EMC Design Fundamentals

James Colotti
EMC Certified by NARTE
Staff Analog Design Engineer
Telephonics - Command Systems Division
Outline

♦ Introduction
  - Importance of EMC
  - Problems with non-compliance

♦ Concepts & Definitions

♦ Standards
  - FCC, US Military, EU, RTCA

♦ Design Guidelines and Methodology
  - EM Waves, Shielding
  - Layout and Partitioning
  - Power Distribution
  - Power Conversion
  - Signal Distribution

♦ Design Process

♦ References and Vendors
Introduction
Importance of EMC

♦ Electromagnetic Compatibility (EMC) requires that systems/equipment be able to tolerate a specified degree of interference and not generate more than a specified amount of interference

♦ EMC is becoming more important because there are so many more opportunities today for EMC issues

♦ Increase use of electronic devices
  - Automotive applications
  - Personal computing/entertainment/communication

♦ Increased potential for susceptibility/emissions
  - Lower supply voltages
  - Increasing clock frequencies, faster slew rates
  - Increasing packaging density
  - Demand for smaller, lighter, cheaper, lower-power devices
# Problems with Non-Compliance

- Product may be blocked from market
- Practical impact can be minor annoyance to lethal ...and everything in between

<table>
<thead>
<tr>
<th>Annoyance, Delays</th>
<th>Lost Revenue, Minor Property Loss</th>
<th>Significant Property Loss</th>
<th>Death or Serious Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM/FM/XM/TV</td>
<td>Critical communications</td>
<td>RAIDER, Landing System</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interference</td>
<td>Interruption</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cell Phone</td>
<td>Erroneous Ordnance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interference</td>
<td>Firing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Improper Deployment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>of Airbags</td>
<td></td>
</tr>
<tr>
<td><strong>Major</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Non-Compliance (continued)

- Fortunately, industry is well regulated and standards are comprehensive
- Major EMC issues are relatively rare
- For cost-effective compliance
  - EMC considered throughout product/system development
Concepts & Definitions
Electromagnetic Interference (EMI)
- Electromagnetic emissions from a device or system that interfere with the normal operation of another device or system
- Also referred to as Radio Frequency Interference (RFI)

Electromagnetic Compatibility (EMC)
- The ability of equipment or system to function satisfactorily in its Electromagnetic Environment (EME) without introducing intolerable electromagnetic disturbance to anything in that environment
- In other words:
  Tolerate a specified degree of interference,
  Not generate more than a specified amount of interference,
  Be self-compatible
For an EMC problem to exist:
- System/Device that generates interference
- System/Device that is susceptible to the interference
- Coupling path

Mitigation of EMC Issues
- Reduce interference levels generated by culprit
- Increase the susceptibility (immunity) threshold of the victim
- Reduce the effectiveness of the coupling path
- Combination of the above

<table>
<thead>
<tr>
<th>Source (Culprit)</th>
<th>Coupling Path</th>
<th>Receiver (Victim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modify Signal Routing</td>
<td>Increase Separation</td>
<td>Modify Signal Routing</td>
</tr>
<tr>
<td>Add Local Filtering</td>
<td>Shielding</td>
<td>Add Local Filtering</td>
</tr>
<tr>
<td>Operating Freq Selection</td>
<td>Reduce # of Interconnections</td>
<td>Operating Freq Selection</td>
</tr>
<tr>
<td>Freq Dithering</td>
<td>Filter Interconnections</td>
<td></td>
</tr>
<tr>
<td>Reduce Signal Level</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Standards
Some of the Institutes that Establish EMC Standards

- Federal Communication Commission (FCC)
- US Military
- European Union (EU)
- Radio Technical Commission for Aeronautics (RTCA)

This lecture’s main focus is on EMC Fundamentals, not:
- Electro Static Discharge (ESD)
- Direct Lightning Effects
- Antenna Lead Conducted Emissions/Susceptibility
- RF Radiation Safety
## FCC Part 15

### Conducted Emissions

<table>
<thead>
<tr>
<th>Class</th>
<th>Frequency (MHz)</th>
<th>Quasi-Peak Limit (dBuV)</th>
<th>Average Limit (dBuV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>0.15 – 0.5</td>
<td>79</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>0.5 – 30.0</td>
<td>73</td>
<td>60</td>
</tr>
<tr>
<td>Class B</td>
<td>0.15 – 0.5</td>
<td>66 to 56 *</td>
<td>56 to 46 *</td>
</tr>
<tr>
<td></td>
<td>0.5 – 5</td>
<td>56</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>5 - 30</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>

