emc STANDARDS

Another EMC resource
from EMC Standards

1. The Physical Basis of SI, PI and EMC

Updated for 2021 - Version 4.1

Helping you solve your EMC problems

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Module 1: The Physical Basis of SI, PI, and EMC

Part of the background material provided free with our EMC courses

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This course module is effectively: "Maxwells Equations without maths"

- **It helps ordinary engineers (who don't want to be EMC specialists) *to visualise* EMC…**
  - **to help understand the practical design techniques described in the remainder of the course modules…**
  - **and to help understand how to adapt them successfully (if/when necessary)**
- **This understanding/visualisation makes good cost-effective SI, PI, EMC design *easy*…**
  - **helping to save time and cost, reducing financial risks, increasing profitability and chances of project success…**
    - ***because EMC is no longer 'black magic'!***

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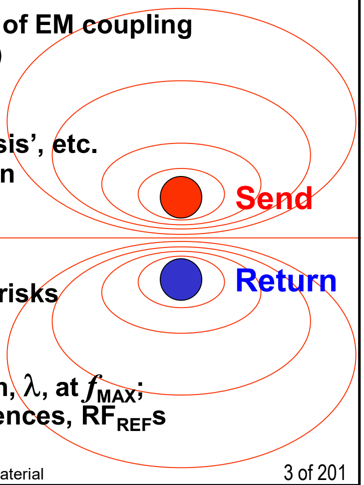


This module mostly deals with radio frequency (RF) techniques

– because low-frequency SI, PI and EMC issues are easy to understand using normal circuit design techniques

with strays included, *see later…*

- This module focuses on the SI, PI and EMC issues that most engineers find difficult…
  – because of the *apparently* weird things that can happen at frequencies above a few MHz
    - EMC = Electromagnetic Compatibility: controlling emissions and immunity so radiocommunications and other equipment don't cause or suffer Electromagnetic Interference (EMI)

1. The Physical Basis of SI, PI, and EMC

1.1

Electromagnetic fields and waves, and the importance of the return current path

From [4]: "It is very important to understand that the signal energy is transmitted by the electromagnetic fields in dielectrics (or vacuum) and not by currents in the conductors.

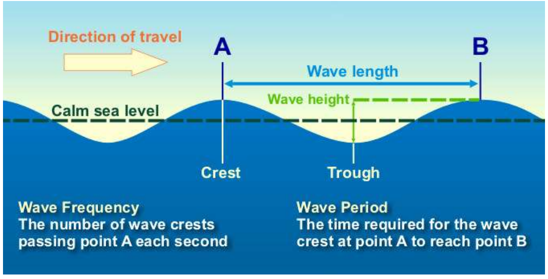
Electromagnetic (EM) fields

- ***Every*** **voltage/current** (power, signal, data, etc. or stray, parasitic, sneak, leak) **is *really* a propagating EM wave...**
  - guided by send and return conductors *and* the insulators (dielectrics) that surround them (e.g. air, PVC)…
    [*Strictly:* Transverse Electromagnetic: 'TEM' waves]
  - EM waves spread out and create EM fields
    like ripples spreading out on a pool of water

- **Design for good SI, PI and EMC is mostly about controlling fields: so they are high where we want our signals, data or power to be…**
  - and low where we don't want them to be,
    to control crosstalk, noise, emissions and susceptibility

Of course, a wave has different amplitudes along its path

- **So a long conductor *can't* have the same voltage or current over its whole length, at the same time…**



  - **and this is what causes the 'EMC weirdness'!**
  - **the ratio between wavelength (λ) and conductor dimension is what is important…**
  - **we can usually ignore 'wave effects' for any dimension that is < λ/100 e.g. at 1GHz: < 3.0mm in air (λ = 300mm)**
    < 1.5mm in FR4 (λ = 150mm)

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Importance of the return current path

- ***All* currents *always* flow in closed loops**
  ***all* power, signals, data, *and* stray / parasitic / sneak / leaked currents etc…**
  - **and we can control their E and H field patterns by designing their send and return current paths…**
    - **which can include flowing through dielectrics (air, plastic, etc.) as "displacement currents"**
- **Currents *always* "prefer" to flow in loops with lower *overall* impedances, at any given frequency…**
  - **generally the loops with least enclosed areas, *because they have the most compact E and H field patterns*…**
    - **i.e. the laws of nature/physics are trying to help us achieve good SI, PI and EMC – we just have to work *with* them!**

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Importance of return current path continued…

- At any given frequency, current will automatically divide up between the available loops, in inverse proportion to their overall loop impedances…
    - just like DC current divides up between parallel resistors…
  - this generally means that return currents will always "choose" to flow as physically close to their send currents as they can…
    - by flowing through any/all nearby conductive structures (whatever their function, whatever their circuit voltage, or none) and through the air or other dielectrics…
  - so we can easily achieve good, cost-effective SI, PI, and EMC by creating send/return loops that have very low overall impedances for all frequencies we want to control

1. The Physical Basis of SI, PI, and EMC

1.2

Field theory, permittivity, permeability, wave impedance and velocity

We don't need field theory – just a few basic concepts

- **Fluctuating voltages create Electric fields (E)**
  - **which are measured in Volts/metre (V/m)**
- **Fluctuating currents create Magnetic fields (H)**
  - **which are measured in Amps/metre (A/m)**
- **EM waves have power (P)**
  - **measured in Watts/square metre (W/m^2)**
    (i.e. the rate at which energy passes through an area)

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Permeability (μ) and permittivity (ε)

- ***All* media or materials have conductivity/resistivity**
  (i.e. loss of EM energy, turned into heat), μ and ε…
  - **in vacuum (and air):** $\mu_0 = 4\pi \cdot 10^{-7}$ **Henries/metre…**
    - **i.e. the vacuum can contain magnetic field energy**
  - **And:** $\varepsilon_0 = (1/36\pi) \cdot 10^{-9}$ **Farads/metre**
    - **i.e. the vacuum can also contain electric field energy**
- **Other media and materials are characterised by their *relative* permeability (μ_R) and permittivity (ε_R)**
  - **so their *absolute* permeability is: $\mu_0\mu_R$**
    and their *absolute* permittivity is: $\varepsilon_0\varepsilon_R$

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Permeability (μ) and permittivity (ε) continued...

