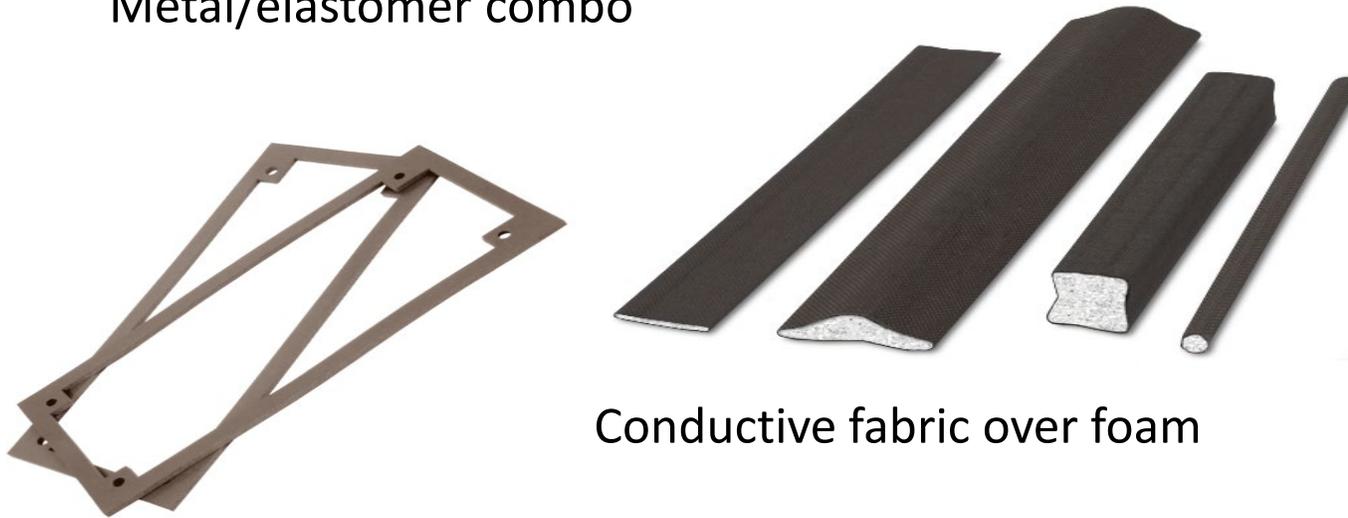
Conductive elastomer

Conductive fabric over foam
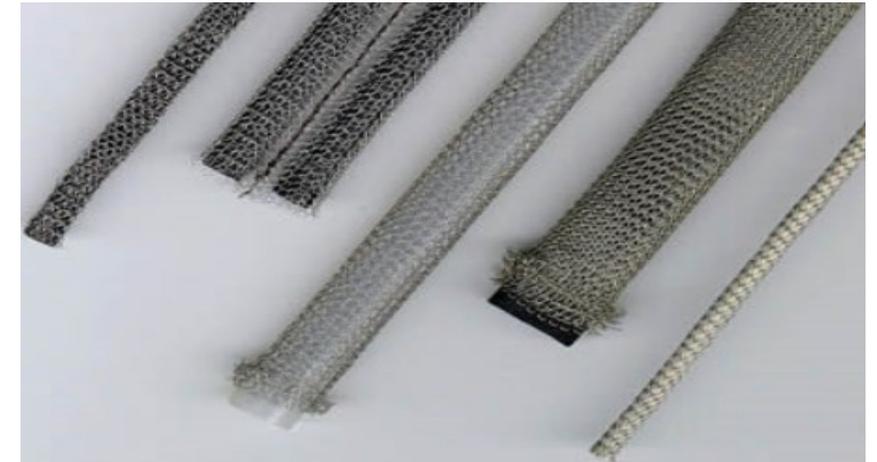
Knit wire mesh with foam core

Gasket Installation Methods
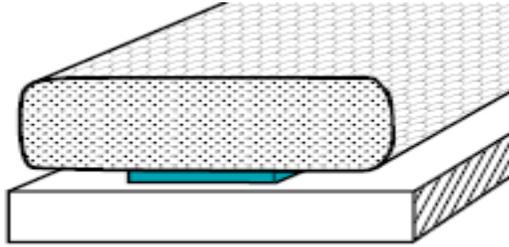
Adhesive Strips
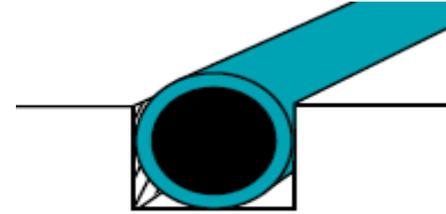
Machined Groove
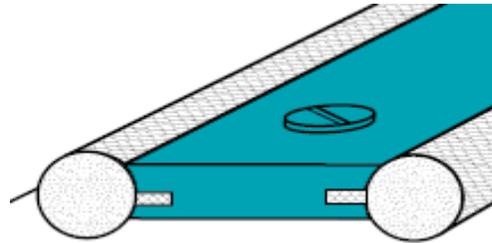
Framed Slot
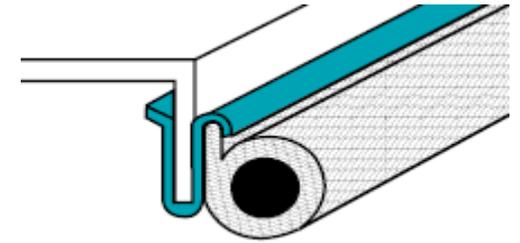
Metal Clips
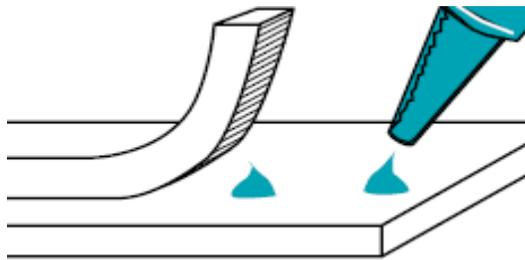
Adhesive Compounds
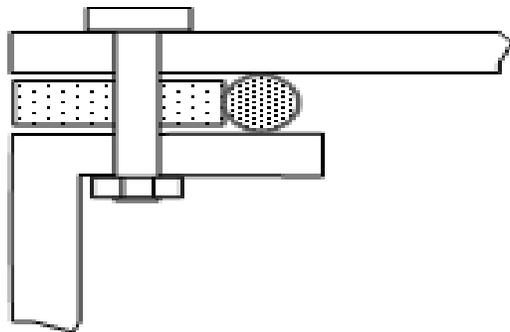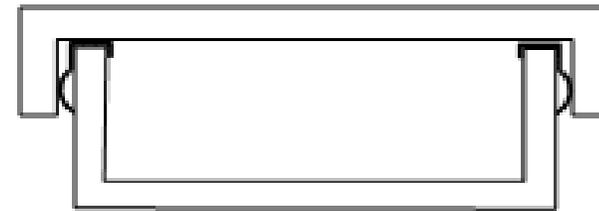
Friction Fit

More Gasket Installation Methods
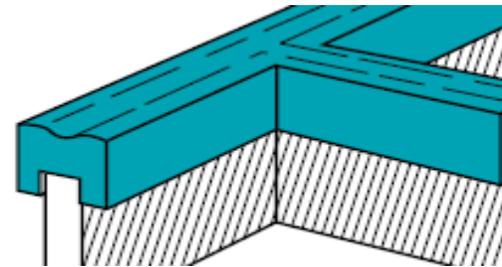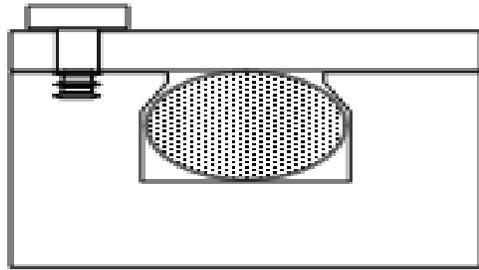
Gasket captured in
groove
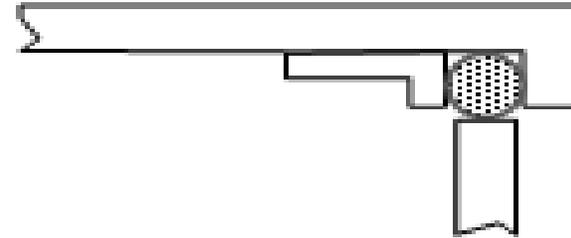
Difficult to maintain good alignment over
the whole gasket perimeter

Combination EMI/environmental
gasket

Spring fingers
No fasteners needed

Ventilation Port Dilemma

- **Required for air flow and cooling**

- **Will potentially degrade enclosure shielding**

- **ME wants to minimize pressure drop, hence large air flow openings**

- **EMI/EMC wants to minimize the openings**

- **Solution is mesh or a perforated sheet**

- **Assembly of small diameter slots**

- **Shielding effectiveness is inversely proportional to the number of slots**

- **Many small slots constitutes better EMI/EMC design than fewer larger slots**

Waveguide Below Cutoff

- **Additional attenuation (shielding) can be obtained from an aperture if it has sufficient depth**
- **At frequencies below the waveguide cutoff frequency (f_c), the aperture is an effective attenuator.**
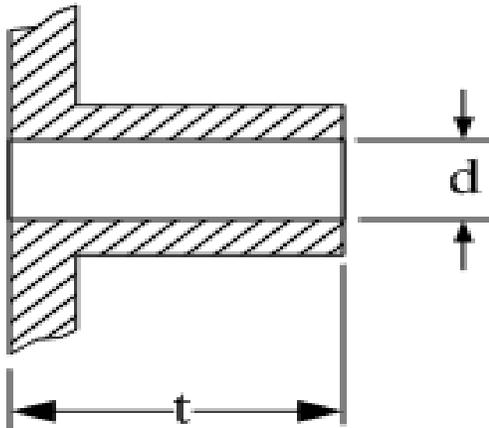
$$SE = 32\frac{t}{d}\,dB \qquad \text{Round Waveguide}$$

$$SE = 27.2\frac{t}{l}\,dB \qquad \text{Rectangular Waveguide}$$

$$d = \text{ Diameter (in)} \qquad t = \text{ Depth (in)}$$

$$l = \text{ Largest dimension (in)}$$

$$Valid\ for\ f_o \ll\ f_c:$$

$$f_c = \frac{6.9}{d}\ \text{GHz (round)}$$

$$f_c = \frac{5.9}{\ell}\ \text{GHz (rectangular)}$$

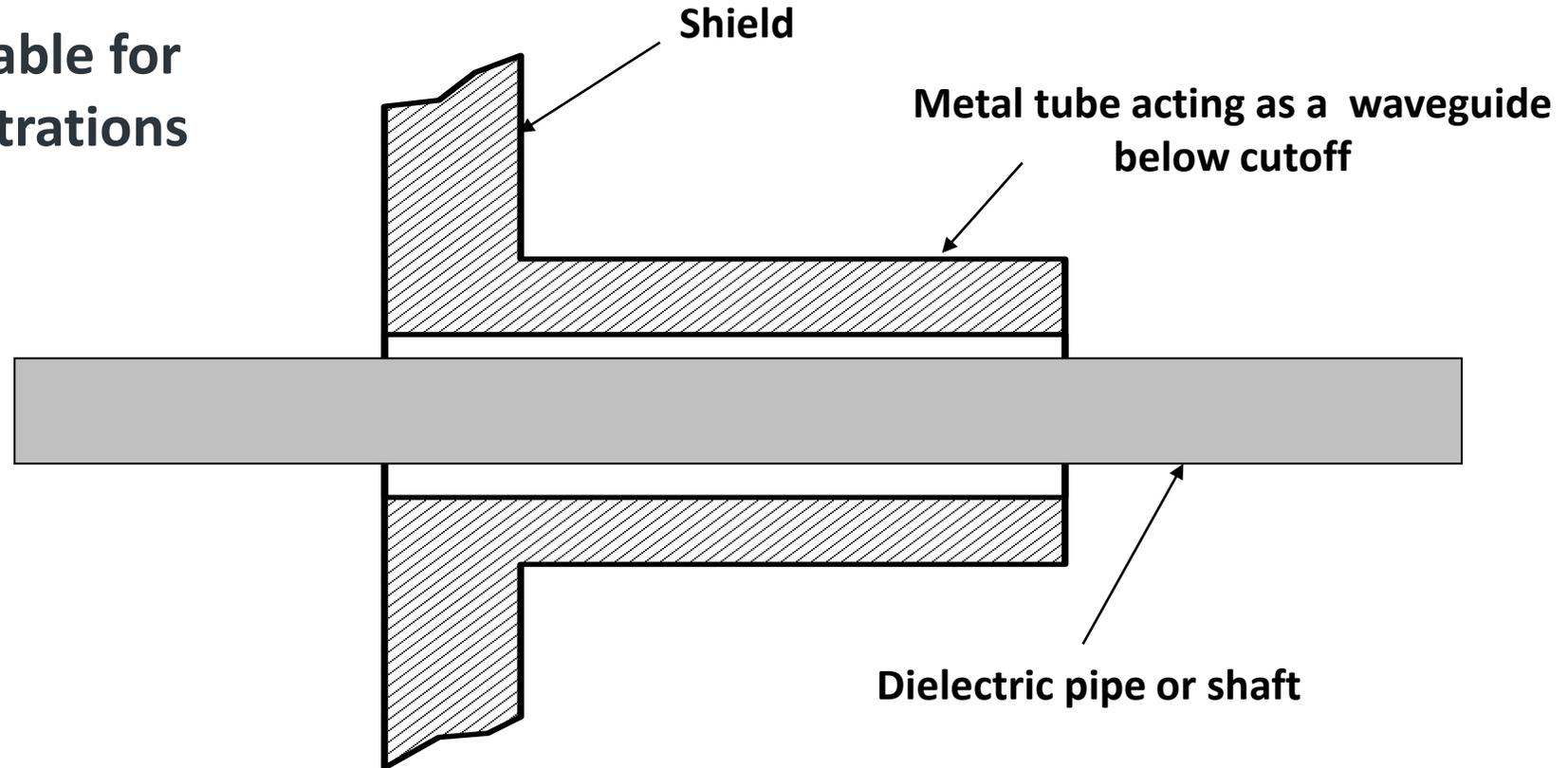# Honeycomb Vents

Advantages:

- Greater attenuation than equivalent perforated hole array

- Cell wall can be as thin as possible, even to foil size

- Minimum pressure drop

Disadvantages:

- Cost

- Installation requires more effort

- Vent must be mounted in a rigid frame and gasketed to the housing

- Must have continuous electrical connection between cells.
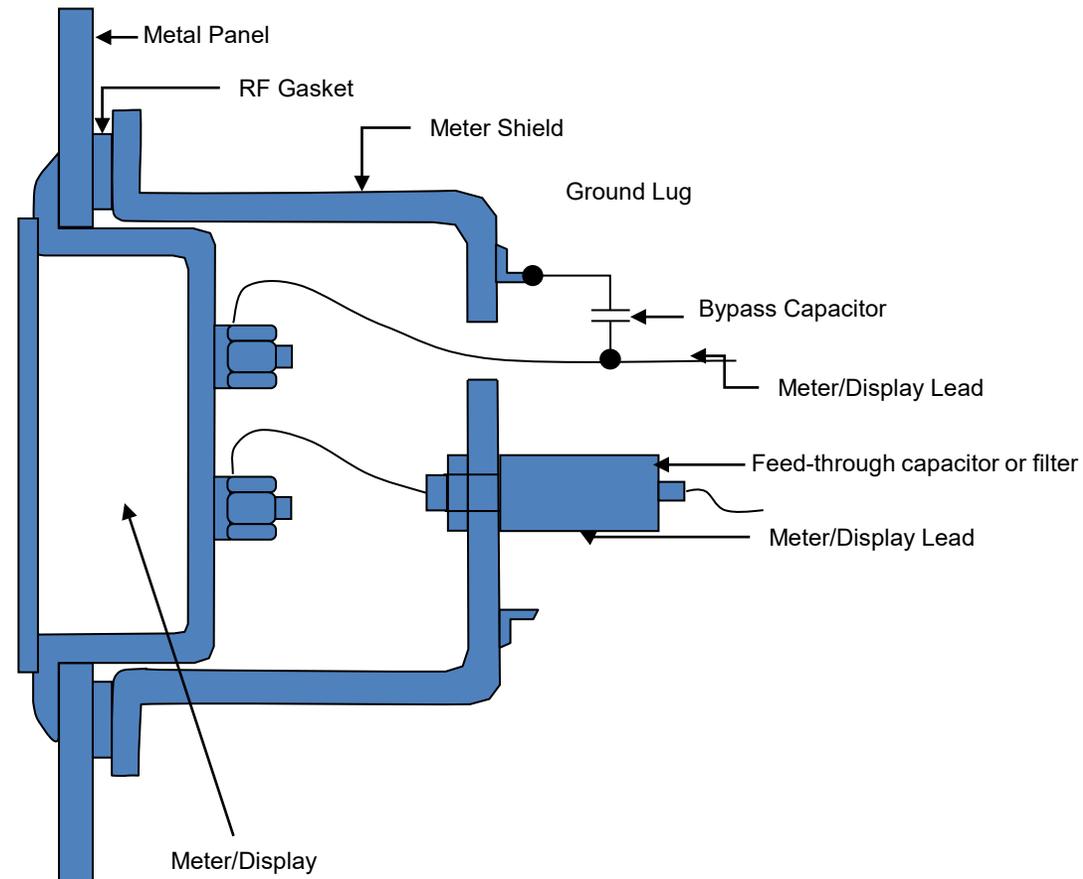
Non Conductive Penetrations
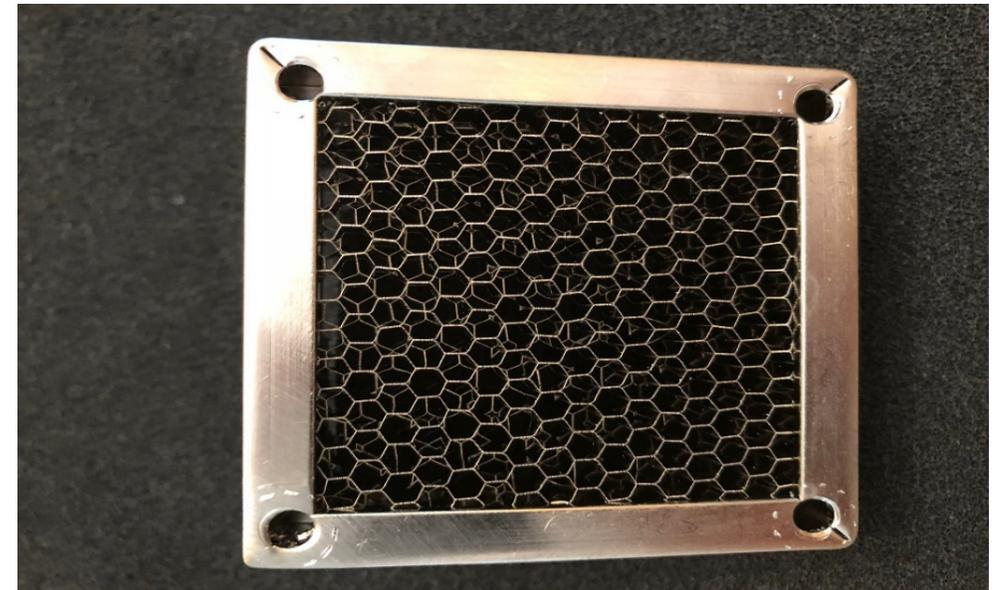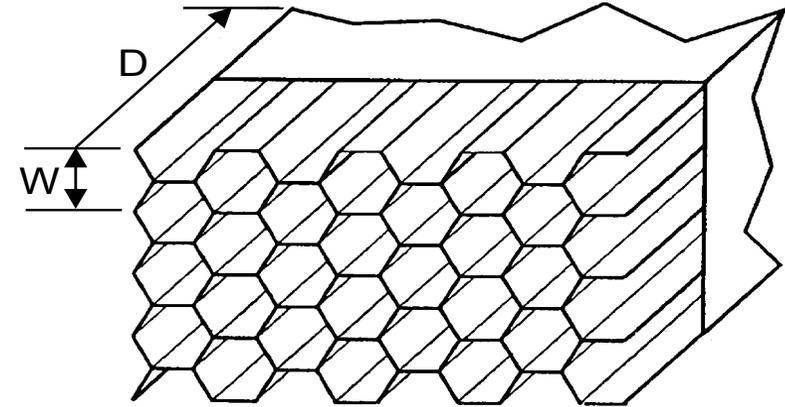
Particularly suitable for fiber optic penetrations

Shield

Metal tube acting as a waveguide below cutoff

Dielectric pipe or shaft

Not For Use With Conductive Interfaces Such as Wires and Cables!

Visual Requirements

- **Displays**
- **Panels**
- **Meters**
- **Lights**

Common Shielding Solutions:

- Shielding and filtering the display elements
- Conductive mesh screen across the viewing port
- Plating the transparent face of the display

Metal Panel

RF Gasket

Meter Shield

Ground Lug

Bypass Capacitor

Meter/Display Lead

Feed-through capacitor or filter

Meter/Display Lead

Meter/Display

Shielding Summary

- **The perfect shielding design is a Faraday Cage, however, in the real world that does not exist.**

- **The dominant factor in leakage through seams and apertures is the slot length which can be controlled by fastener spacing.**

- **Various types of gasket options exist when direct metal to metal contact is not an option. Each type has pros and cons.**

- **Holes and perforations for ventilation or for any other purposes will decrease the shielding effectiveness of the case. A larger number of small holes is preferred over a single larger hole.**

Shielding Summary (continued)

- **Designing an enclosure with a plane-wave shielding effectiveness of 30-40 dB is fairly straightforward (approximate frequency range 10 MHz – 1 GHz).**

- **Enclosures with a plane-wave shielding effectiveness of 60-70 dB are challenging and require careful attention to detail in design and implementation.**

- **Shielding effectiveness > 100 dB can be obtained, but with difficulty and usually at significant cost.**

Shielding Effectiveness Demo

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Cable Shielding
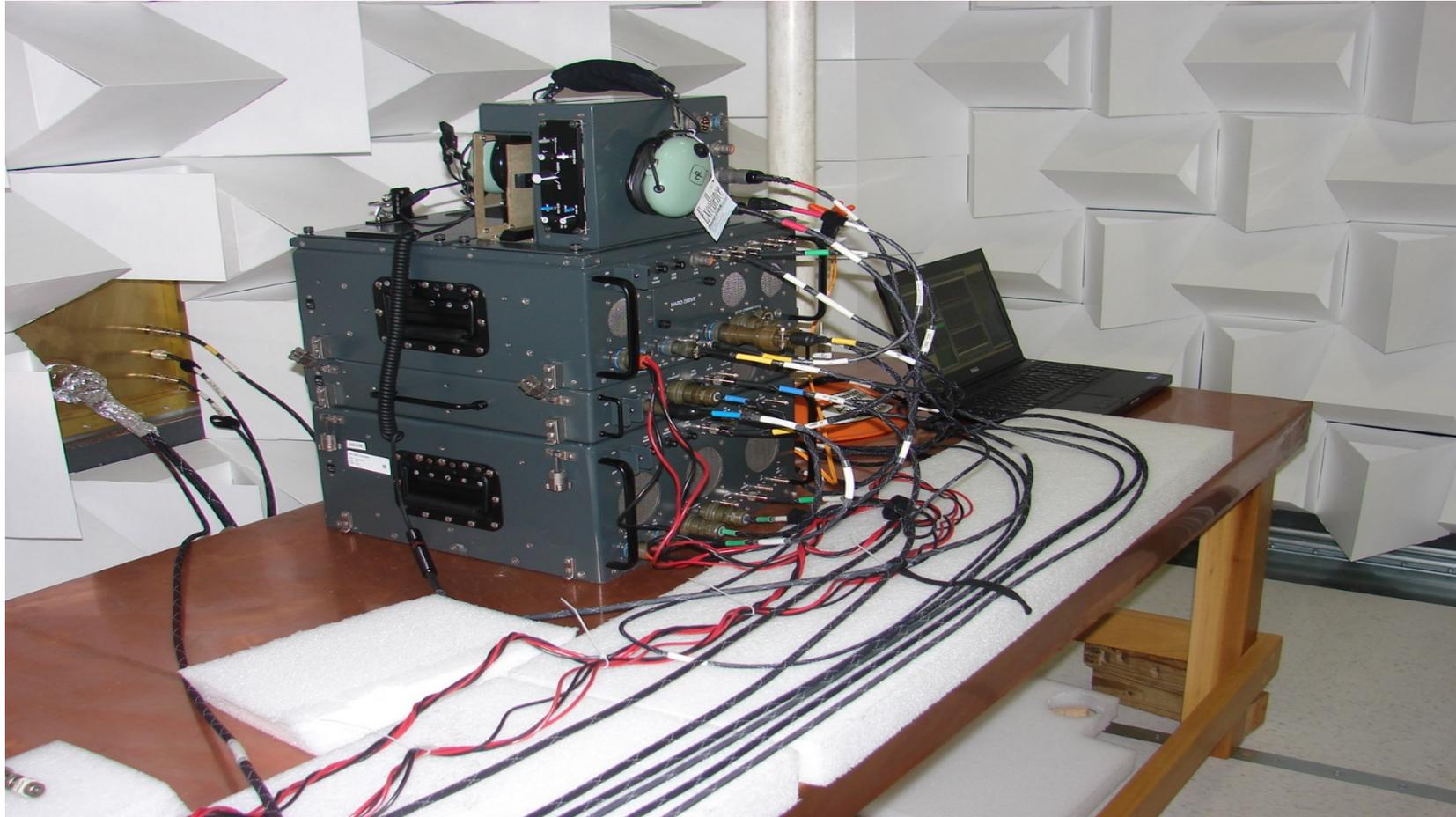
The Majority of EMI Related Problems!

Simple Example

- **An unshielded cable of length "L" is used to provide data between two pieces of equipment (or even a shielded cable that is not terminated).**

- **It is routed through an open hole with diameter "d" in "Equipment A" and connects to a circuit board inside.**

- **Assume that the hole diameter, d, is much less than the cable length, L.**
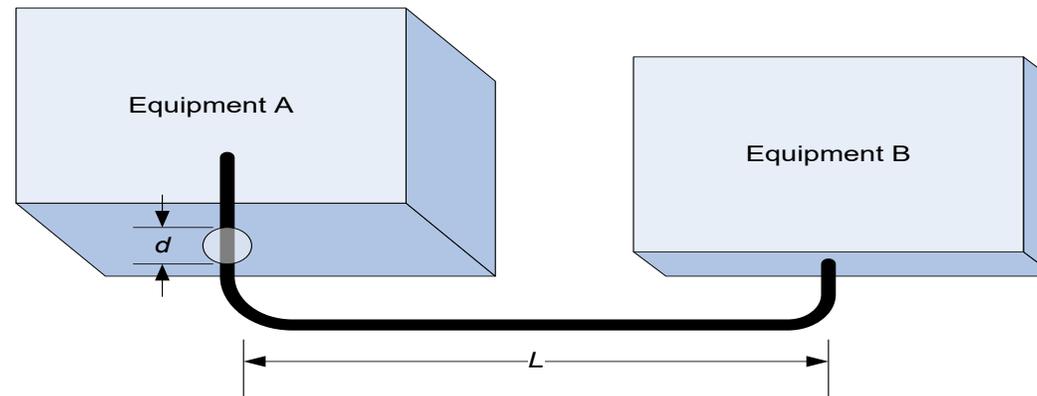
What is the greater concern from an EMI/EMC perspective?

Answer...

- **While the open hole in the equipment chassis is a concern, the greater concern is the unshielded or even shielded, but unterminated cable.**

- **The small size of the opening will be of concern at very high frequencies (diameter dependent).**

- **The long length of cable will act as a long wire antenna and thus will couple and radiate frequencies over a much larger range.**

Cables and E3 Testing
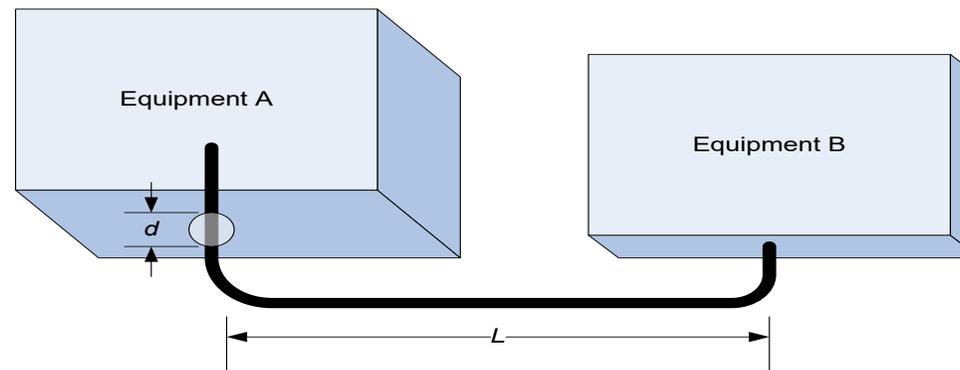
- **MIL-STD-461 and MIL-STD-464 testing includes production representative cable interfaces**

- **Regardless of who provides the cables**

- **Bad cable design by the procuring agency is not a pass on responsibility for meeting MIL-STD-461 requirements**

Shield Transfer Impedance
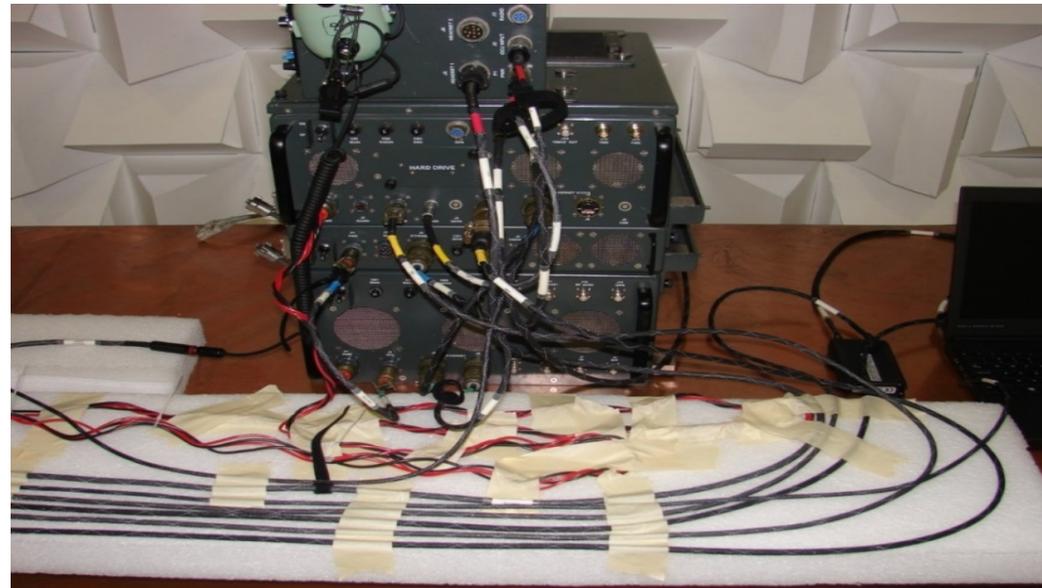
- **Shield transfer impedance (Z_T) relates the current flow on the outside of the shield to the voltage induced on the inside (between core conductor and shield)**
- **It is a property of the cable only**
- **The concept is focused on noise pickup (circuit susceptibility) but is applicable to emissions problems as well (reciprocity principle)**
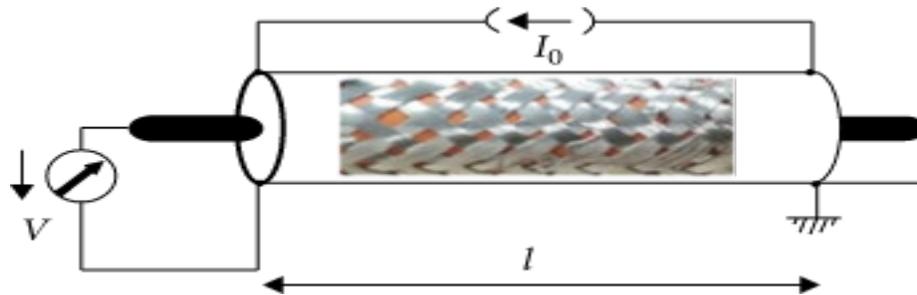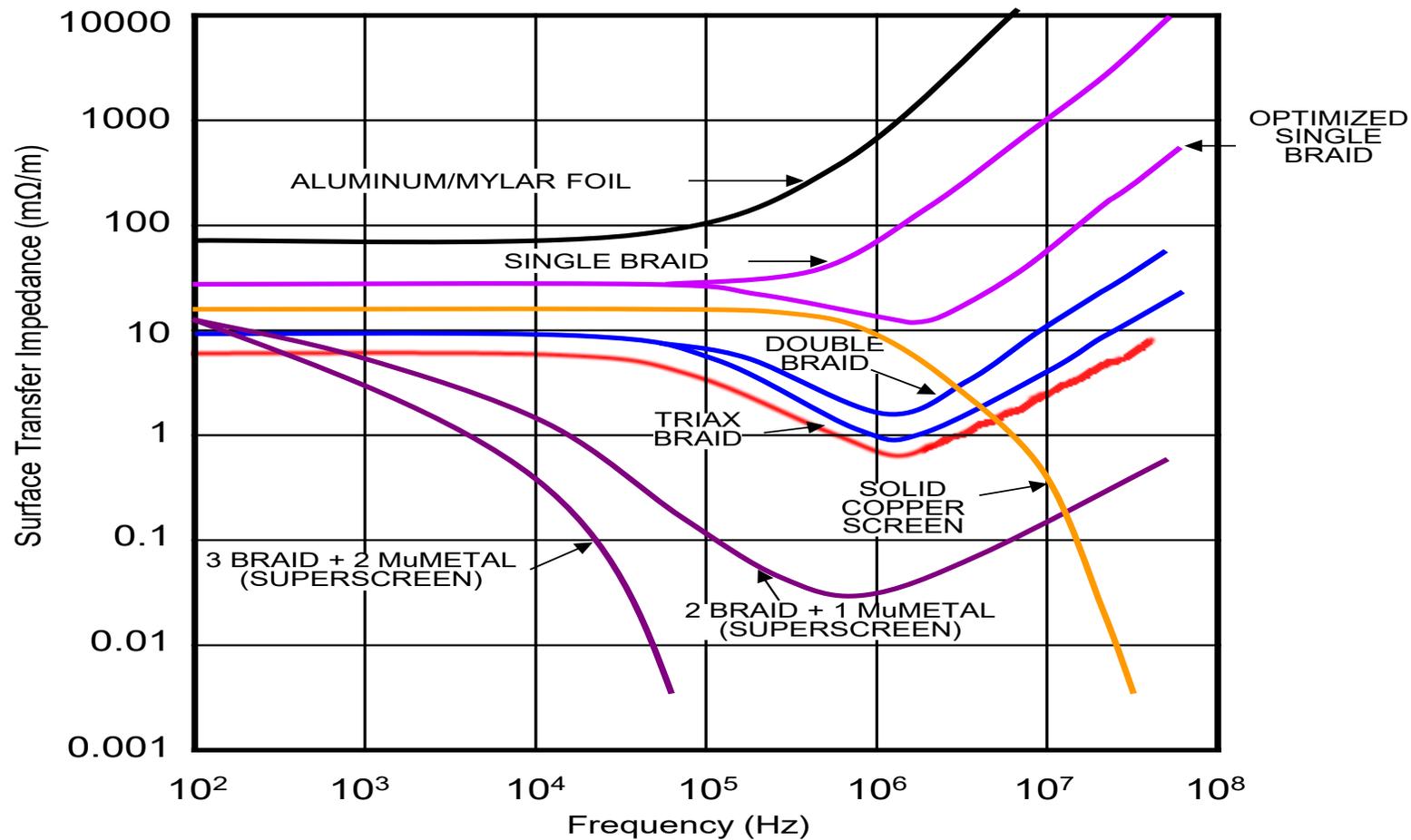

$$Z_T = \frac{1}{I_s} \frac{dV}{dz}$$

$V =$ Voltage induced between the inner wire and the shield

$I_s =$ Current on the outer shield surface (external source)

For electrically short cables: $V = I_s Z_T \ell$ where $\ell =$ length

Typical Transfer Impedances

- **Lower is better**
- **At low frequencies (below ~100 kHz), Z_T ≈ shield resistance**

How a cable shield works

- **From basic inductance principles:**
  - if the current on the outer shield is uniform, then all of the flux due to the shield current encircles all of the core conductor as well.
  - So, the self-inductance of the shield is (nearly) equal to the mutual inductance.
- **With the shield connected to ground at both ends:**
  - Noise current flowing on the outside of the shield induces a voltage along the outer shield (self-inductance).
  - But an equal voltage is generated along the core conductor, due to the mutual inductance.
 - The net result is a voltage distributed across the two loads equal to I_S x R_S

    (= I_S x Z_T at higher frequencies)
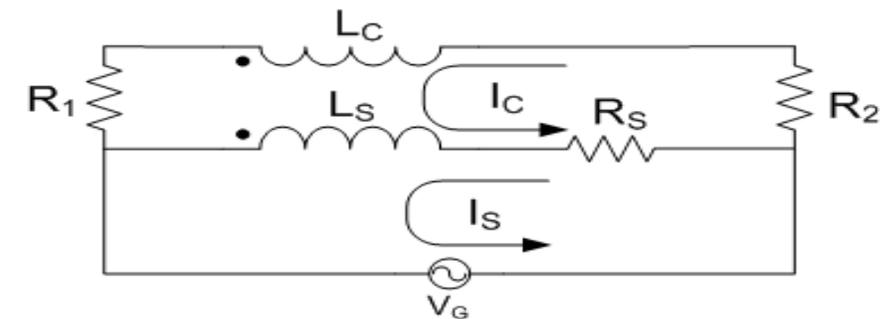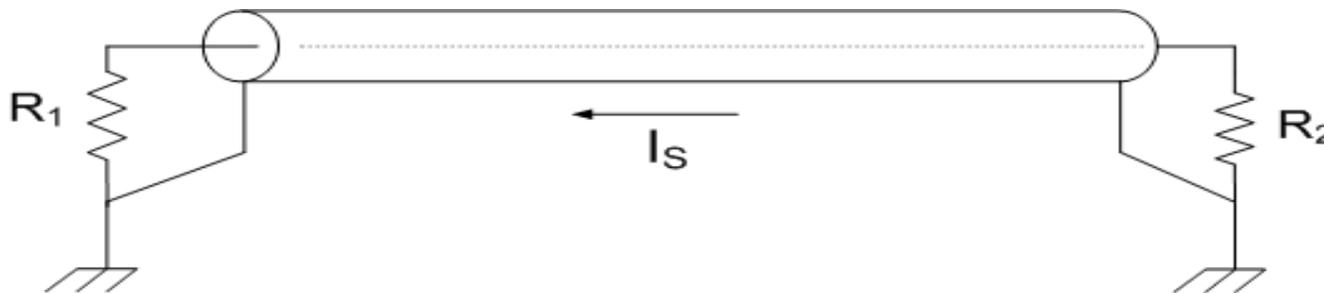
$$L_C \cong L_S \cong M$$
$$V_{R_1} + V_{R_2} = I_S \cdot R_S$$

Shield Terminations

- Shielding is only as good as the termination method

- Cables with shielded lines must have connector interfaces that accommodate:

  - 360 degree shield termination for overall shields

  - For individual pair shields, use special adapters in the backshell or similar method that grounds each individual shield directly

  - For coax/triax, use Individual grounded connectors or "ground plate connector inserts" for multiple coax/triax cables carried into a multipin connector shell.