*Decrease as logarithm of frequency*
## General Radiated Emission

<table>
<thead>
<tr>
<th>Class</th>
<th>Frequency (MHz)</th>
<th>Field Strength Limit (μV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10 meters)</td>
<td>30 – 88</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>88 – 216</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>216 – 960</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>above 960</td>
<td>300</td>
</tr>
<tr>
<td><strong>Class B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3 meters)</td>
<td>30 – 88</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>88 – 216</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>216 – 960</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>above 960</td>
<td>500</td>
</tr>
</tbody>
</table>
MIL-STD-461E

- Requirements for the Control of EMI Characteristics of Subsystems & Equipment

<table>
<thead>
<tr>
<th>Req’t</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE101</td>
<td>Conducted Emissions, Power Leads, 30 Hz to 10 kHz</td>
</tr>
<tr>
<td>CE102</td>
<td>Conducted Emissions, Power Leads, 10 kHz to 10 MHz</td>
</tr>
<tr>
<td>CE106</td>
<td>Conducted Emissions, Antenna Terminal, 10 kHz to 40 GHz</td>
</tr>
<tr>
<td>CS101</td>
<td>Conducted Susceptibility, Power Leads, 30 Hz to 50 kHz</td>
</tr>
<tr>
<td>CS103</td>
<td>Conducted Susceptibility, Antenna Port, Intermodulation, 15 kHz to 10 GHz</td>
</tr>
<tr>
<td>CS104</td>
<td>Conducted Susceptibility, Antenna Port, Rejection of Undesired Signals, 30 Hz to 20 GHz</td>
</tr>
<tr>
<td>CS105</td>
<td>Conducted Susceptibility, Antenna Port, Cross Modulation, 30 Hz to 20 GHz</td>
</tr>
<tr>
<td>CS109</td>
<td>Conducted Susceptibility, Structure Current, 60 Hz to 100 kHz</td>
</tr>
<tr>
<td>CS114</td>
<td>Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz</td>
</tr>
<tr>
<td>CS115</td>
<td>Conducted Susceptibility, Bulk Cable Injection, Impulse Excitation</td>
</tr>
<tr>
<td>CS116</td>
<td>Conducted Susceptibility, Dampened Sinusoidal Transients, Cables &amp; Power Leads, 10 kHz to 100 MHz</td>
</tr>
<tr>
<td>RE101</td>
<td>Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz</td>
</tr>
<tr>
<td>RE102</td>
<td>Radiated Emissions, Electric Field, 10 kHz to 18 GHz</td>
</tr>
<tr>
<td>RE103</td>
<td>Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz to 40 GHz</td>
</tr>
<tr>
<td>RS101</td>
<td>Radiated Susceptibility, Magnetic Field, 30 Hz to 100 kHz</td>
</tr>
<tr>
<td>RS103</td>
<td>Radiated Susceptibility, Electric Field, 10 kHz to 40 GHz</td>
</tr>
<tr>
<td>RS105</td>
<td>Radiated Susceptibility, Transient Electromagnetic Field</td>
</tr>
</tbody>
</table>
## EU Standard Examples (Emissions)

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN50081-1</td>
<td>Generic emissions standard for residential, commercial and light industrial environments.</td>
</tr>
<tr>
<td>EN50081-2</td>
<td>Generic emissions standard for industrial environment</td>
</tr>
<tr>
<td>EN55022</td>
<td>Limits and methods of measurement of radio disturbance characteristics of information technology equipment</td>
</tr>
<tr>
<td></td>
<td>(Also known as CISPR-22)</td>
</tr>
<tr>
<td>EN55011</td>
<td>Industrial, scientific and medical (ISM) radio frequency equipment - Radio disturbance characteristics - Limits and methods of measurement</td>
</tr>
<tr>
<td></td>
<td>(Also known as CISPR-11)</td>
</tr>
<tr>
<td>EN55013</td>
<td>Limits and methods of measurement of radio disturbance characteristics of broadcast receivers and associated equipment</td>
</tr>
<tr>
<td>EN55014-1</td>
<td>Emission requirements for household appliances, electric tools and similar apparatus</td>
</tr>
<tr>
<td>EN55015</td>
<td>Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment</td>
</tr>
<tr>
<td>EN61000-3-2</td>
<td>Limits for harmonic current emissions (equipment input current up to and including 16 A per phase)</td>
</tr>
<tr>
<td>EN61000-3-3</td>
<td>Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems</td>
</tr>
</tbody>
</table>
## EU Standard Examples (Immunity)