- **In conductors (e.g. wires, PCB traces): μ and ε are what causes them to have inductance (L) and capacitance (C)…**
  - so ***whenever*** there is a fluctuating *voltage* (V) there is ***always*** an associated *current* (I), and vice-versa
- **In insulators (e.g. PVC, FR4, air): μ and ε cause effects *similar to* inductance and capacitance…**
  - so ***whenever*** there is a fluctuating *electric field* (E) there is ***always*** an associated *magnetic field* (H), and vice-versa

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μ and ε govern an EM wave's impedance, and its propagation velocity

- **For the wave's 'far field' impedance …**

$Z = E/H =$ V/m ÷ A/m $= \sqrt{(\mu_0\mu_R/\varepsilon_0\varepsilon_R)}\ \Omega$

$Z = 377\Omega$ in air or vacuum

$Z = 377\sqrt{(\mu_R/\varepsilon_R)}$ in a medium or material

- **For the velocity of the wave's propagation …**

$v = 1/\sqrt{(\mu_0\mu_R\varepsilon_0\varepsilon_R)}$ metres/second

$v = 3.10^8$ m/s in air or vacuum (i.e. the speed of light)

$v = 3.10^8/\sqrt{(\mu_R\varepsilon_R)}$ m/s in a medium or material

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And the velocity of wave propagation (v) links frequency (f) to wavelength (λ)

$$v = f\,\lambda$$

- In vacuum or air: $v = c =$ 300 million metres/second
  - $1/\sqrt{(\mu_0\varepsilon_0)}$, equivalent to 3ns/metre, 3ps/millimetre
- But in media or materials with μ_R and/or ε_R >1.0, v is *slower* than c
  - so the wavelength (λ) is shorter (for a given f)
    - e.g. for a printed-circuit board trace, v is approx. 50% of c ….so a λ is approx. 50% of what it would be in air

1. The Physical Basis of SI, PI, and EMC

1.3

Near Field and Far Field

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Near-field and Far-field

- **Near fluctuating voltages or currents, E and H fields have complex patterns: field strengths vary as $1/r^3$, $1/r^2$ and $1/r$**
  - **where r is the radial distance from the source**
  - **because of stray capacitance and stray mutual inductance effects (i.e. E and H field coupling)**
- **But, far enough away, the fields become EM waves (E and H fields in the ratio of the wave impedance: Z)…**
  - **and have simple 'plane wave' spherical distributions with field strengths that vary as $1/r$**

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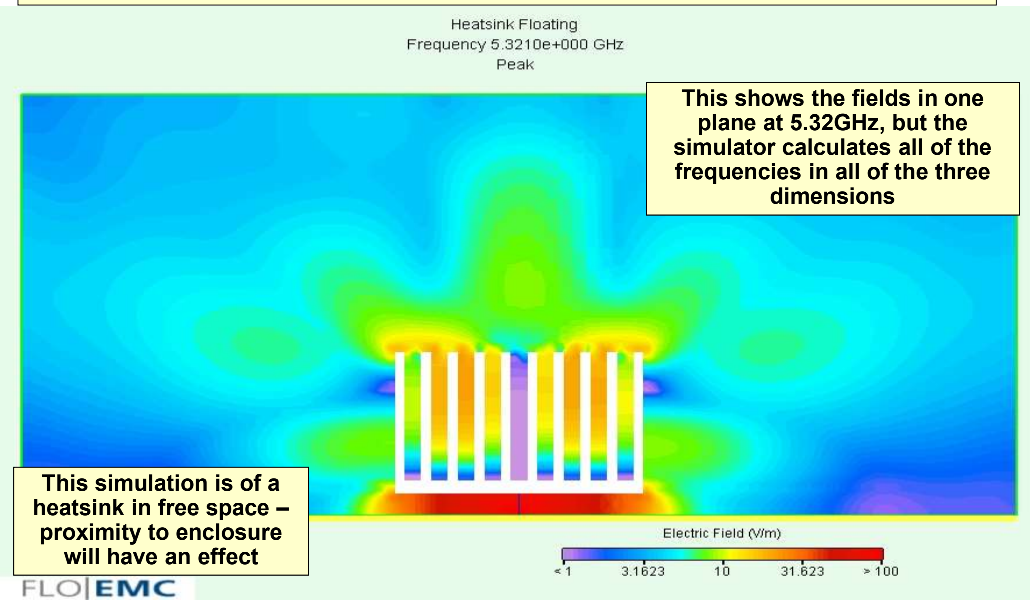
An example of a near-field field distribution



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Near-field and Far-field continued…