- Minimize the use of pigtails for grounding shields
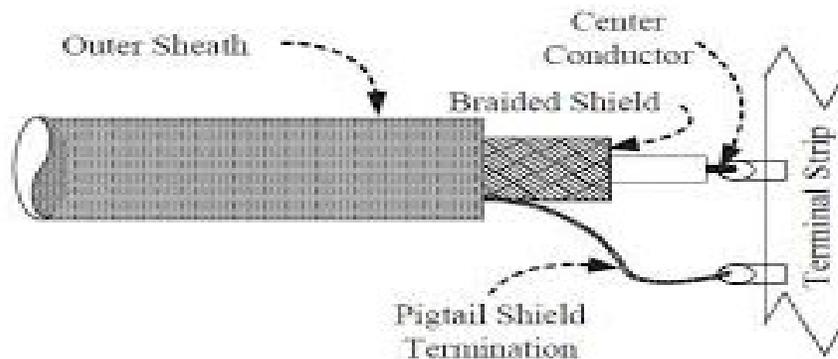
- High speed signal activity will result in radiated emissions (RE102) failures caused by long pigtails

- Pigtail length should be minimized (1/2 inch or less, as required)

Threaded Assembly

- The shield is placed through the ground ring and flared over and around the ring, and may be secured to the ring with a spot tie. The ground ring is then slid into the rear of the sleeve, which has a tapered base. Tightening the cable clamp onto the end of the sleeve assures positive 360 degrees grounding of the shield, and provides a strain relief for the cable.

SLEEVE

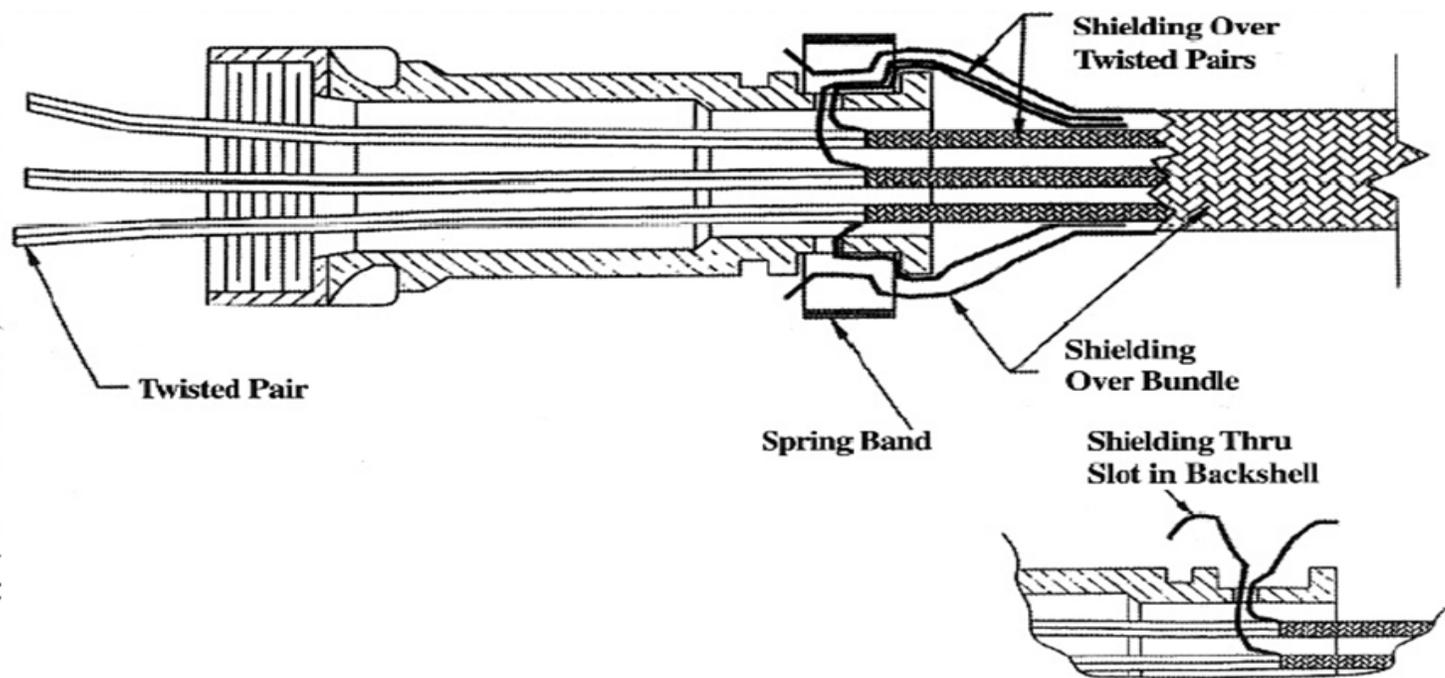SHIELD

CABLE CLAMP

WIRE SEAL RING

CONNECTOR

GROUND RING
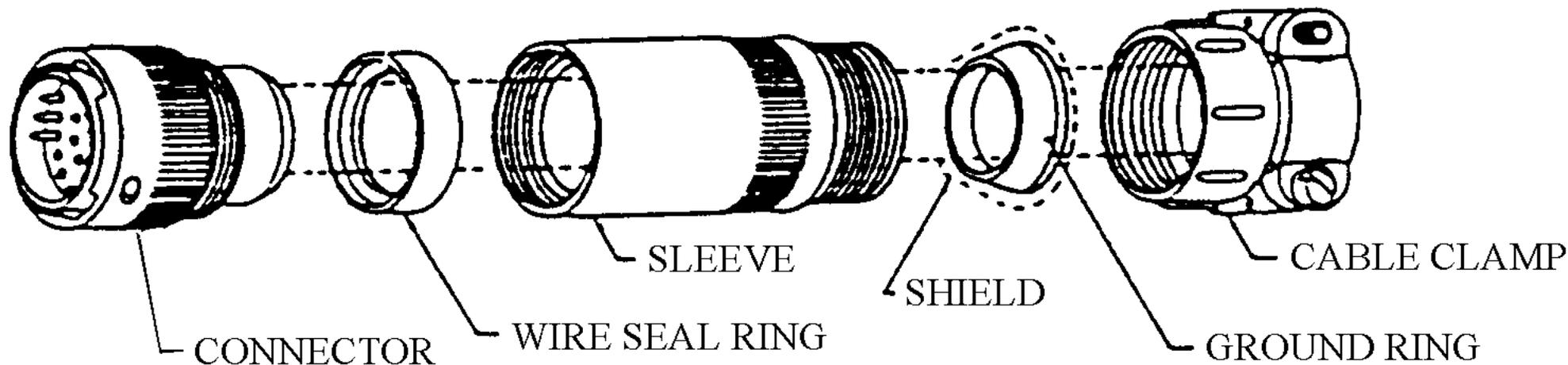
Banding Clamp

- **A stainless steel band peripherally clamps the shield to the backshell.**

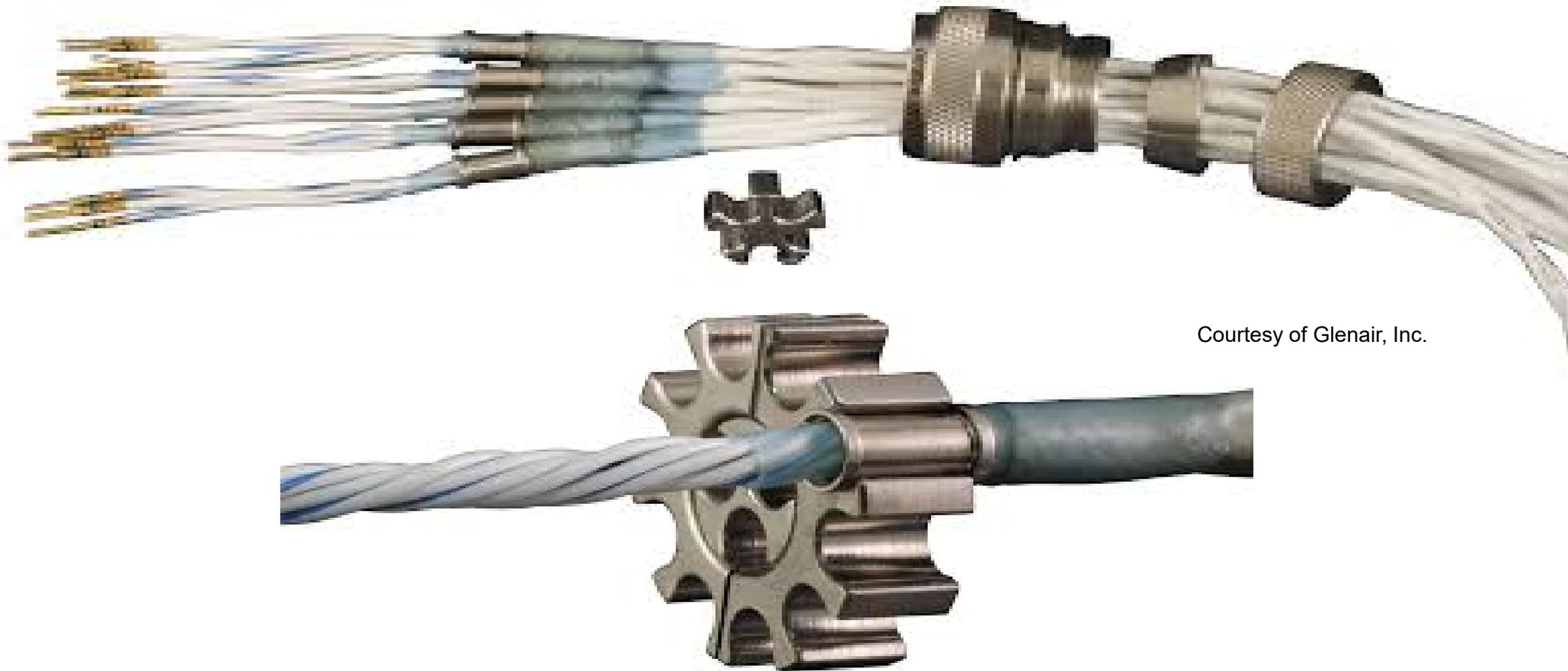

Courtesy of Glenair, Inc.

Twisted Shielded Pairs

- **When several TSPs are bundled in the same cable assembly, the individual shields may be folded back over a gross braid and secured using a spring band.**

Zero Length Shield Terminations

Courtesy of Glenair, Inc.

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Cable Shielding Summary

- Cables are the most prominent source of EMI/EMC problems. Cable shielding must be addressed early in the design of the system (regardless of who supplies the cables).

- Cable shielding is only as good as the termination technique.

- 360-degree shield termination methods are usually mandatory.

- EMI backshells are typically required.

- **Rule #1**: Don't allow an unfiltered, unshielded cable to leave a shielded enclosure.

- Doing so effectively negates all work done to shield the enclosure. The noise current on the unfiltered, unshielded cable will radiate, effectively bypassing the enclosure shield.

Grounding

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- **IEEE Definition**
  - Ground (earth). A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth.

- **Alternate definition**
  - An equipotential point or plane which serves as a reference voltage for a circuit or system, which may or may not be at earth potential.

- **Alternate definition**
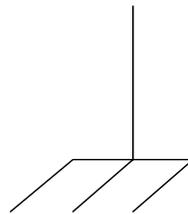 - Low-impedance path for current to return to its source

- **Various types of grounds exist and are often confused, even by experienced engineers.**

What "Ground" really is

- **A reference potential**
- **A signal return path**
- **A power common**
- **Local structure**
- **Equipment chassis**
- **Connection to earth**

- **Some grounds carry current intentionally**
  - power return
  - signal return
- **Some do not**
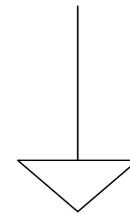 - safety ground (except for the fault current)
  - chassis ground

## Some experts suggest: "If it's a signal or power return, don't call it a ground!"
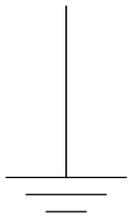
Earth Ground   Chassis Ground   Common Return

Grounding Purpose/Objectives

- **Safety (shock and lightning protection)**
  - Carry fault currents (or lightning strike current) without causing safety hazard

- **Establish a current return path**
  - Provide a low-impedance path for signal currents
  - Return the current through the smallest possible loop

- **EMI control**
  - Carry high frequency current on shields and structure without causing excessive RF voltages
  - Minimize noise voltages due to common-impedance coupling
  - Minimize noise voltages due to inductive coupling (loop area reduction)

- **Key is to know where the current flows.**

- **Methods of minimizing ground noise**
  - Lower the current path impedance
  - Make the current flow through a specific path

Scope of Grounding

- **Printed Circuits**
- **Electronic Modules**
- **Power Distribution**
- **Chassis**
- **Racks**
- **Conduit/Ductwork/Cable Trays**
- **Platform/Building Structure**
- **Earth**
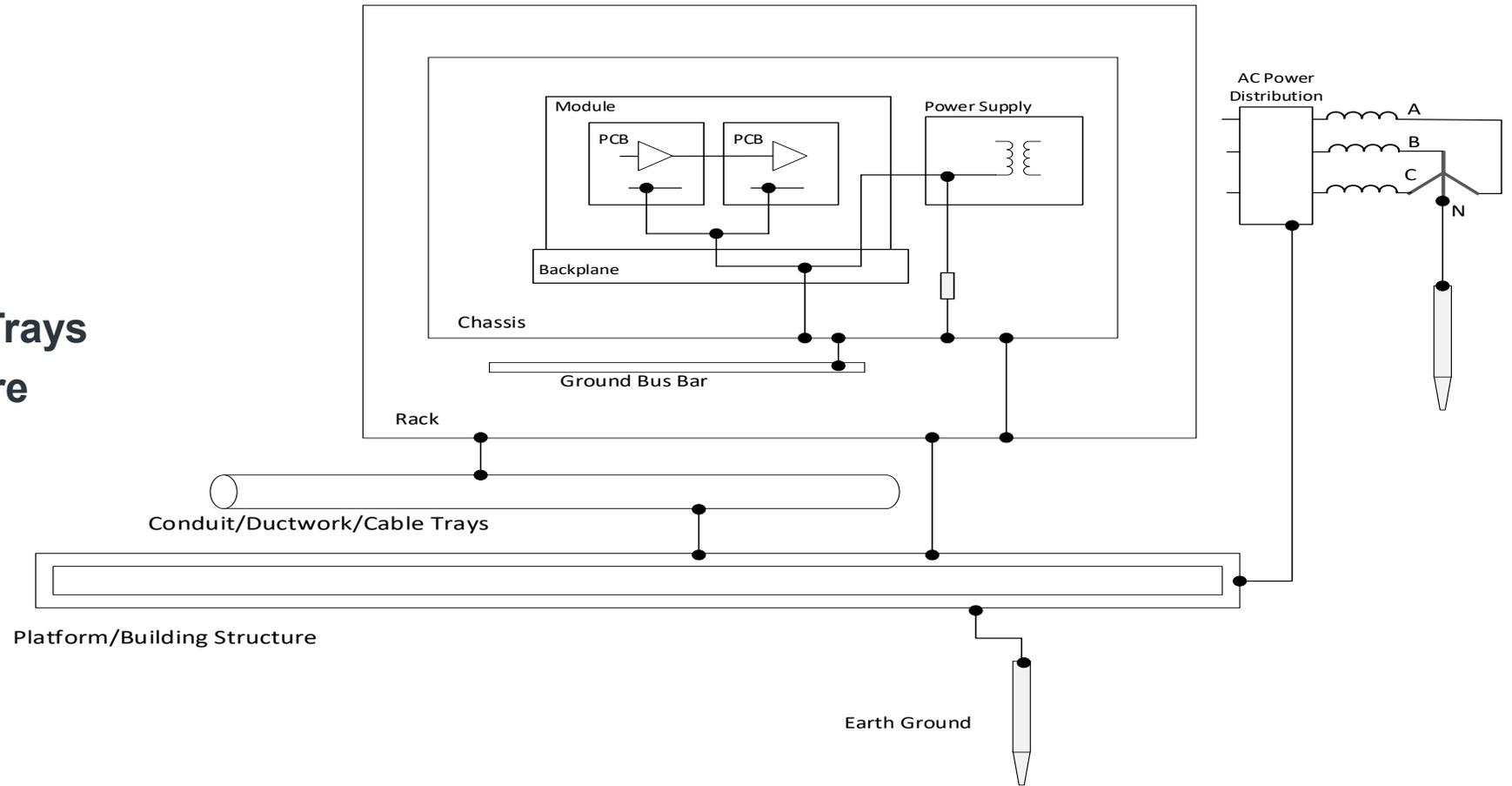
A systems approach is required

A Few Grounding "Myths"

- **The earth is an equipotential, and an infinite sink for noise currents.**

- **To be noise-free, circuits should be referenced to a separate "quiet ground" point (such as earth).**

- **A single point ground is always necessary to minimize EMI.**

- **Low impedance bonding of equipment chassis to structure will eliminate all EMI problems.**

These falsehoods still persist!

Grounding Approaches by Platform Type

- **Fixed Facilities**
  - Equipment safety ground (green wire) for fault protection
  - Common ground reference (at building entry point)
  - Current returns always wired (power neutral)
  - Earth electrode (single ground rod or array)
  - Lightning protection system (usually separate from other building grounds)

- **Aircraft**
  - Metallic airframe is the safety ground and lightning protection system
  - Airframe is also partial faraday cage for EMI control
  - Sometimes airframe is used for current return (weight savings)

- **Ships**
  - Metallic hull is the safety ground and lightning protection system
  - Hull and ship structure is never used for current return
  - Hull is also a faraday cage for EMI/EMC control
  - Hull penetrations (cables, apertures) are major design focus

Grounding Approaches by Platform Type
(continued)

- **Spacecraft**
  - Safety ground usually not applicable
  - Control of static charging is usually important
  - Power and signal returns never carried on structure
  - Major EMI design focus: isolation of DC power from structure

- **Tactical Vehicles**
  - Safety ground usually not applicable (unless higher voltages are involved)
  - Power current return on structure or cabled (or mix)
  - Focus is on earth grounding (ground rods or equivalent)
  - Lightning protection may be included as separate entity/structure

Equipment/System Configurations

- ## Isolated Systems
  - − All functions contained within a single enclosure with no external signal connections to other grounded systems

- ## Clustered Systems
  - − Multiple equipment enclosures located in a small area with multiple interconnections, but not to other grounded systems

- ## Distributed Systems
 - − Multiple equipment enclosures that are physically separated such as in different rooms and/or buildings

- **Simplest to ground**

- **All circuitry contained within a single chassis**

- **Enclosure connected to AC power ground as required ("Green Wire")**

- **No I/O signals need be considered**

- **Examples: Laptop, portable radio**

Clustered Systems

- **Good example is multiple equipment enclosures located in a small volume (such as a rack)**

- **Safety grounds per NEC**

- **Signal grounds**

- **Each enclosure grounded in some manner**
  - Cable shields and/or safety grounds
  - Auxiliary ground conductors or wide metal straps – better
  - Direct connection to structure - best

Ground Plane

- **Multiple equipment enclosures that are physically separated**

- **Safety grounds treated individually**

- **Signal grounds are key**
  - Higher likelihood of ground loops
  - Each interface must be evaluated individually
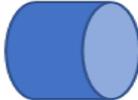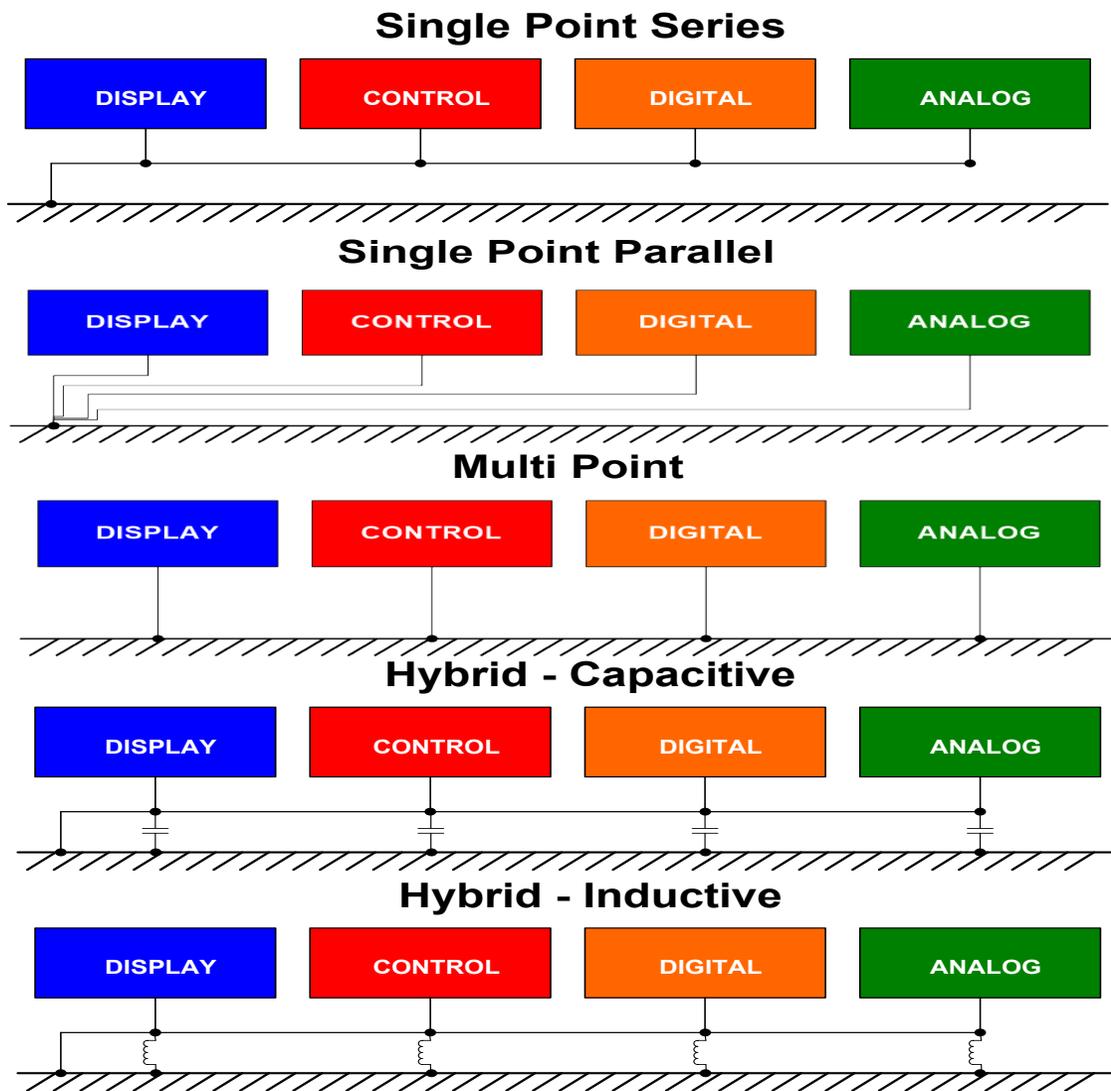 - Best approach for one type of I/O may not be best for all

Real-World Ground Conductors
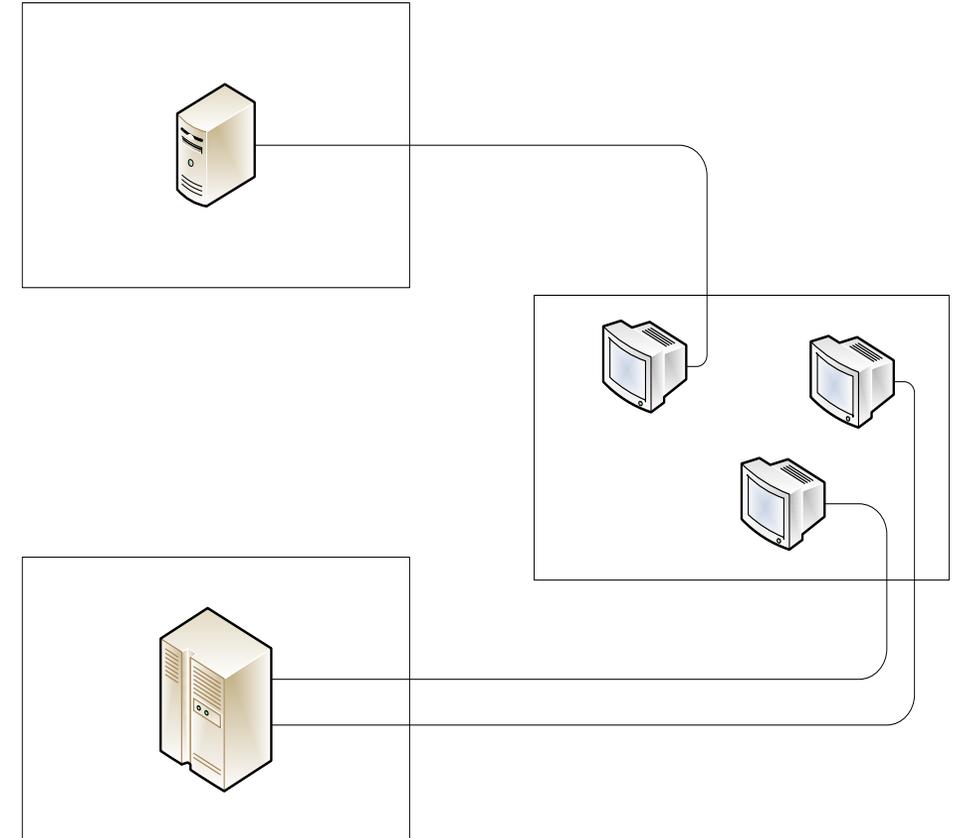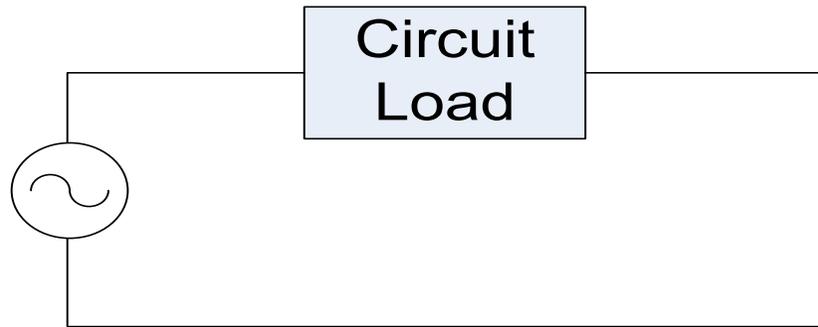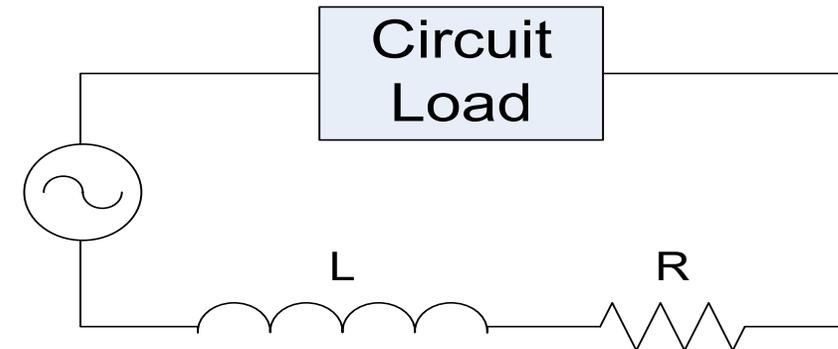
Ideal Ground with Z = 0 Ω   Real Ground with Z ≠ 0 Ω

The inductance presents a high impedance as frequency increases, resulting in noise voltages!

$$X_L = 2\pi f L \qquad Z = \sqrt{R^2 + X_L^2}$$

Rule of thumb: Ground conductors should be less than 1/20th of a wavelength at the highest frequency of interest

Impedance of Conductors (in ohms)

Configuration			60 Hz	100 kHz	2 MHz	100 MHz
0.5 inch length		#26	1.6 m	10 m	0.2	9.9
		0000	2 u	4 m	91 m	4.5
		2" wide	24 u	3 m	59 m	2.9
10 inches		#26	33 m	0.2	4.0	198
		0000	40 u	91 m	1.8	91
		2" wide	0.5 m	59 m	1.2	59
10 m		#26	1.3	7.8	156	7811
		0000	1.6 m	3.6	72	3590
		2" wide	18 m	2.3	46	2310

Signal Grounding Topologies

Single Point Series

DISPLAY | CONTROL | DIGITAL | ANALOG

Single Point Parallel

DISPLAY | CONTROL | DIGITAL | ANALOG

Multi Point

DISPLAY | CONTROL | DIGITAL | ANALOG

Hybrid - Capacitive

DISPLAY | CONTROL | DIGITAL | ANALOG

Hybrid - Inductive

DISPLAY | CONTROL | DIGITAL | ANALOG

- **These schemes can be applied at any hierarchical level:**
  - circuits on PCB,
 - PCBs within module,
  - modules within equipment,
  - equipment within rack.

Single Point Series
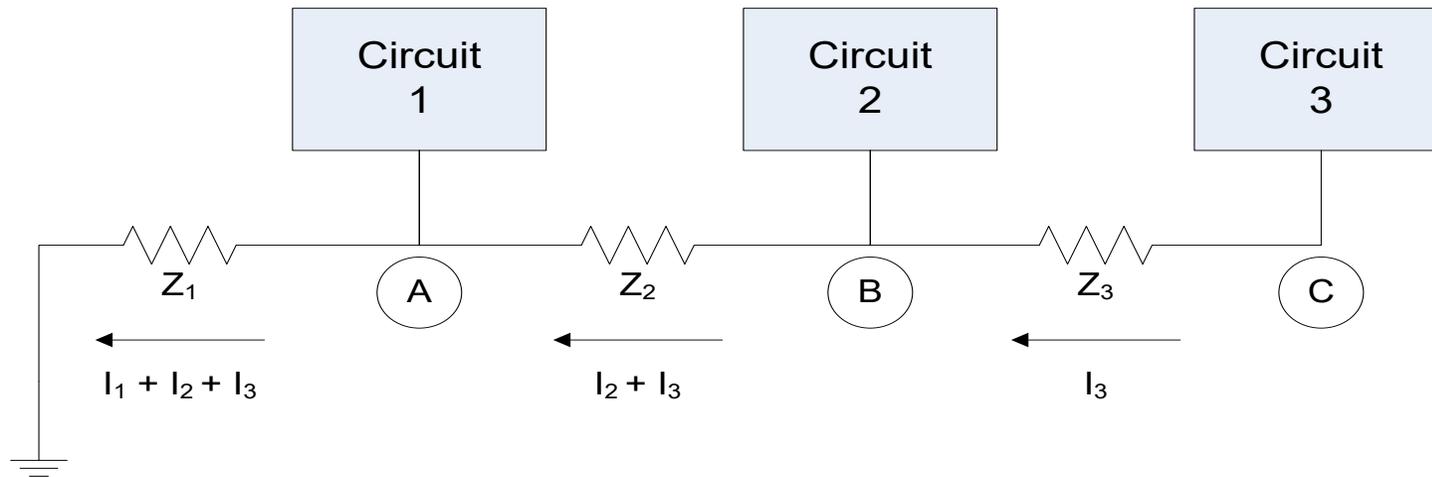
- **Also known as "Daisy Chain"**
- **Easy to implement**
- **May be suitable for non-critical applications (isolated or clustered)**
- **Not suitable for circuits using vastly different current levels**
- **Most critical circuit should be located nearest the ground point**
- **Sometimes used within equipment racks (where distances are short and the common-impedance voltage is small).**

Single Point Parallel
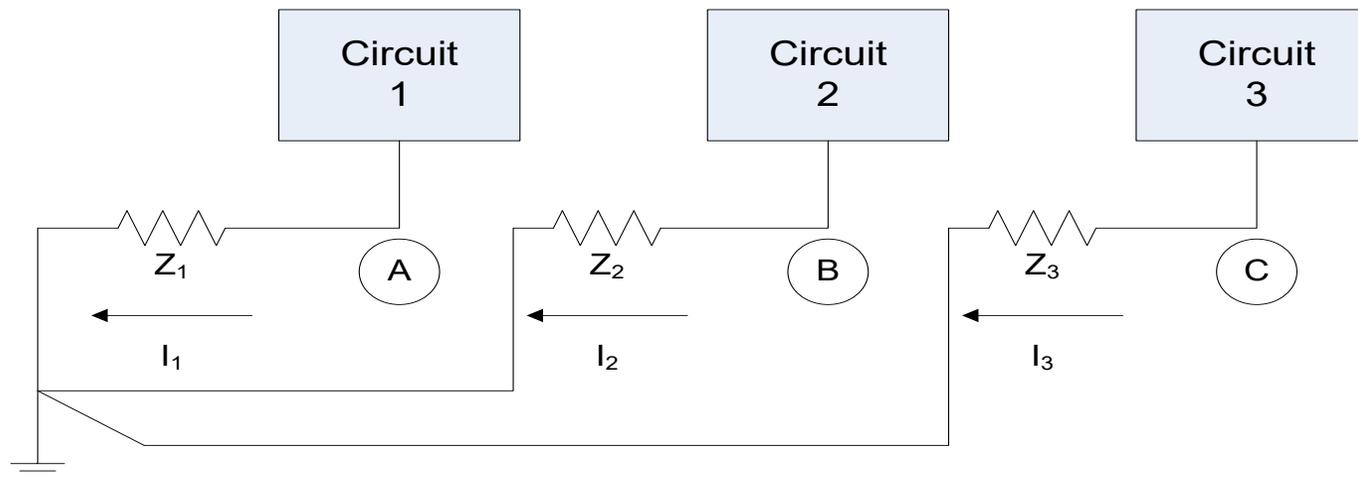
- **Also known as "Separate" or "Star"**
- **No common coupling between ground currents from different circuits**
- **Ground potential depends only on the individual circuit ground current and impedance**
- **May be physically cumbersome (extra wiring)**
- **Typically used in low-frequency analog circuits/systems, where millivolts of drop could adversely affect sensitive circuits.**
- **Not recommended for circuits operating > 100 kHz, due to excessive conductor inductance/impedance.**

More on Single Point Grounds

- Most single point ground schemes are a combination of series and parallel

- Compromise between minimizing electrical noise and avoiding excessive wiring

- Grounds should be selectively grouped such that circuits of widely varying power and noise levels do not share the same ground

- Single point ground schemes are undesirable at higher frequencies

- Ground conductor inductance increases ground impedance

- At still higher frequencies, grounds can act as antennas (when wire length is a significant fraction of a wavelength)

Single Point Ground Schemes – for circuits operating below 100 kHz

Multipoint
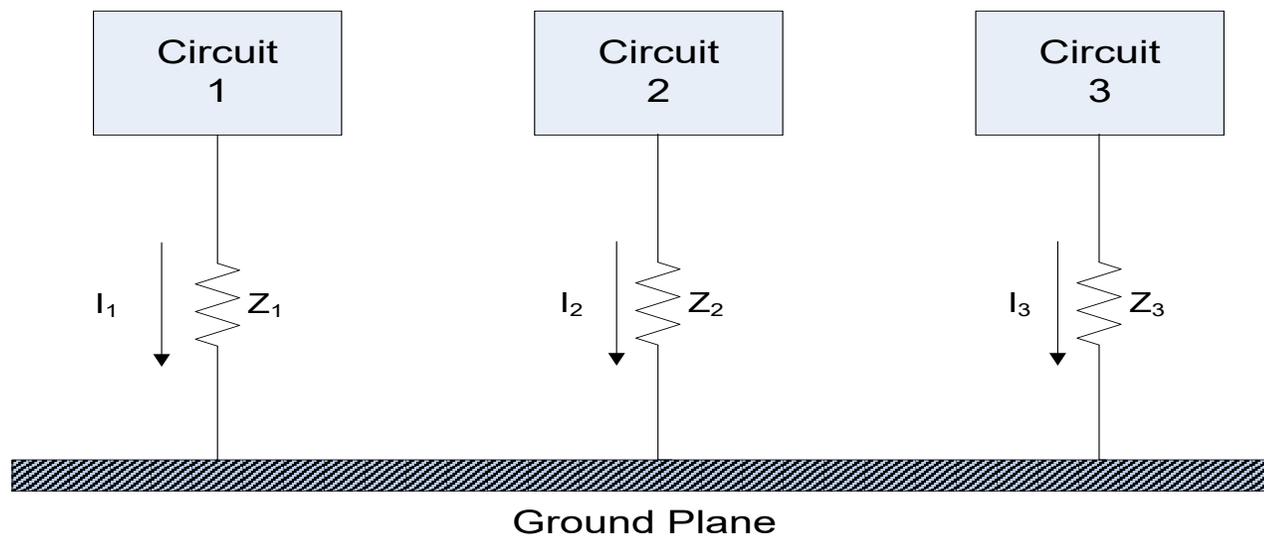
- **Mandatory at operating frequencies above a few MHz.**
- **Use of ground plane or grid minimizes the ground impedance**
- **Inductance can be minimized by multiple connections**
- **Ground connections as short as possible (in some cases fractions of an inch)**
- **Ground plane allows for use of controlled impedance transmission lines for signal interconnections**
- **Typically used for RF and high speed digital logic circuits.**

Composite Ground System

- **When a system comprises several types of circuits, a composite grounding topology may be used:**

- **Single point grounding, for low frequencies (< 100 kHz)**

- **Multi-point grounding for high frequencies (> 100 kHz)**

Ground Trees
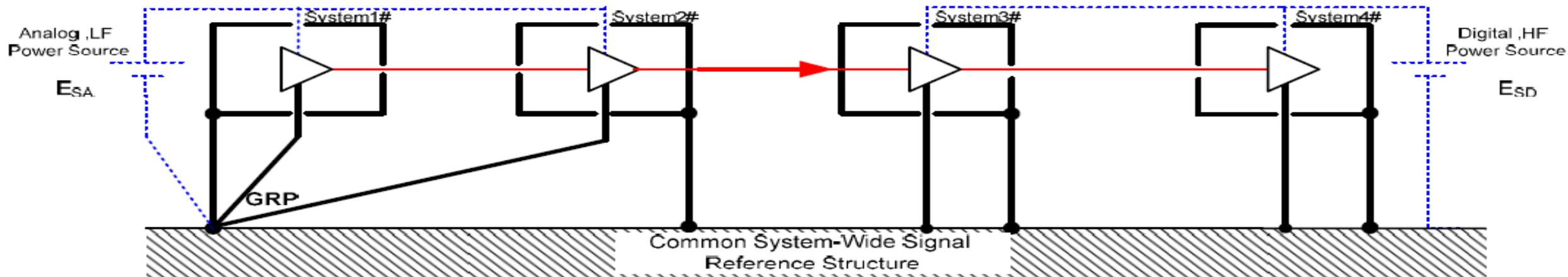
- **Provide a graphical depiction of the grounding of the entire system**
  - AC Power
  - DC Power
  - Digital
  - RF
  - Analog
  - Chassis
- **Useful for identifying ground loops and other potential problems**