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN61000-4-2</td>
<td>Electrostatic Discharge</td>
</tr>
<tr>
<td>EN61000-4-3</td>
<td>Radiated Susceptibility Test</td>
</tr>
<tr>
<td>EN61000-4-4</td>
<td>Electrical Fast Transient/Burst Test</td>
</tr>
<tr>
<td>EN61000-4-5</td>
<td>Surge Test</td>
</tr>
<tr>
<td>EN61000-4-6</td>
<td>Conducted Immunity Test</td>
</tr>
<tr>
<td>EN61000-4-8</td>
<td>Power Frequency Magnetic Test</td>
</tr>
<tr>
<td>EN61000-4-11</td>
<td>Voltage Dips and Interruptions Test</td>
</tr>
<tr>
<td>EN61000-6-1</td>
<td>Immunity for residential, commercial and light-industrial environments</td>
</tr>
<tr>
<td>EN61000-6-2</td>
<td>Immunity for industrial environments</td>
</tr>
<tr>
<td>EN61547</td>
<td>Equipment for general lighting purposes — EMC immunity requirements</td>
</tr>
<tr>
<td>EN12016</td>
<td>Electromagnetic compatibility — Product family standard for lifts, escalators and passenger conveyors — Immunity</td>
</tr>
</tbody>
</table>
## Standard Example - RTCA

- **DO-160, Environmental Conditions & Test Procedures for Airborne Equipment**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Power Input</td>
<td>115 VAC, 28 VDC and 14 VDC Power Voltage/frequency range, interruptions, surges</td>
</tr>
<tr>
<td>17</td>
<td>Voltage Spike</td>
<td>Power Leads Up to 600 V or 2x Line Voltage</td>
</tr>
<tr>
<td>18</td>
<td>Audio Frequency Conducted Susceptibility – Power Inputs</td>
<td>0.01 - 150 kHz or 0.2 - 15 kHz</td>
</tr>
<tr>
<td>19</td>
<td>Induced Signal Susceptibility</td>
<td>Interconnection Cabling E field and H Field 400 Hz – 15 kHz and spikes</td>
</tr>
<tr>
<td>20</td>
<td>Radio Frequency Susceptibility (Radiated and Conducted)</td>
<td>Conducted: 0.01-400 MHz Radiated: 0.1-2, 8 or 18 GHz</td>
</tr>
<tr>
<td>21</td>
<td>Emission of Radio Frequency</td>
<td>Power Lines: 0.15-30 MHz Interconnecting Cables: 0.15-100 MHz Radiated: 2-6,000 MHz</td>
</tr>
<tr>
<td>22</td>
<td>Lightning Induced Transient Susceptibility</td>
<td>Pin &amp; Bulk injection, Pulse &amp; Dampened Sine</td>
</tr>
</tbody>
</table>
Standard Summary

♦ Numerous EMC standards exist

♦ Common Fundamental Theme
  - Conducted Emission Limits
  - Radiated Emission Limits
  - Conducted Susceptibility (Immunity) Limits
  - Radiated Susceptibility (Immunity) Limits
Design Guidelines and Methodology
Electromagnetic Waves

- Electromagnetic waves consist of two orthogonal fields
  - Electric, E-Field (V/m)
  - Magnetic, H-Field (A/m)
- Wave Impedance, $Z_W = E/H \ \Omega$
Electromagnetic Waves

- E-Fields, high impedance, wire (dipole)
- H-Fields, low impedance, current loops (xformer)
- In far field, all waves become plane waves

\[ d > \frac{\lambda}{2\pi} \]

Far Field for a Point Source

\[ Z_W = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \sqrt{\frac{4\pi \cdot 10^{-7} \frac{H}{m}}{\frac{1}{36\pi} \cdot 10^{-9} \frac{F}{m}}} = 120\pi = 377 \ \Omega \]

Impedance of Plain Wave
Shielding

- **Enclosure/Chassis**
  - Mechanical Structure
  - Thermal Path
  - Can form an overall shield (important EMC component)
  - Can be used as “first” line of defense for Radiated emission/susceptibility

- **Some Applications Cannot Afford Overall Shield**
  - Rely of other means of controlling EMC

- **Enclosure material**
  - Metal
  - Plastic with conductive coating
    (Conductive paint or vacuum deposition)
Shielding Illustration

- Incident Wave
- Reflected Wave
- Absorptive Loss (A)
- Secondary Reflections
- Transmitted Wave
- Shield Thickness (t)
Shielding Effectiveness

Shielding effectiveness (SE) is a measure of how well an enclosure attenuates electromagnetic fields.

\[ SE_{dB} = 20 \log_{10} \left( \frac{E_{\text{Inside}}}{E_{\text{Outside}}} \right) \]