- For sources with their largest dimension (D) << λ their near/far field boundary radius (r) is given by…

$$r = \lambda/2\pi$$

  – i.e. gets closer to the source, as the frequency increases…

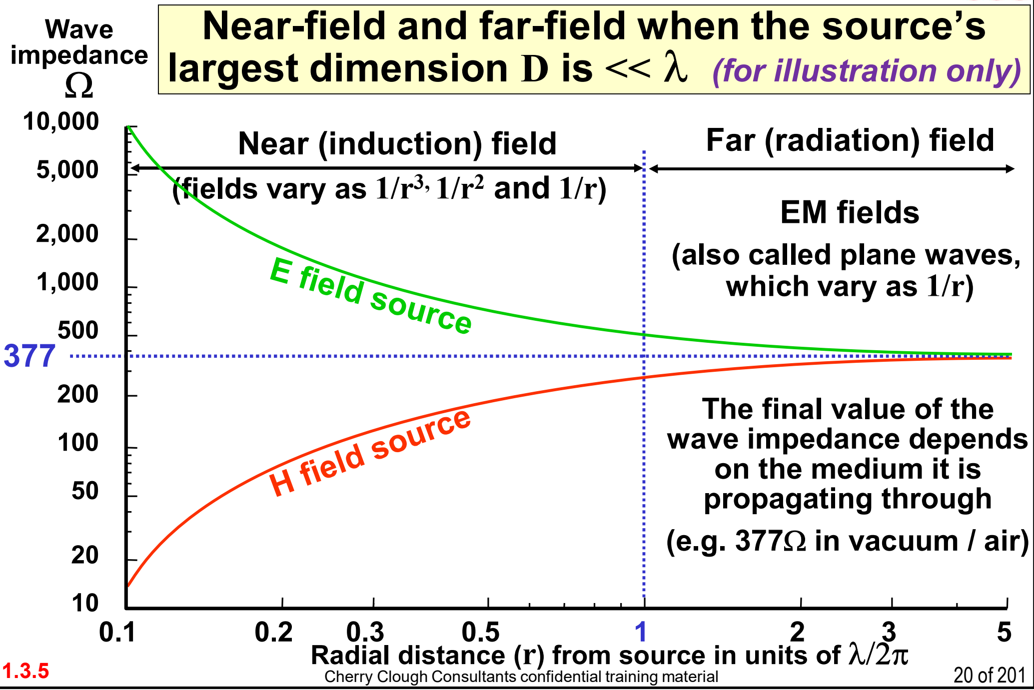
  – e.g. r = 48m when *f* = 1MHz, 48mm when *f* = 1GHz

- But for sources with D >λ, r is given by…

$$r = 2D^2/\lambda$$

  – i.e. gets further away from source, as frequency increases
  e.g. if D = 1m: r = 48m when *f* = 1MHz (D is still << λ)
  r = 6.7m when *f* = 1GHz (D is now > λ)

Near-field and far-field when the source's largest dimension D is << λ *(for illustration only)*



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1. The Physical Basis of SI, PI, and EMC

1.4

Three types of analysis
(including Skin Effect, Proximity Effect, and three different types of resonance)

SI, PI & EMC use three types of analysis

- For conductor dimensions < λ/6 we can use '*lumped circuit analysis*' methods (based on R, L, C)
- When conductor dimension is > λ/6 along one axis (e.g. a wire) we must use '*transmission line*' analysis
- But when conductors are > λ/6 in two or three dimensions we must use '*full-wave analysis*'
  – based on Maxwell's Equations
    - only practical for very simple situations, or when using computers to do the analysis

Resonances

- *All* circuits and conductors have resonant modes
  - where their currents or voltages experience resonant gain, called their 'Q factor'...
  - Qs of 100 or more are common (i.e. gains of 40dB or more)
- As the voltage peaks, the current nulls, and vice-versa (to maintain a constant energy as the wave propagates)
- High levels of emissions (and poor immunity) tend to occur at resonances…
  - so we often need to control them to achieve good SI, PI and EMC

Lumped analysis… *everything* has resistance (R), inductance (L), and capacitance (C)

- including all components, wires, cables, PCB tracks, connectors, silicon metallisation, bond wires, etc
- also including their 'stray' or 'parasitic' Rs, Ls, and Cs
  - which can be intrinsic (e.g. the self-inductance of a wire lead)
  - or extrinsic (e.g. stray C or L coupling due to proximity to other objects)
- Resistance increases with f due to Skin Effect

Lumped analysis: Resistance and 'Skin Effect'

- **DC currents travel through the whole cross-sectional area of a conductor…**
  - **but AC currents are forced to flow close to the surface, which is known as the "skin effect"**
- **So, high-frequency currents only penetrate weakly into the depth (thickness) of a conductor…**
  - **increasing the resistance in their path, and preventing AC currents from flowing *through* any appreciable metal thickness…**
    - **a very important effect, that is *totally ignored* by circuit design textbooks and Spice circuit simulators**

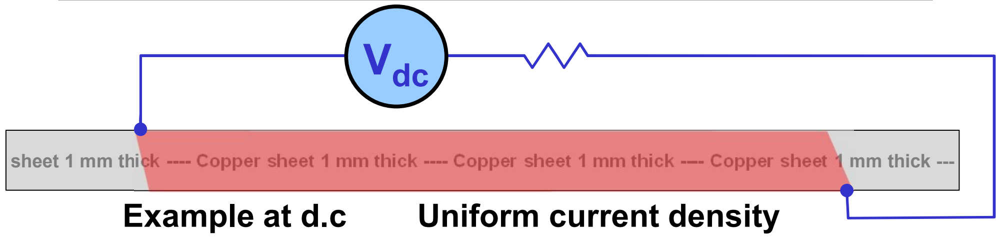
Resistance and Skin effect (2)

- **One skin depth, δ_S, is the increase in depth within the metal which causes the current density to reduce by $1/e$ (roughly 1/3, i.e. approx. -9dB)…**

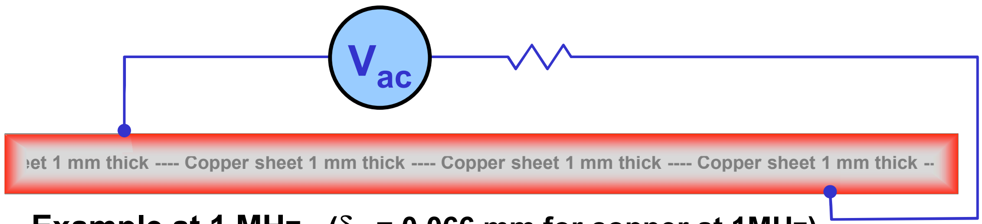
$$\delta_S = \frac{1}{\sqrt{(\pi \cdot f \cdot \mu_0 \cdot \mu_R \cdot \sigma)}} \quad \text{metres}$$