Ground Tree Example

Common Impedance Coupling
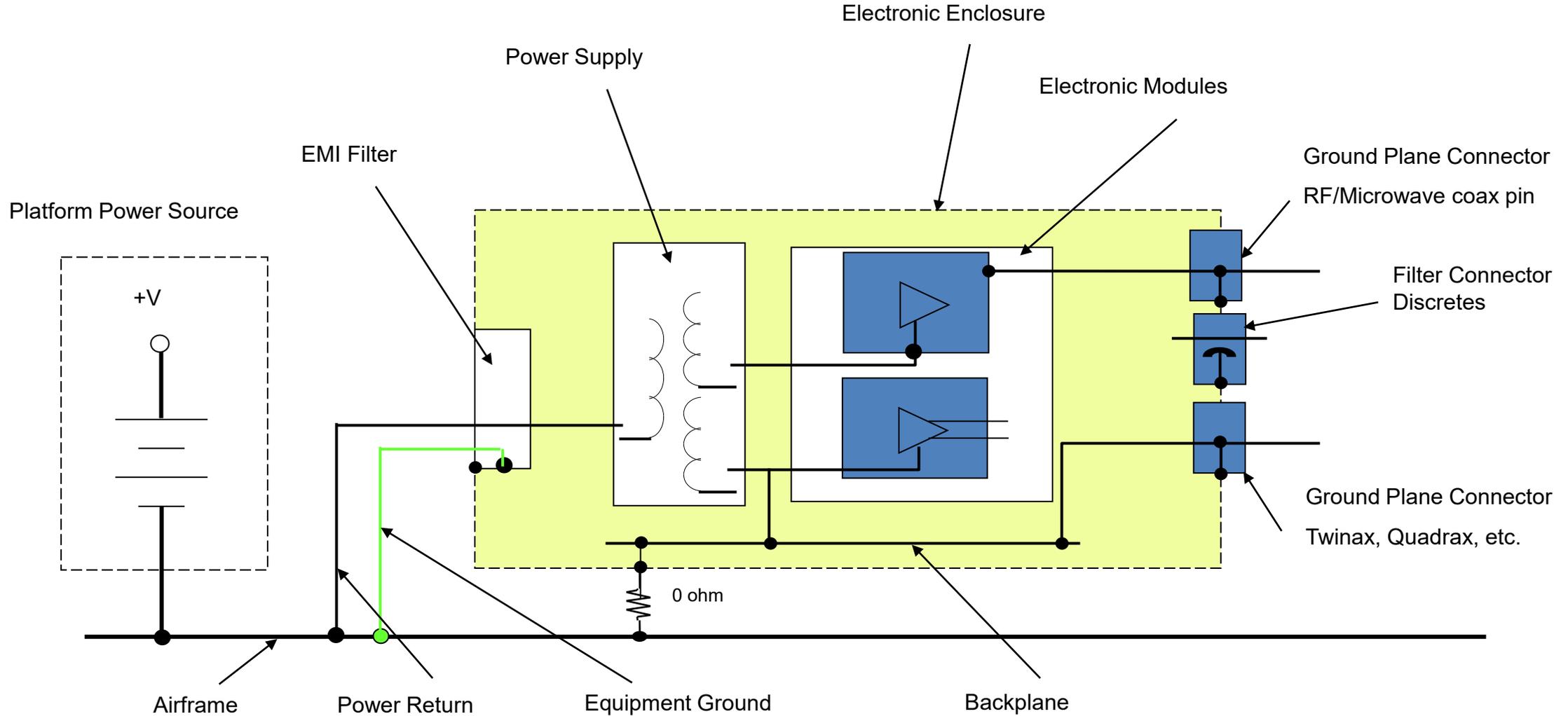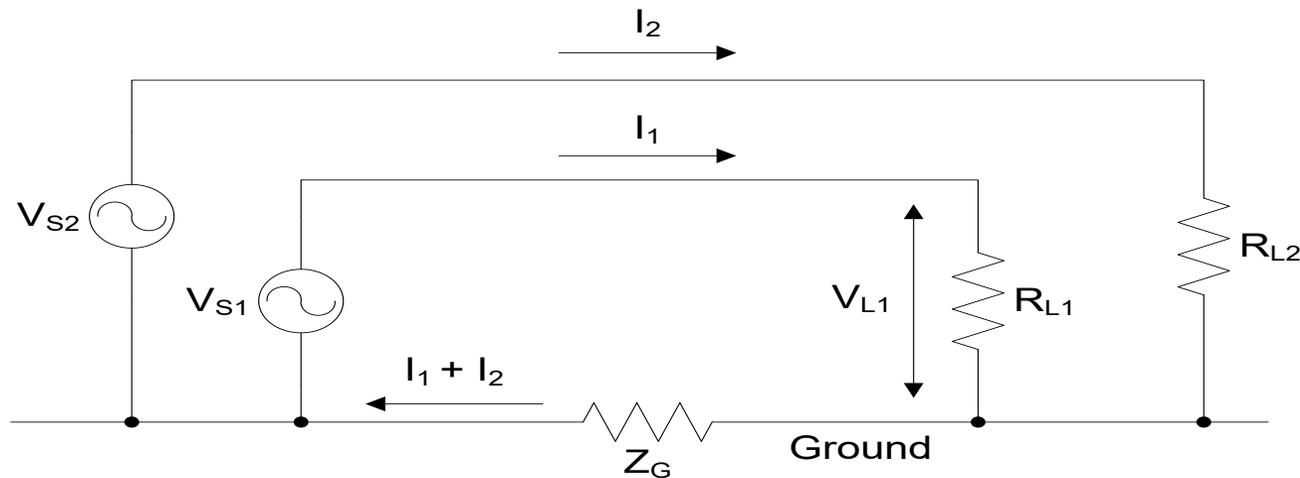
Source Voltage   Desired Signal   Noise

$$V_{S1} = V_{L1} + Z_G(I_2)$$

- **Two or more circuits sharing a common ground**

- **Voltage across R_{L1} is not just a function of I_1**

- **Problem occurs if the voltage induced by common ground impedance is above the noise margin of a sensitive circuit connected to it.**

- **Single point ground solves this problem at low frequencies by controlling where ground current flows**

- **Multipoint ground solves this problem at high frequencies by reducing ground inductance**

Ground Loops

- Loop formed by signal conductors and ground

- Ground voltage (V_G) couples noise voltage (V_N) into connected circuits

- Magnetic fields will induce noise voltages into the loop

- Multiple return paths for signal current at low frequencies

- Typically problematic for physically separated equipment at low frequencies

- Example is the 60 Hz "hum" in audio systems

DISA
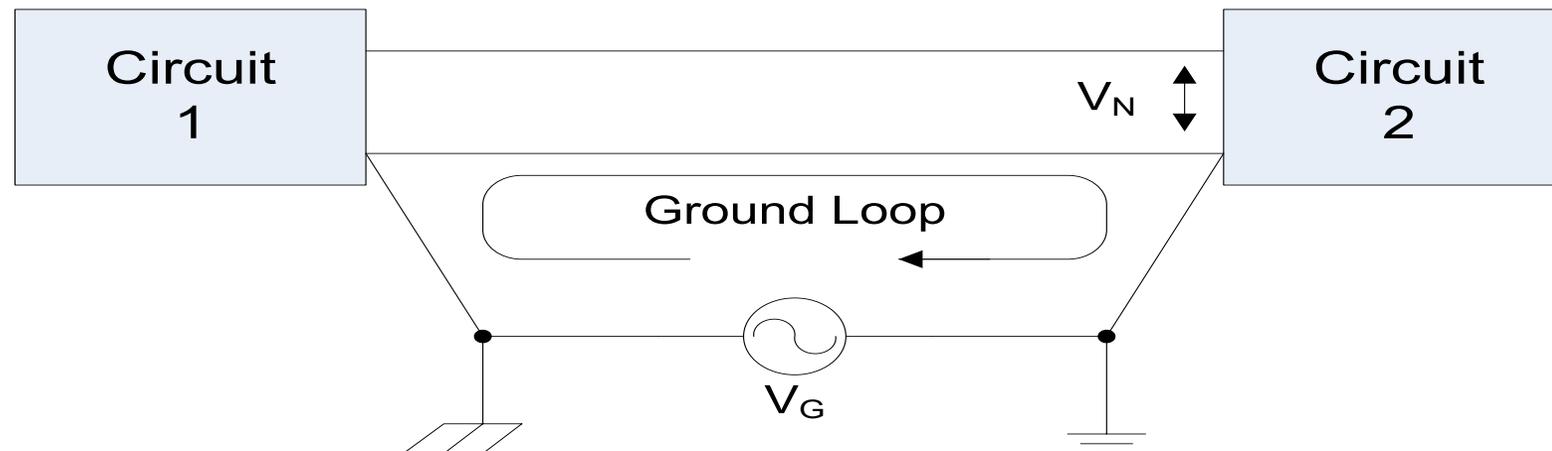
Options

- **Live with them by controlling ground impedance or by increasing circuit noise immunity levels**

- **Avoid them by using single point or hybrid ground schemes**
  - Effective for low frequencies
  - Not recommended for circuits > 100 kHz (may create new problems!)

- **Break the loop at the interface**
  - Transformers
 - Common-Mode Chokes
  - Optical Couplers/Isolators

Transformer

- **Noise voltage (V_N) now dropped across the primary and secondary windings and not into the circuit**

- **Further improvements by using a Faraday shield between the windings**

- **Some disadvantages**

  - Size

  - Limited frequency response

  - Cost

  - Each signal set requires its own transformer
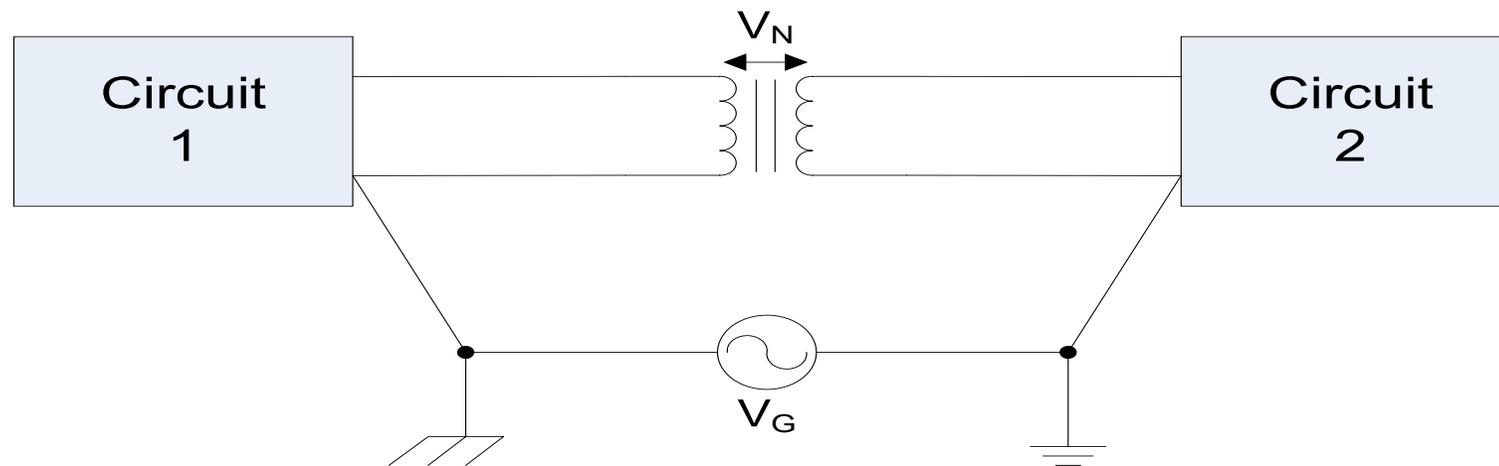
Common-Mode Choke

- **Noise voltage (V_N) now dropped across the primary and secondary windings and not into the circuit**
- **Allows DC and differential mode signals while rejecting common mode noise**
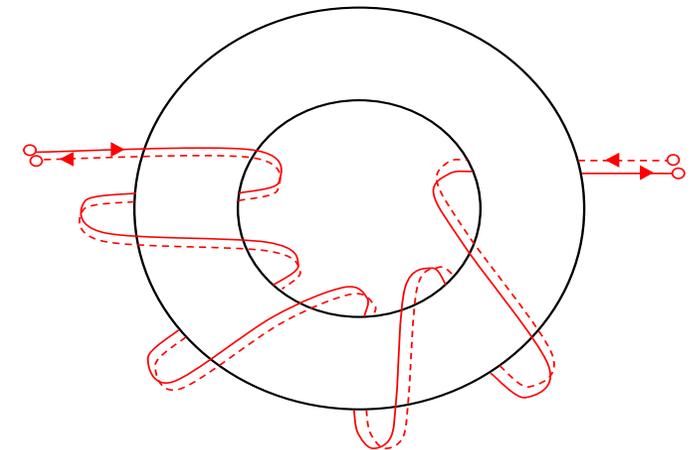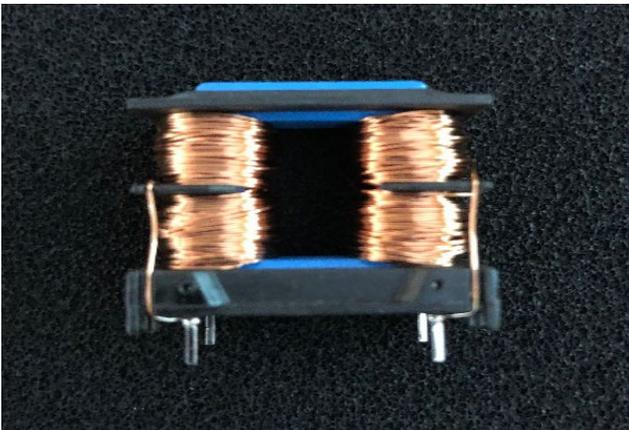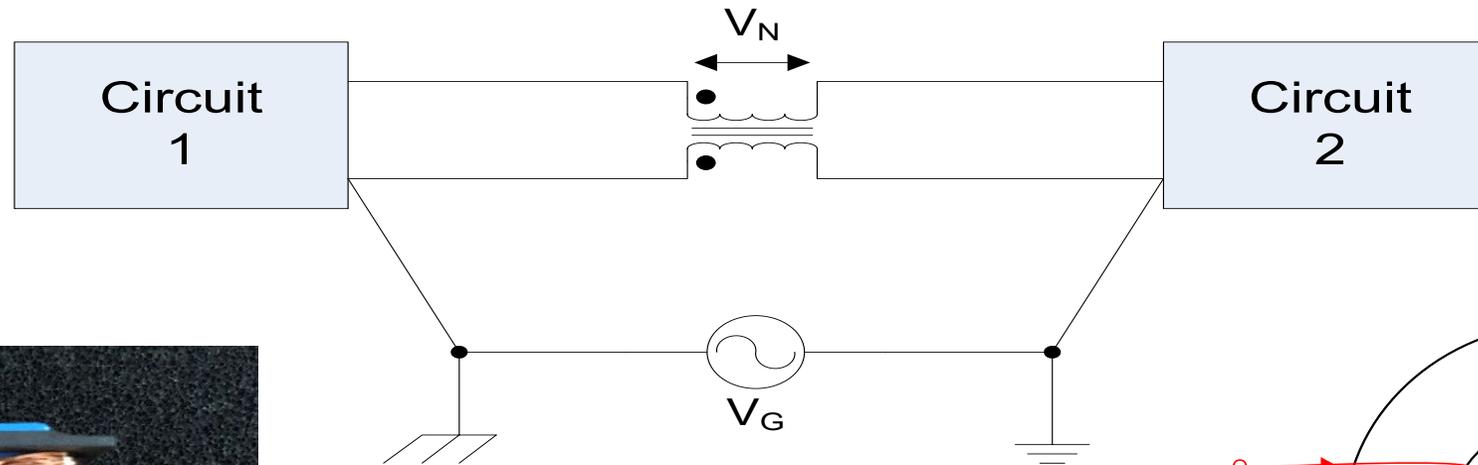
Optical Couplers

- **Noise voltage (V_N) now dropped across the optical coupler and not into the circuit**
- **Especially useful in digital circuits**
- **Not easily employed for analog circuits due to non-linearity through the coupler**

Balanced Circuitry
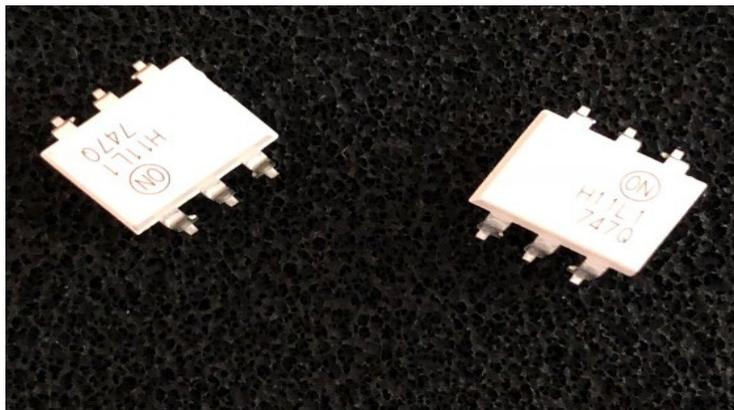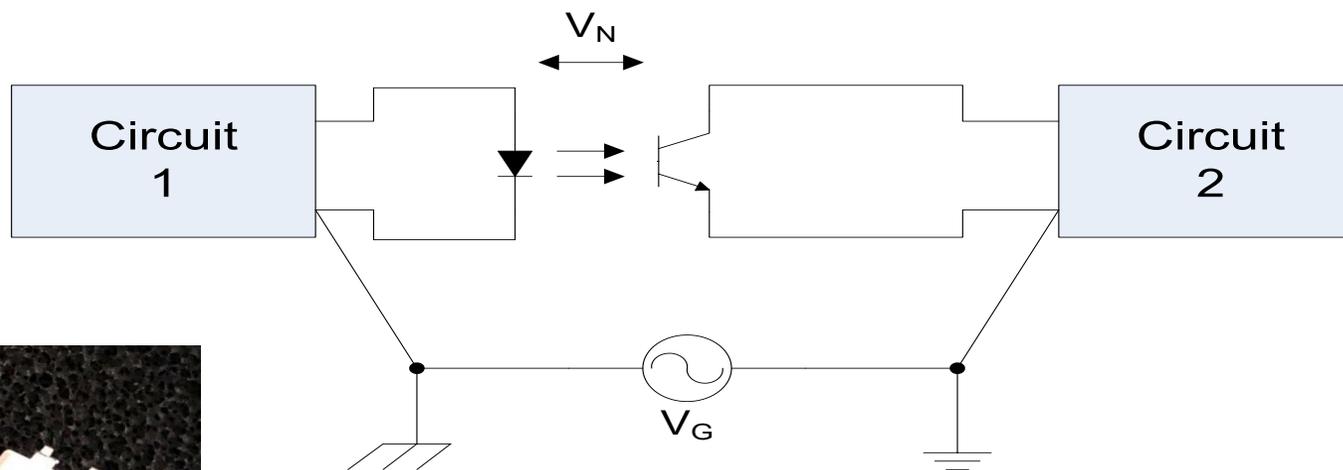
- **Two-conductor circuit in which the conductors and all interfacing circuits have the same non-zero impedance with respect to ground**

- **Noise coupling is equal and in phase for both conductors**

- **Common-mode noise is cancelled at the load**

- **Both interfacing conductors are closely spaced or twisted**

Common-Mode Rejection Ratio
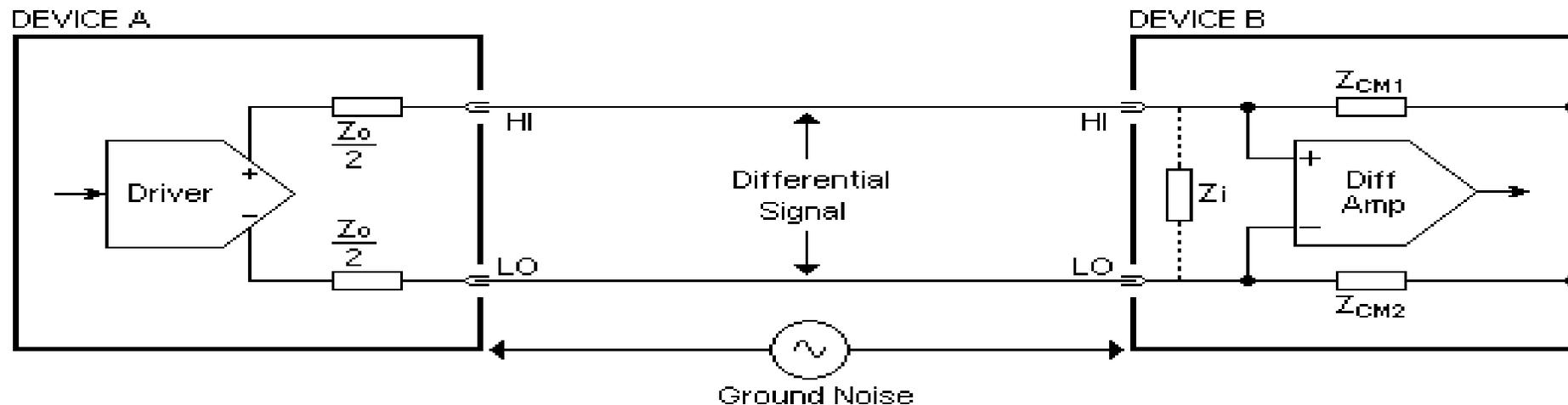
CMRR quantifies the effectiveness of a balanced circuit in rejecting common-mode voltages
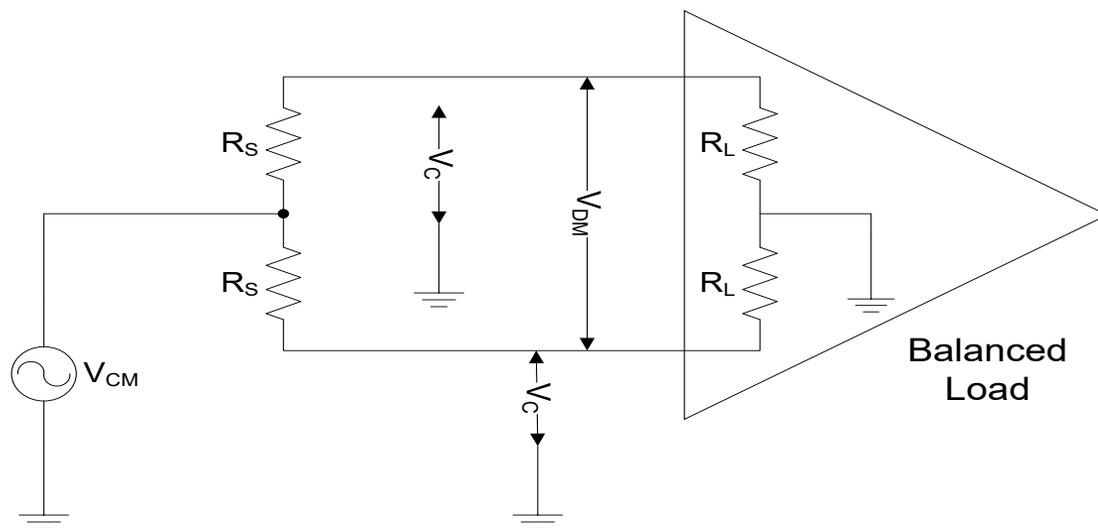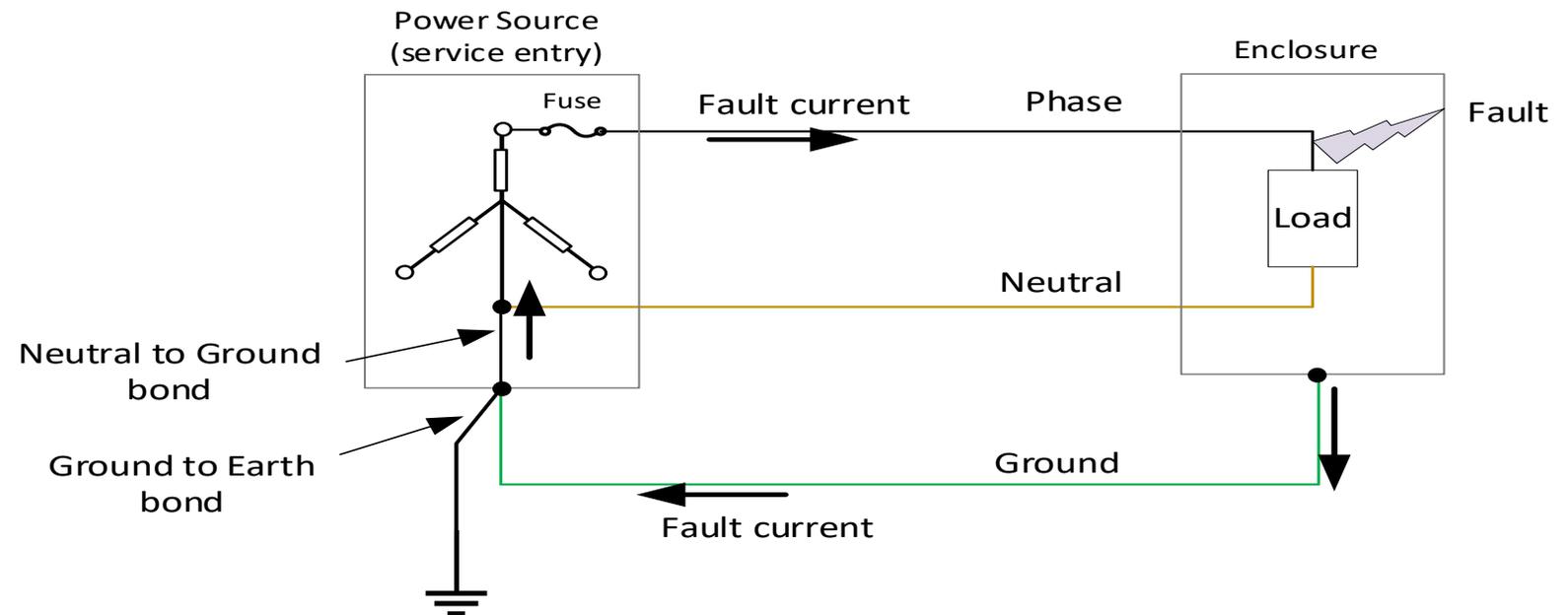

$$CMRR = 20Log\left(\frac{V_{CM}}{V_{DM}}\right)dB$$

- Ideally V_{DM} = 0 for a balanced system, but slight imbalances cause VDM ≠ 0
- Typical CMRR values for a well-designed circuit: 40 to 80 dB

Grounding Examples and Applications

- **Power System Grounding**

- **Building Lightning Protection**

- **Rack Grounding**

- **Tactical Vehicle Grounding**

- **Shipboard Grounding and Bonding**

- **Grounding Guidance for Spacecraft**

- **Case Study - Nuclear Power Plant Grounding**

Power System Grounding and Fault Protection

- **Neutral is typically "solidly" grounded at a single point.**

- **Grounding conductors (green-wire) ensure a low resistance path back to the source via the neutral.**

- **High current flows through the faulted conductor and activates circuit protection (fuse or breaker trip)**

Power Source (service entry)

Fuse

Fault current

Phase

Enclosure

Fault

Load

Neutral

Neutral to Ground bond

Ground to Earth bond

Ground

Fault current

Building Lightning Protection

- **Basic building lightning protection consists of a network of air terminals, down conductors and grounding rods.**

- **Designed to "attract" the lightning leader, capture the direct strike current and guide it to earth.**

- **Usually bonded to metallic building parts.**

- **Will prevent direct strike damage but may not prevent damage to power/electronics attached to building I/O lines.**

Rack Grounding Approaches
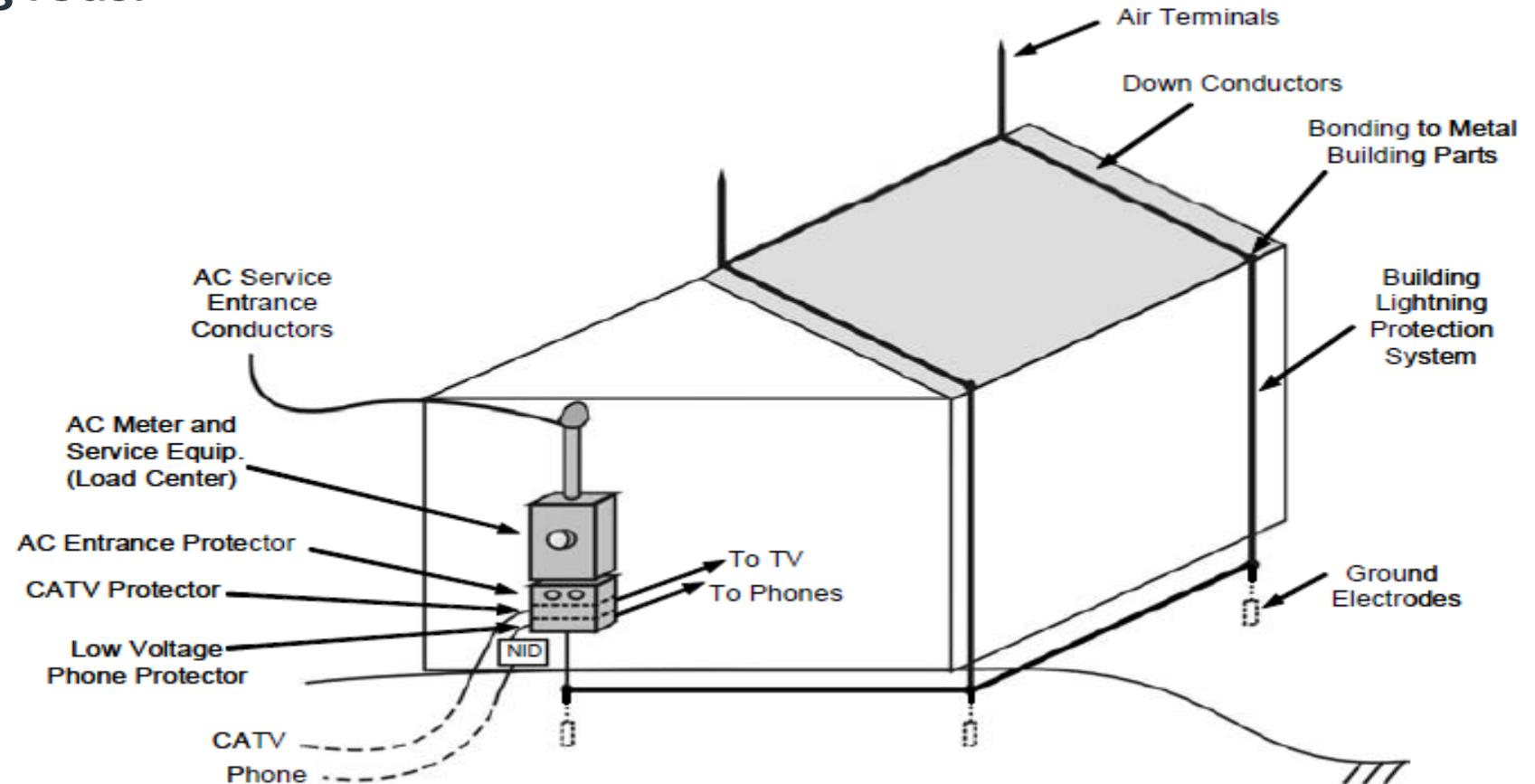
Equipment grounding within rack (isolated bus bar vs non-isolated)

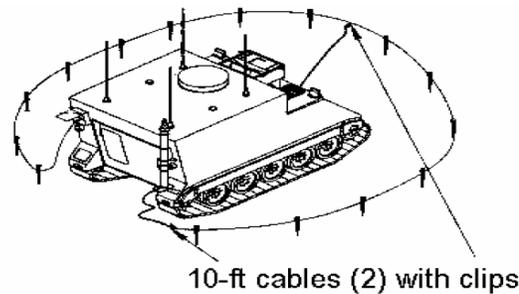Isolated Equipment Bonding

Non-Isolated Equipment Bonding
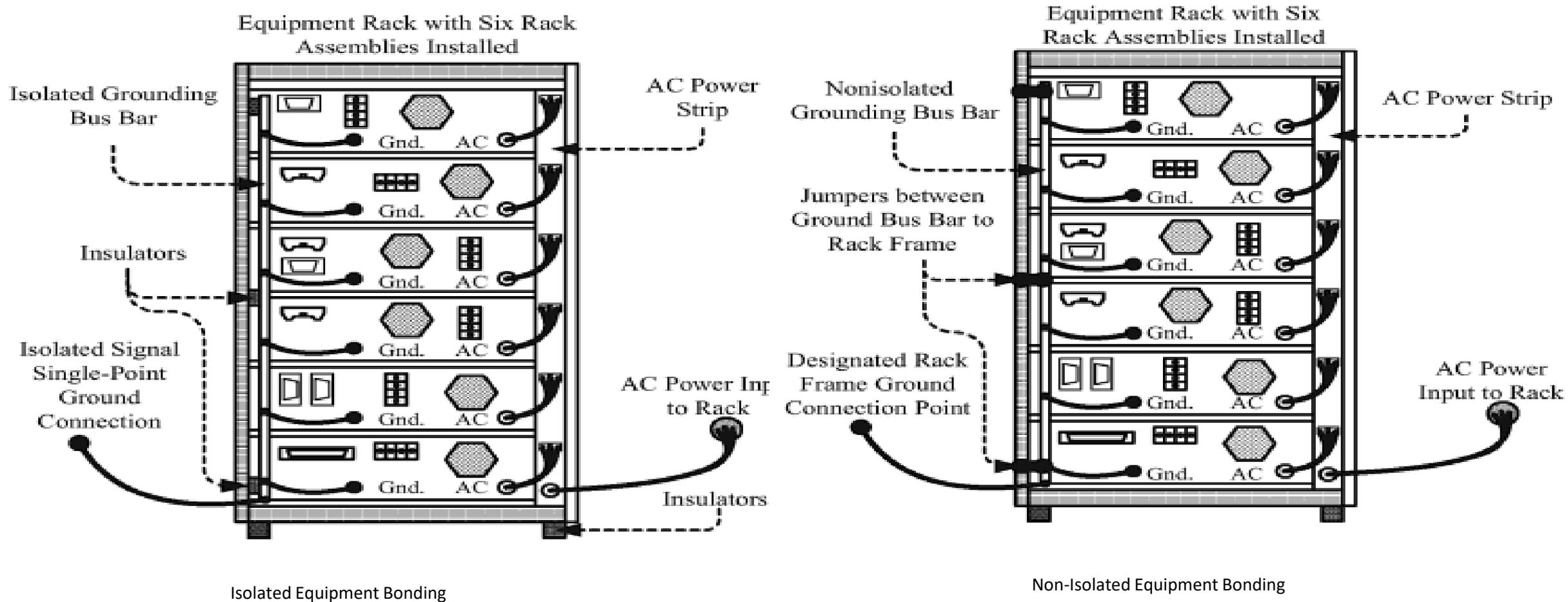
Grounding Guidance for Tactical Vehicles
(from Army TC 6-02.6 and CECOM TR-98-6)

- Focus is on fault protection and lightning protection for tactical comms systems

- Earth electrode "design" and installation (ground rod, ground plate, SWGS)

- Bond collocated equipment/shelters together

- Resistance to earth goal = 10 ohms. Not always achievable (terrain and soil conditions)
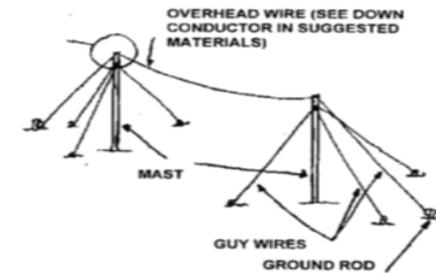
- External lightning protection structure
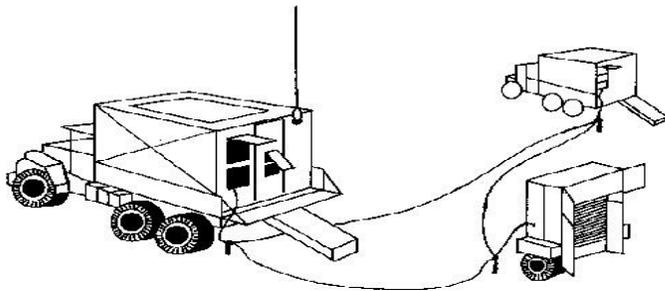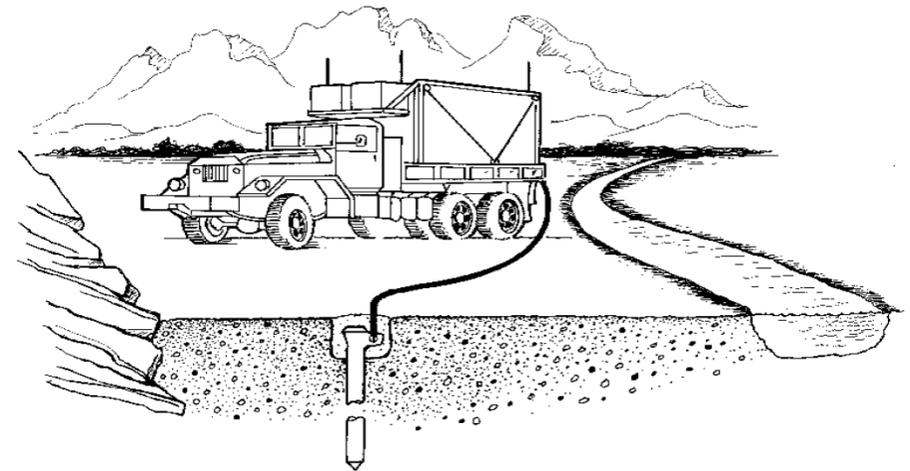

Colocated Equipment Bonding

Surface Wire Grounding System

10-ft cables (2) with clips

Overhead Wire (for lightning protection)

OVERHEAD WIRE (SEE DOWN CONDUCTOR IN SUGGESTED MATERIALS)

MAST

GUY WIRES

GROUND ROD

Grounding Guidance for Shipboard

From MIL-STD-1310H

- Metal hull is designated as "ground potential".
- All metallic items are bonded to ground.
- Bond Classes: A welded or brazed   B bolted   C ground strap or jumper
- Class A = Ship's ground plane. Includes metallic superstructure, equipment foundations and racks, and equipment mounting studs/brackets.
- Equipment cases, cabinets, racks, etc are generally Class B or Class C bonded.
- Shock-mounted equipment is generally Class C bonded.
- Equipment/hardware that is Class B or C bonded to the ship's ground plane is designated as grounded but cannot be used as a means of grounding other items.
- Equipment mounted within racks are grounded by a conductor within the cable harness.
- Cables penetrating through hull must be shielded, with shields peripherally terminated at entry point.
- (Safety) All non-current-carrying metallic parts of equipment are grounded by direct attachment to ship structure, ground strap, or by receptacle grounding terminal.
- (Safety) Resistance of 0.1 ohms or less between the equipment enclosure and an adjacent ground point.