Theoretical SE of homogeneous material
- Reflective losses, R
- Absorption losses, A and
- Secondary reflective losses, B (ignore if A > 8 dB)

\[ SE = R + A + B \Rightarrow SE = R + A \]
SE Equations

\[ R_h = 20 \log_{10} \left[ \left( \frac{0.462}{r} \right) \sqrt{\frac{\mu_r}{f \sigma_r}} + \frac{0.136r}{\sqrt{f \sigma_r}} + 0.354 \right] \]

Magnetic Field Reflective Loss

\[ R_e = 354 - 10 \log_{10} \left( \frac{f^3 \mu_r r^2}{\sigma_r} \right) \]

Electric Field Reflective Loss

\[ R_p = 168 + 10 \log_{10} \left( \frac{\sigma_r}{\mu_r f} \right) \]

Plane Wave Reflective Loss

\[ A = 0.003338 t \sqrt{\mu_r \sigma_f} \]

Absorptive Loss

where:
- \( t \) = Material thickness (mils)
- \( \mu_r \) = Material permeability relative to air
- \( \sigma_r \) = Material conductivity relative to copper
- \( f \) = Frequency (Hz)
- \( r \) = Source to shield distance (inches)
### SE Theoretical Examples

<table>
<thead>
<tr>
<th>Freq (Hz)</th>
<th>Aluminum (60 mils)</th>
<th>Cold Rolled Steel (60 mils)</th>
<th>Copper (3 mils)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnetic (dB)</td>
<td>Electric (dB)</td>
<td>Plane (dB)</td>
</tr>
<tr>
<td>10k</td>
<td>58</td>
<td>&gt;200</td>
<td>141</td>
</tr>
<tr>
<td>100k</td>
<td>101</td>
<td>&gt;200</td>
<td>165</td>
</tr>
<tr>
<td>1M</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>10M</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>100M</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>1G</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>

- $r = 12''$
- $\mu_r = 1$ (Aluminum), 180 (Cold Rolled Steel), 1 (Copper)
- $\sigma_r = 0.6$ (Aluminum), 0.17 (Cold Rolled Steel), 1 (Copper)
SE Practical Considerations

♦ SE is typically limited by apertures & seams
  - Removable Covers
  - Holes for control/display components
  - Holes for ventilation
  - Holes for connectors

♦ Mitigation of apertures and seams
  - Minimize size and number of apertures and seams
  - Use gaskets/spring-fingers to seal metal-to-metal interface
  - Interfaces free of paint and debris
  - Adequate mating surface area
  - Avoid Galvanic Corrosion
  - Use of EMI/conductive control/display components
Holes/Apertures $d > t$

- **Single Hole**
  
  - If $\frac{\lambda}{2} < d$ \quad SE \approx 0\text{dB}
  
  - If $\frac{\lambda}{2} > d$ \quad SE \approx 20\log_{10} \frac{\lambda}{2d}

- **Multiple Holes**
  
  - If $s < \frac{\lambda}{2} > d$ and $\frac{s}{d} < 1$
  
  \[ SE \approx 20\log_{10} \frac{\lambda}{2d} - 10\log_{10} n \]

Where:
- $t$ = Material thickness
- $n$ = Number of Holes
- $s$ = edge to edge hole spacing

Notes:
1. $d$ is the longest dimension of the hole.
2. Maximum SE is that of a solid barrier without aperture.
Holes/Apertures d<t (w<t)

- Behaves like a waveguide below cutoff

\[ \lambda_c = 2w \]  
Cutoff wavelength

\[ \alpha = \frac{2\pi}{\lambda_c} \sqrt{1 - \left( \frac{f}{f_c} \right)^2} \]  
Absorption factor of WG below cutoff

\[ \alpha = \frac{2\pi}{\lambda_c} = \frac{\pi}{w} \]  
For frequencies well below cutoff

\[ A = 8.686\alpha t = 27.3 \frac{t}{w} \]  
Absorption loss

<table>
<thead>
<tr>
<th>t/w</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>&gt;200</td>
</tr>
<tr>
<td>6</td>
<td>164</td>
</tr>
<tr>
<td>4</td>
<td>109</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
</tr>
</tbody>
</table>
Enclosure Seams

- SE can be limited by the failure of seams to make adequate contact
  - Contact area must be conductive
  - Adequate cross-section of overlap
  - Adequate number of contact points
- Gasketing helps ensure electrical contact between fasteners
Gasketing Examples

♦ Fingerstock (≈100 dB @ 2GHz)
  - Large Selection (shape, size, plating)
  - Wide mechanical compression range
  - High shielding effectiveness
  - Good for frequent access applications
  - No environmental seal