  - **where σ = the metal's conductivity in mho/meter (i.e. Siemens)**
- ***Alternatively:*** $\delta_S = \sqrt{(\rho \cdot f \cdot \mu_0 \cdot \mu_R)}$ **metres**
  - **where ρ is the metal's resistivity, in Ohm-meters**

Examples of cross-sectional current density in a copper sheet



Example at d.c **Uniform current density**



Example at 1 MHz (δ_S = 0.066 mm for copper at 1MHz)

Just because a schematic calls a metal part: chassis; earth; ground, etc. does not mean that RF currents will travel throughout it all !

Resistance and Skin effect (3)

- **The δ_s of copper at 1MHz is 0.066mm, so in the previous slide the current density that "gets through" to the other side of the 1mm copper sheet is about $(1/3)^{14}$, i.e. about -133dB, a negligible amount…**
  - **this is excellent when using the copper sheet for shielding against magnetic fields…** *see Module 4*
  - **but if using copper as an RF conductor it means that the cross-sectional-area (CSA) carrying the current is much less at 1MHz, so the series resistance is much higher…**
    - **e.g. a 2mm diameter copper wire with a circular cross-section has a DC resistance of ≈ 5mΩ/m at 25°C, but at 1MHz it has ≈ 38mΩ/m (≈ 58 times the loss/heating effect) and at 100MHz it has ≈ 380mΩ/m (≈ 5800 times loss/heating effect)**

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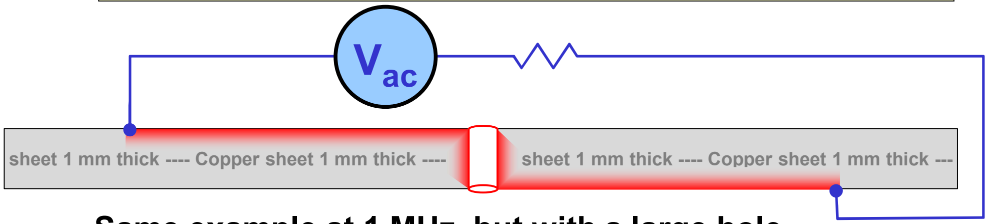
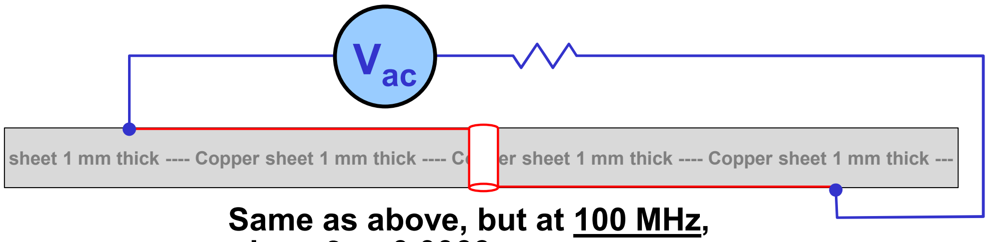
More examples of surface currents



Same example at 1 MHz, but with a large hole drilled in the middle of the copper sheet (δ_S = 0.066 mm at 1 MHz)



Same as above, but at 100 MHz, where δ_S = 0.0066 mm (for copper)

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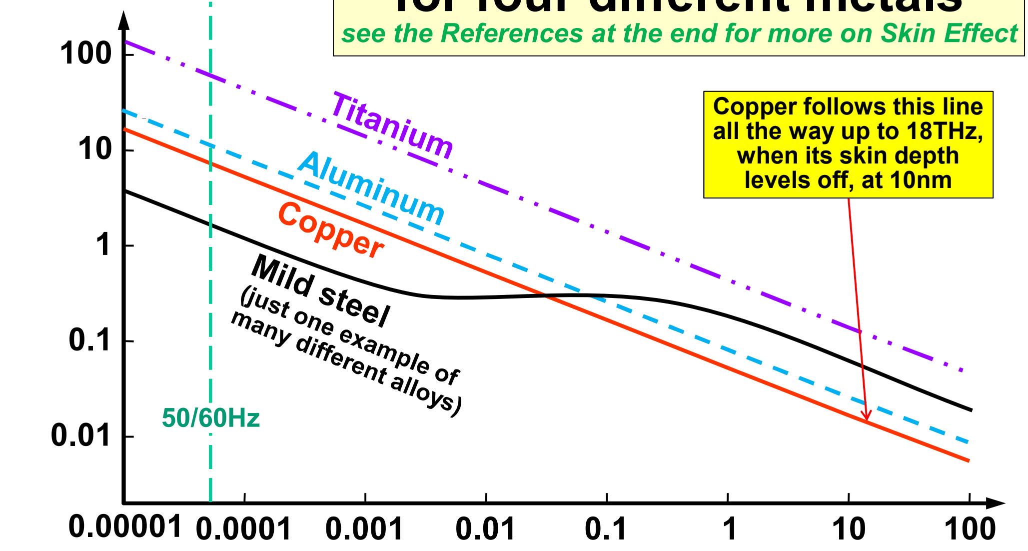
Graph of skin depths for four different metals

see the References at the end for more on Skin Effect

Skin depth (δ_S) in mm



For *much* more detail on Skin Effect, see Reference [4] near the end

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Surface currents and near-fields

– as we saw: Skin Effect causes any/all RF currents to flow on conductor surfaces: called Surface Currents…

– but there is a 1:1 relationship between a conductor's surface currents and its E and H near-fields…