Grounding Guidance for Spacecraft
From NASA-HDBK-4001

- **Objective is EMI control (not electrical safety)**

- **Focus is on maintaining DC isolation between equipment**
  - Single voltages to user loads (users derive secondary voltages)
  - Users isolate primary power return from chassis

- **Recommended system grounding approach is multiple single-reference ground system**
  - Circuit common and chassis each grounded locally at the equipment level
  - Power interfaces isolated via transformer
  - Signal interfaces isolated via transformer or balanced differential or other method
  - Exceptions for RF interfaces
  - Exceptions for cable overshields (must be grounded at both ends)
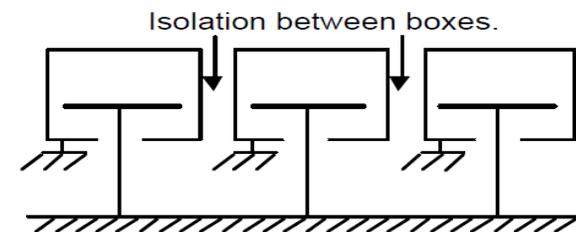
FIGURE 6. Multiple, Single Reference Ground System
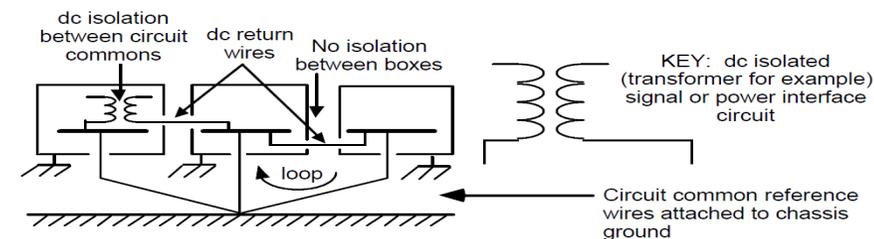
FIGURE 3. DC Isolated Ground and Not Isolated Ground

Ground a cable shield at one end or both?

- **If radiated emissions and immunity is a concern, and the interface is high-frequency (i.e. > 100 kHz), then ground the shield to chassis at <u>both ends</u>.**

- **If the circuit being shielded is sensitive to low frequency noise (such as 60 Hz), and the external RF EME is low (not likely), and there is no concern for RE102 (also not likely), then ground the shield at one end only.**
  - Ground the end corresponding to how the circuit is grounded (ie. If the source side of the circuit is grounded, then ground the shield at the source end also).

- **But what if the circuit being shielded is very sensitive to audio frequency noise, and we have RF requirements such as RE102 and RS103? Or the circuit has both audio and RF components (e.g. a video signal)?**
  - Possible options include:
    - hybrid grounding technique (ground one side via shunt cap),
    - triaxial cable or equivalent (inner shield terminated one end, outer shield grounded both ends), or
    - circuit isolation technique (e.g transformer or opto-isolator) described elsewhere

"Ground Bounce" Effect in Integrated Circuits

- Current from high-speed IC gates simultaneously switching from high to low induces a voltage spike across package and trace ground inductances

- The resultant spike shows up on a chip-to-board I/O line, which may produce an unwanted response if the spike amplitude is above the circuit threshold

Case Study: Nuclear Power Plant Grounding
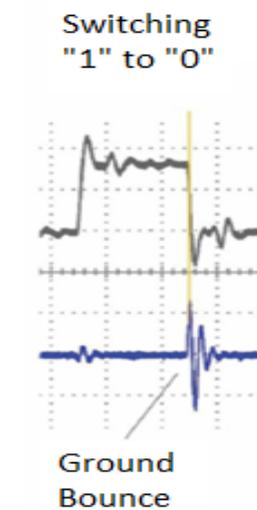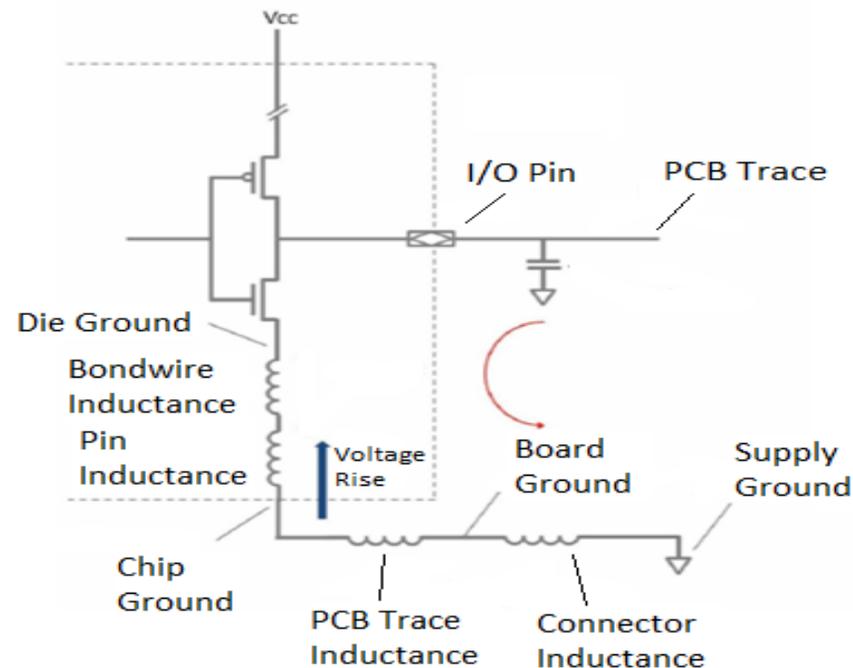
Case Study: Nuclear Power Plant Grounding (2)
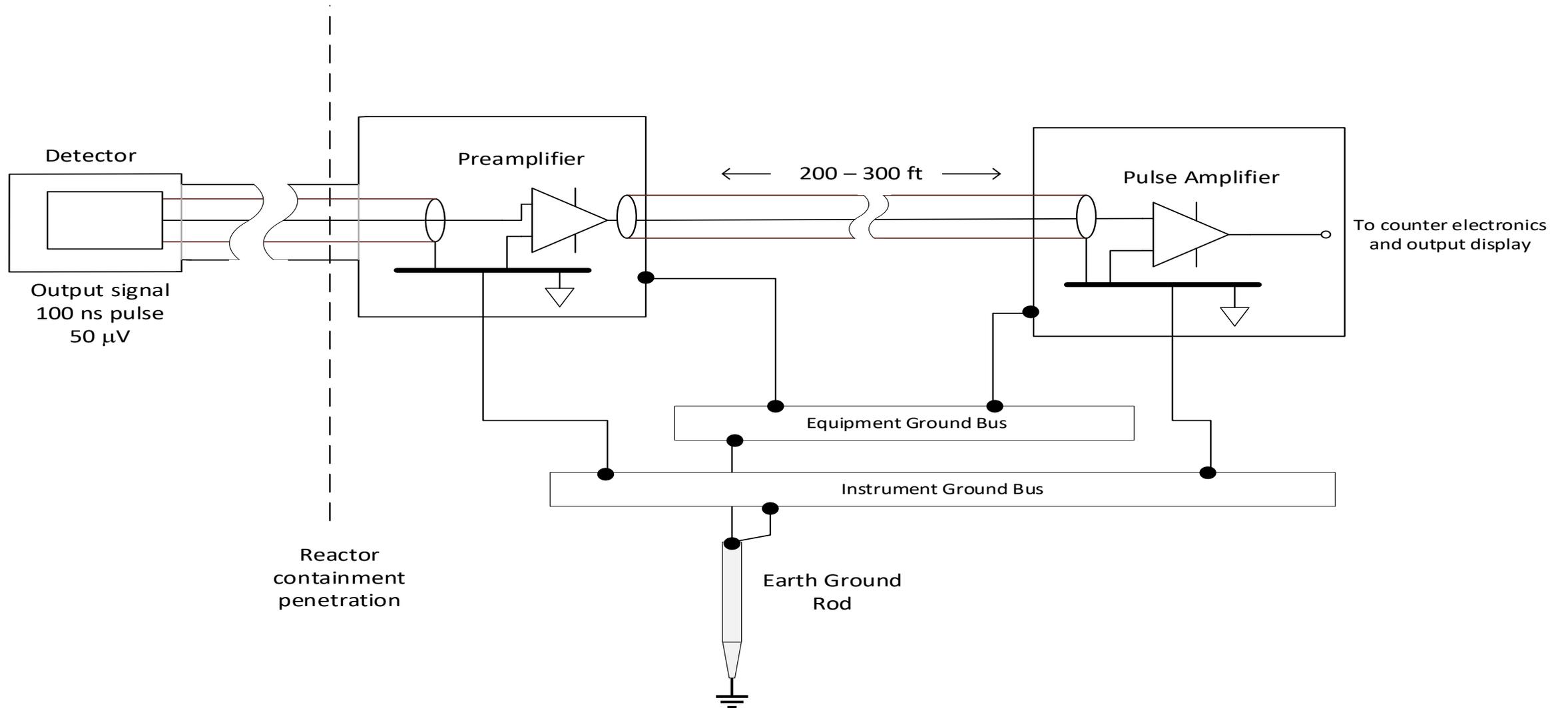
- Grounding implementation in several pre-operational nuclear power plants
- Neutron detection subsystem
- Components distributed over several hundred feet
- Separate "instrument ground bus (IGB)" and "equipment ground bus (EGB)".
- EGB was connected to each equipment chassis.
- IGB was connected to each equipment signal ground.
- Regulatory guides dictated a "hard' SPG for the IGB, with no connections to chassis anywhere, except at the earth ground connection
- Baseline system as installed was not usable due to excessive neutron counts well above system sensitivity.
- Solution #1: Implement triaxial cable between console and preamp. Outer shield connected to each chassis at both ends.
- Solution #2: Implement common-mode filter (choke) on signal cabling.

Grounding Summary

- **For best results, grounding design should be based on a systems approach.**
- **Beware of blindly applying grounding "rules". Each case is different.**
- **All conductors have finite impedance comprised of resistance and inductance**
- **Inductive impedance dominates at higher frequencies**
- **Any ground conductor longer than 1/20λ is not low impedance**
- **Various types of grounding topologies are available:**
  - Single point series and parallel
  - Multipoint
  - Hybrid
- **Best grounding solution for multiple interconnected pieces of RF/digital equipment is usually a multipoint approach with very low ground impedance (ground plane or grid)**
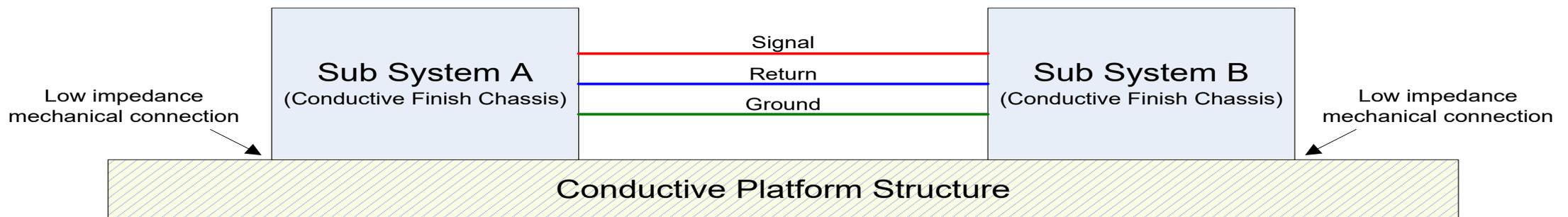
Grounding Summary (cont)

- **The selected grounding scheme must consider the frequency of the and sensitivity of the circuits as well as the physical characteristics of the grounding conductors.**
- **Rules of Thumb:**
  - Single point grounds should only be used for frequencies less than 100 kHz
  - Multipoint grounds should be used for operating frequencies greater than 100 kHz (most digital and RF circuits)
- **Ground noise is minimized by:**
  - Controlling the ground topology for low frequencies
  - Controlling the ground impedance at high frequencies
- **Ground loops can be broken by:**
  - Isolation transformers
  - Common-mode chokes
  - Optical couplers
- **Balanced circuits can be used to minimize or eliminate common-mode noise problems**

Bonding

A Ground and a Bond Are Different

Although often used interchangeably, the two terms have very different meanings to an EMI/EMC Engineer:

EMI/EMC Definitions	
Grounding	**Bonding**
Grounding is the establishment of an equipotential point or plane which serves as a reference voltage for a circuit or system. Grounding is most often associated with circuit references, and the control of those references is critical to achieving EMC.	Bonding is the establishment of a low impedance path between two metal surfaces. Bonding is focused on achieving a mechanically strong, low impedance interconnection between metal structures and to minimize differences in potential between points. IEEE definition: The electrical interconnecting of conductive parts, designed to maintain a common electrical potential.

Low impedance mechanical connection

Sub System A
(Conductive Finish Chassis)

Signal
Return
Ground

Sub System B
(Conductive Finish Chassis)

Low impedance mechanical connection

Conductive Platform Structure

Reasons for Bonding

- **Electrical power and signal current return paths**
  - When metallic structure is used for returns

- **Attaining adequate antenna patterns and gain**
  - When needed for antenna performance

- **Shock Hazards**

- **Preventing ignition of flammable vapors**

- **Lightning protection**

- **Preventing coupling of EMI**

- **Preventing static buildup**

Bonds are categorized by class per MIL-B-5087B: A, C, H, L, R and S

Antenna Installations

- Antenna structures relying on a counterpoise require an RF bond to structure such that RF currents flowing on the skin have a low impedance path to and through the counterpoise.

- Many antennas will only function properly with an adequate counterpoise.

- From MIL-STD-464: "Antennas shall be bonded to obtain required antenna patterns and meet the performance requirements for the antenna. Compliance shall be verified by test, analysis, inspections, or a combination thereof."

- No bonding resistance is specified.

Transmitting antenna with counterpoise
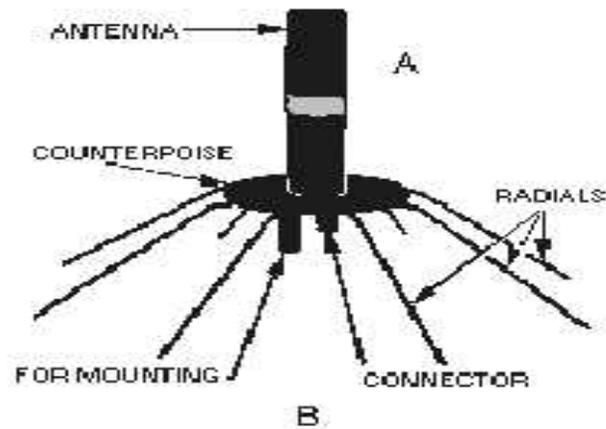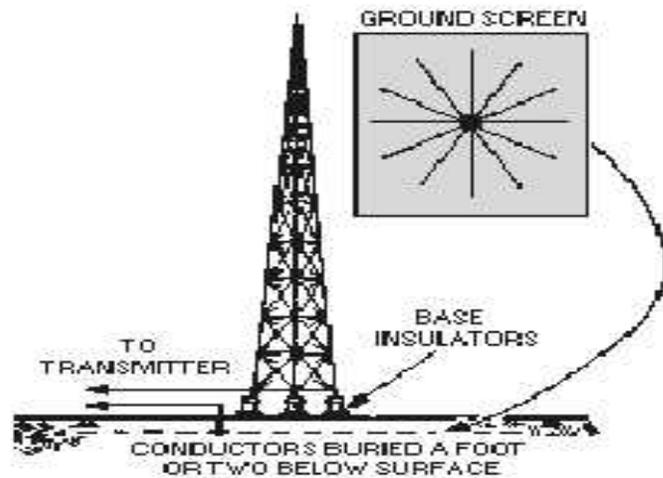
Typically needed for antennas operating at LF, VLF

Current Return Path

- **When platforms use structure for power return currents, bonding provisions must be provided such that the total voltage drop between the point of regulation for the power system and the electrical loads are within the tolerances of the applicable power quality standard.**

- **Returning power current on existing metal structure saves 75% of power bus wiring mass compared to wire returns.**

- **Impedance limited by the maximum allowable voltage drop.**

- **Not for ships.**

- **Power quality standards: MIL-STD-704, MIL-STD-1399 or MIL-STD-1275 for ground vehicles.**

Shock Hazard

- To prevent shock hazards to personnel, all exposed conductive items subject to fault condition charging shall be bonded as necessary to limit potentials to less than 30 VDC or 10 VAC between the item and ground.

- All exposed conductive items which could become charged due to an electrical fault condition must be bonded to the ground subsystem. (necessary to clear faults).

- DC resistance less than 100 mΩ (per MIL-STD-1310 and other standards).

Lightning Protection

- **For aircraft, provide bonding at all points of lightning entry, including, but not limited to: antennas, navigation lights, refueling booms, fuel system components and control surfaces.**

- **Bonds must withstand thermal effects and magnetic forces associated with direct strike current.**

- **DC resistance not specified in MIL-B-5087, but 2.5 mΩ is typically applied for aircraft**

- **For space systems, provide low-impedance path between attach and exit points. Bonded joints must be low-inductance, withstand thermal and magnetic effects, and not exceed 500 volts.**

- **For ground-based systems, minimum provisions include: a grounding conductor and earth ground rod (or equivalent). Additional options include air terminal, overhead wire, and/or protective mast.**

Class R and Class S Bonds

- **Class R - RF Potentials**
  - Electrical and electronic equipment which produces RF energy must have a continuous low impedance path between the equipment enclosure and structure.
  - DC resistance less than 2.5 mΩ
  - MIL-STD-1310G: recommends less than 25 ohms at 30 MHz for all electrical equipment to structure

- **Class S – Static Charge**
  - Isolated conducting items subject to triboelectric or deposited charging (i.e. P-static) must be bonded to the ground subsystem in order to avoid a differential build-up of charge that would result in an electrostatic discharge.
  - Bond resistance much be such that charging current multiplied by bond resistance < breakdown potential.
  - Typical range of Class S bond resistance = 10 kΩ – 1 MΩ

Direct Bonding Methods

Welding	A bond using weld alloy or parent metal filler that closely matches the basic enclosure material.
Brazing	Similar to welding. Not recommended for magnetic shielding
Soldering	Excellent conductivity across mechanically rigid joints and seams. Not reliable for structural purposes.
Bolts	Provides flexibility and accessibility. The bolts should not be relied on to carry current, but rather to provide adequate force between the two surfaces.
Rivets	Ease of installation Limited clamping force (depending on method used) Limited corrosion protection
Conductive Adhesive	Should be used in conjunction with other fasteners. Limited load-handling capability.

When direct bonding is not an option

- **Use a bonding strap, wire, or jumper.**

- **The conductor must:**
  - Have low impedance to fault current (Class H)
  - Have low impedance to high-frequency currents (Class R)
  - Be electrically small (length not to exceed 1/20 of a wavelength at the highest frequency of interest)

- **High-frequency impedance can be calculated from the bond strap self-inductance:**

$$Z = 2\pi f L$$

Z = impedance, ohms
f = frequency, MHz
L = inductance in μH

Bond Wires vs Bond Straps

Inductance Calculations

$$L = 0.002l \left(ln\frac{4l}{d} - 1 \right)$$
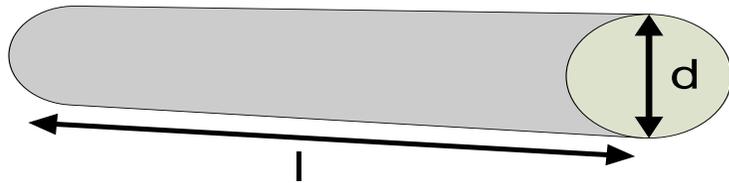
$$L = 0.002l \left[ln\frac{2l}{T + W} + 0.5 + 0.2235 \left(\frac{W + T}{l} \right) \right]$$

$l =$ Length (cm)

$d =$ Diameter (cm)
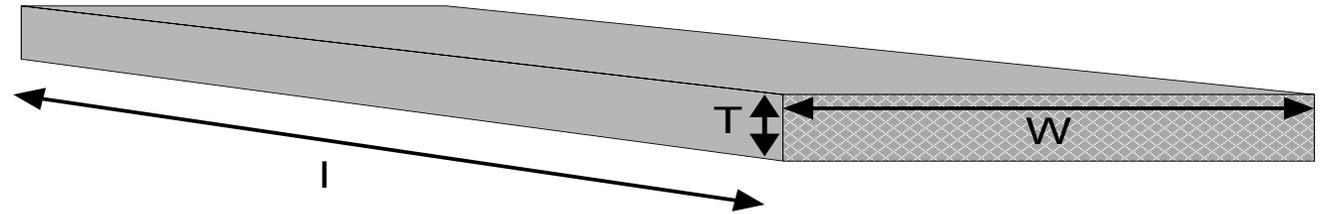
$T =$ Thickness (cm)

$W =$ Width (cm)

Applicable to "isolated" conductors – not close to ground plane or structure

Bond Wires vs Bond Straps

Impact of Cross Section and Length

How A Bond Corrodes
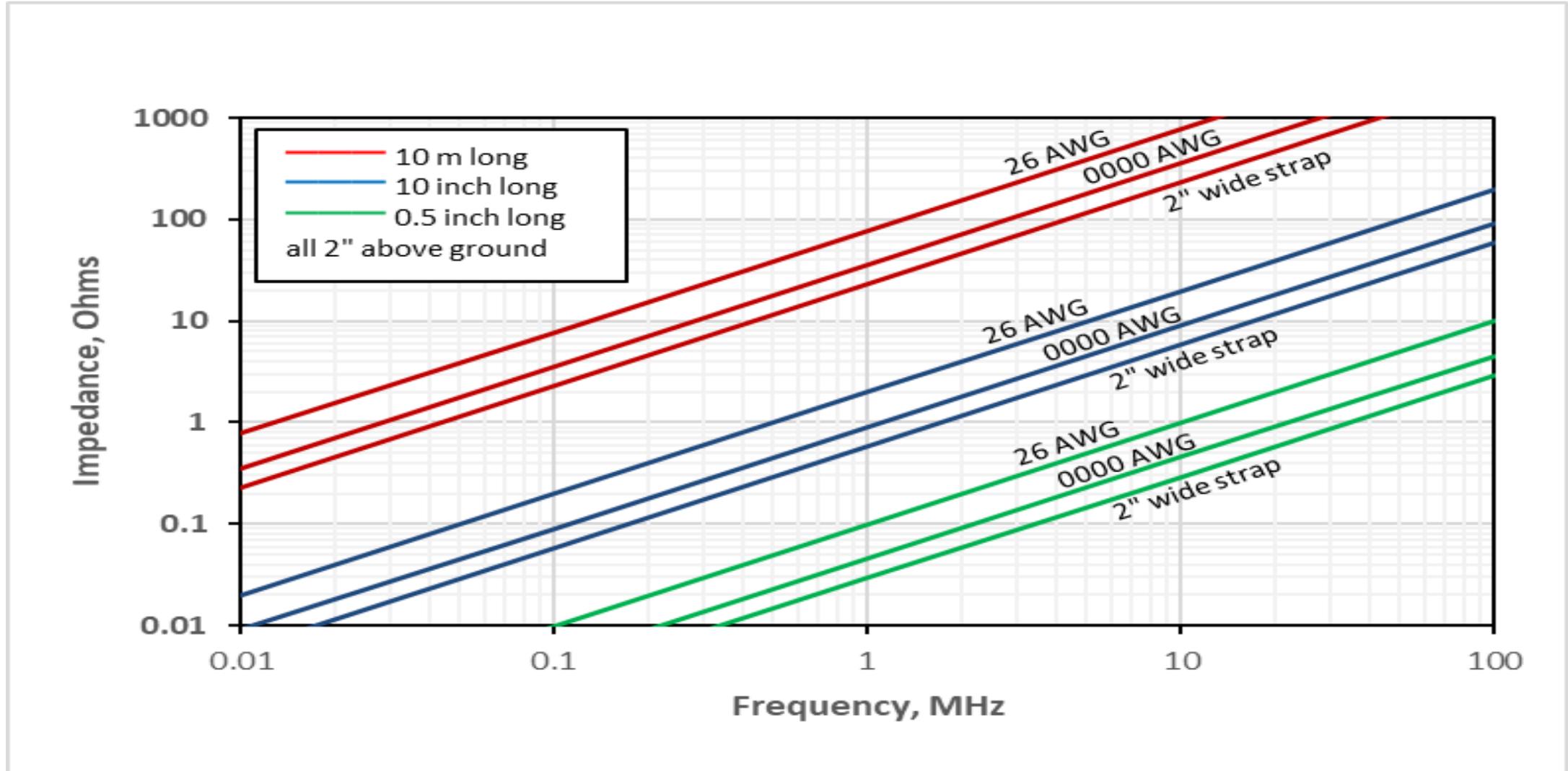
- **Electrochemical cell is formed**

- **Anode with a positive potential**

- **Cathode with a negative potential**

- **Complete path for current flow**

- **Electrolyte or conducting fluid**

- **The electrochemical series is a set of potentials determined under a standard set of conditions**

Electrolytic Environment

Current Flow

Anode　　　　　**Cathode**
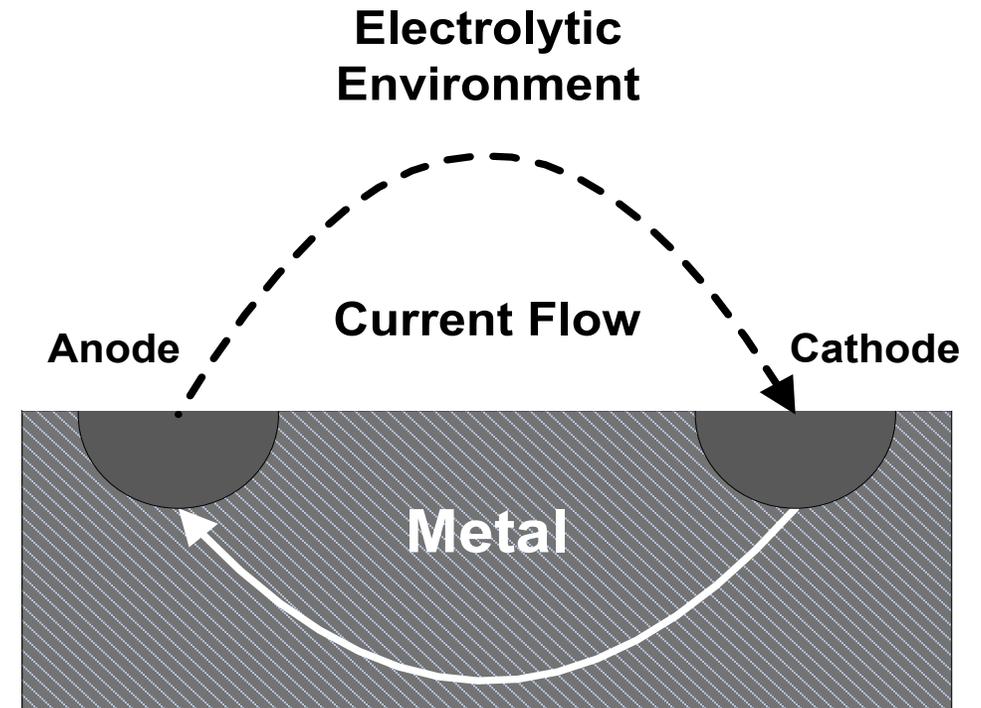
Metal

Increased Potential Difference = Increased Corrosion

Corrosion Considerations

- **Bonds are typically created between dissimilar metals.**

- **For example, copper wires bonded via steel bolts, washers and nuts to an aluminum chassis**

- **Most bonds live in an atmosphere with some degree of humidity**

- **When selecting dissimilar metals to be in contact, it's important to consider which components are replaceable in the event of corrosion**

- **Replaceable components - grounding jumpers, washers, bolts and clamps**

- **Non replaceable - structural members and equipment enclosures**

- **Bond materials should be selected such that they are as close as possible in the galvanic chart to minimize the corrosive process**

Electro-Chemical Series

Metal	Electrode Potential V	
Magnesium	-2.375	Anodic
Beryllium	-1.700	
Aluminum	-1.670	
Zinc	-0.7628	
Chromium	-0.740	
Iron	-0.441	
Cadmium	-0.402	
Nickel	-0.230	
Tin	-0.1406	
Lead	-0.1263	
Copper	+0.346	
Silver	+0.7996	
Platinum	+1.200	
Gold	+1.420	Cathodic

SAE ARP1481

(Corrosion Control and Electrical Conductivity)

A	Compatible
B	Requires Sealing Only if Exposed to Salt Atmosphere or High Humidity. Edge Priming may be satisfactory
C	Requires Sealing if Exposed to Humid Environment
D	Compatible in Environment of Controlled Temperature and Humidity Only
E	Requires Sealing Regardless of Exposure
F	Because of the Inherent Corrodibility of the Material, the Couple Should Not be Used at All
X	Not Usable

Material/Finish Pros/Cons

Material/ Finish	Pros/Cons
Tin	Low contact resistance Malleable, low contact pressure required Compatible with most other materials Tin whisker growth possible
Nickel	Harder than tin Stable in most environments Low contact resistance achievable with adequate pressure
Stainless Steel	No plating or finishing needed Stable in most environments Inherently less conductive than other base metals/finishes

Material/Finish Pros/Cons
(continued)

Material/Finish	Pros/Cons
Aluminum, Chromate Conversion Coating	Untreated aluminum will quickly form a thin non-conductive oxide layer. Typically protected using chromate conversion coating, which is itself non-conductive (very thin film). Relatively high contact pressure (~200 psi) required to "break through" the coating to achieve electrical conductivity. MIL-DTL-5541F Class 3 is typically specified for best electrical performance
Aluminum, Anodized	Thick nonconductive oxide layer. Not acceptable for electrical bonding. Bonding surfaces must be masked and suitably treated.

MIL-STD-464 Bonding Requirements

For instances where specific controls have not been established ..., the following direct current (DC) bonding levels shall apply throughout the life of the system:

- **10 milliohms or less from the equipment enclosure to system structure, including the cumulative effect of all faying surface interfaces.**

- **15 milliohms or less from cable shields to the equipment enclosure, including the cumulative effect of all connector and accessory interfaces.**

- **2.5 milliohms or less across individual faying interfaces within the equipment, such as between subassemblies or sections.**

Why is connector bonding so important?

- **Connectors are the key link in the cable shielding "chain".**

- **A good connector to chassis bond ensures:**
  - EM environment outside the box stays outside
  - EM environment inside the box stays inside
  - Minimum radiation from the cable
  - Minimum pickup of EME to internal circuitry

- **Connector to backshell bond is equally important**

- **Ensures shielding quality of the cable is not compromised**

Typical flange mount connector with areas identified to be cleaned to ensure a low impedance bond between the connector and the chassis

CLEAN AREA TO BASE METAL 0.25"
LARGER THEN CONNECTOR UNLESS
MOUNTING MATERIAL IS FINISHED.

REFINISH AFTER INSTALLATION
1.25 DIAMETER OF CLEANING AREA

CONNECTOR

MOUNTING SURFACE

LOCK NUT

Bonding Example – Cable Shield to Backshell
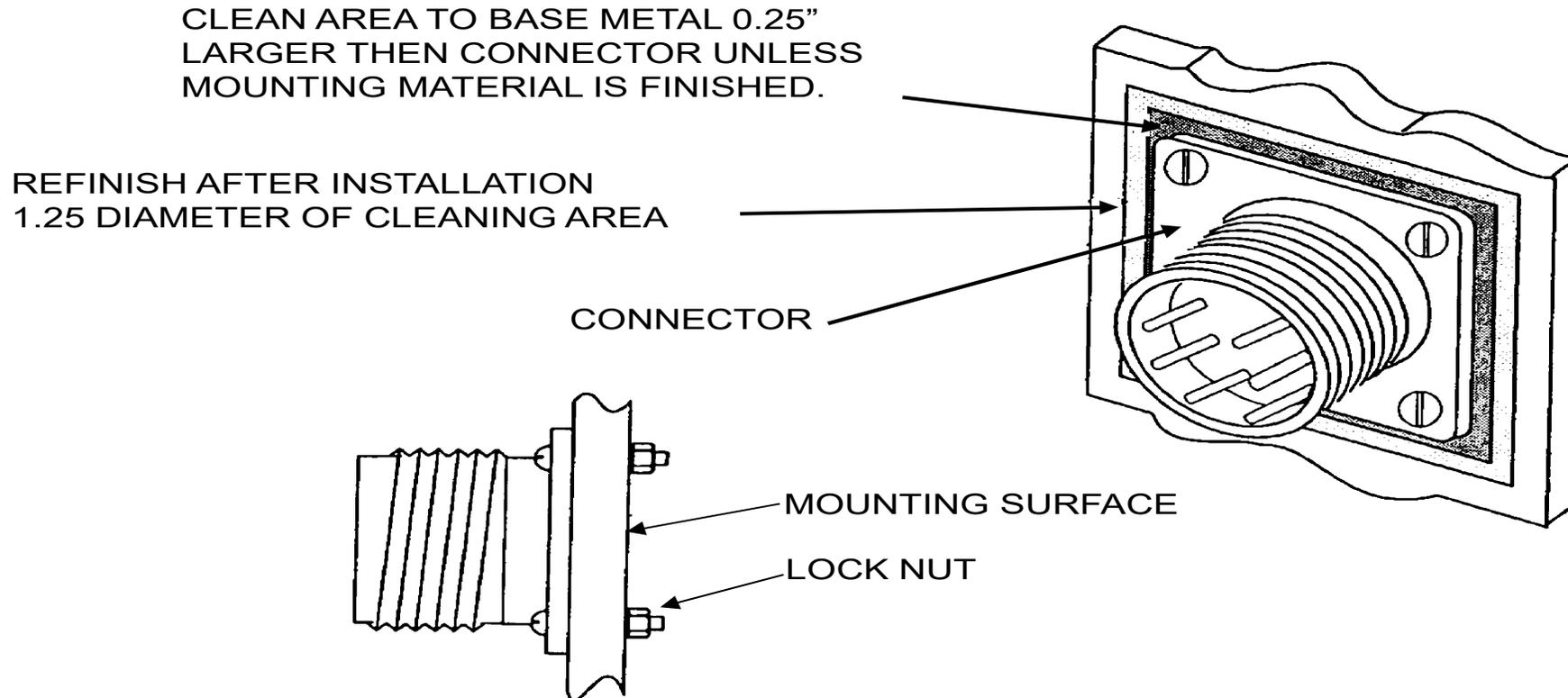
- **Typical method for bonding a cable shield to a connector backshell.**

- **The shield is terminated in a 360 degree fashion using an internal compression ring as the connector backshell is tightened to provide a low impedance bond.**

SHIELD

CONNECTOR

CABLE

IRIS COMPRESSION RING

MIL-STD-1310 Bonding Examples
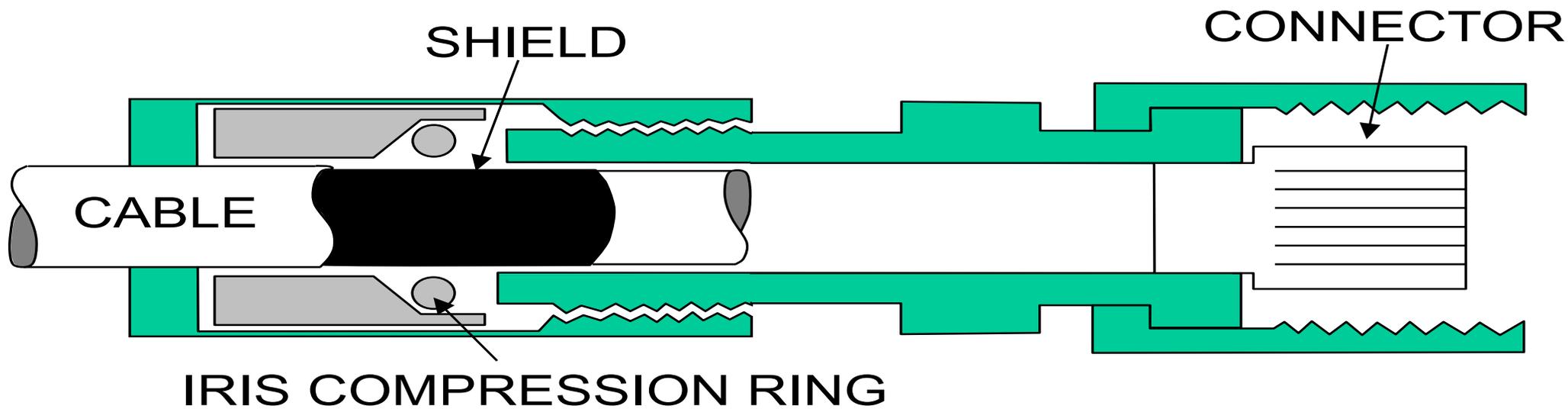
Shielded cables shall be 360-degree bonded at the point of entry into the hull, superstructure, deck, bulkhead, shielded compartment, or wireway trunk.

Bonding Examples

## Typical equipment chassis using a front attachment screw to compress the chassis to the shock mount and bond the two together

Electronic Equipment Box

NOTE 1

Shock Mount

NOTE 2
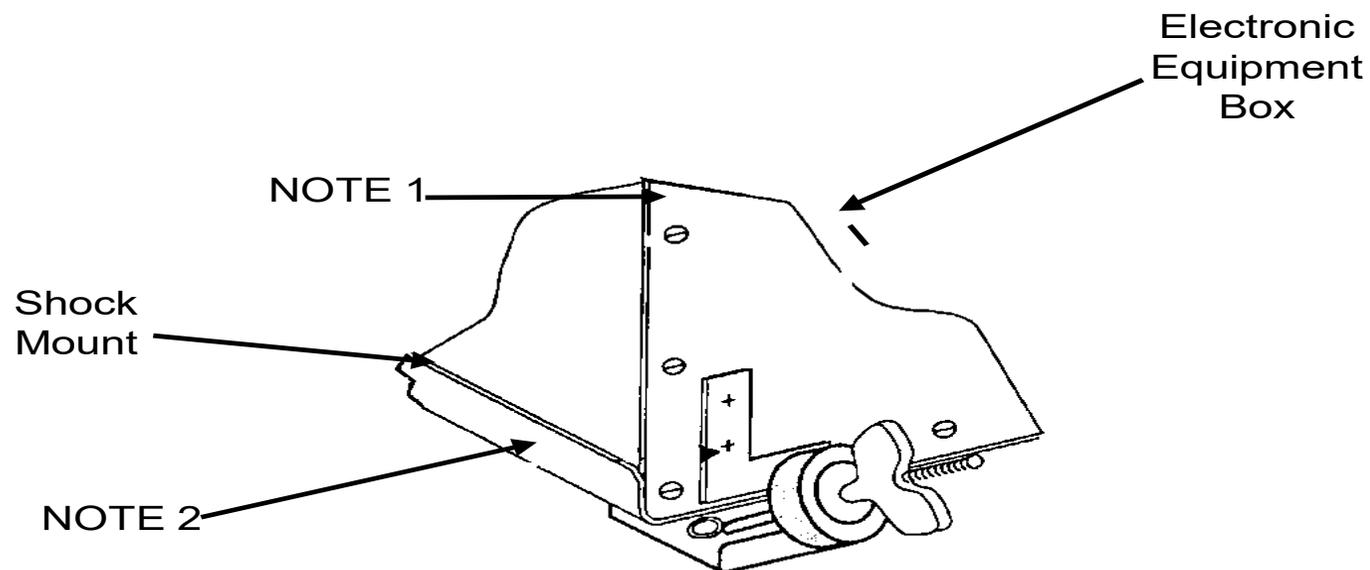
NOTES:

1. The front face of the unit (and back if separate) shall bon to the case.

2. If equipment case does not bond to the shock mount, bond the fitting to the front face of the electronic equipment box.