♦ Oriented Wire (≈80 dB @ 2GHz)
  - Provides both EMI and Moisture Seal
  - Lower SE than all-metal gaskets
  - Sponge or Solid Silicone, Aluminum or Monel
  - Mechanically versatile – die cut

♦ Conductive Elastomers (≈80 dB @ 2GHz)
  - Provides both EMI and Moisture Seal
  - Lower SE than all-metal gaskets
  - Mechanically versatile – die cut or molded

Courtesy of Tecknit
Panel Components

Air Ventilation Panels

EMC Switch Shield

Shielded Windows

Courtesy of Tecknit
Galvanic Series

- Galvanic Corrosion
  - Two dissimilar metals in electrical contact in presence of an electrolyte
## Galvanic Series Table

<table>
<thead>
<tr>
<th>Metallurgical Category</th>
<th>Anodic Index (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gold</strong>, Wrought Platinum, Graphite Carbon</td>
<td>0.00</td>
</tr>
<tr>
<td>Rhodium Plating</td>
<td>0.10</td>
</tr>
<tr>
<td>Silver, High-Silver Alloys</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Nickel</strong>, Nickel-Copper Alloys, Titanium, Titanium Alloys, Monel</td>
<td>0.30</td>
</tr>
<tr>
<td>Beryllium Copper, Low Brasses or Bronzes, Silver Solder, Copper, Ni-Cr Alloys, Austenitic Corrosion-Resistant Steels, Most Chrome-Moly Steels, Specialty High-Temp Stainless Steels</td>
<td>0.35</td>
</tr>
<tr>
<td>Commercial Yellow Brasses and Bronzes</td>
<td>0.40</td>
</tr>
<tr>
<td>High Brasses and Bronzes, Naval Brass, Muntz Metal</td>
<td>0.45</td>
</tr>
<tr>
<td>18% Cr-type Corrosion Resistant Steels, Common 300 Series Stainless Steels</td>
<td>0.50</td>
</tr>
<tr>
<td>Chromium or Tin Plating, 12% Cr type Corrosion Resistant Steels, Most 400 Series Stainless Steels</td>
<td>0.60</td>
</tr>
<tr>
<td><strong>Tin-Lead Solder</strong>, Terneplate</td>
<td>0.65</td>
</tr>
<tr>
<td>Lead, High-Lead Alloys</td>
<td>0.70</td>
</tr>
<tr>
<td>Wrought 2000 Series Aluminum Alloys</td>
<td>0.75</td>
</tr>
<tr>
<td>Wrought Gray or Malleable Iron, Plain Carbon and Low-Alloy Steels, Armco Iron, Cold-Rolled Steel</td>
<td>0.85</td>
</tr>
<tr>
<td>Wrought Aluminum Alloys (except 2000 series cast Al-Si alloys), <strong>6000 Series Aluminum</strong></td>
<td>0.90</td>
</tr>
<tr>
<td>Cast aluminum Alloys (other than Al-Si), Cadmium Plating</td>
<td>0.95</td>
</tr>
<tr>
<td>Hot-Dip Galvanized or Electro-Galvanized Steel</td>
<td>1.20</td>
</tr>
<tr>
<td>Wrought Zinc, Zinc Die Casting Alloys</td>
<td>1.25</td>
</tr>
<tr>
<td>Wrought and Cast Magnesium Alloys</td>
<td>1.75</td>
</tr>
<tr>
<td>Beryllium</td>
<td>1.85</td>
</tr>
</tbody>
</table>
Galvanic Series Notes

♦ For harsh environments
- Outdoors, high humidity/salt
- Typically design for < 0.15 V difference

♦ For normal environments
- Storage in warehouses, no-temperature/humidity control
- Typically < 0.25 V difference

♦ For controlled environments
- Temperature/humidity controlled
- Typically design for < 0.50 V difference

♦ Mitigation of Galvanic Corrosion
- Choosing metals with the least potential difference
- Finishes, such as MIL-C-5541, Class 3 using minimal dip immersion
- Plating
- Insulators, as electrically/thermally appropriate
System Partitioning/Guidelines

- Minimize interconnections between WRAs/LRUs
- Minimize the distribution of analog signals
- Control interference at the source
Control Interference at the Source

- Preferred Approach – Shield/Filter the Source (Culprit)

- Alternate Approach – Shield/Filter Potential Receivers (Victims)
CCA Layout and Partitioning

♦ Layout is 3 Dimensional
  - Component placement (X & Y)
  - Signal and Power Routing (X & Y)
  - PWB Stack Up (Z)

♦ Dedicate layer(s) to ground
  - Forms reference planes for signals
  - EMI Control (high speed, fast slew rate, critical analog/RF)
  - Simpler impedance control