– which means we can choose to work with either near-fields, *or* with surface currents – they are just different ways of understanding propagating EM energy…

- this will be a very important design tool when we get to the modules on shielding and filtering, where the equivalent of stopping EM fields from leaking (immunity and/or emissions)…
- is to design so that *internal* surface currents stay on the *inside surfaces* of the shields…
- and *external* surface currents stay on the *outside surfaces* of the shields

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Skin depth – a useful Figure from Reference [4]

see slide 1.19.2

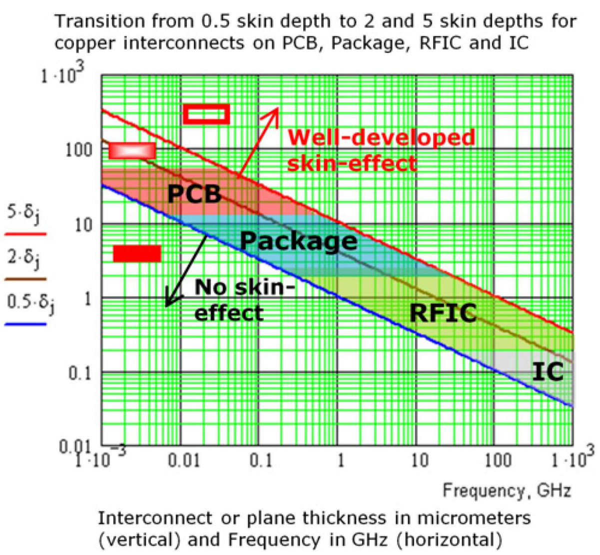

Fig. 6. ***Transition frequencies for copper conductors.*** *Strip or plane thickness in micrometers is the vertical axis and frequency in GHz is the horizontal axis. Strip thickness equal to 0.5 of skin depths and below (blue line) is considered as area with uniform current distribution (low frequencies). Strip thickness equal to 5 skin depths (red line) and higher is considered as area with well-developed skin-effect (high frequencies).*

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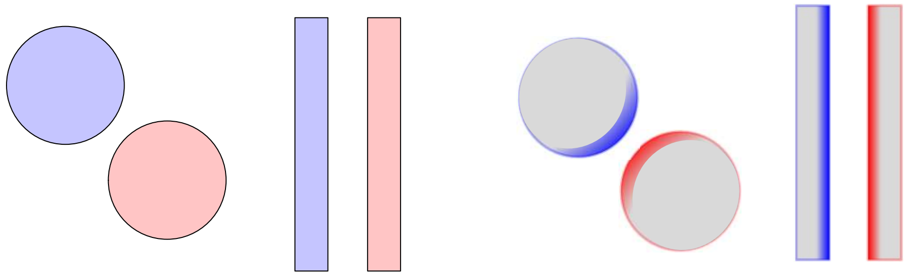
‘Proximity Effect’ *also* increases series resistance, for AC and RF

see 1.19.4 in the References for more detail on Proximity Effect

- **Differential currents ‘prefer’ to flow in close proximity to each other** *(see slides 1.1.4 and 1.1.5)*
  - e.g. round and flat conductor pairs, in cross-section: red: positive, ‘send’, phase; blue: negative, ‘return’, antiphase



At DC: uniform current density   At RF: skin effect + proximity effect

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Lumped analysis: Stray Inductance

- **E.g. a thin wire has self-inductance of about 1μH per metre** (1nH per mm)
  - this assumes its return current path is very far away
  - a close return path reduces the overall inductance experienced by the send/return current
- **Close proximity to ferromagnetic materials** (e.g. steel) **with $\mu_r > 1$ will *increase* its self-inductance**
- **But close proximity to conductors** (e.g. cables, metalwork, etc.) **will *decrease* self-inductance**

Lumped analysis: Stray Capacitance

- E.g. a thin wire on its own in free space has about 40pF per metre length (approx. 0.04pF per mm)....
  - this is its 'space charge' capacitance....
  - close proximity to dielectrics ($\varepsilon_r > 1$) will add more stray space charge capacitance
- Proximity of conductors adds stray capacitance...
  - (8.8/d) nF/square metre in air (d is the spacing in mm)
  - ($8.8\ \varepsilon_r$/d) nF/sq. m., when d is the spacing through insulation

Lumped Analysis: Resonances

- L and C store energy in their H and E fields
  - this is true for intentional Ls and Cs (e.g. components) and 'stray' or 'parasitic' Ls and Cs
- *All* types of circuits have L and C (even if they are only strays) and these cause resonances, at:

$$f_{RES} = 1/(2\pi\sqrt{LC})$$

- These resonances are 'damped' by the resistances in the circuit

Transmission line analysis… all send/return conductors have *characteristic impedance* (called Z_0)

- The L and C *associated with a small length* governs the velocity (v) with which EM waves travel *through that length…* $v = 1/\sqrt{(LC)}$
- And the ratio of the L to the C governs the characteristic impedance (Z_0) *of that length…*

$$Z_0 = \sqrt{(L/C)}$$

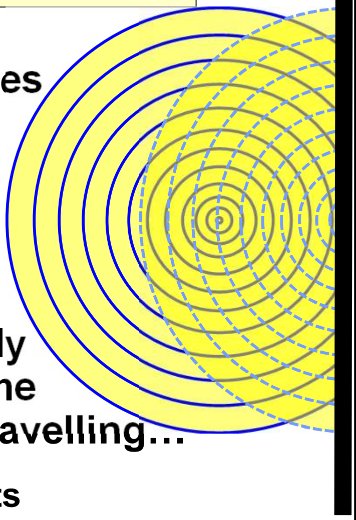
  - *Note:* the L and C values used in the above expressions are 'per unit length' (e.g. 1µH/metre, 100pF/metre) where the unit lengths used must be shorter than λ/6