Bonding Examples (cont)

Side and top views of typical bonding strap across a shock mount installation with the bonding strap in a "U" shape and secured between the mounting structure and mounting base using screws and lock washers

MOUNTING BASE

LOCK WASHER

BONDING STRAP
GOES UNDER
SHOCK MOUNT PAD

MOUNTING STRUCTURE
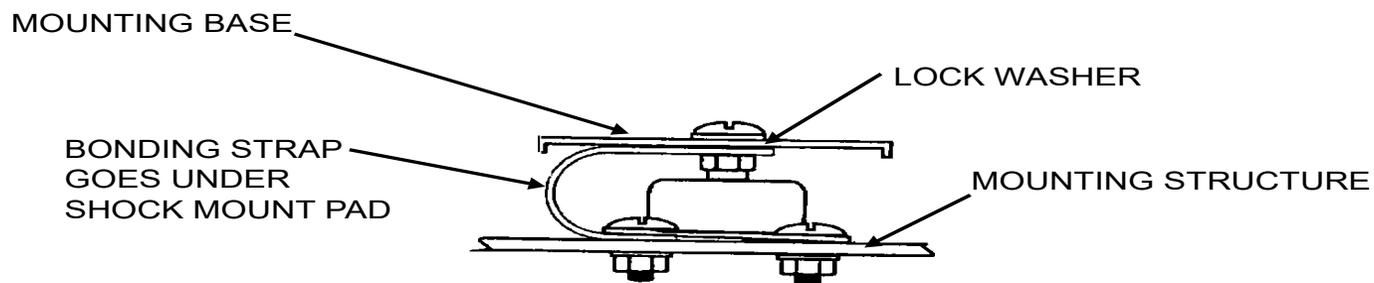
CLEAN TO PARENT METAL MOUNTING BASE 1.5" WIDTH
OF BONDING STRAP AND BONDING STRAP IN CONTACT
WITH MOUNTING BASE.
REFINISH AFTER INSTALLATION 1.5" AREA CLEANED.

CLEAN MOUNTING STRUCTURE TO BASE METAL
1.5 WIDTH OF BONDING STRAP, CLEAN BONDING
STRAP IN CONTACT WITH MOUNTING STRUCTURE.
REFINISH AREA AFTER INSTALLATION 1.5 AREA CLEANED.
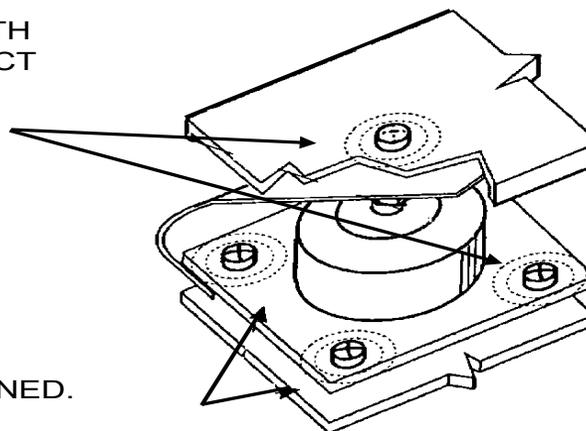
- **Bonds are used to create a low impedance connection between metal parts.**

- **Bonds should provide a low impedance connection under adverse mechanical strain and environmental conditions, for the life of the equipment.**

- **Wires and straps can be used for bonding, depending on the bond class. Typical wire impedances generally make them unusable for Class R.**

- **When metals are finished for corrosion protection, the finish itself must be conductive (or allow for metal-to-metal contact).**

Bonding Summary (cont)

- **The bond must be mechanically secure. Welds, brazes, or bolts are best.**

- **Solder, paint, and adhesives should be used to bond only if the bond is mechanically secure.**

- **Gaskets can be used as a bond if they are properly designed (more info in Shielding section).**

- **Dissimilar metal bonding must be designed to discourage corrosion. This is done by plating the base metal or sealing out moisture.**

- **A good bond will generally have a resistance of a few milliohms.**

Additional Training Available At:

https://www.dau.edu/cop/e3/Pages/Topics/E3 - SS Awareness Training and E3 - Spectrum Conferences.aspx
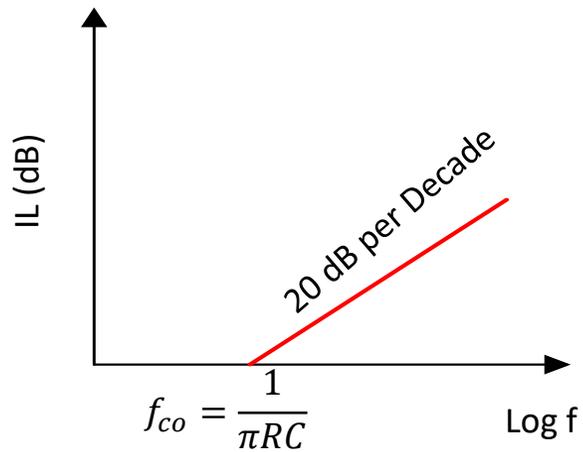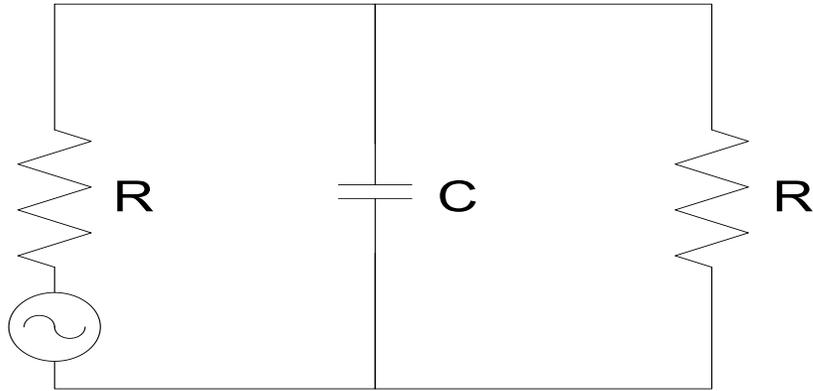
Questions

DISA: TRUSTED TO CONNECT, PROTECT AND SERVE!

Filters

DISA: TRUSTED TO CONNECT, PROTECT AND SERVE!
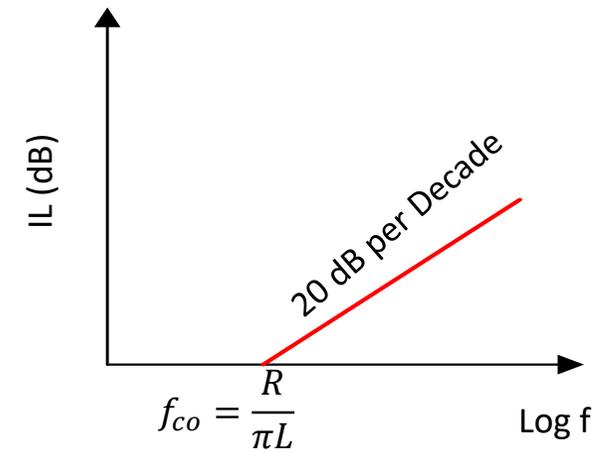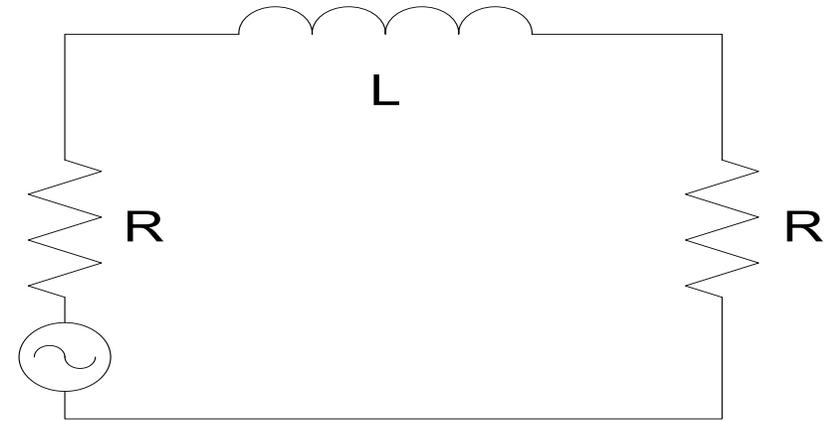
Filters

- **Filter Types**
  - Absorptive or Reflective
  - Common-Mode or Differential Mode
  - Lowpass, Highpass, Bandpass
  - Single element or multi-element
- **EMI control usually requires the use of low-pass filters**
- **The basic characteristic used to describe filter performance is insertion loss.**
  - Defined as the ratio of voltages appearing across the system terminals immediately beyond the point of insertion of a filter, before and after insertion.
  - Insertion loss depends on impedances at either end (often unknown).
  - Off-the-shelf filters are typically characterized with 50 ohm source and load impedance – actual performance may be very different.
- **Filter effectiveness is optimized when impedances are mismatched (i.e. low source impedance should look into high filter impedance).**

Single Element vs. Multi-element

- **Advantage of single element filter: just one component**

- **Advantage of multi-element filter:**

  - Provides more attenuation than single element

  - Provides sharper transition between pass/stop bands.

- **The more stages, the less the filter attenuation is dependent on external impedances.**

- **Common multi-element configurations: L, T and π**

- **Choose configuration for the best mismatch of source and load impedances.**

- **Series element (ferrite or inductor) typically faces low impedance**

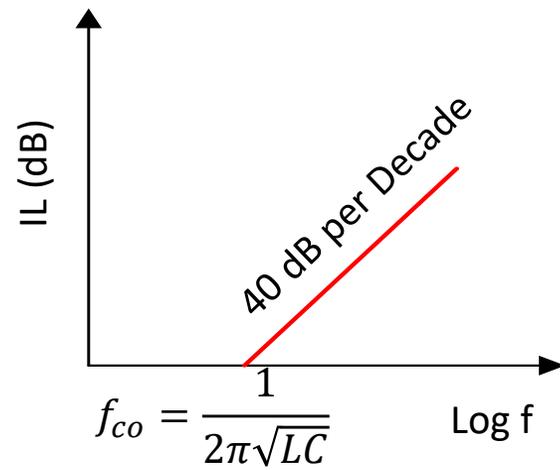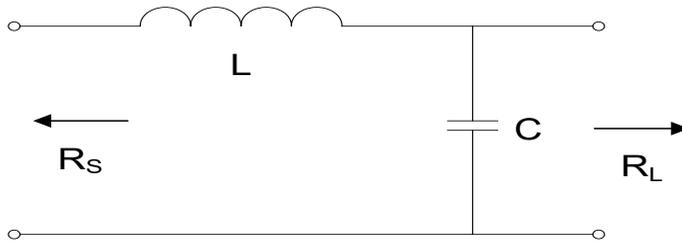- **Shunt element (cap) typically faces high impedance**

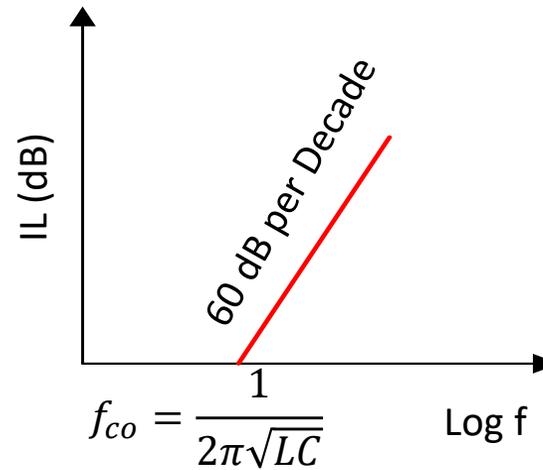# Single Element Low-Pass Filters

Shunt Capacitor

Series Inductor

$$f_{co} = \frac{1}{\pi RC}$$

$$f_{co} = \frac{R}{\pi L}$$

Multi-Pole Filters

"L" Section

"π" Section

"T" Section

IL (dB)

40 dB per Decade

$$f_{co} = \frac{1}{2\pi\sqrt{LC}}$$

Log f

IL (dB)

60 dB per Decade

$$f_{co} = \frac{1}{2\pi\sqrt{LC}}$$

Log f

IL (dB)

60 dB per Decade

$$f_{co} = \frac{1}{2\pi\sqrt{LC}}$$

Log f
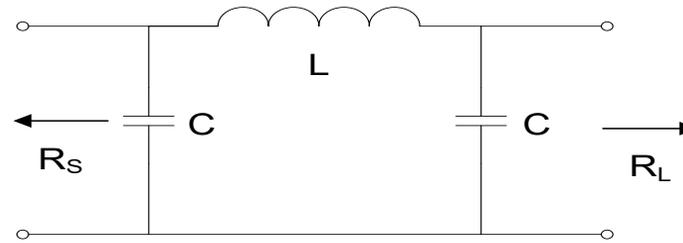
Absorptive vs. Reflective
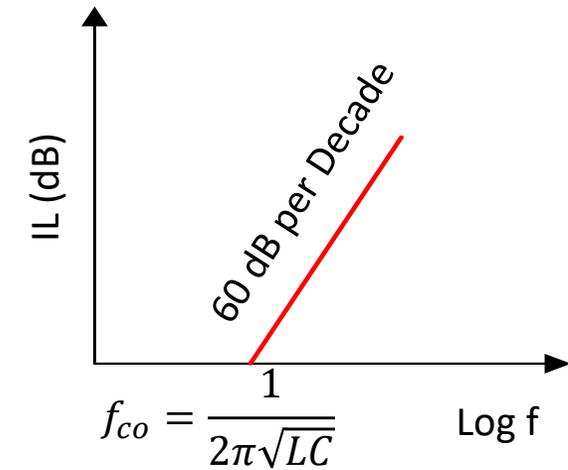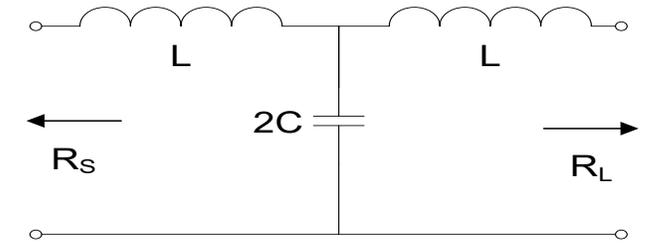
- **Absorptive components**
  - Resistors
  - Ferrites

- **Reflective components**
  - Capacitors
  - Inductors

- **Absorptive filters will dissipate noise but also some of the desired signal**

- **Reflective filters will exhibit resonances that must be understood and controlled**

- **Can combine both types for optimum high-frequency performance.**

Common-Mode Filtering

- **CM filters are generally more difficult to design**

- **Source, load Z is usually not known**

- **Filter must not affect the intentional (differential mode) signal on the line**

- **CM filter components**
  - CM choke (no effect on DM signal)
  - Line-to-ground capacitors (some effect on DM signal)
 - Ferrite bead (no effect on DM signal)

Filter Selection Parameters

- **Operating Voltage**
- **Operating Currents**
- **Operating Temperature Range**
- **Source and Load Impedance**

Filter Circuit		Best Filtering Application
PI	FERRITE	Unknown or medium source and load impedance
LRC	FERRITE	Low source and high load impedance
CLR	FERRITE	High source and low load impedance
C		High source and high load impedance
T	FERRITE FERRITE	Low source and low load impedance

High source or load impedance >100ohms   Low source or load impedance <10ohms

- **Transient Voltage Requirements**
- **Insertion Loss Performance**

Pi Filter Typical Performance
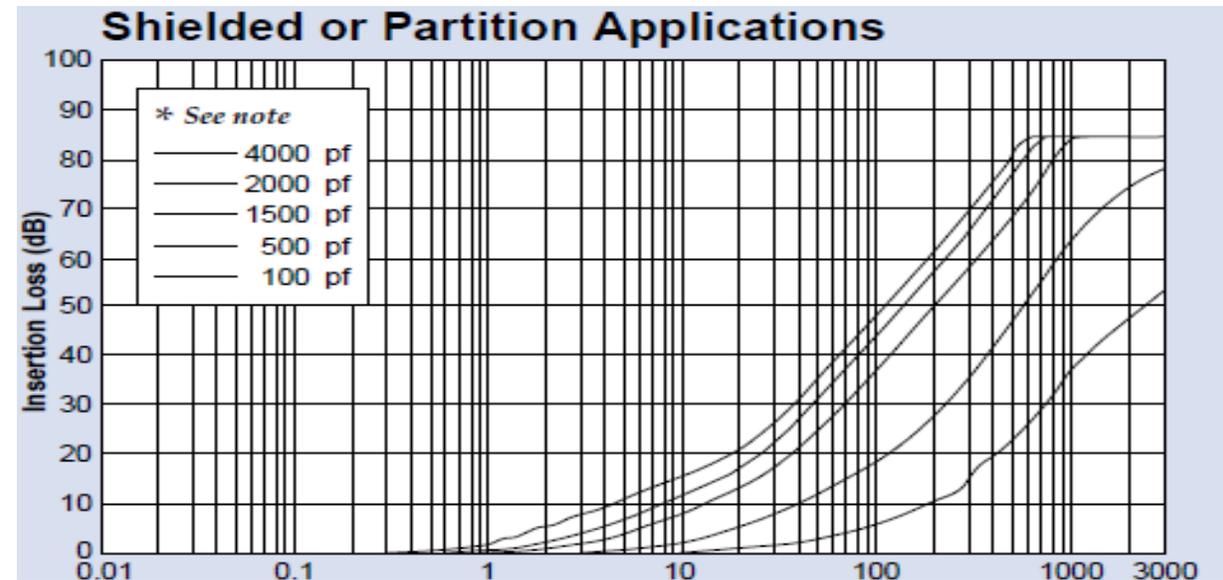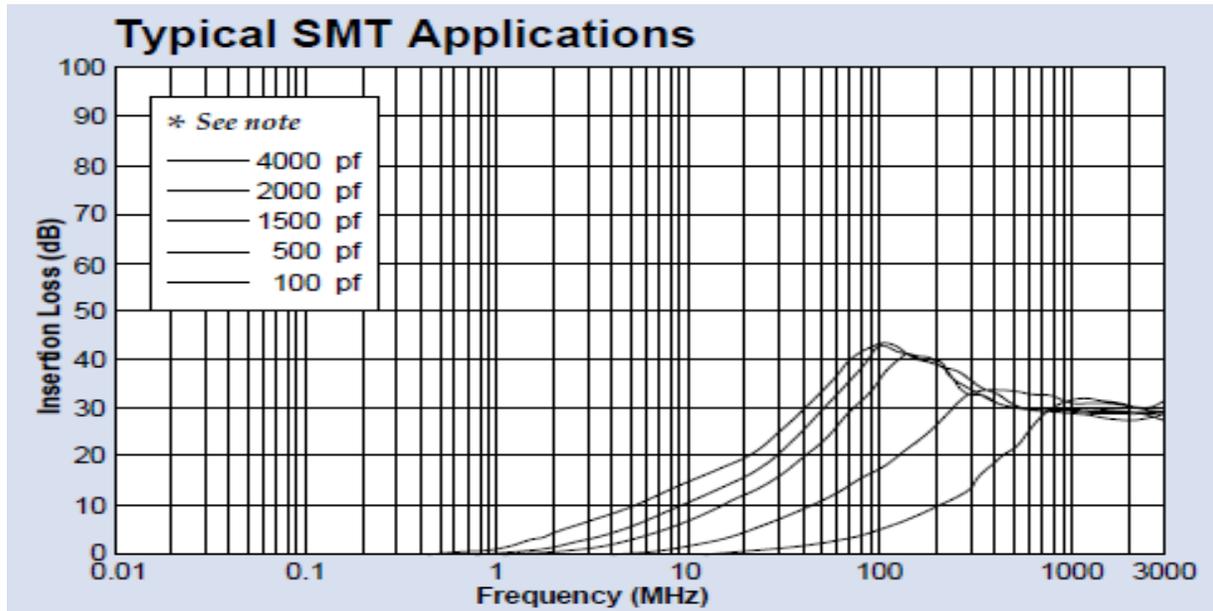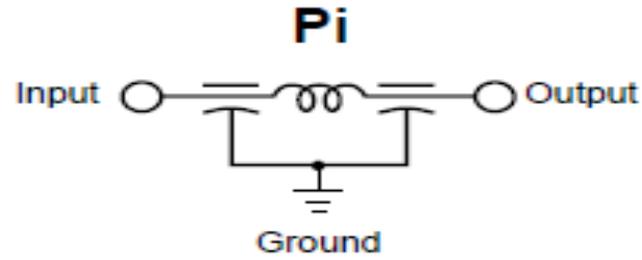
Higher frequency performance is installation dependent

Powerline Filters

- **A primary contributor to EMI problems are power cables and circuits**

- **Power supplies are rich sources of noise**

- **Power cables are often not shielded**

- **Long lengths allow coupling over a wide range of frequencies**

- **Proper filtering at the primary power input is critical to ensure EMC**
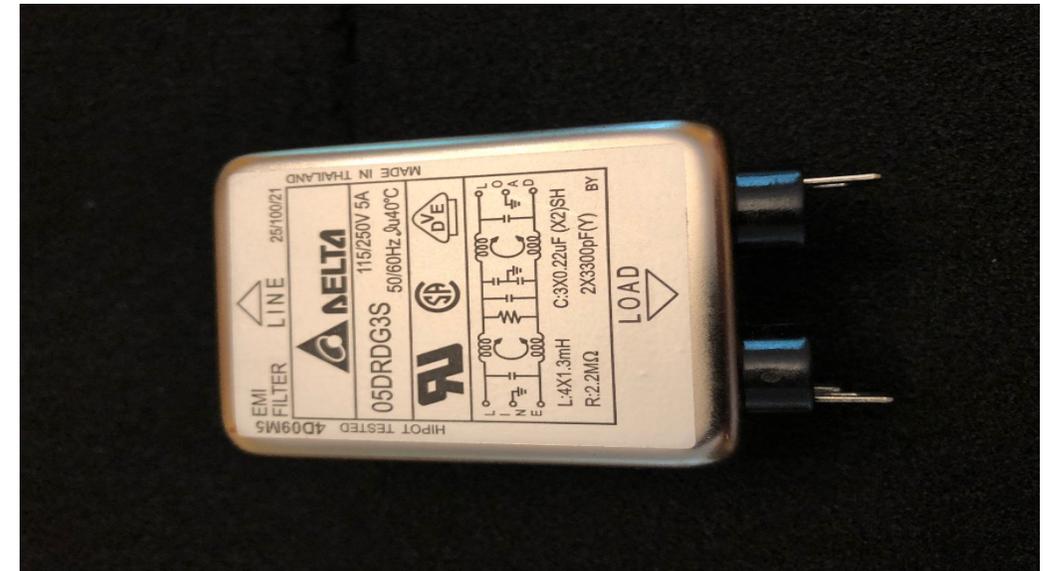
Powerline Filter

Typical Schematic and Insertion Loss

Common Mode Choke
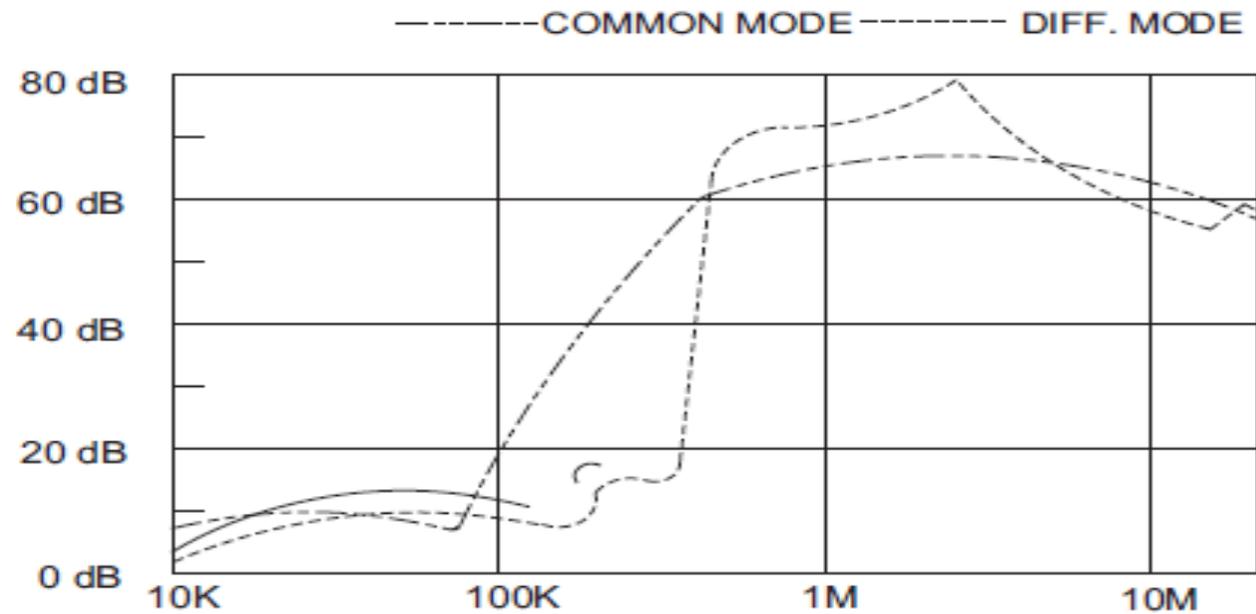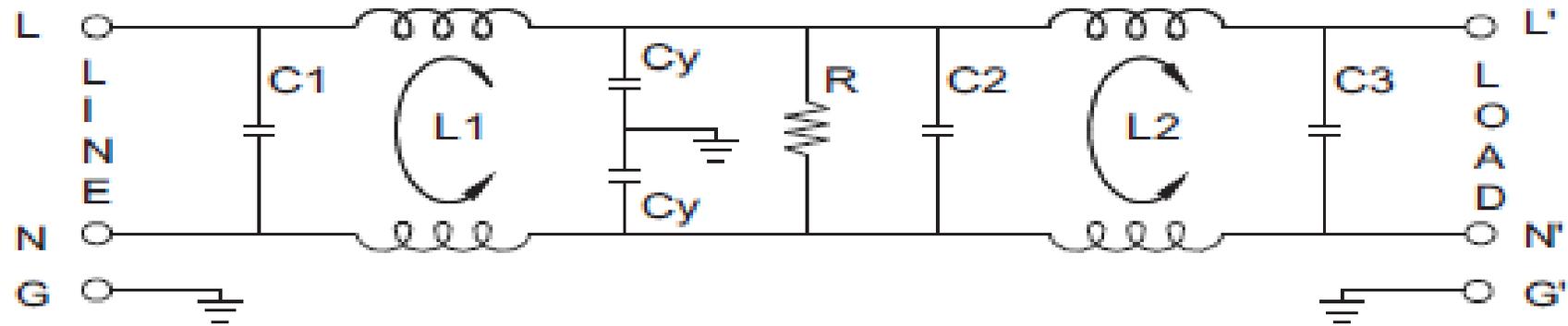
- **A CM choke is a wrapping of multiple wires (each from the same CM current carrier) in the same sense, around a ferrite core.**

- **The inductance has no effect on the DM signal (or noise), due to cancellation of the magnetic fields, but it significantly attenuates the CM noise.**

Current of Common Mode (Noise)
Current of Differential Mode (Signal)
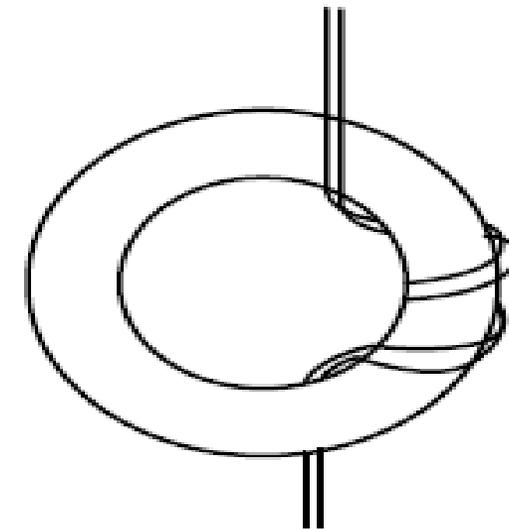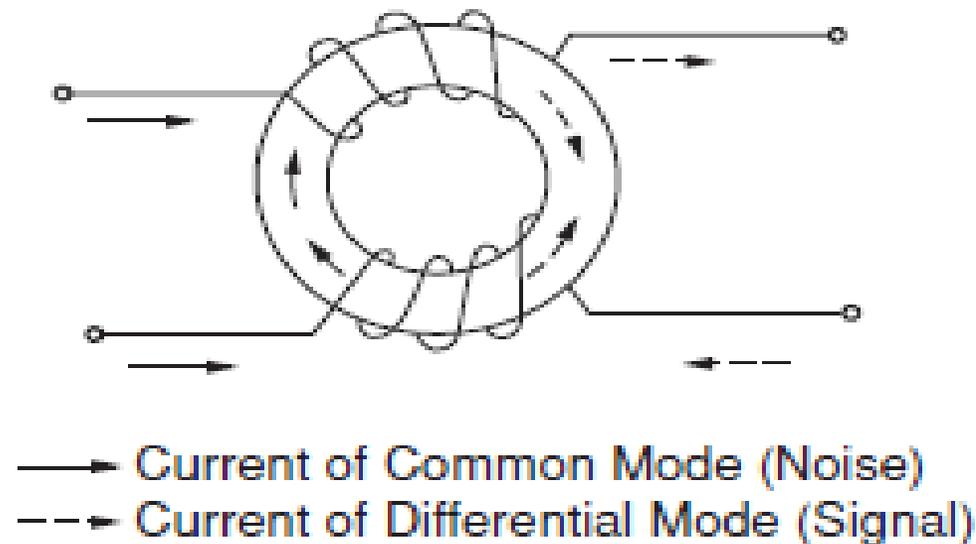
This family is optimized for power supply switching frequency suppression

Power Line Filter Installation Issues

EMI From Switch Mode Power Supplies (SMPS)
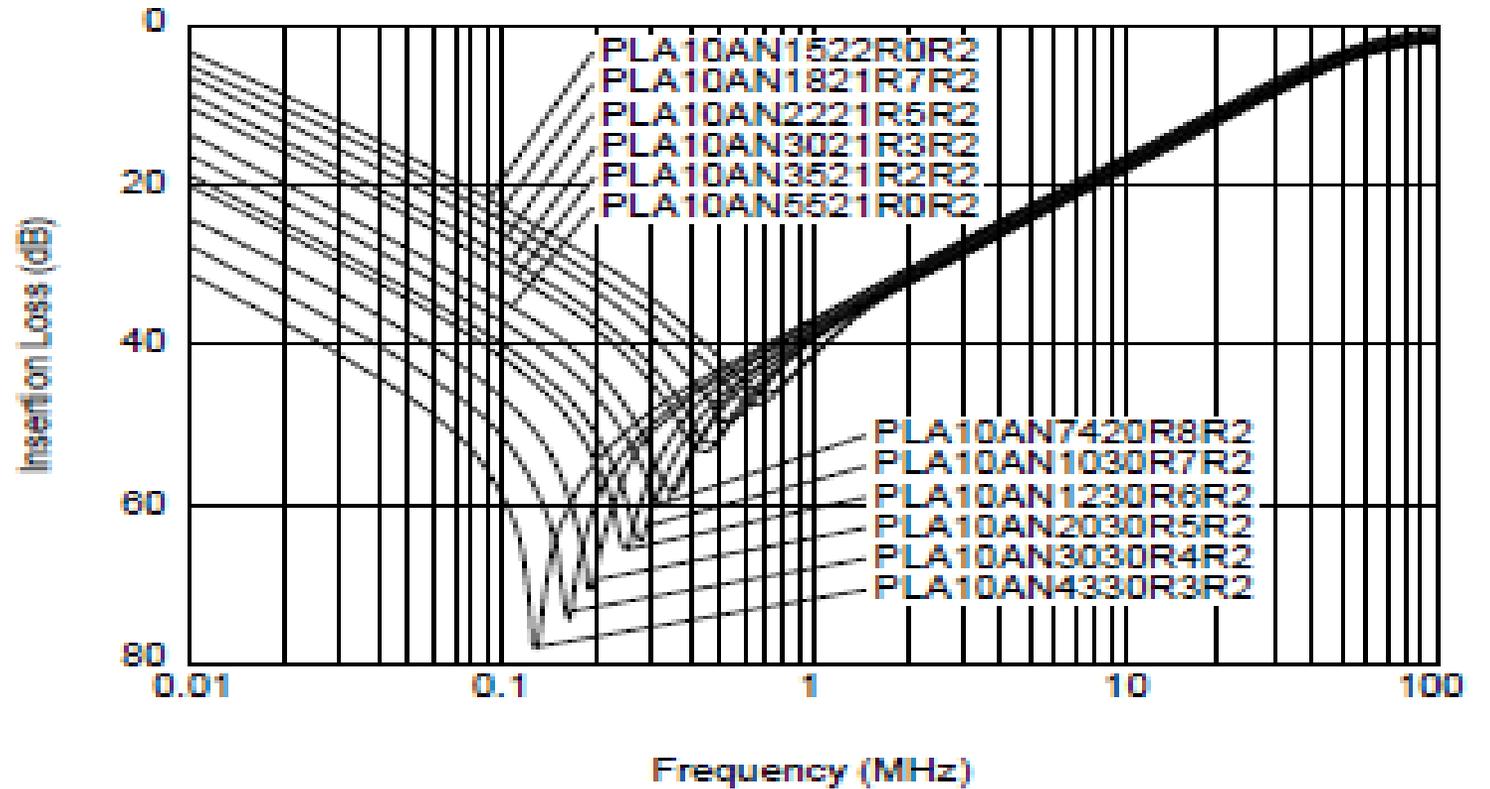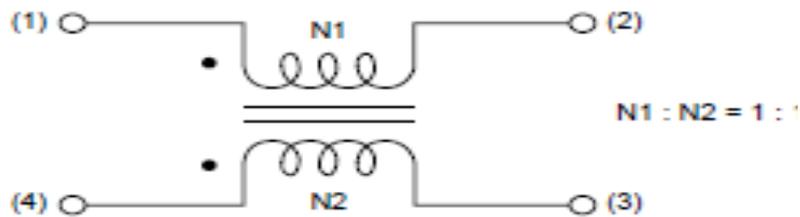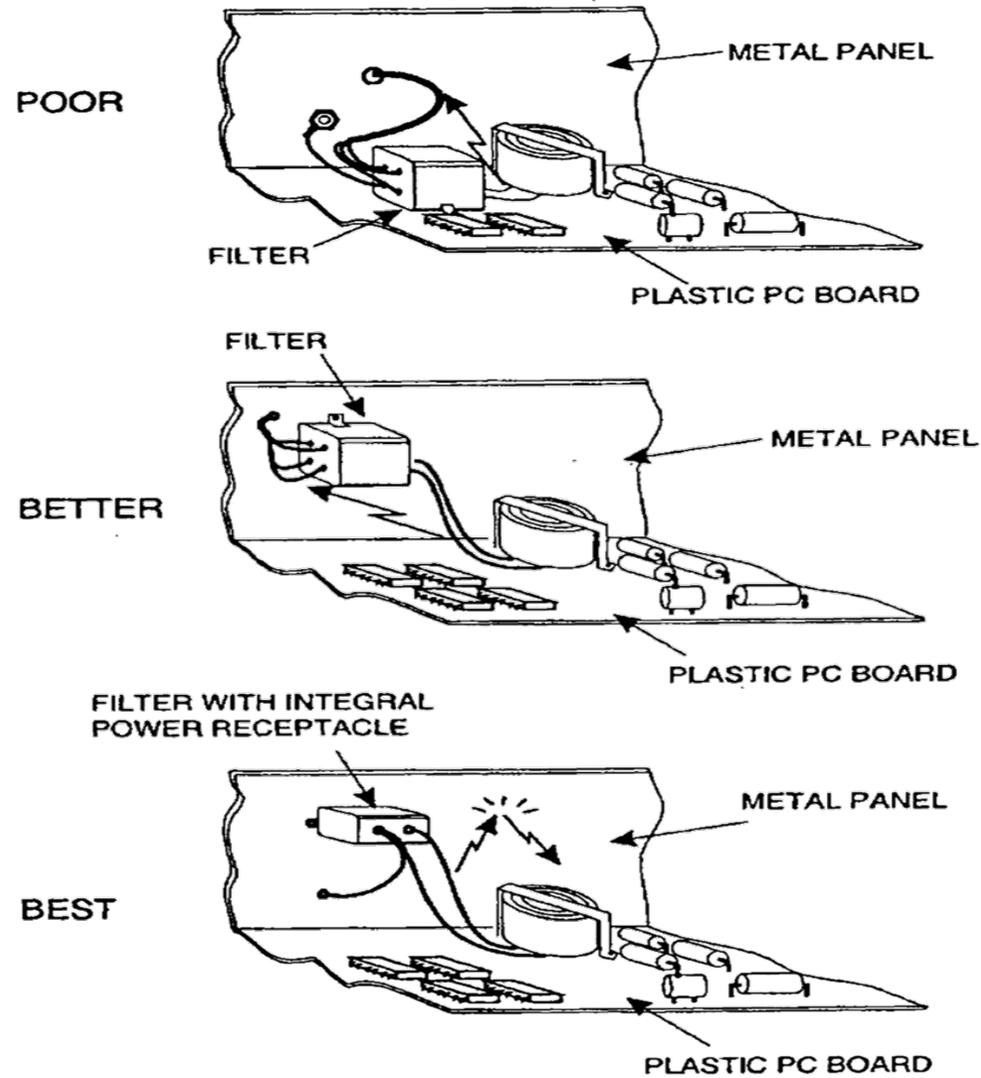
- **Rectifier diodes generate significant harmonic currents.**

- **Switch transistor generates significant DM and CM noise (switch frequency and harmonics).**

- **A power supply without input line filtering will usually dramatically fail CE102.**

SMPS Differential Mode (DM) Emissions
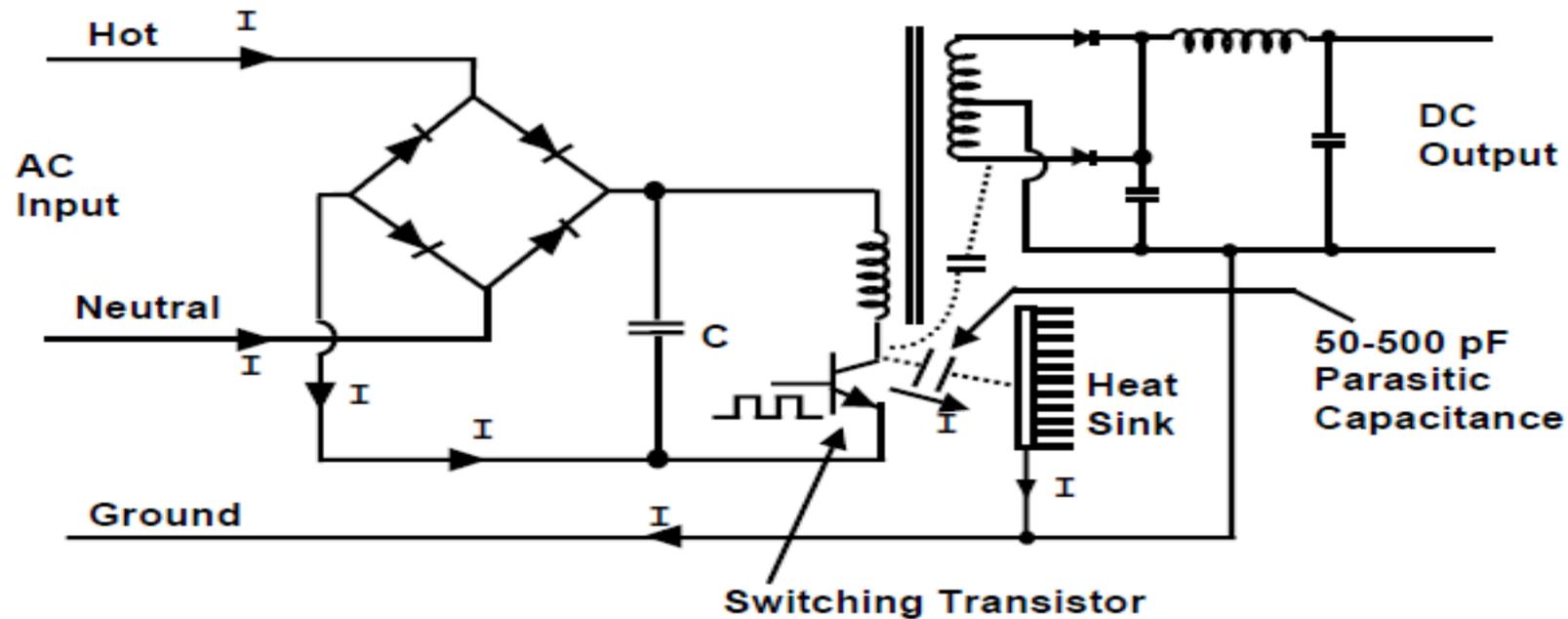
DM conducted emissions result from:

1) On-off switching activity of the SMPS (at switch frequency and harmonics)

– Several kHz to several hundred MHz

2) Rectification of AC powerline

– 60 Hz up to tens of kHz

- **DM emissions must be carefully filtered**

- **Must not increase the power source impedance seen by the SMPS significantly.**

- **Line to line capacitance is commonly used to supply the bulk of the SMPS current demand.**

- **DM inductance may help bring harmonic emissions in spec.**

SMPS Common Mode (CM) Emissions

- SMPS CM emissions result mainly from parasitic capacitance between circuit elements

- Parasitic capacitance can develop between a heat-sinked switching element and the grounded equipment enclosure, or across the windings of the SMPS transformer.