♦ Dedicate layer(s) to Supply Voltages
  - In addition to dedicated ground layers
  - Low ESL/ESR power distribution
One and Two Layer

One Sided
- Signals, Grounds, Supplies
- Dielectric

- Inexpensive
- Difficult to control EMI without external shield
- Difficult to control impedance

Two Sided
- Signals, Ground, Supplies
- Dielectric
- Ground Plane

- Inexpensive (slightly more than 1 sided)
- EMI mitigation with ground plane
- Impedance control simplified with ground plane
Radiation Example, 50 MHz Clock

- Adding ground plane reduces emission of fundamental $\approx 40$ dB

PWB: 2” x 6” x 0.060” (FR4)
Trace: 5” x 0.050”
E-Field Probe Spacing: 2”
(Emco 7405-004)
Source: 50 MHz, 4 ns rise/fall, 3 Vp
Multi-Layer Stack Up Examples

1. High Speed Digital PWB
   - High Density
   - Ten Layers
   - Two Micro-Strip Routing Layers
   - Four Asymmetrical Strip-Line Routing Layers
   - Single Supply Plane
   - Two Sided

2. High Speed Digital PWB
   - Moderate Density
   - Six Layers
   - Two Micro-Strip Routing Layers
   - Two Buried Micro-Strip Routing Layers
   - Single Supply Plane
   - Two Sided

3. Mixed Analog/RF/Digital PWB
   - Moderate Density
   - Ten Layers
   - Two Micro-Strip Routing Layers
   - Four Asymmetrical Strip-Line Routing Layers
   - Single Digital Supply Plane
   - Analog supplies on inner layers
   - Routing Clearance Considerations
   - Improved isolation
   - Two Sided
Three Channel, L-Band VME Receiver
- Shield removed for clarity

IF Processing
Video ADCs
FPGA & Support Logic
High Speed Digital I/O

VME I/O Digital & Power
RF Sections
CCA Level Shielding

- Used in conjunction with PWB ground plane(s)
- Supplement shielding of overall enclosure or instead of overall enclosure
- Isolate sections of CCA
  - Local Oscillators, Front Ends, High Speed Digital, Low Level Analog (audio, video)

Metal CCA Shield Examples

Metalized Plastic Shield Examples

Attenuation (dB) vs. Frequency (MHz)

Courtesy of Leader Tech

Revision 3
Copyright Telephonics 2003-2005
COTS Power Supply Selection
(AC/DC Power Converters)

♦ EMC Selection Considerations
  - AC Input EMC Specification Compliance
  - Radiated emission/immunity compliance
  - Open frame, enclosed, stand-alone
  - Hold-Up Time
  - DC to AC Noise Isolation
  - DC to DC Noise Isolation (Multi-output)
  - DC to DC Galvanic Isolation (Multi-output)

♦ Non-EMC Selection Considerations
  - Safety compliance
  - Size & weight
  - Efficiency
  - Line/Load/ Temperature Regulation
  - Operating/ Storage Temperature Ranges
DC/DC Converter Design/Selection

♦ Small Converters at CCA Level
  - Local regulation in critical applications
  - Generate unavailable voltages (3.3 to 1.25 VDC for FPGA core)
  - Many complete COTs solutions available (Vicor, Interpoint, etc.)
  - Many discrete solutions available (Linear Tech, National, etc.)

♦ Linear
  - Inherently Quiet
  - Provide noise isolation, input to output
  - Typically much less efficient (depends on $V_{\text{In}}-V_{\text{Out}}$ difference)
  - Three terminal devices provide no Galvanic isolation

♦ Switching
  - Can be configured for Galvanic isolation
  - Typically noisier than Linear (however mitigation options exist)
  - Pulse Width Modulation, Controlled $\text{di/dt}$ and $\text{dV/dt}$
  - Pulse Width Modulation, Spread Spectrum
  - Resonant mode (zero current switching)
PWM, Controlled Transition, Spread Spectrum

- Linear Technology LT1777 (Controlled di/dt & dV/dt)

- Linear Technology LTC3252 (Spread spectrum 1.0-1.6 MHz)
PWM, Resonant Mode Comparison

- Resonant Mode Vs PWM
  - 48 VDC Input, 5 VDC Output
  - 100 kHz to 30 MHz, Input Noise

![Spectrum Analysis](image)

Courtesy of Vicor
Power Distribution – System Level

- **Distributed DC**
  - One Primary Converter
  - Multiple Secondary Converters at each load
  - Typical Application: Large ground based system

- **Direct DC**
  - One Primary Converter for all loads
  - Typical Application: Home Computer