The effects of keeping Z_0 constant

- If Z_0 is constant from source to load, almost 100% of the wave (i.e. the signal, data or power) is communicated
  - which means that there must be <u>low emissions</u> from the wanted signal, data or power (because there is very little energy lost)
- This is called *matched transmission line* design…
  - and a matched transmission line is a very inefficient antenna *(see later)…*
    - which is why all general purpose RF test equipment has 50Ω inputs and outputs, connected with '50Ω cable'

Changes in Z_0 over dimensions greater than $\lambda/6$

- **These cause propagating EM waves** (whether signals, data or power) **to be reflected…**
  - – like the ripples in a swimming pool reflecting from a wall



- **EM filtering and shielding both rely on creating changes in the Z_0 of the medium in which EM waves are travelling…**
  - – to reflect noise away from the circuits they are protecting

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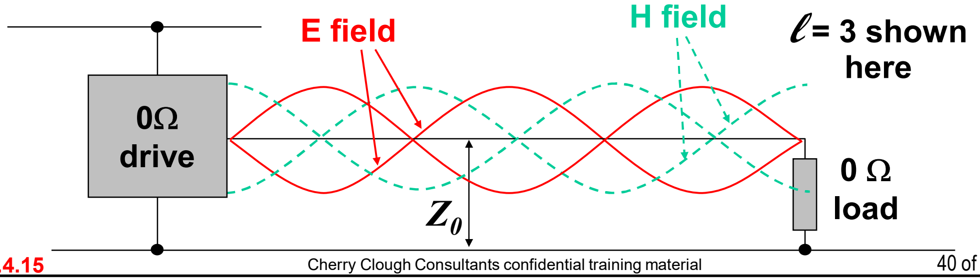
Transmission-line analysis: Resonances

- **When a conductor has the *same type* of Z_0 discontinuity at *each* end** (whether the source and load impedances are both too high, or too low)…
  - – resonances occur when conductor length is a <u>whole</u> number of <u>half</u>-wavelengths... $f_{res} = 150\,\ell/L$ (air dielectric)

    where ℓ is an integer (1, 2, 3, etc.),

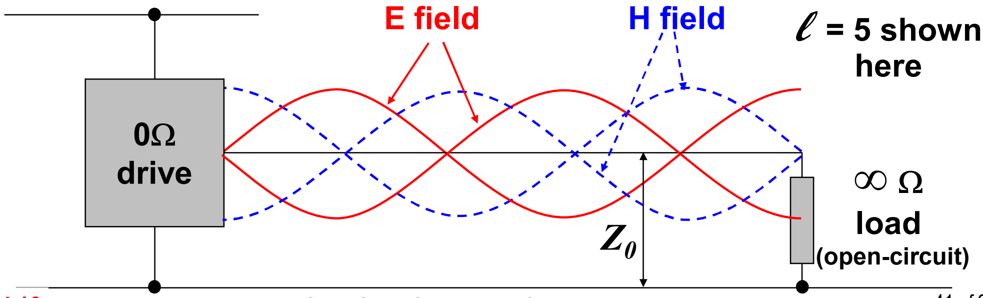
    L is conductor length (metres), and f_{res} is in MHz



Transmission-line resonance analysis continued...

- **When a conductor has *opposing types* of Z_0 discontinuity at its ends…**
  - **resonances occur when conductor length is an odd number of quarter-wavelengths…** $f_{res} = 75\ \ell/L$ **(air dielectric)**

    where ℓ is an *odd-numbered* integer (1, 3, 5, etc.), L is conductor length (metres), and f_{res} is in MHz



2-dimensional structural resonances:

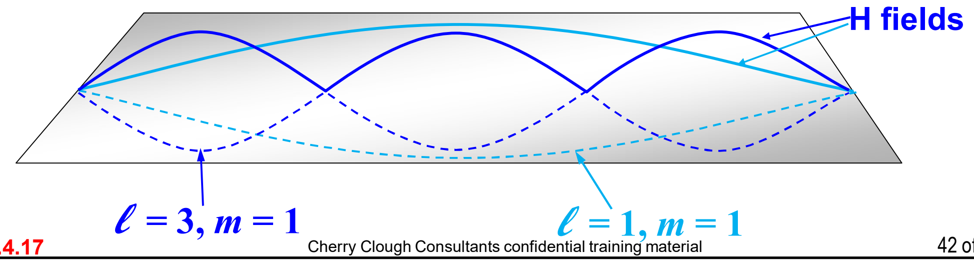
'standing waves' from reflections from the edges of metal plates

[*Strictly:* Transverse Electric (TE) and Transverse Magnetic (TM) waves, not TEM, because only a single conductor]

- **can only occur at integer multiples of half-wavelengths:**

  $f_{res} = 150\ \sqrt{\{(\ell/L)^2 + (m/W)^2\}}$ **(in MHz)**

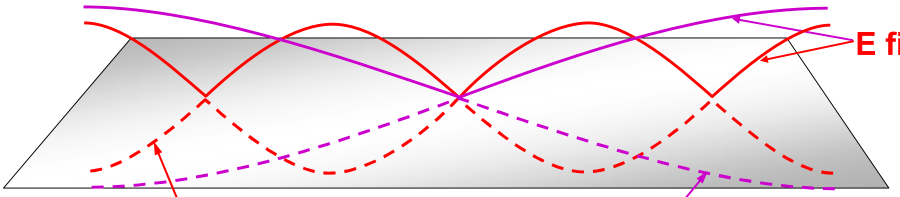
  - **where: ℓ and m are integers (0, 1, 2, 3, etc.) and L and W are the plate's length and width (in metres)**
  - **the lowest (first) resonance frequency is the (1,1) mode**



'Standing waves' caused by reflections at the edges of a metal plate continued...