- Regardless of the source of the parasitic capacitance, CM current is driven into the ground reference.

- The CM current divides more or less equally between the high and return wires.

- Filtering relies on low impedance shunt of the power source within the equipment (line-to-ground capacitance) and raising the impedance of the CM current path (CM inductance).

SMPS Filtering

- **Best approach is to "design in place" (custom filter)**

- **Next best solution is an off-the shelf filter**

- **Published insertion loss values may not agree with actual performance**

- **Be aware of line-to-ground capacitance limits (0.1 uF per phase for 60 Hz lines).**

- **Power line filters must have output side Z(f) much less than power supply input Z(f) to avoid potential power supply instability.**

Harmonic Currents due to Rectification
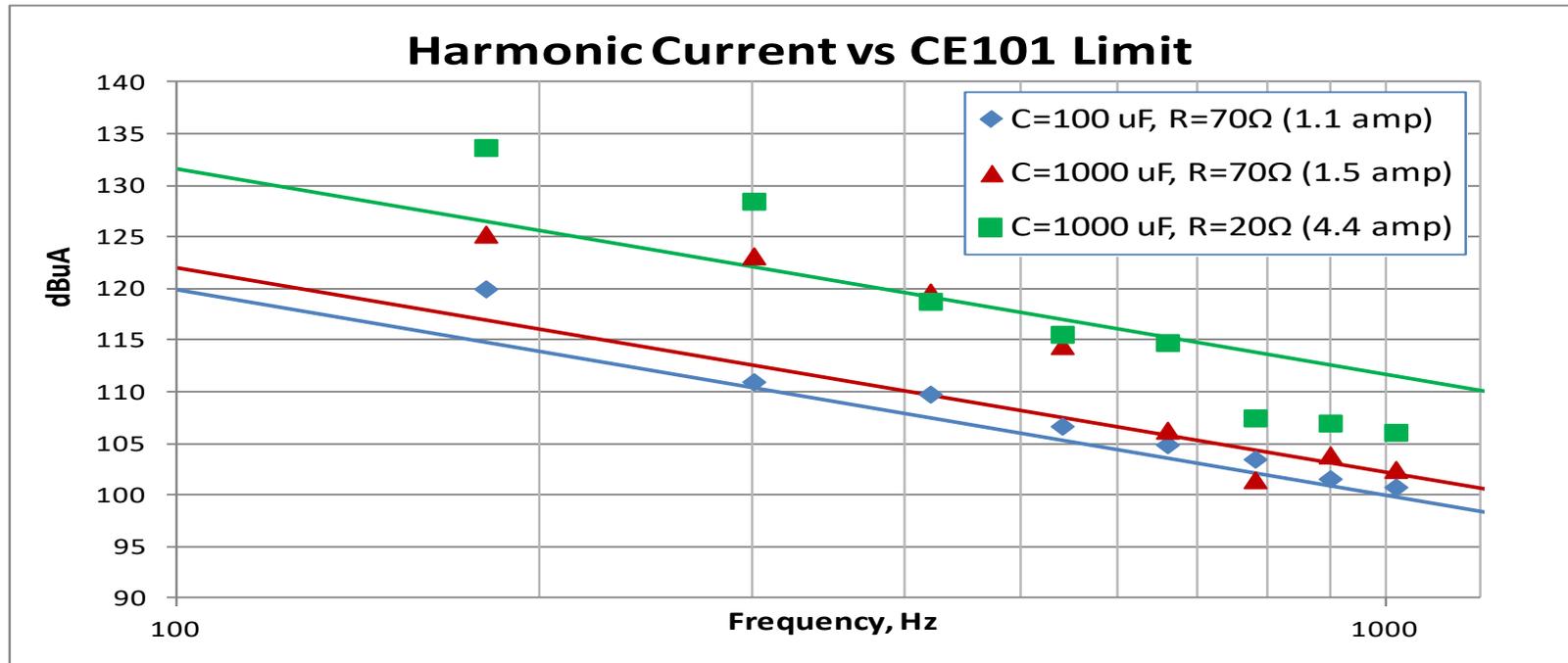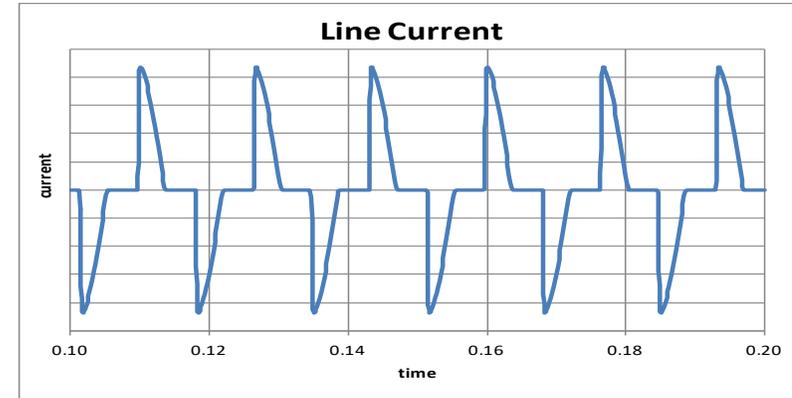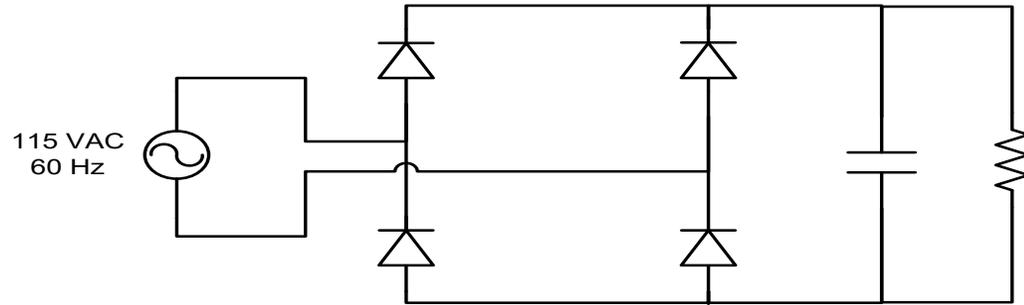
CE102 emissions profile of an inadequately filtered SMPS

Switch mode power supply harmonics

SMPS Noise Voltage Prediction Model
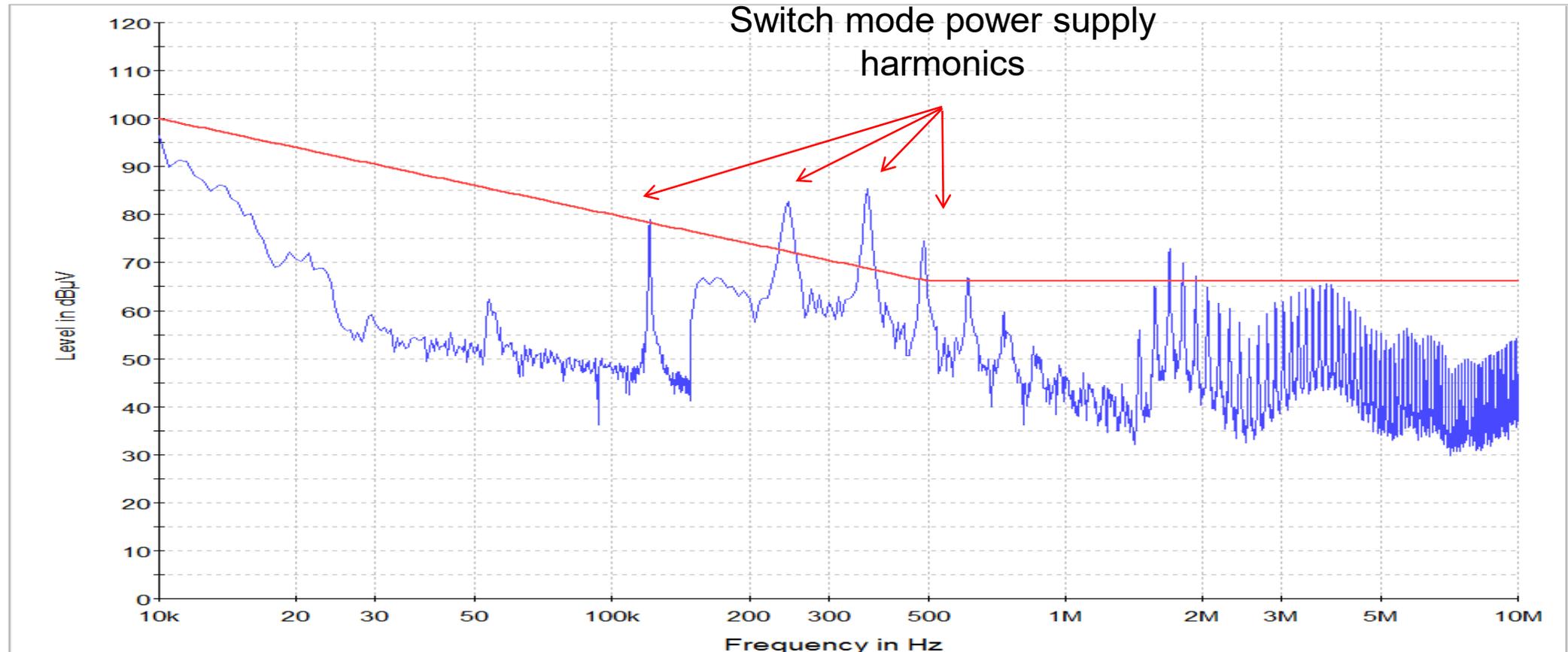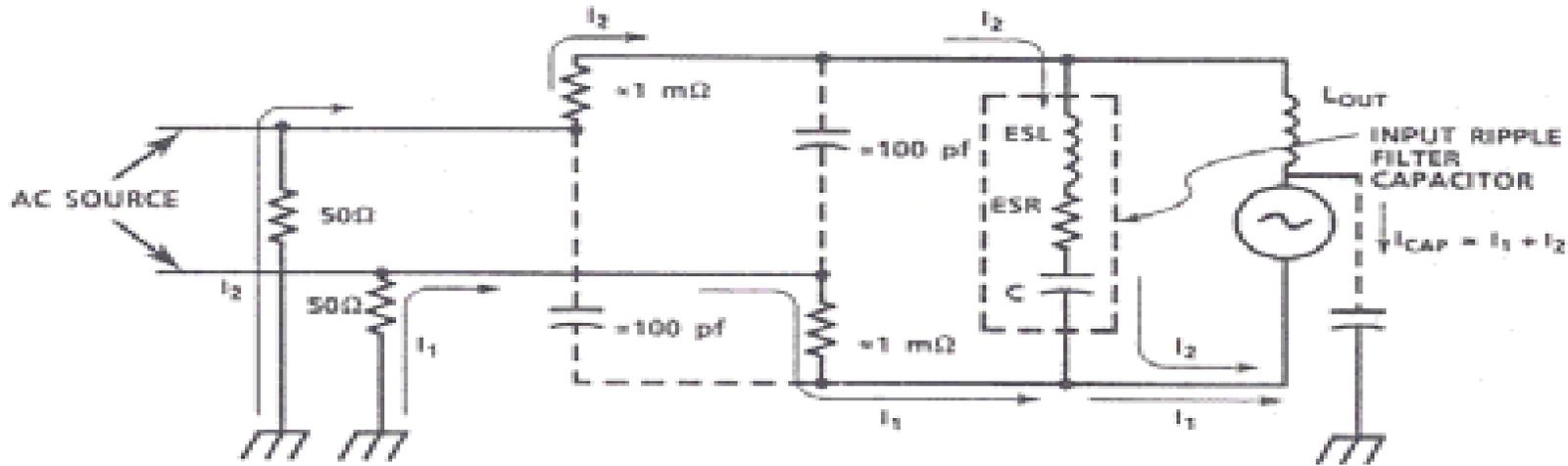
$$V_{DM}(f) = \frac{V_{coll}(f)\omega^2 L_c C_p}{4}$$

$$V_{CM}(f) = 25\omega C_p V_{coll}(f)$$

$V_{DM}(f) = $ differential−mode voltage seen at LISN
$V_{CM}(f) = $ common−mode voltage seen at LISN
$V_{coll}(f) = $ collector voltage (as a function of frequency)
$C_p = $ switch transistor heatsink capacitance to ground
$L_c = $ filter cap parasitic inductance

From Nave, M.J., *"Prediction of Conducted Emissions in Switch Mode Power Supplies",* 1986 IEEE EMC Symposium Record.

Feedthrough Capacitor/Filter

- **Special cap designed for very high frequency performance (1 GHz and above)**

- **Extremely low inductance design**

- **One electrode is connected to housing, the other to the feedthrough bus.**

- **Enclosure or subassembly shield (peripherally terminated) provides highest possible input/output isolation.**

Lead Foils
(Connected to
Feed-Through)

Ground
Foils

Feed-Through
Bus

Ground
Foils

DISA

Feedthrough Capacitor/Filter
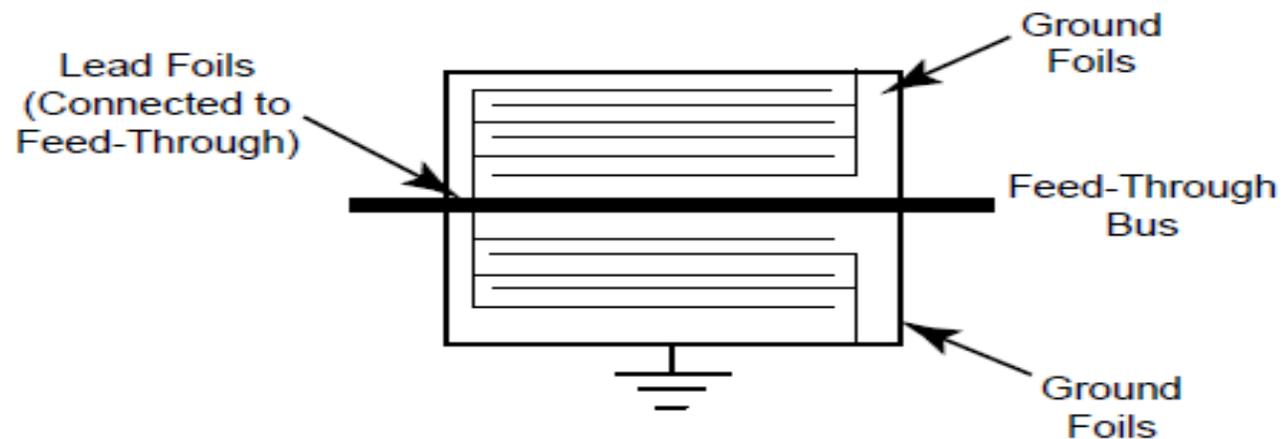
Typical Performance

Filtered Connector
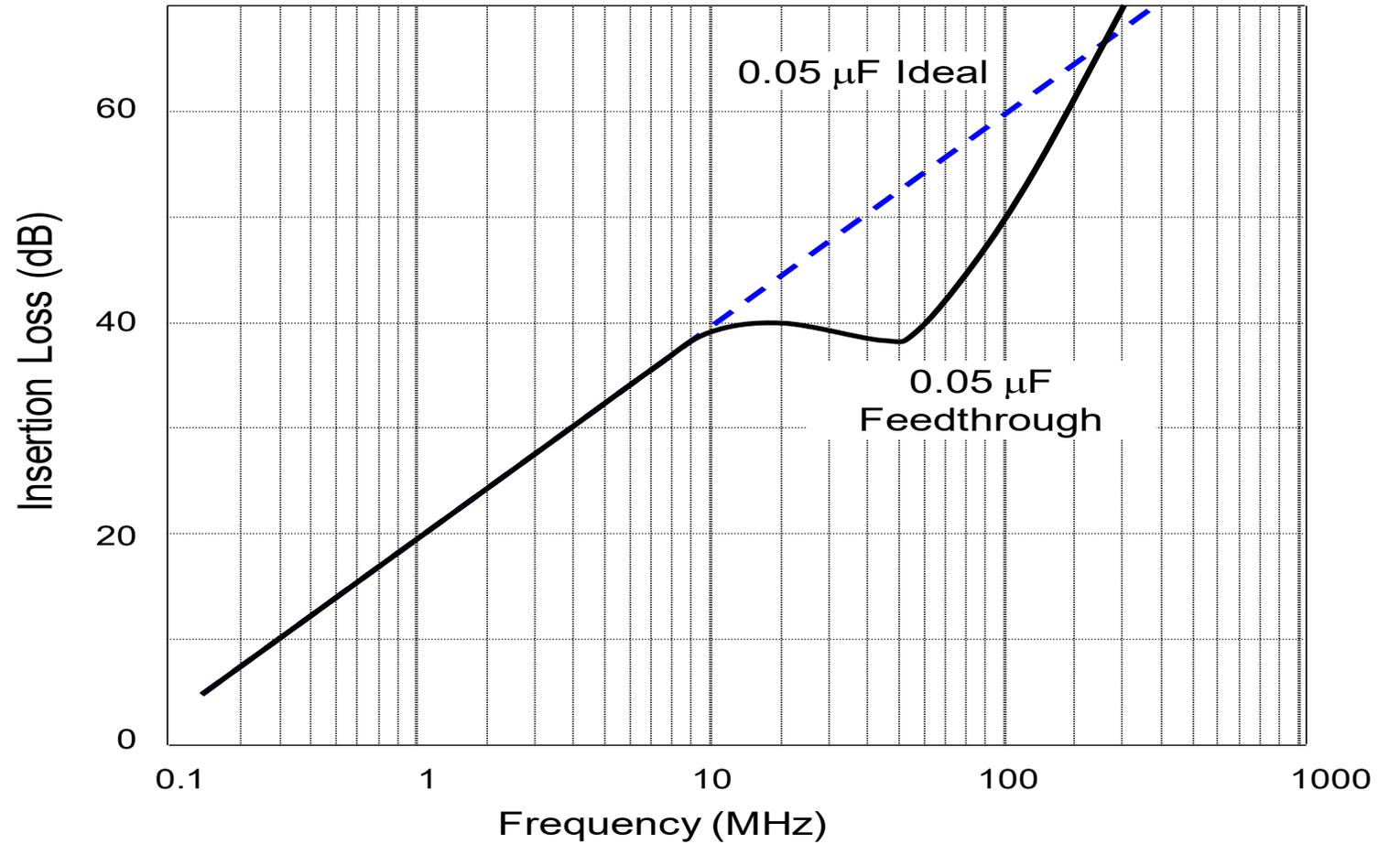
Feedthrough filter packaged into a multipin connector

Ferrite Beads and Cores
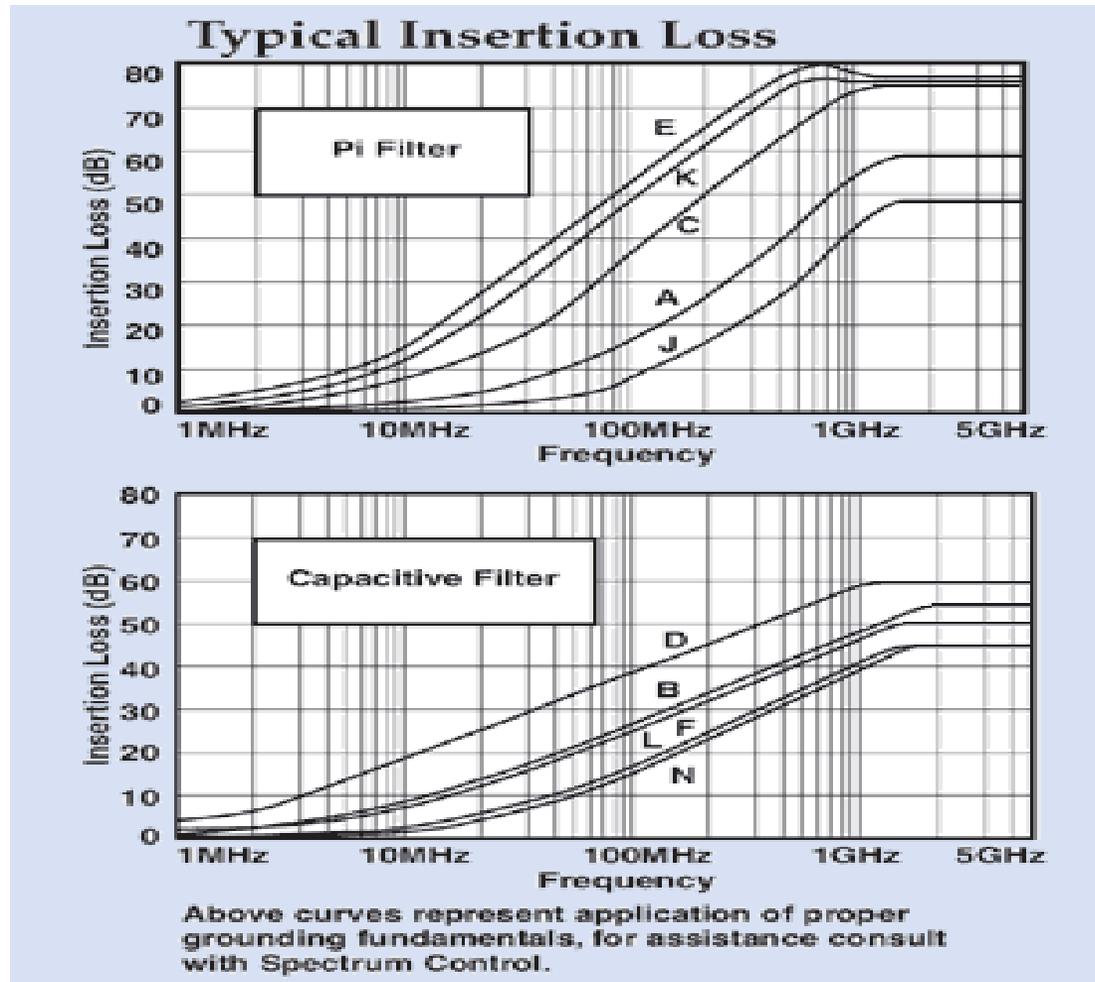
- Ferrites are magnetic ceramic materials (combination of oxides of manganese/zinc/nickel blended with iron oxides) designed to yield high magnetic permeability and high electrical resistivity.

- EMI suppression ferrites are typically effective from about 20 MHz up to 300 MHz.

- Ferrites for inductors are optimized for lower frequencies (~50 kHz to 5 MHz).

- Many forms available (bead, toroid, split-bead, multi-hole, chip).

Ferrite Beads
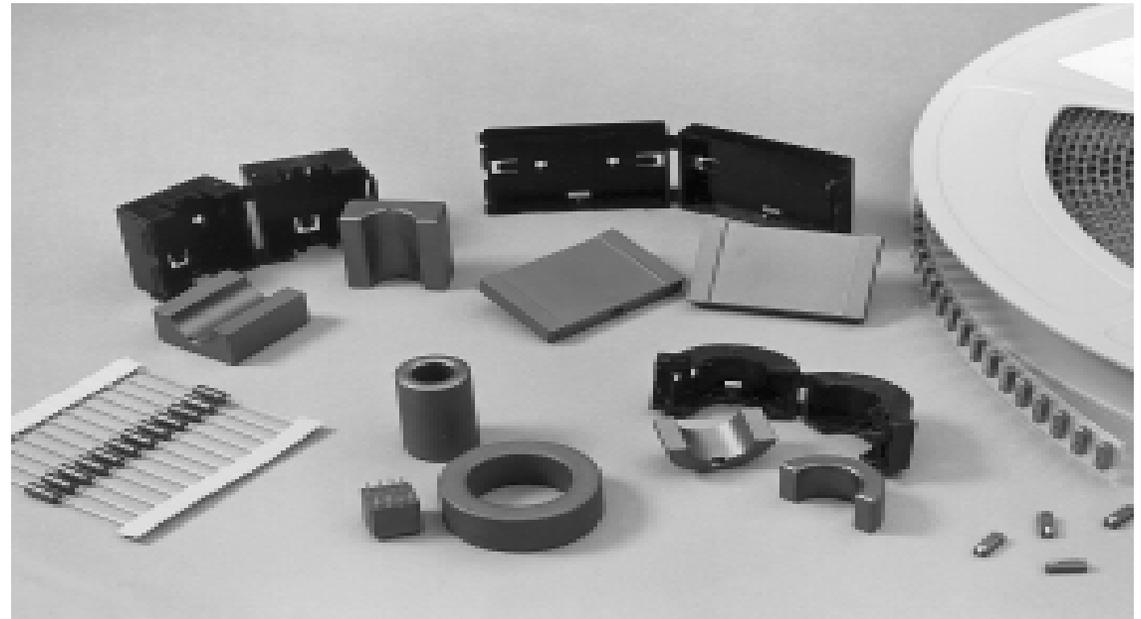
- **Advantages**
  - No significant effect on desired (differential mode) signal (when applied to conductor group)
  - Easy to apply
  - Inexpensive
  - No ground reference required
  - Minimal impact to hardware design
- **Disadvantages**
  - Suppression level typically not nearly as good as shielding or a conventional filtering solution.
  - 3-10 dB improvement is considered good.
  - Ferrite will do nothing if the interference frequency is outside the ferrite's "operating range", or if the source impedance is high.

Ferrite Impedance

- **Impedance is primarily determined by the specific part shape, size, material type, and # turns.**
- **Impedance is also affected by geometry (parasitic capacitance), DC bias, and temperature.**
- **Impedance can vary significantly from part to part.**

Filter Installation
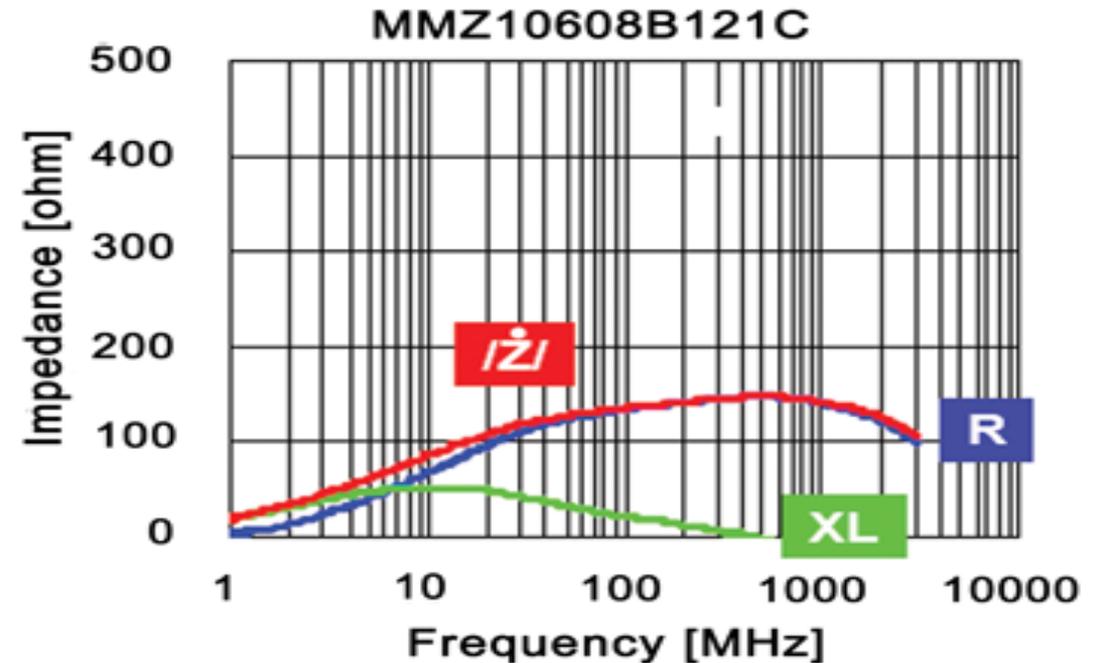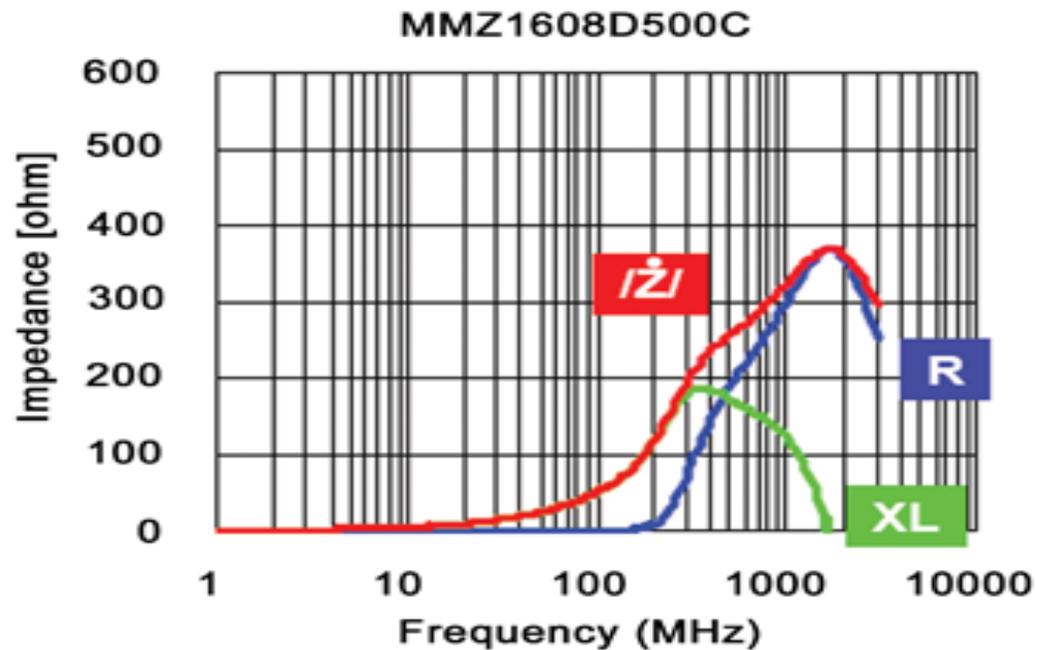
- DM filter should be placed close to source (to minimize current loop area)
- CM filter is usually placed at enclosure exit point (to "short-out" the radiating cable impedance).
- Input and output lines must be isolated to ensure filter is not bypassed.
- Good layout is essential to minimize parasitics.
- For CM filters, all lines in a group (i.e. all I/O conductors) must be filtered, including any ground leads.
- Maximum isolation is achieved by mounting the filter onto a shielded partition.

Filtering Summary

- EMI filters are generally low-pass type, with one or more reactive components, capacitors and inductors.

- Filter performance is measured by the insertion loss (i.e., ratio of the load noise voltage before and after the filter has been inserted in the line).

- The insertion loss is usually expressed in dB as a function of frequency with a 50-ohm input and output resistor as loads.

- Filters are common-mode, differential-mode or combinations of the two.

- Installation of filters is a prime factor in their performance. Coupling between "noisy" input lines and "clean" output lines can compromise the filter at high frequencies.

Backup Material

DISA: TRUSTED TO CONNECT, PROTECT AND SERVE!

Spectrum of Trapezoidal Pulse

Pulse Characteristics	Spectrum Envelope	Power Spectral Density Values

A = Amplitude (V)
d = Pulse Width (s)
t_r = Rise Time (s)

Frequency, Hz

f = Frequency (Hz)

$$P_1 = 2Ad$$

$$P_2 = \frac{2A}{\pi f}$$

$$P_3 = \frac{2A}{\pi^2 f^2 t_r}$$
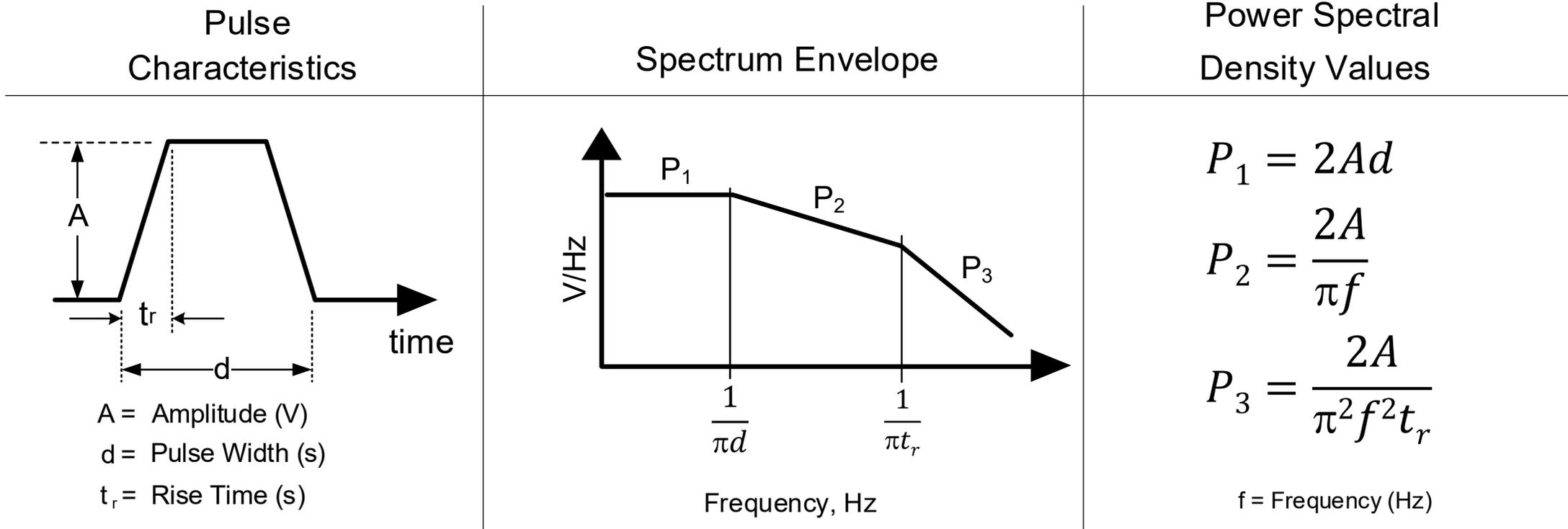
- **Pulse width determines the first frequency breakpoint**
- **Pulse rise time determines the second breakpoint**
- **Short pulses and fast rise/fall times yield more energy at higher frequencies**

Inductive (Magnetic) Coupling

- **Current flowing in a conductor creates a magnetic field (flux density) which is dependent on the current and the distance from the conductor.**

- **Self inductance = total magnetic flux generated by a current, divided by the current that causes the flux**

- **Mutual inductance = portion of the flux generated by #1 that passes through loop #2, divided by current in loop #1**

$$L = \frac{\Phi_{11}}{I_1}$$

$$M = \frac{\Phi_{12}}{I_1}$$
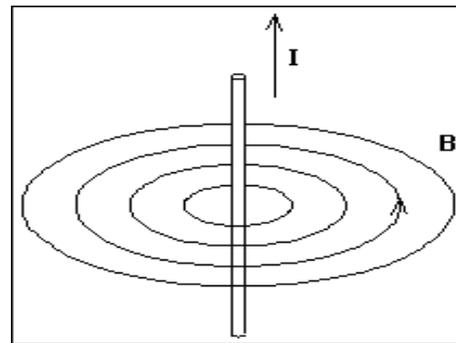
$\Phi = $ magnetic flux $= BA$
$B = $ magnetic field (flux density)
$A = $ current loop area

Magnetic field lines due to current I

Some of the flux encircles conductor #1 without going around conductor #2

#1   #2

Faraday's Law
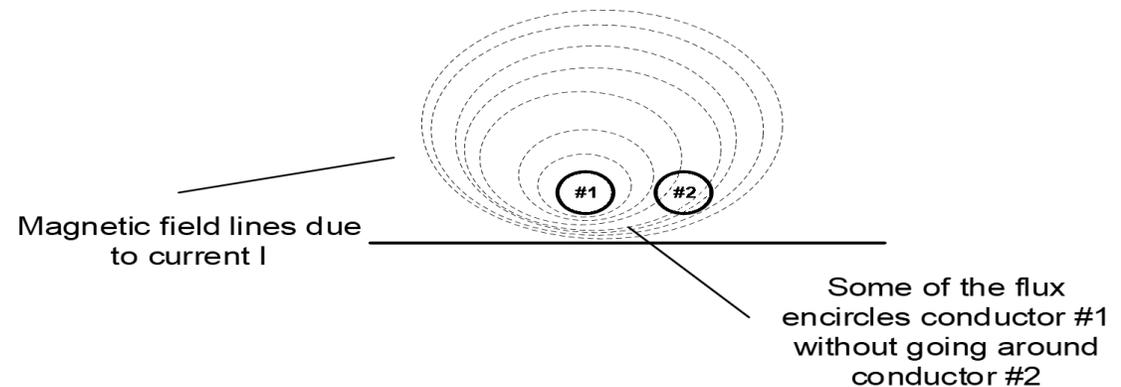
- **When an alternating magnetic field passes through a circuit loop, a voltage is induced.**
- **The voltage equals the rate of change of magnetic field through the loop (B), times the area enclosed by the loop (A).**
- **The magnetic field can originate from the loop circuit itself, or from another source.**

$$V_N = j\omega BA\cos\theta$$

R_1 Area A R_2
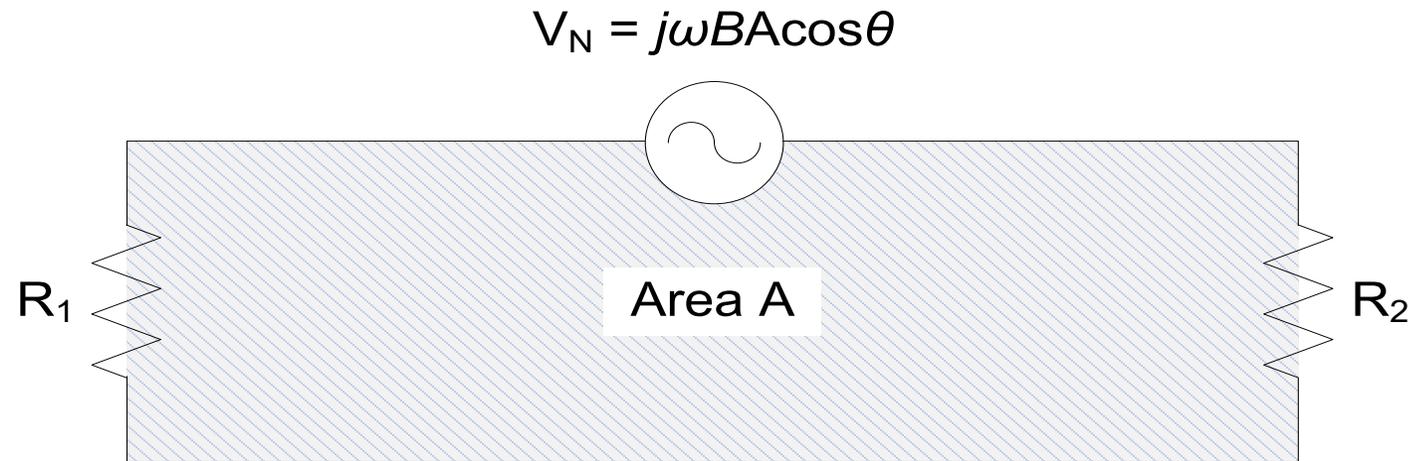
$$V = -\frac{d\Phi}{dt} = -A\frac{dB}{dt}$$

The minus sign indicates that the induced voltage opposes the current flow that created the field.