- **Separate Primary**
  - One AC/DC Converter per unit
  - Typical Application: RADAR System housed in multiple units
Power Distribution Examples

AN/APS-147 LAMPS RADAR
(Separate Primary Distribution)

Multiple Access
Beamforming
Equipment
(Distributed DC)

Personal Computer
(Direct DC Distribution)

Courtesy of Dell
# Power Distribution Comparison

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Load Ground Loops</th>
<th>Load Reg</th>
<th>Power Effic</th>
<th>Load Iso</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distributed DC</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>Only one Converter is directly exposed to input.</td>
</tr>
<tr>
<td>Direct DC</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>May not be practical on large systems with heavy current demands and/or tight regulation requirements</td>
</tr>
<tr>
<td>Separate Primary</td>
<td>x</td>
<td>x</td>
<td>+</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

- **Legend:**
  - ‘+’ Advantage
  - ‘-’ Disadvantage
  - ‘x’ Neutral
Signal Distribution

- Avoid routing analog signals over long distances in harsh environments, but if unavoidable:
  - Differential
  - Amplify at source and attenuate/filter at destination
- Inter-Unit (LRU or WRA)
  - Digital preferred over analog
  - Differential preferred over single ended
  - Minimize number of interconnects
Cable Shields

- Shields of external interconnecting cables
  - Essentially extensions of the chassis enclosure

- Shielding Effectiveness and Transfer Impedance
  - Properties of material
  - Degree of coverage
  - Geometry

- Shields are an important part of EMC design, especially in systems that require compliance to EMP and/or Indirect Lightning Effects
Cable Shield Termination

- Maintaining quality SE and Transfer Impedance depends on effective termination of shields at both ends
  - 360 Degree Backshells
  - If high frequency isolation is needed, avoid using long leads to terminate shields

Coax Shield Terminated with Excessive Lead Length

- Unassembled 360 Degree Backshell for D Connector
- Circular D38999 Mil Connector with 360 Degree Backshell
- Exploded View of 360 Degree Backshell for D38999 Connector
# Shield Example

## 95% Coverage Double Copper Shield

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Shielding Effectiveness</th>
<th>Xer Z (Ω/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnetic (dB)</td>
<td>Electric (dB)</td>
</tr>
<tr>
<td>1 k</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>10 k</td>
<td>16</td>
<td>100</td>
</tr>
<tr>
<td>100 k</td>
<td>36</td>
<td>100</td>
</tr>
<tr>
<td>1 M</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>10 M</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>100 M</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>1 G</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>10 G</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>
Transfer Impedance Example

\[ Z_T = \frac{V_i}{I_s} \] (\(\Omega\) per meter)

Induced Voltage of 22 mV is well below damage/upset threshold of most logic families.
Coupling Example #1, 0.3-200 MHz

- Two Parallel Lines, One shielded, One unshielded
  - 0.5” Over Ground Plane, 10” Long, Separated by 2”
  - Shielded Line has 0.5” exposed

Both ends of shield ungrounded

Both ends of shield grounded with 3” loop (60 nH)

Both ends of shield directly grounded

Both shielded ends grounded with 1” loop (19 nH)

Continuous shield with both ends of grounded directly
Coupling Example #2, 0.3-200 MHz

- Two Parallel Lines, One shielded, One unshielded
  - 0.5” Over Ground Plane, 10” Long, Separated by 0.5”
  - Shielded Line has 0.5” exposed

Both ends of shield ungrounded

Both ends of shield grounded with 3” loop (60 nH)

Both shielded ends grounded with 1” loop (19 nH)

Both ends of shield directly grounded

Continuous shield with both ends of grounded directly
Filter Connectors

- Applications for connectors with integral filtering and/or transient suppressors
  - Shields not permitted on interconnection cables
  - Isolation needed between assemblies (WRAs, LRUs)
- Filtering effectiveness is typically much better than discrete filters
  - Parasitics
  - Interconnection Coupling (between filter & connector)

Courtesy of G&H Technology
Discrete Filter vs. Filter Connector

- Portable RADAR System, I/O Cables Unshielded
- RADAR Headset cable interferes with 100 - 200 MHz Communication band

Baseline

Discrete LC Filter at Connector (1nH, 8200pF)

Filter Connector (1nH, 8000 pF)
Signal Spectra & Filter Connectors

- Come in many types and filter capabilities
  - Filter Topologies: Pi, C, LC
  - Various cutoff frequencies
  - In some cases, not larger than standard non-filtered version

- Selection Considerations
  - Spectrum of Signals
  - Source/Sink Capability of Driver
  - Source/Load Impedances
  - Cable effects