[*Strictly:* TE and TM waves, not TEM, because only a single conductor]

- **Magnetic field standing waves must have minima at the edges of the metal plate**
  (air has much higher impedance than metal)…
  - **whilst electric fields must have maxima at the edges…**



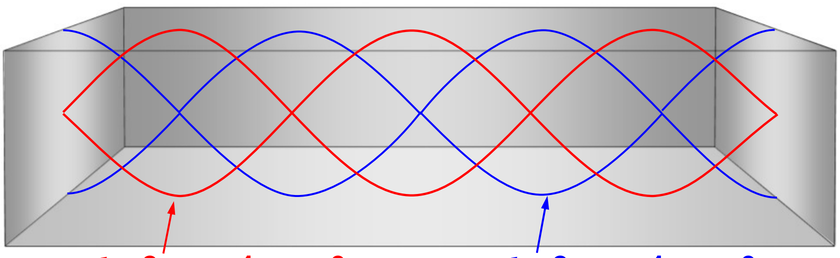
3-dimensional structural resonances: 'standing waves' from reflections inside a metal box

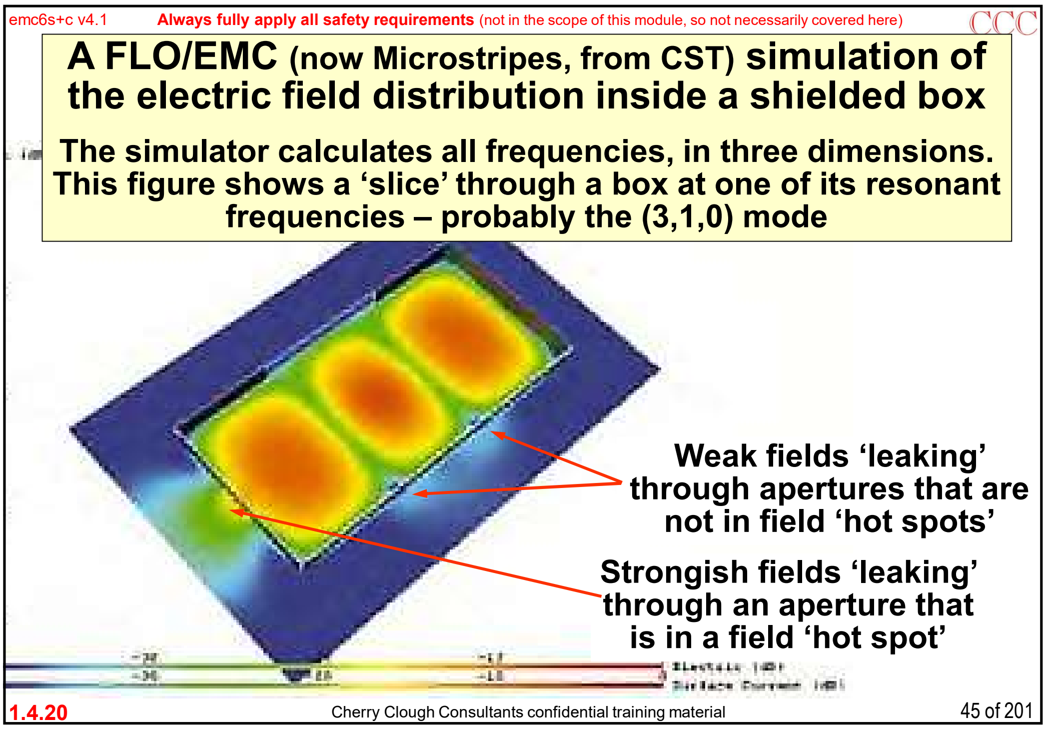
[*Strictly:* TE and TM waves, not TEM, because only a single conductor]

- **can *only* occur at integer multiples of half-wavelengths:**

  $f_{res} = 150\ \sqrt{\{(\ell/L)^2 + (m/W)^2 + (n/H)^2\}}$ **(in MHz)**

  where: ℓ, m, n are integers (0, 1, 2, 3, etc.) and L, W, H are the box's length, width, height (in metres), and the lowest (first) resonance frequency is the (1,1,0) mode