Common Mode vs Differential Mode

DISA

Common Mode
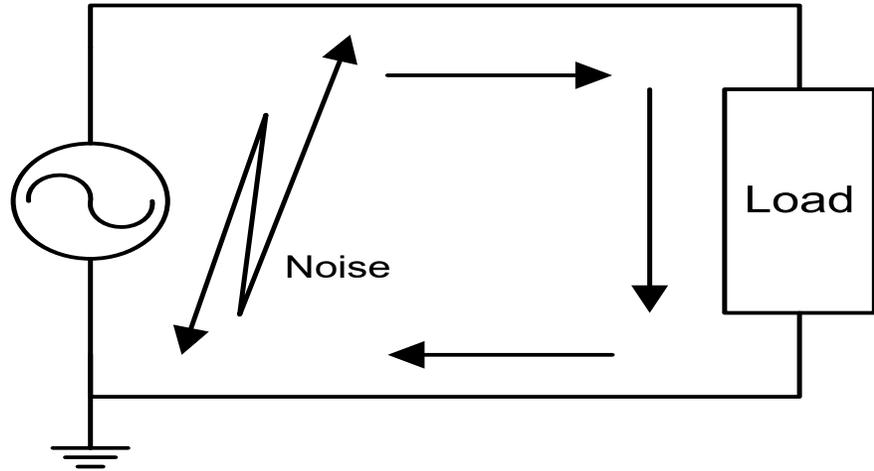
Differential Mode
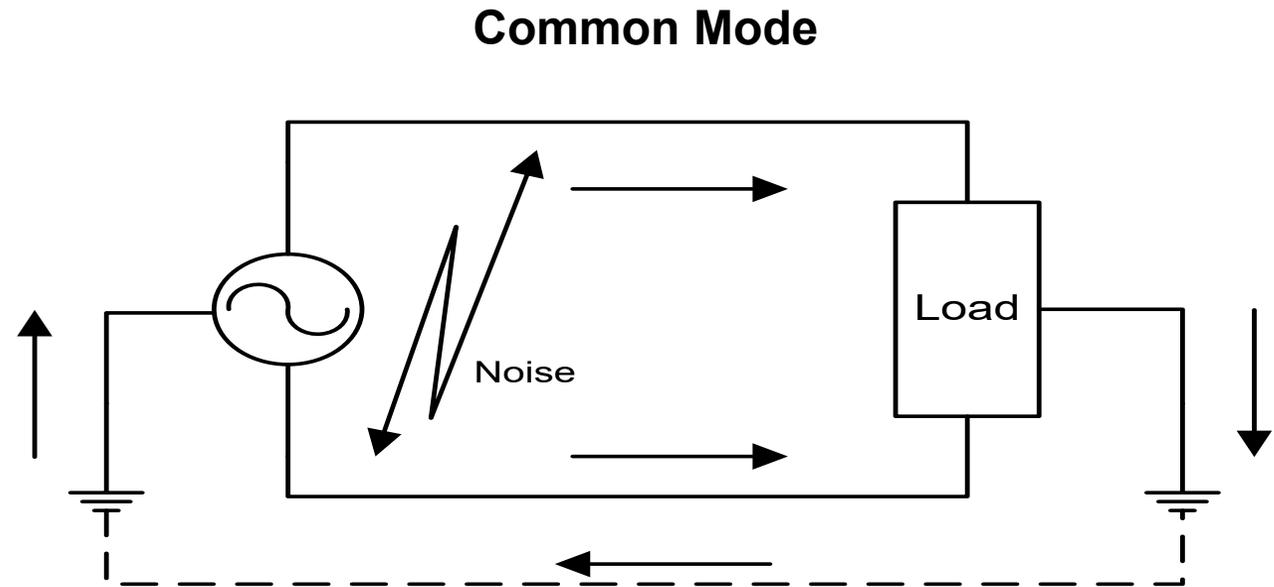
Least Impedance Principle

- **Current always takes the path of least impedance**
- **At low frequencies, current will return along the path of lowest resistance (shortest distance).**
- **At high frequencies, current will return along the path of lowest inductance (underneath the signal track).**

PCB with full ground plane

Low Frequency

High Frequency

Least Impedance Principle
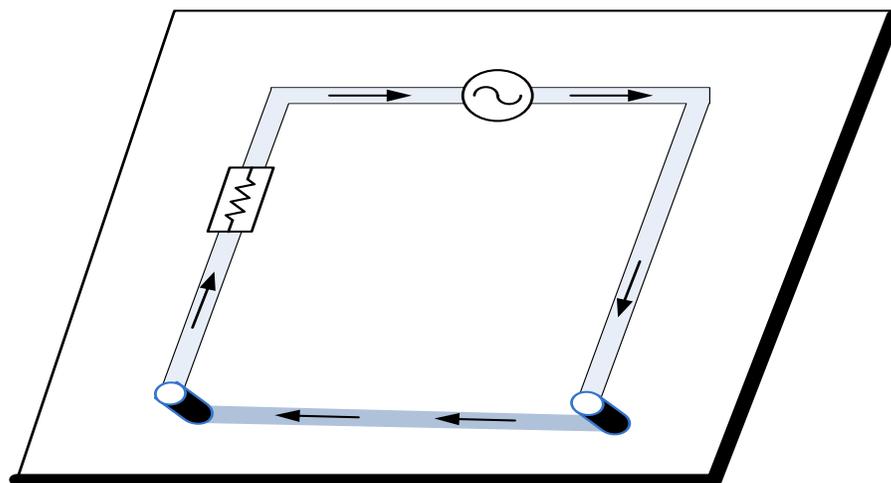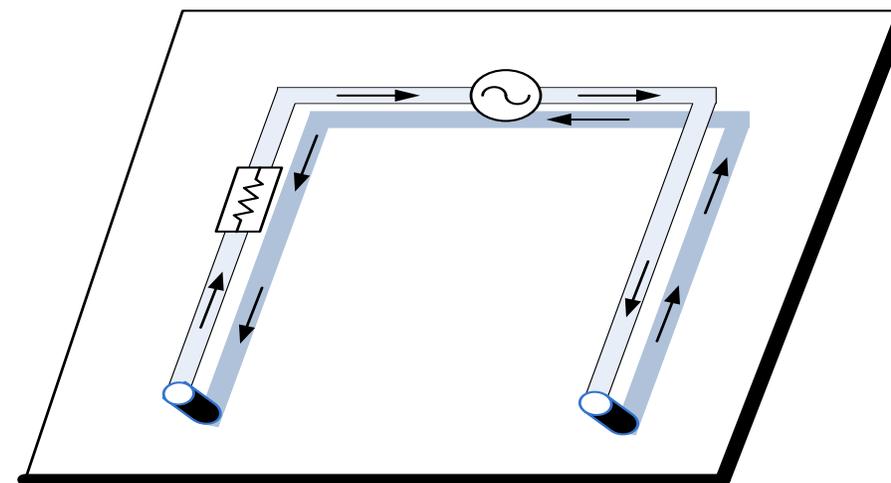
- **Coaxial cable, grounded at both ends**
  - At low frequencies, current will return on the ground plane
  - At high frequencies, current will return on the cable shield

Low Frequency

High Frequency

UNCLASSIFIED

Hybrid
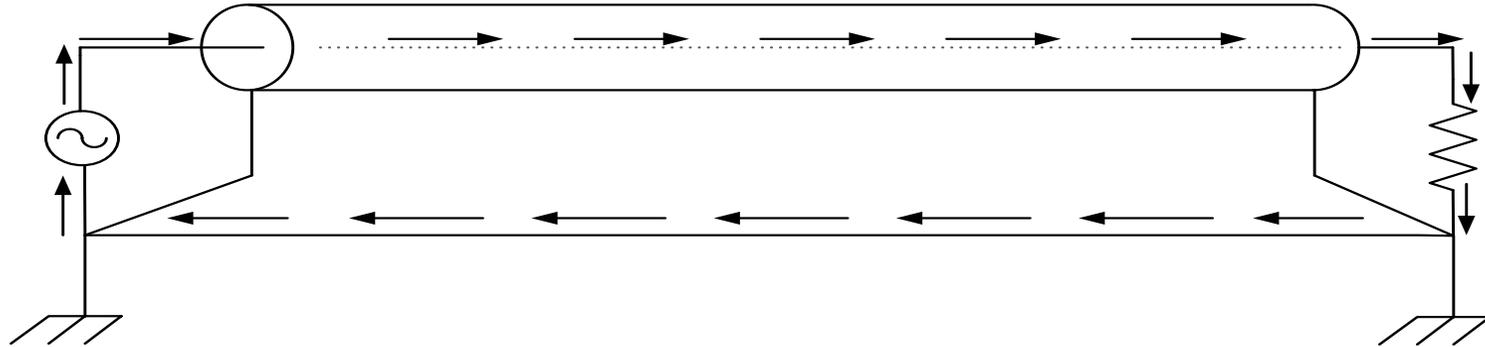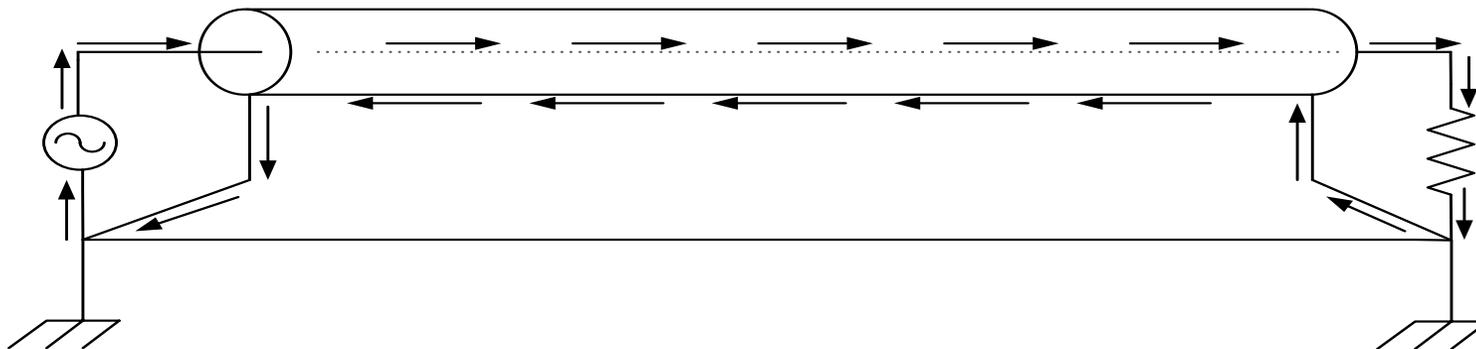
- **Could be used with circuits that employ a wide range of frequencies, both above and below 100 kHz, such as a video signal**
- **Ground behavior differs with frequency**
- **Capacitive variation acts a single point ground at low frequencies, but a multipoint ground at high frequencies**
- **Inductive variation acts a multipoint ground at low frequencies, but a single point ground at high frequencies**

PCB and Chassis Grounds
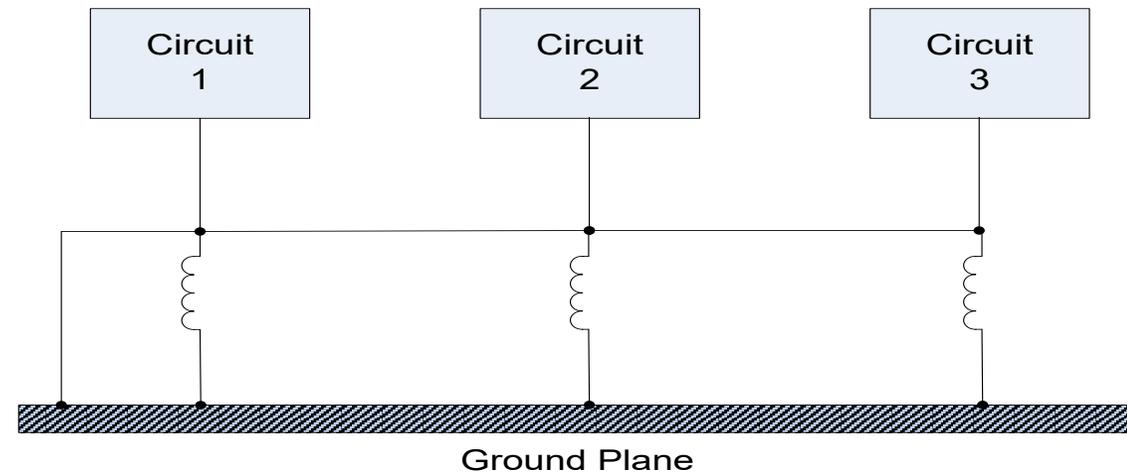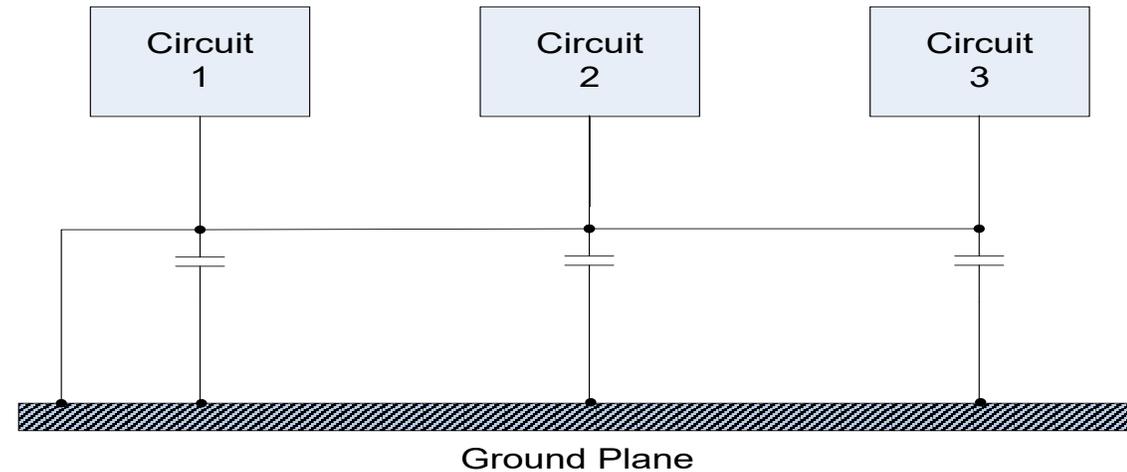
- PCB ground voltage (V_G) causes common-mode current (I_{CM}) to flow on the attached I/O cable

- Cable acts as a dipole antenna, causing radiated emissions

- Connecting to chassis ground at the end of the PCB opposite the I/O will maximize the common-mode current

- Connecting to chassis ground at the I/O end of the PCB will minimize the common-mode current

Ground Plane Inductance
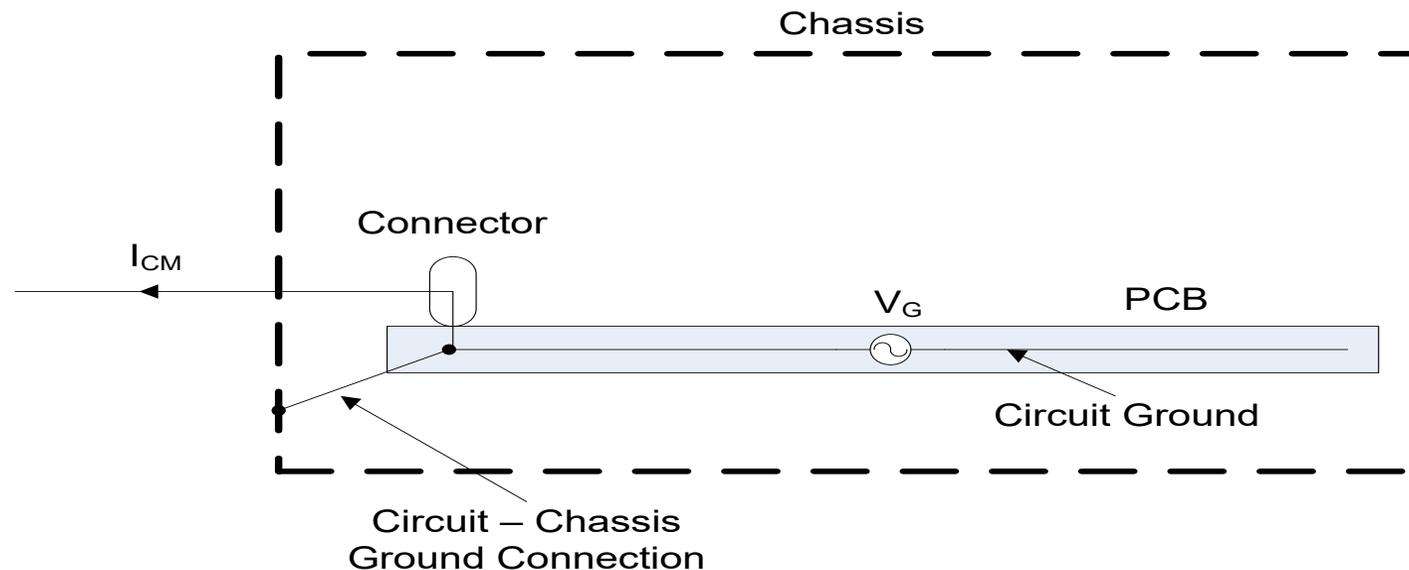
Plane inductance is about two orders of magnitude less than trace or wire inductance.

Common Ground Issues
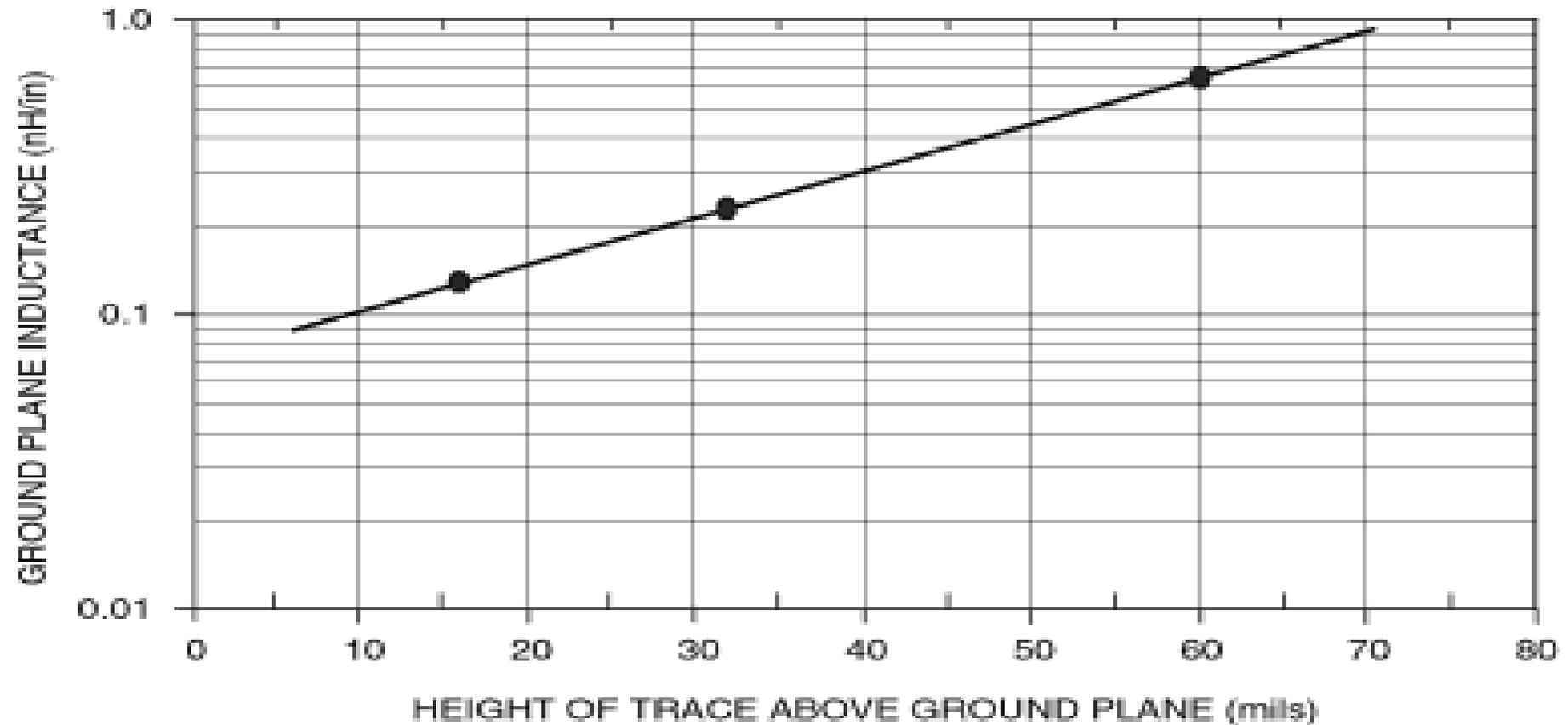
- **Coupling of case attached external transients, such as ESD, to sensitive internal circuits through common impedance path**

- **Radiated emission outages caused by clock frequencies radiating from the power return lead due to a ground loop**

- **Compatibility issues between two systems located a distance apart and sharing the same ground**

Conversion Coatings for Aluminum

MIL-DTL-5541F

- **Class 1A - For maximum protection against corrosion, painted or unpainted.**

- **Class 3 - For protection against corrosion where low electrical resistance is required.**

- **Class 3 preferred for bonding, Class 1A preferred for corrosion protection.**

- **Trade names**
  - Alodine
  - Iridite
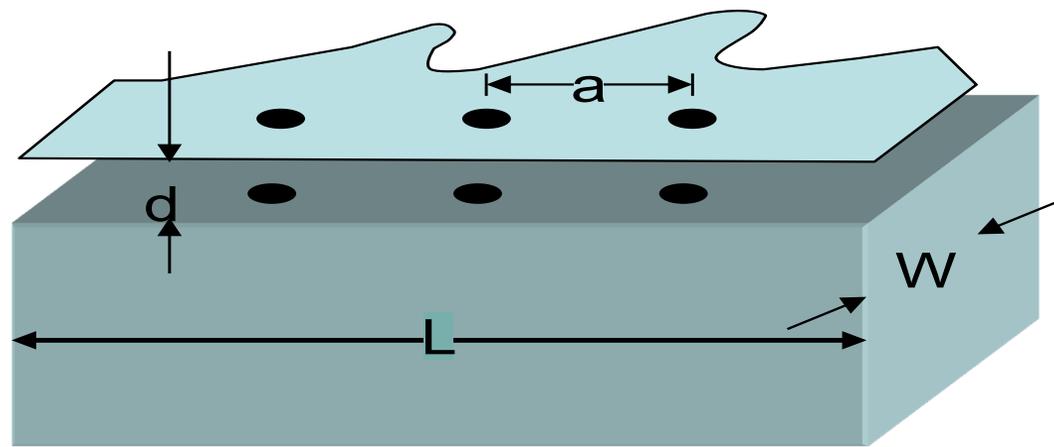
Apertures/Slots

- **Apertures create slot antennas for receiving or radiating**
- **Every aperture reduces the overall shielding effectiveness**
- **For most apertures, the slot depth (W) is typically small compared to the slot length (a), so absorption is insignificant.**
- **The primary consideration is the reflection losses.**
- **The dominant factor is the slot length (L)**
- **Most efficient radiation occurs when length is a half wavelength:**

$$L = {}^1/_2 \lambda \qquad\qquad SE \approx 20 Log\left(\frac{\lambda}{2L}\right) dB$$

Multiple Apertures

- **For a linear array of closely spaced apertures:**

$$SE = 20\log\left(\frac{150}{f_{MHz}L\sqrt{n}}\right) \text{ dB}$$

L = maximum aperture dimension, meters
n = number of apertures

- **This is also applicable to a 2-D aperture array (considering just the first row of holes).**

- **A large number of small holes provides better shielding than one large hole of the same total area.**

Galvanic Series

NAVAIR 01-1A-509
T.O. 1-1-691
TM 1-1500-344-23

Table 2-1. Galvanic Series of Metals and Alloys in Sea Water

ANODIC (High Corrosion Potential)

■ Lithium
　　Magnesium Alloys
　　　Zinc (plate)
　　　　Beryllium
　　　　　Cadmium (plate)
　　　　　　Uranium (depleted)
　　　　　　　Aluminum Alloys
　　　　　　　　Indium
　　　　　　　　　Tin (plate)
　　　　　　　　　　Stainless Steel 430 (active)
　　　　　　　　　　　Lead
　　　　　　　　　　　　1010 Steel
　　　　　　　　　　　　　Cast Iron
　　　　　　　　　　　　　　Stainless Steel 410 (active)
　　　　　　　　　　　　　　　Copper (plate)
　　　　　　　　　　　　　　　　Nickel (plate)
　　　　　　　　　　　　　　　　　AM 350 (active)
　　　　　　　　　　　　　　　　　　Chromium (plate)
　　　　　　　　　　　　　　　　　　　Stainless Steels 350, 310, 301, 304 (active)
　　　　　　　　　　　　　　　　　　　Stainless Steels 430 410 (passive)
　　　　　　　　　　　　　　　　　　　　Stainless Steel 13-8, 17-7PH (active)
　　　　　　　　　　　　　　　　　　　　Brass, yellow, Naval
　　　　　　　　　　　　　　　　　　　　　Stainless Steel 316L (active)
　　　　　　　　　　　　　　　　　　　　　　Bronze 220
　　　　　　　　　　　　　　　　　　　　　　Copper 110
　　　　　　　　　　　　　　　　　　　　　Stainless Steel 347 (active)
　　　　　　　　　　　　　　　　　　　　Copper-Nickel 715
　　　　　　　　　　　　　　　　　　　Stainless Steel 202 (active)
　　　　　　　　　　　　　　　　　　Monel 400
　　　　　　　　　　　　　　　　　　Stainless Steel 201 (active)
　　　　　　　　　　　　　　　　　　Stainless Steels 321 316 (active)
　　　　　　　　　　　　　　　　　　Stainless Steels 309 13-8 17-7 PH (passive)
　　　　　　　　　　　　　　　　　　Stainless Steels 304, 301 321 (passIve)
　　　　　　　　　　　　　　　　　Stainless Steels 201 31 6L (passive)
　　　　　　　　　　　　　　　　Stainless Steel 286 (active)
　　　　　　　　　　　　　　　AM355 (active)
　　　　　　　　　　　　　　Stainless Steel 202 (passive)
　　　　　　　　　　　　　Carpenter 20 (passive)
　　　　　　　　　　　　AM355 (passive)
　　　　　　　　　　　Titanium Alloys
　　　　　　　　　　AM350 (passive)
　　　　　　　　Silver
　　　　　　　　Palladium
　　　　　　Gold
　　　　　Rhodium
　　　　Platinum
　　　Carbon/Graphite

CATHODIC (Low corrosion potential)

Bonding Examples (cont)

Typical dagger pin method for bonding a piece of internal equipment to a chassis. The dagger pins are contained in the rear of the chassis. The equipment slides into the chassis and the strike plate is compressed against the dagger pins.
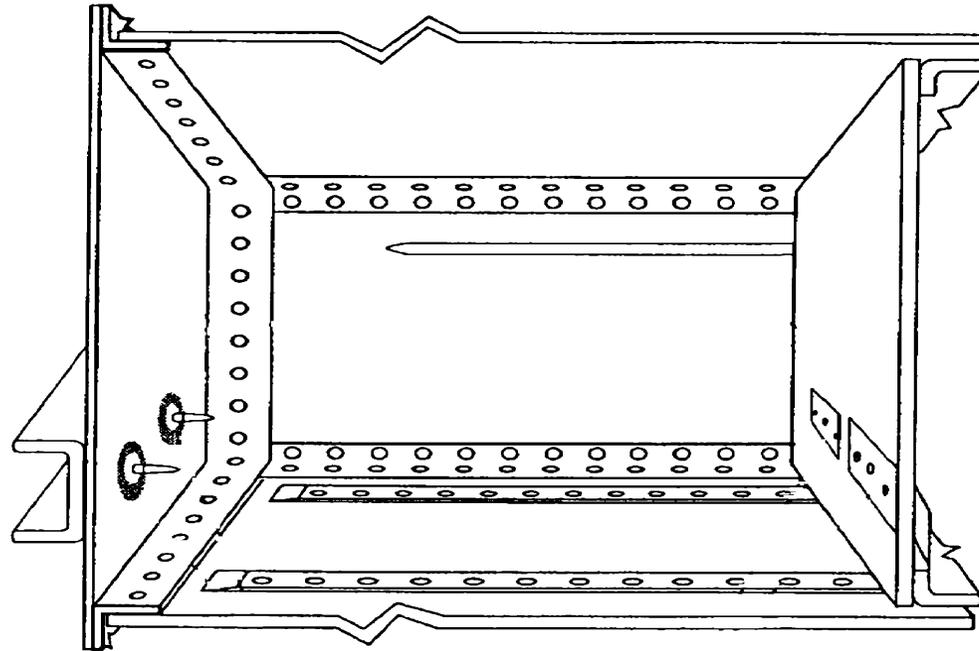
CLEAN TO BASE METAL 1.5 AREA OF CONTACT. REFINISH AFTER INSTALLATION 1.5 AREA CLEANED

CLEAN TO BASE METAL BOTH THE BACK OF EQUIPMENT AND STRIKE PLATE. REFINISH AFTER INSTALLATION OF STRIKE PLATE 1.5 AREA CLEANED

Bond Strap Current and Magnetic Field

CURRENT FLOW
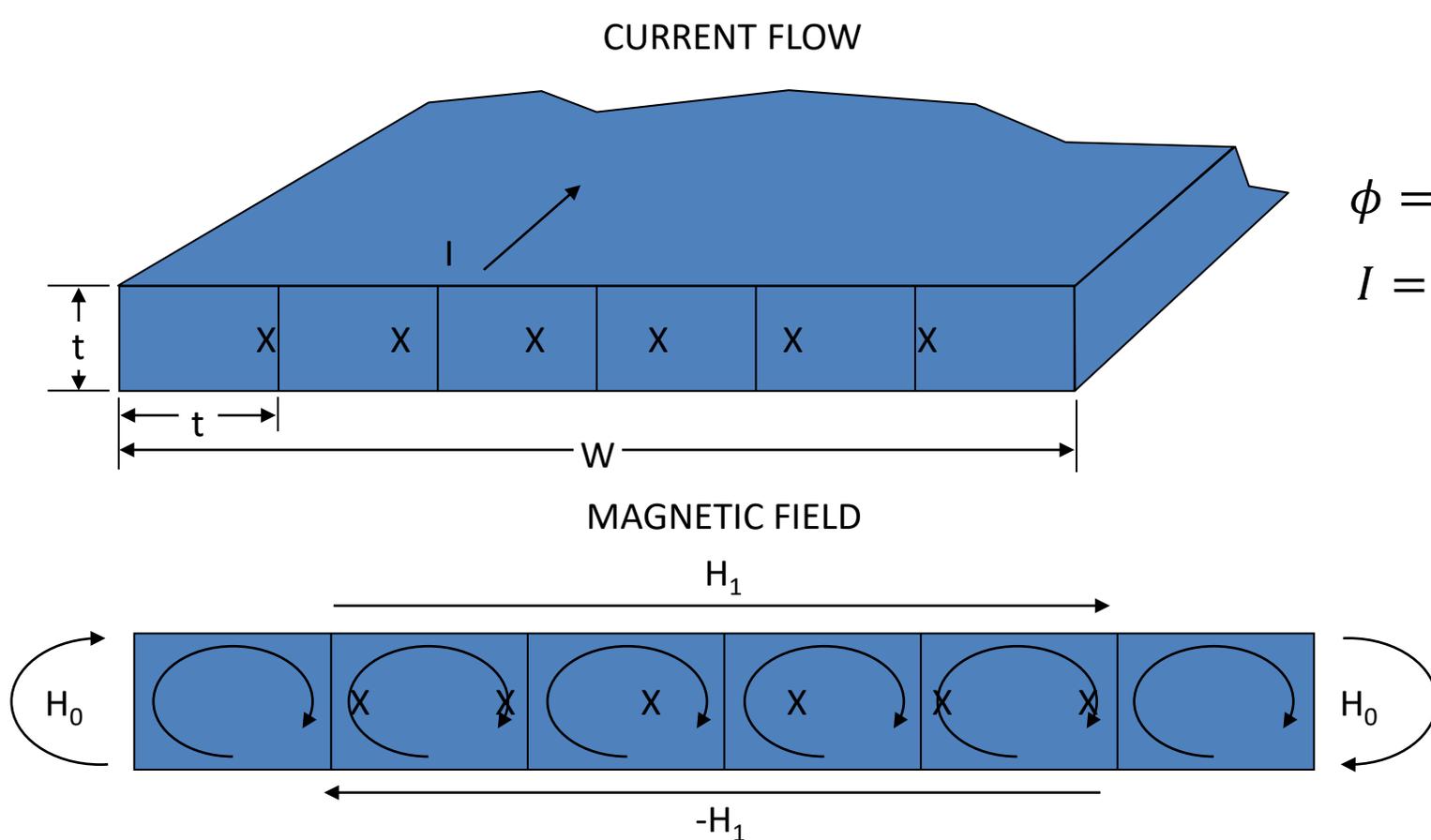
MAGNETIC FIELD

$$L = \frac{\phi}{I}$$

$\phi =$ conductor magnetic flux

$I =$ current

$$H = I \left(\frac{t/w}{\pi r} \right)$$

$t =$ thickness

$w =$ width

$r =$ radius

Wider and thinner bond straps have less inductance

Basic Transmission Line Theory

- **When $Z_L = Z_0$, all of the wave's power will be absorbed into the load and hence no reflections.**

Characteristic Impedance = Z_o

Forward

Reflected

$Z_L = Z_o$

- **When $Z_L \neq Z_0$, there will be an impedance mismatch that will cause the wave to be reflected away from the load.**

Characteristic Impedance = Z_o

Forward

Reflected

$Z_L \neq Z_o$

- **The reflection coefficient is given as:**

$$\rho = \left(\frac{Z_L - Z_0}{Z_L + Z_0} \right)$$

- **Shielding materials behave in a similar manner with Z_L being the shield impedance and Z_0 being the impedance of the transmission medium**

Shield Reflection and Absorption
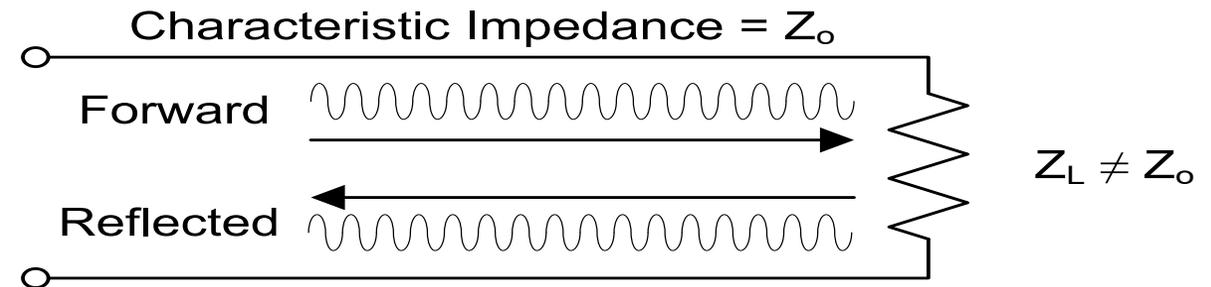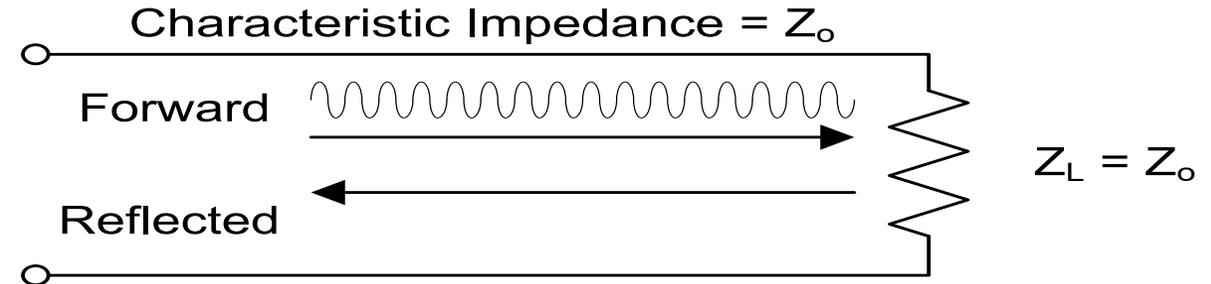
- The shield will reflect the wave if its impedance is appreciably different from that of the transmission medium. The medium is typically air with a plane wave impedance of 377 ohms.

- If the impedance of the wave is greatly different from the intrinsic impedance of the material, most of the energy will be reflected, and very little will be transmitted across the boundary.