Typical 50 MHz Clock Example

\[
\begin{align*}
f_1 &= \frac{\frac{1}{\pi t_w}}{\pi (20ns)} = 15.9MHz \\
f_2 &= \frac{2}{\pi} \left( \frac{1}{t_r + t_f} \right) = \frac{2}{\pi} \left( \frac{1}{(2ns + 2ns)} \right) = 159MHz
\end{align*}
\]
EMC Design Process
Design Process

♦ Starts with a System/Device Specification
  - Describes the applicable EMC Requirement(s)

♦ Develop and Implement an EMC Control Plan
  - Details EMC Requirements and clarifies interpretation
  - Lists applicable documents
  - Defines management approach
  - Defines the design procedures/techniques
  - EMC design is most efficiently accomplished when considered early in the program

♦ Process Example
  - Intended for large system
  - Can easily be tailored for smaller system or a single device.
EMC Design Flow Diagram

System/Device Specification
- Cull EMC Requirements from System/Device Specification and clarifies interpretation
- Summarize applicable documents, specifications and standards
- EMC Program Organization and Responsibilities
- Defines design procedures and techniques

Generate EMC/EMI Control Plan

Mechanical Design
- Shielding
- Material Selection
- Gasketing
- Covers

Electrical Design
- Single vs. Multi Point Ground
- Chassis component bonding
- System functional allocation
- Separation of analog, RF, digital and power
- Micro-strip, stripline
- Number of layers
- Ground layers
- Separation of analog, RF, digital and power
- Conversion Topology Linear, Resonant, PWM
- Connector Selection Filter/Non-Filter
- Filter location/type
- Single Ended, Differential
- Logic Family
- Connector Selection Filter/Non-Filter
- Filter location/type
- Cable harnessing and shielding
- Signal Spectrum

System Design
- Hardware Partitioning and Location
- PWB Layout and Construction
- Power Conversion and Distribution
- Signal Distribution
- Mechanical Design
## Typical EMC Engineer’s Involvement

<table>
<thead>
<tr>
<th>Pre-Award</th>
<th>Design</th>
<th>Manufacture</th>
<th>Test</th>
</tr>
</thead>
</table>
| Prepare EMC Section of Proposal
| Contract/SOW Review and Recommendations | Interference Prediction
| Design Testing     | Interference Control Design     | Preparation of EMC Control Plan
|                   | Preparation of EMC Control Plan | Subcontractor and Vendor EMC Control |
|                   | Internal Electrical and Mechanical Design Reviews | EMC Design Reviews with the Customer |
|                   | EMC Design Reviews with the Customer | Interference Testing of Critical Items |
|                   | Interference Testing of Critical Items | Amend the EMC Control Plan, as Necessary |
|                   | Amend the EMC Control Plan, as Necessary | Liaison with Manufacturing |
|                   | Liaison with Manufacturing | In-Process Inspection During Manufacturing |
|                   | In-Process Inspection During Manufacturing | Preparation of EMC Test Plan/Procedure |
|                   | Preparation of EMC Test Plan/Procedure | Performance of EMC Qualification Tests |
|                   | Performance of EMC Qualification Tests | Redesign and Retest where Necessary |
|                   | Redesign and Retest where Necessary | Preparation and Submittal of EMC Test Report or Declaration |
References
References


♦ “Electromagnetic Compatibility Design Guide”, Tecknit

♦ “Metals Galvanic Compatibility Chart”, Instrument Specialties

♦ “EMI Shielding Theory”, Chomerics

♦ “Shield that Cable!”, Bruce Morgen, Electronic Products, 1983 August 15


♦ “Electronic Systems Failures & Anomalies Attributed to EMI” NASA Reference Publication 1374
Committees and Organizations

♦ Comité Internationale Spécial des Perturbations Radioelectrotechnique (CISPR)
♦ Radio Technical Commission for Aeronautics (RTCA) www.RTCA.org
♦ National Association of Radio & Telecommunications Engineers (NARTE), www.NARTE.org
Gasket and Shielding Vendors

- www.Chomerics.com
- www.LairdTech.com
- www.Tecknit.com
- www.Spira-EMI.com
- www.WaveZero.com
- www.LeaderTechInc.com
Backshell Vendors

- www.SunBankCorp.com
- www.TycoElectronics.com
Filter Connector Vendors

- [www.GHtech.com](http://www.GHtech.com)
- [www.SpectrumControl.com](http://www.SpectrumControl.com)
- [www.EMPconnectors.com](http://www.EMPconnectors.com)
- [www.Sabritec.com](http://www.Sabritec.com)