- Most metals have an intrinsic impedance on the order of milliohms. Therefore…

- For low impedance fields (H dominant), less energy is reflected, and more is absorbed, because the metal is more closely matched to the impedance of the field. This is why it is more difficult to shield against magnetic fields.

- For high impedance fields (E dominant) most of the energy is reflected, because the metal impedance is orders of magnitude lower than the impedance of the field.

Skin Effect and Skin Depth

Skin effect - the tendency of a high-frequency alternating current to flow through only the outer layer of a conductor

Skin depth - distance required for a wave to be attenuated to 37% of its original value

$$\delta = \frac{2.6}{\sqrt{f \mu_r \sigma_r}} \; inch$$

Skin Depth of Various Materials - Inches

Frequency	Copper	Aluminum	Steel
60 Hz	0.335	0.429	0.034
100 Hz	0.260	0.333	0.026
1 kHz	0.082	0.105	0.008
10 kHz	0.026	0.033	0.003
100 kHz	0.008	0.011	0.0008
1 MHz	0.003	0.003	0.0003
10 MHz	0.0008	0.001	0.0001
100 MHz	0.00026	0.0003	0.00008
1 GHz	0.00008	0.0001	0.00004

Skin depth depends on frequency, permeability, and conductivity

Reflection and Absorption Loss

Magnetic Field Shielding
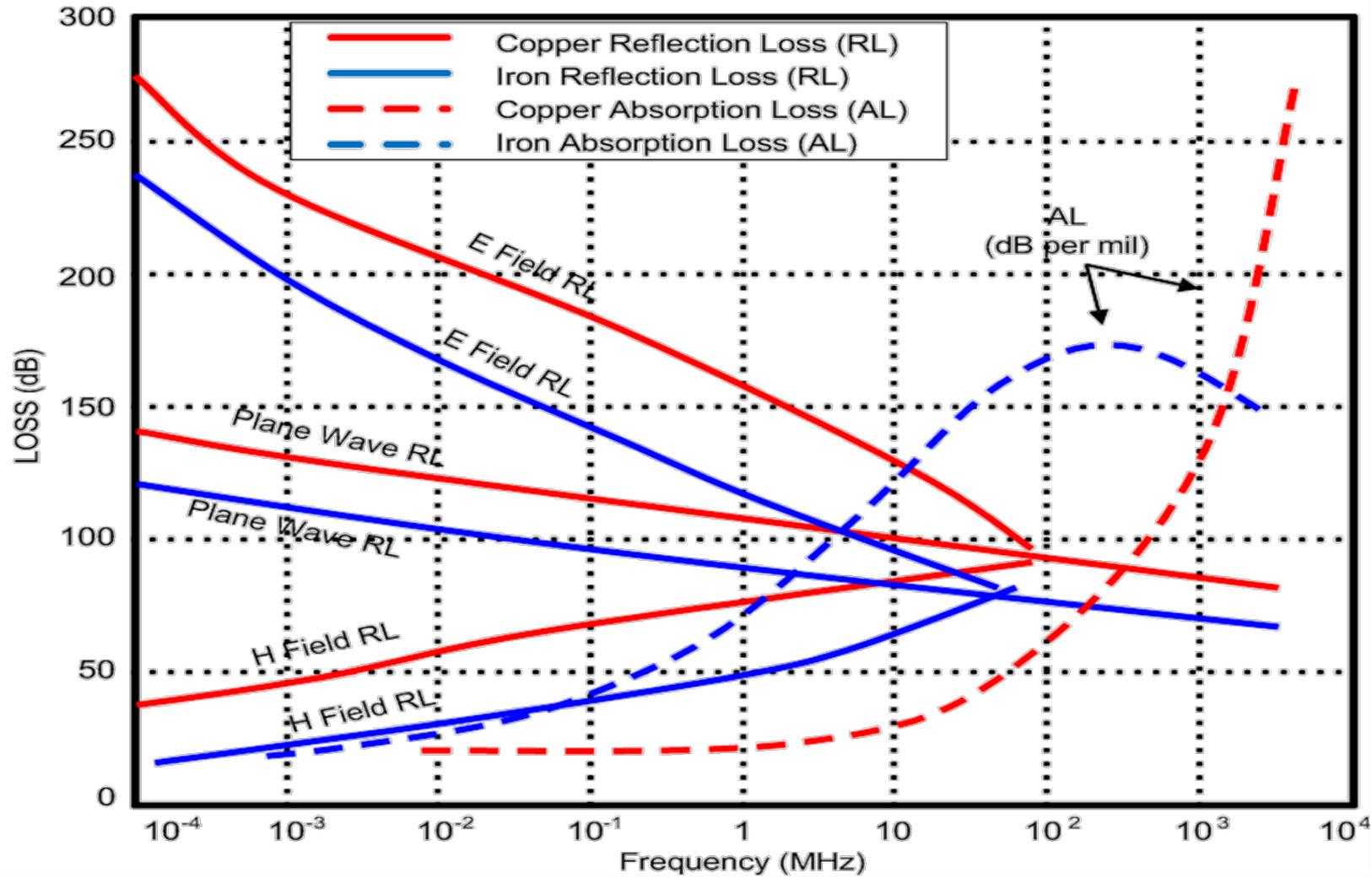
- **Because both reflection loss and absorption loss are low in the near field, low frequency magnetic field shielding is generally difficult**
- **Iron, nickel, their combinations and alloys are more effective in suppressing low frequency magnetic fields**
- **Absorption is the primary mechanism**
- **Use of magnetic material**
  - Increases absorption loss due to higher permeability
  - May decrease shielding of low frequency electric fields due to lower conductivity
- **Specialized materials (high permeability alloys) are available for low frequency magnetic shielding (i.e. Mumetal)**
- **Mechanical distortion or shock will degrade the shielding performance of a high permeability material. This can be corrected by annealing.**

MuMetal

- **Specialized material specifically made for magnetic shielding**

- **MuMetal, an industry reference material defined in MIL-N-14411C**

- **Companies that provide magnetic shielding materials typically offer a version of MuMetal, and some other proprietary alloys**

- **Most of these have a high nickel content, with either 50% or 80% nickel in the mix**

Round Perforations
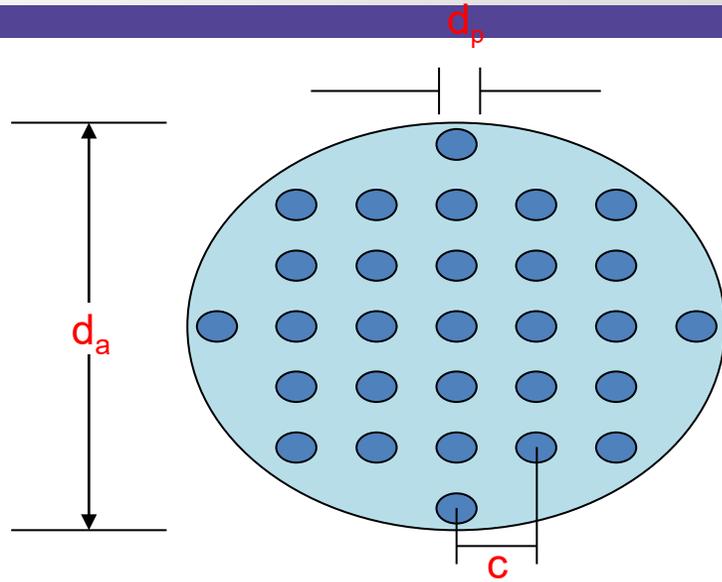
For round perforations and a round aperture:

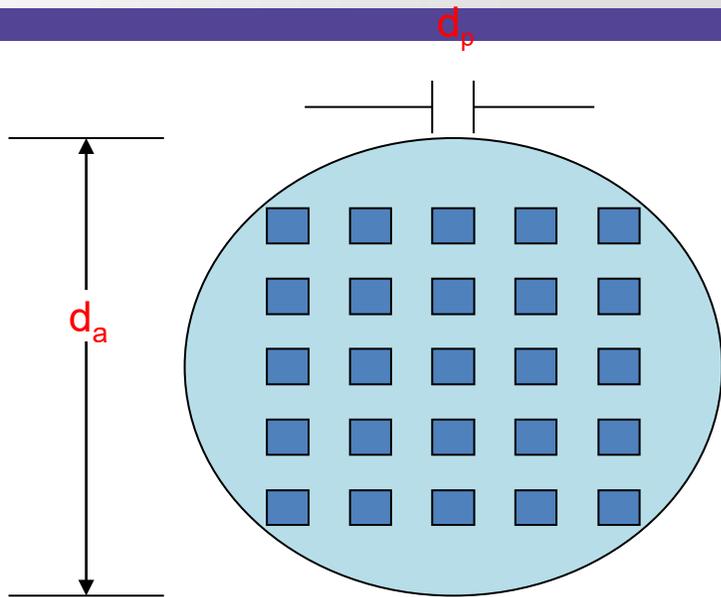$$SE_{high} = 20Log\left(\frac{c^2 d_a}{d_p^3}\right) + 41.8\frac{t}{d_p} + 2.08$$

$$SE_{low} = 20Log\left(\frac{c^2 d_a}{d_p^3}\right) + 32\frac{t}{d_p} + 2.01$$
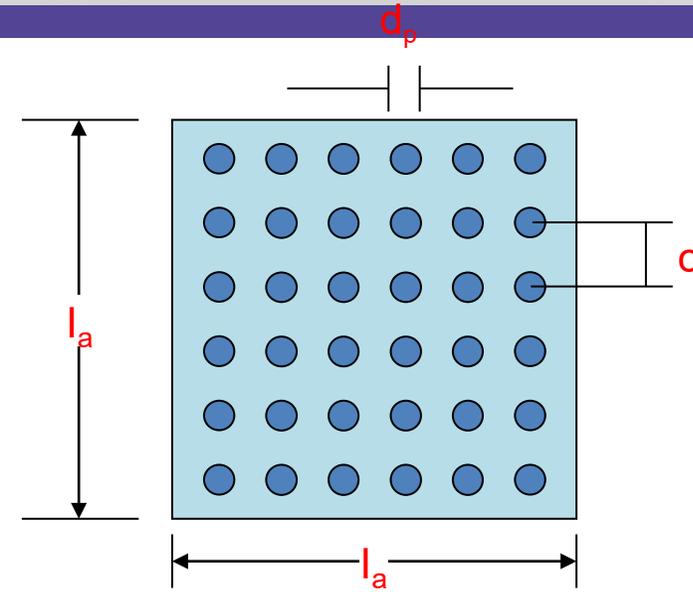
For round perforations and a square aperture:

$$SE_{high} = 20Log\left(\frac{c^2 I_a}{d_p^3}\right) + 41.8\frac{t}{d_p} + 2.68$$

$$SE_{low} = 20Log\left(\frac{c^2 I_a}{d_p^3}\right) + 32\frac{t}{d_p} + 3.84$$

Square Perforations

d_p

l_a

l_p

d_a

c

For square perforations and a round aperture:

$$SE_{high} = 20Log\left(\frac{c^2 d_a}{d_p^3}\right) + 38.6\frac{t}{d_p} + 0.06$$
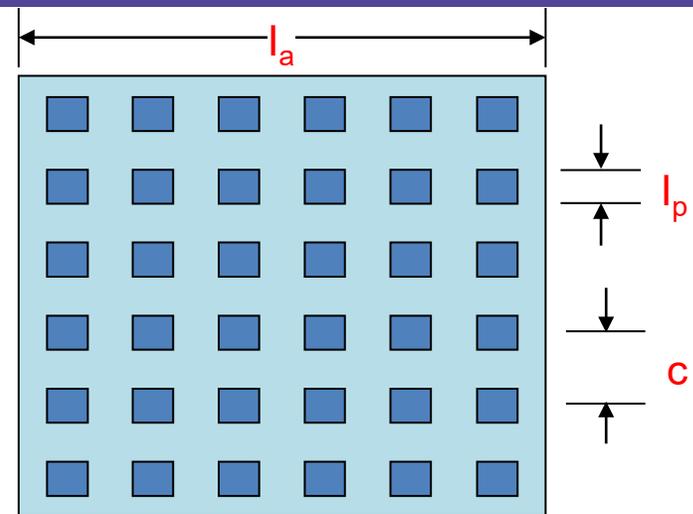
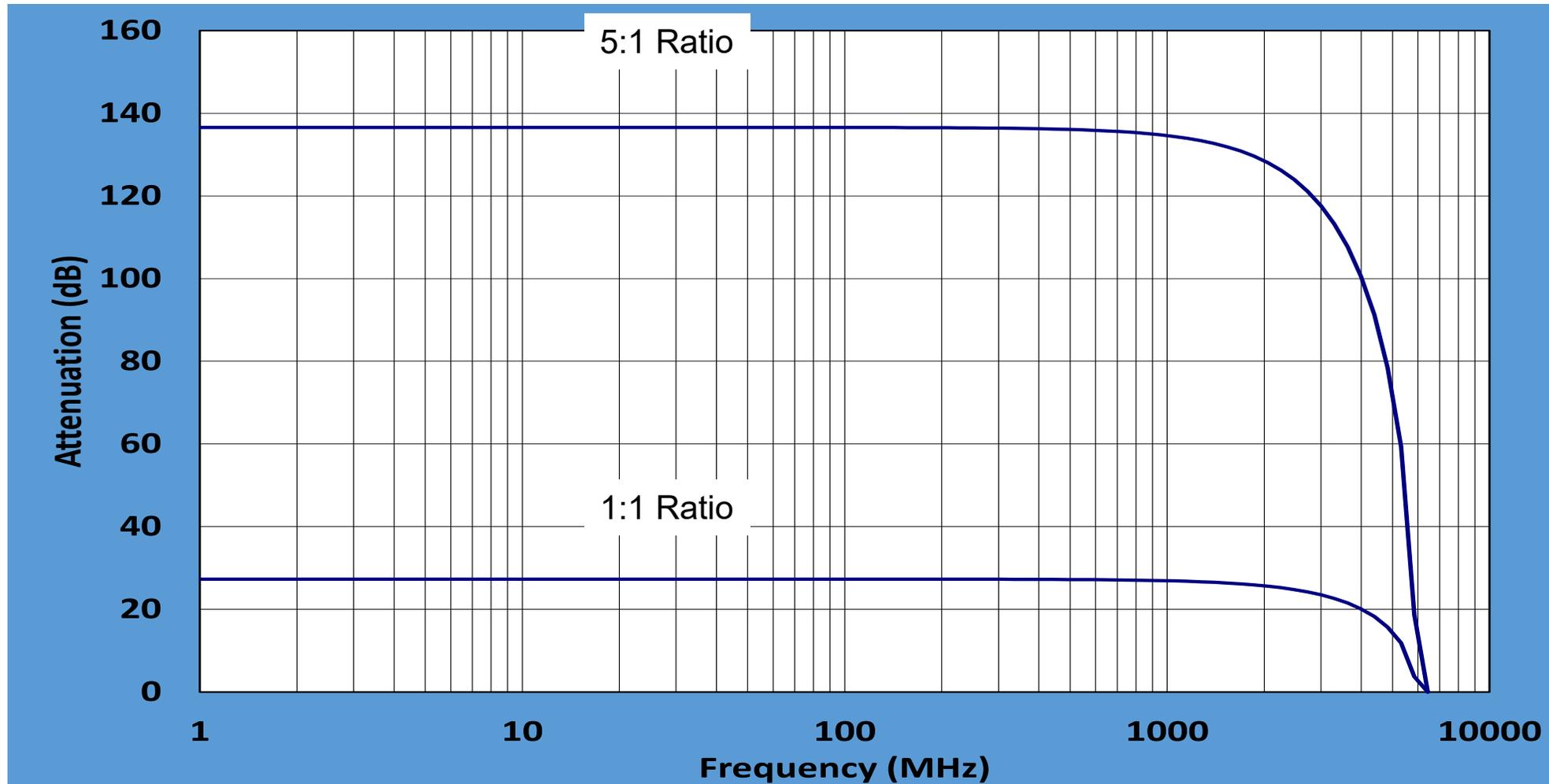$$SE_{low} = 20Log\left(\frac{c^2 d_a}{d_p^3}\right) + 27.3\frac{t}{d_p} + 1.76$$

For square perforations and a square aperture:

$$SE_{high} = 20Log\left(\frac{c^2 I_a}{I_p^3}\right) + 38.6\frac{t}{I_p} + 2.68$$

$$SE_{low} = 20Log\left(\frac{c^2 I_a}{I_p^3}\right) + 27.3\frac{t}{I_p}$$

Waveguide-Below-Cutoff

The higher the depth to width ratio, the higher the attenuation

WOVEN WIRE GASKETS

Characteristics	The woven wire gasket is normally a sheet material that is made up of densely woven wire screen with the openings filled with silicone or neoprene elastromer. This assembly results in a thin, semi-flexible, reinforced sheet that can be utilized as a pressure seal.
Problems or Limitations	If a combination woven wire-environmental seal-type gasket is used, the environmental seal should be installed so as to protect the gasket against an undesirable environment. Note: Enough pressure must be exerted on the woven wire gasket to create a low resistance bond, without causing a compression beyond the elastic properties of the gasket.

ELASTOMER GASKETS

Characteristics	The elastomer gasket is normally a sheet material that is made up of densely woven wire screen with the openings filled with silicone or neoprene elastromer. This assembly results in a thin, semi-flexible, reinforced sheet that can be utilized as a pressure seal.
Problems or Limitations	If a combination woven wire-environmental seal-type gasket is used, the environmental seal should be installed so as to protect the gasket against an undesirable environment. Note: Enough pressure must be exerted on the elastomer gasket to create a low resistance bond, without causing a compression beyond the elastic properties of the gasket.

Fabric Over Foam Gaskets

Characteristics	Typically plated polyester or nylon (woven or non-woven) fabric over urethane or TPE (thermoplastic elastomer) cores. Platings typically are nickel-copper, nickel-silver, copper or carbon-silver. Alternately, aluminum foil fabrics can be used. Fabric over foam gaskets are made either by wrapping pre-cut, cured cores or by dispensing liquid foam into a jacket which is then cured in-line.
Problems or Limitations	Disadvantages can be compression set, (depending on the foam used), and performance in shear.

FINGERSTOCK GASKETS

Characteristics	A fingerstock gasket is a conductive metal finger strip that is fitted to a part of an electric or electronic apparatus that is used to block EMI.
Problems or Limitations	Fingerstock must be protected from damage, since it is unusually brittle and can only be flexed in one direction and is unreliable for magnetic field control unless the finger stock is installed in multiple rows. The use of fingerstock is generally not advisable in most cases because it is expensive and the cost of incorporating it into most design configurations is prohibitive. Maximum attenuation that can be expected from a single row of finger stock is about 60 dB.

CONDUCTIVE SEALING MATERIALS

Characteristics	Pastes and epoxies having a conductive filler.
Problems or Limitations	Can generally only be used on assemblies that are non-repairable. During disassembly, the surfaces to which this material has been applied must be stripped to clean metal, which is generally impractical, if not impossible, to do. Field maintenance facilities must have the exact replacement sealing material available.

Visual Display Solutions

## Commonly Used Shielding Solutions For Visual Displays

Shielding and filtering the display elements	This provides an unobstructed view of the display, but necessitates rather complex shielding and filtering. The salient features of this solution involve shielding the display in its own housing and filtering each and every line into it, with the added expenses of components, packaging and labor.
Using a conductive mesh screen across the viewing port	Using a mesh or transparent conductive coating is a simpler solution which does tend to obstruct the view. Video display terminals and the like use the mesh solution to shielding integrity maintenance. The wire material in the mesh, the wire diameter and the density of the weave measured in strands per inch, are all parameters which determine both the optical and electromagnetic transparency and shielding. Screens provide almost no shielding to low frequency magnetic fields, and values of 40 to 60 dB in electric field shielding for frequencies up to hundreds of MHz are typical. The installation details must provide a peripheral conductive bond of the mesh frame to the panel, using either a conductive gasket or sufficient bolt density to ensure shielding integrity across the screen panel seam.
Plating the transparent face of the display	When mesh screens cannot be used as shields, especially due to optical considerations, a semi-transparent conductive coating is used. The coating is generally applied to the transparent substrate by vaporizing the conductive material onto the substrate. The high temperatures required precludes plastic substrates, so that optical glass is used for this solution. The plating is thin enough that some light passes through it, and thick enough that it is conductive and provides a reflective surface to electromagnetic waves of high impedance (but not to low impedance magnetic fields). The degree of reflection depends on the surface conductivity; the lower it gets, the better the reflection loss and the shielding.

Conductive Paints

- **Binder**

- **Urethane or acrylic**

- **Conductive Pigment**

- **Silver, copper, nickel or graphite**

- **Surface conductivity is typically one or two orders of magnitude less than pure metal**

- **Conductivity only through conductive particles**

- **Inexpensive**

- **Adequate pressure required**

Electroless Plating

- Depositing a metal coating by controlled chemical process

- Two step process

- Thin layer of nickel

- Thick layer of copper

- Uniform coating

- Good conductivity

- Approaching that of pure metal

- Can be used on complex shapes

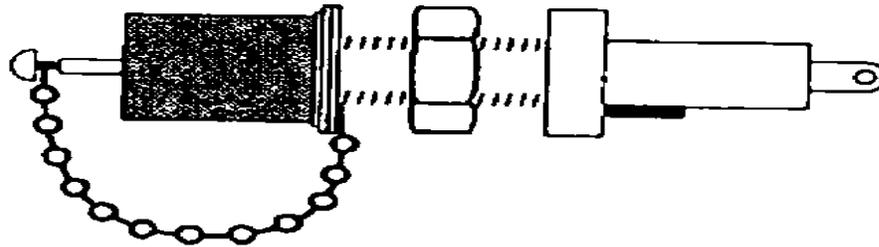- Expensive

Conductively Filled Plastics

- **Conductive agent mixed with plastic resin prior to injection molding**

- **Conductive agent**

- **Aluminum flakes**

- **Nickel or silver coated carbon fibers**

- **Stainless steel fibers**

- **Limited conductivity**

- **Wide ranging and not well controlled**

- **Does not require secondary coating step**
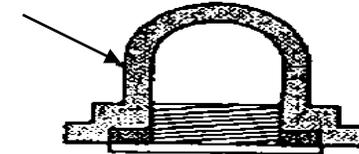
- **Expensive**

Other Shielding Solutions

Knitted Wire Mesh Embedded in a Rubber Boot
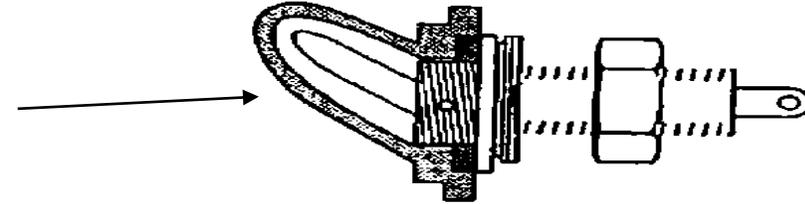
Shielded Toggle Switch

Knitted Monel Wire Mesh In A Rubber Cap

Shielded Pushbutton Switch
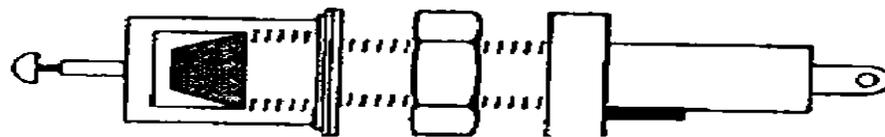
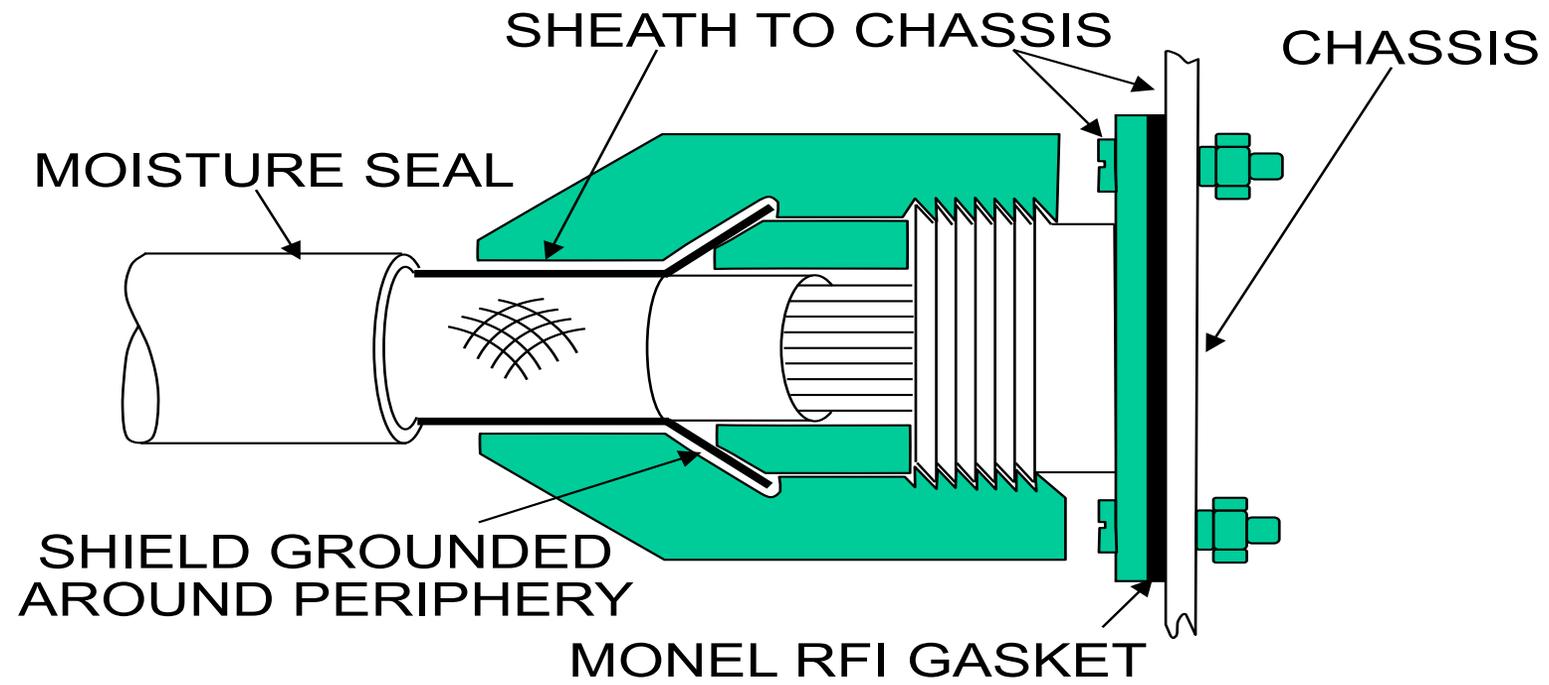Shield Cap Assembly

Shielded Fuse Holder

Knitted Monel Wire Mesh Embedded In A Transparent Plastic Cap

Shielded Panel Lamp

Bonding Examples (cont)

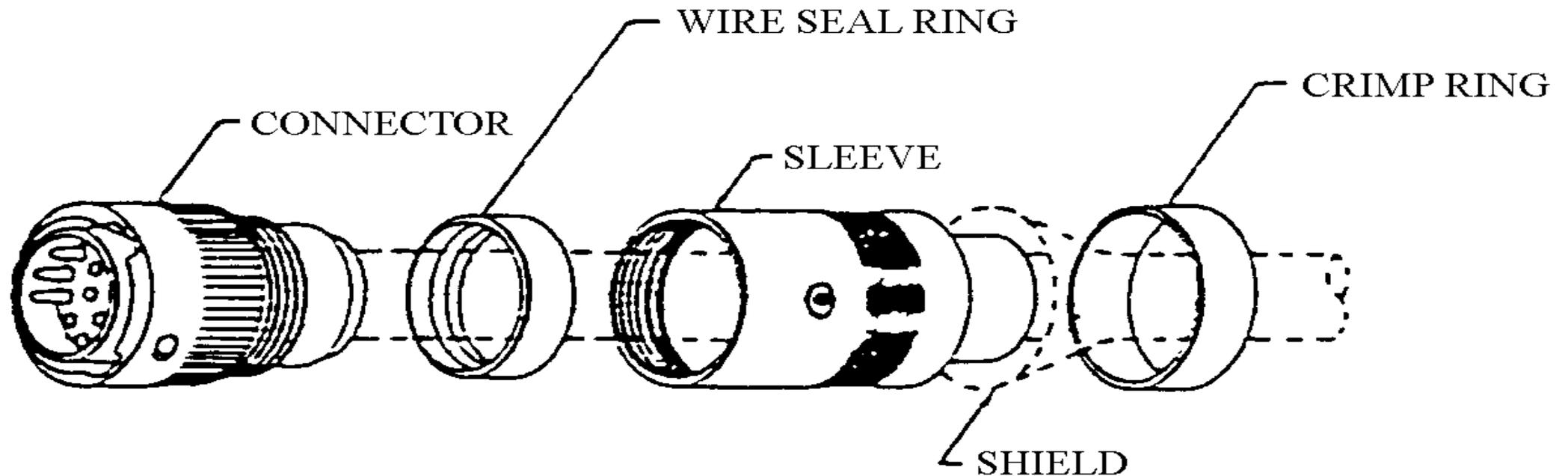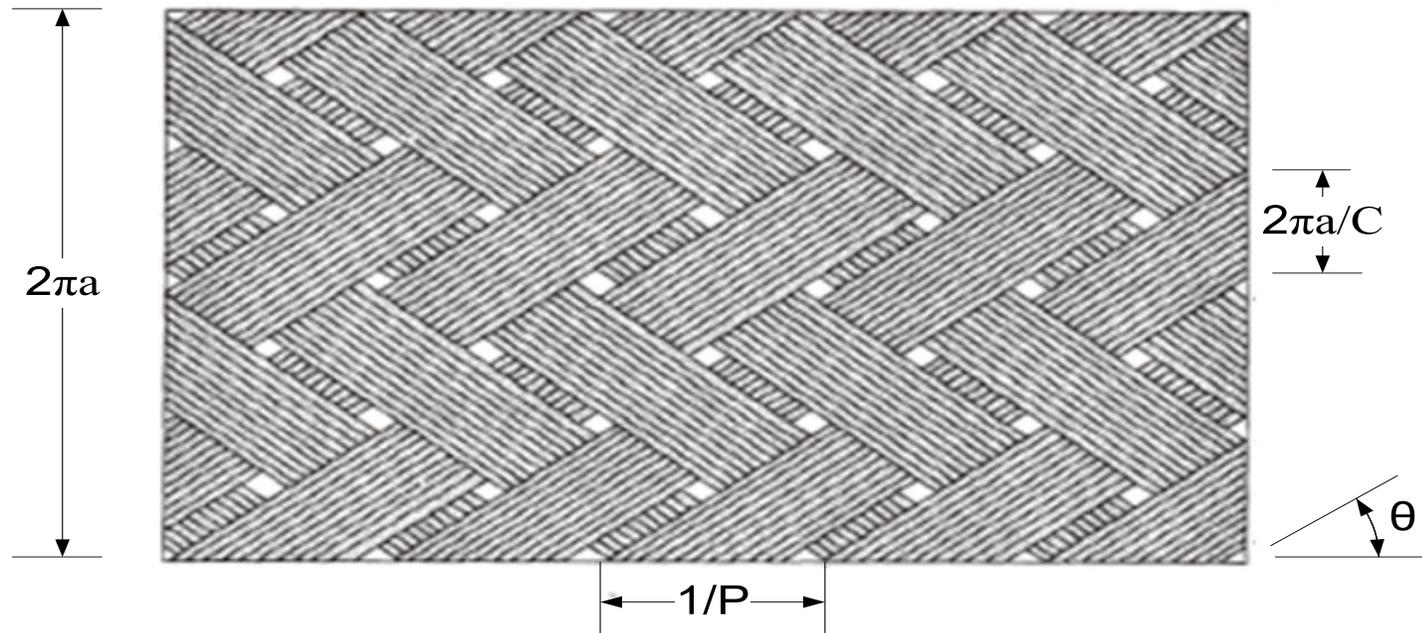**Typical method for bonding a cable shield to a connector using a conical backshell fitting. The shield is bonded to the connector in a 360 degree fashion using the connector backshell to compress the shield**

Crimping

- **In this arrangement the cable shield is flared so that it extends over the rear portion of the sleeve, and the crimp ring is slid into place over the sleeve. A crimping tool is then used to crimp the crimp ring onto the sleeve**
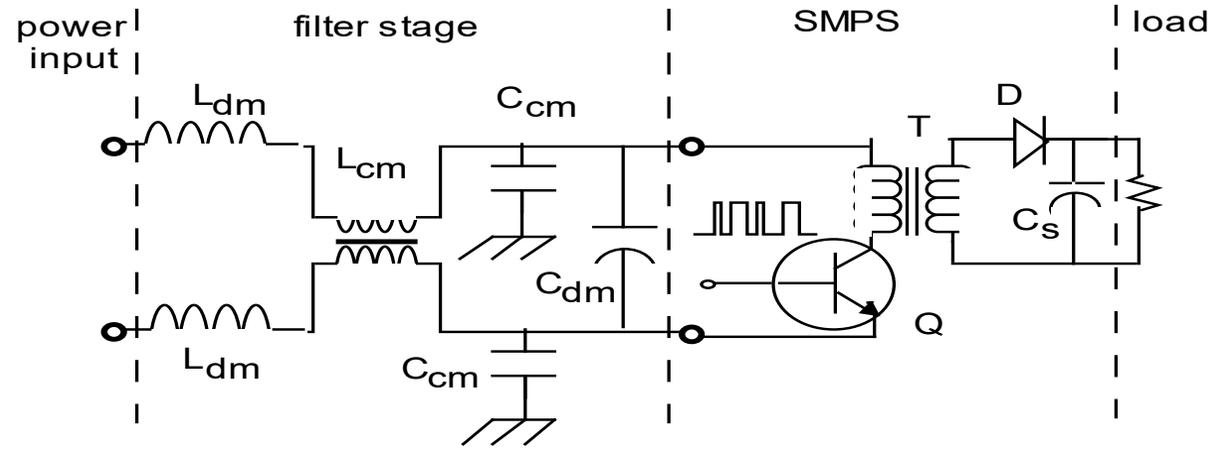
Anatomy of a Cable Shield

Weave Angle

$$\theta = \tan^{-1}\left(\frac{4\pi a p}{C}\right)$$

Fill Factor

$$F = \frac{pNd}{\sin\theta}$$

Optical Coverage

$$OC = 2F \times F^2$$

$N =$ Strands per carrier

$a =$ Radius of the shield

$d =$ Wire diameter

$p =$ Number of picks

$C =$ Carriers

SMPS Generic EMI Filter Configuration

- **L_{dm}** - differential mode choke, typically tens of µH, raises the impedance of the power source at RF and makes the capacitor a more effective decoupling mechanism

- **L_{cm}** - common mode choke, typically presents on the order of 1 mH inductance to common mode currents, raising the impedance of this path in order to make the internal path more effective

- **C_{cm}** - line-to-ground, installation for containing common mode currents inside equipment; provides a low impedance for cm current circulation within the equipment

- **C_{dm}** - line-to-line, large value capacitor, typically electrolytic, provides low source impedance for SMPS; also provides hold-up during power surge/sag

Filter Connectors

- **Filter connectors offer flexibility for cables with a mix of signal types**

- **Planar array consists of planar ceramic capacitor arrays and discrete ferrite inductors assembled concentrically over the contacts and into the connector shell.**

- **Tubular style consists of a ferrite bead and ceramic tubular capacitor assembled onto a machined contact. Grounding is achieved via a ground plate.**
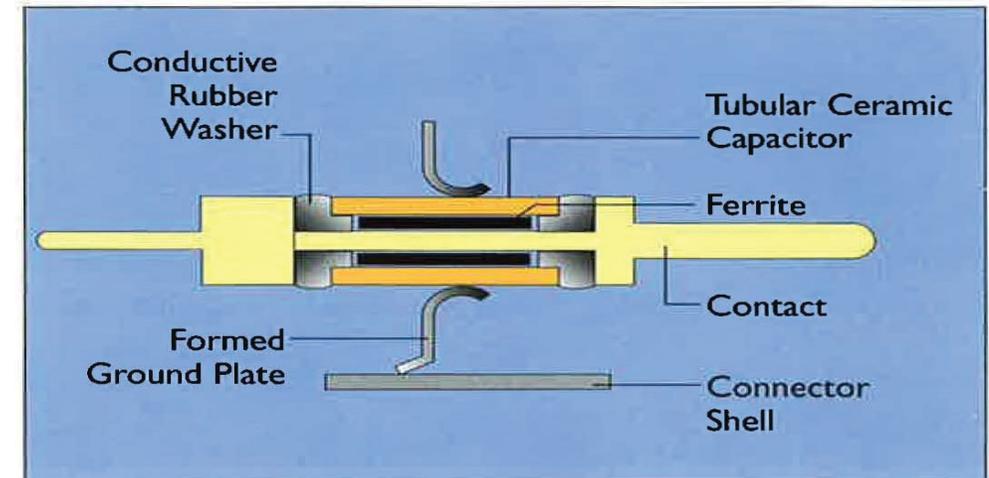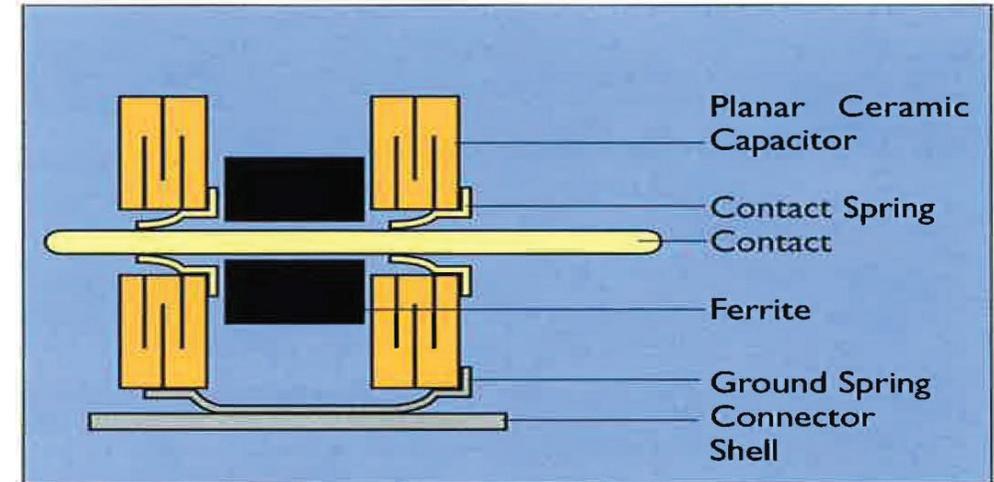
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DISA

Links for Additional Information

Certificates for Completion of Training will be emailed upon receipt of the Training Survey. Request attendees email training surveys to:

- **To: brianb@e3as.com,**
- **Cc: matthew.z.grenis.civ@mail.mil; brianf@e3as.com**

Additional E3/Spectrum information, course descriptions, and to register for courses:

- **DAU - https://www.dau.edu/cop/e3/Pages/Default.aspx**
- **Facebook - https://www.facebook.com/SpectrumE3/**

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