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Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
A FLO/EMC (now Microstripes, from CST) simulation of the electric field distribution inside a shielded box
The simulator calculates all frequencies, in three dimensions. This figure shows a 'slice' through a box at one of its resonant frequencies – probably the (3,1,0) mode
Weak fields 'leaking' through apertures that are not in field 'hot spots'
Strongish fields 'leaking' through an aperture that is in a field 'hot spot'
1.4.20
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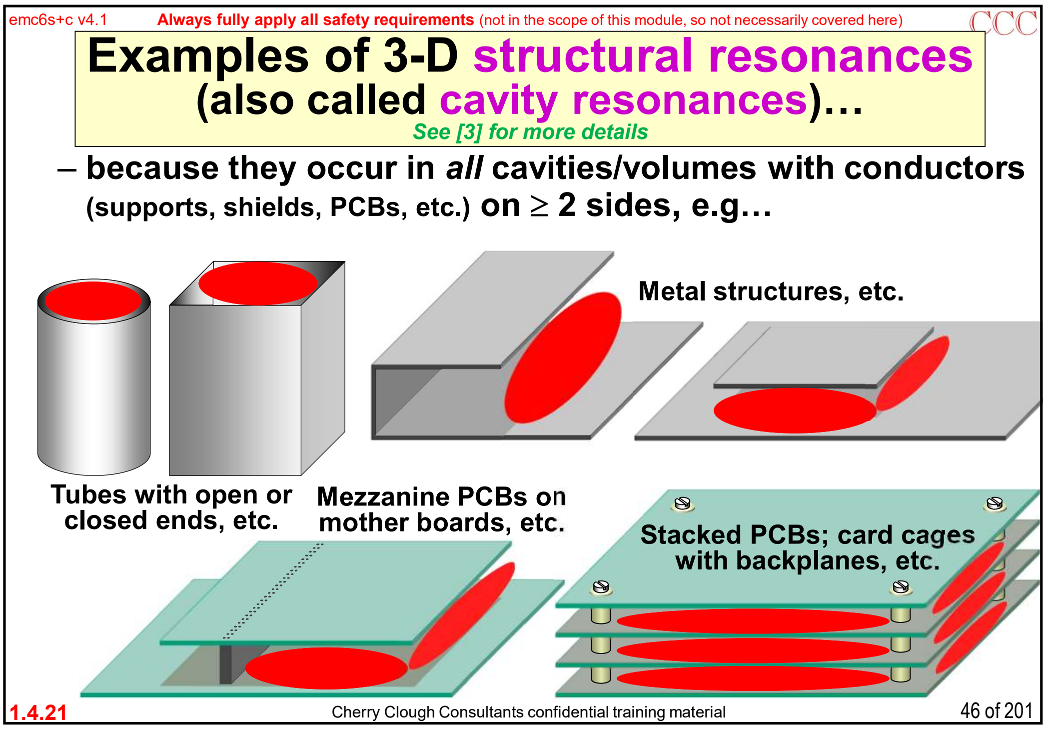
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Examples of 3-D structural resonances (also called cavity resonances)…
See [3] for more details
– because they occur in all cavities/volumes with conductors (supports, shields, PCBs, etc.) on ≥ 2 sides, e.g…
Metal structures, etc.
Tubes with open or closed ends, etc.
Mezzanine PCBs on mother boards, etc.
Stacked PCBs; card cages with backplanes, etc.
1.4.21
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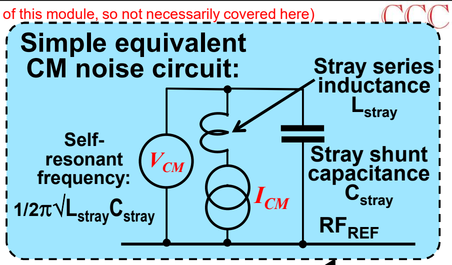
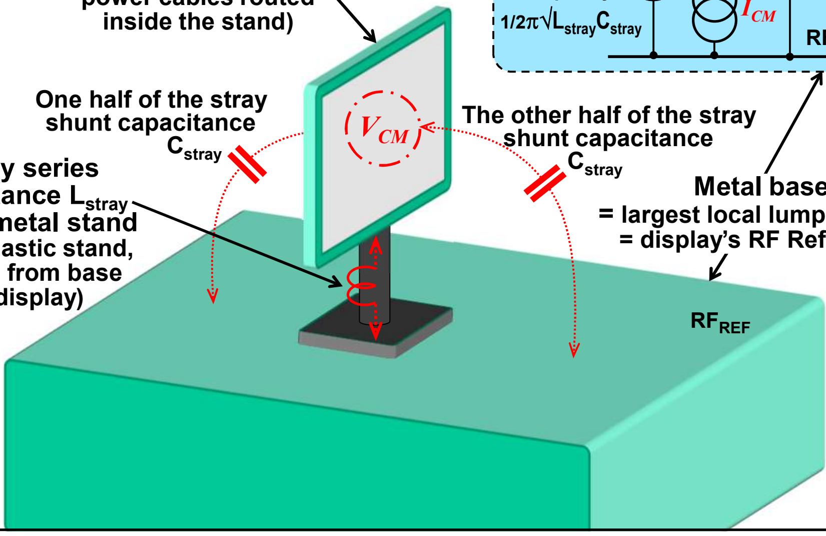
E.g. "Stray LC Resonance" mode…

see [3] for more details





1. The Physical Basis of SI, PI, and EMC

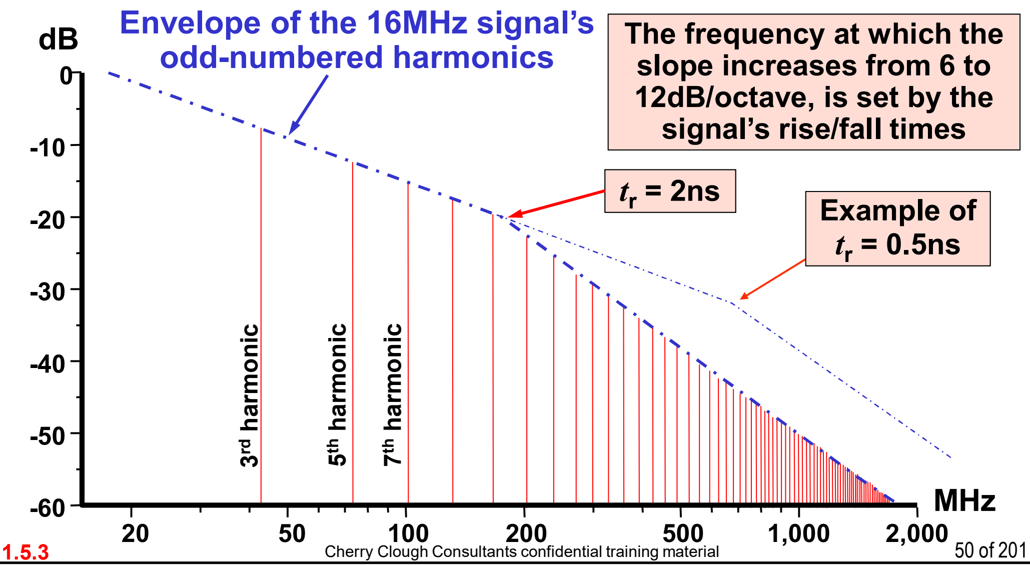
1.5

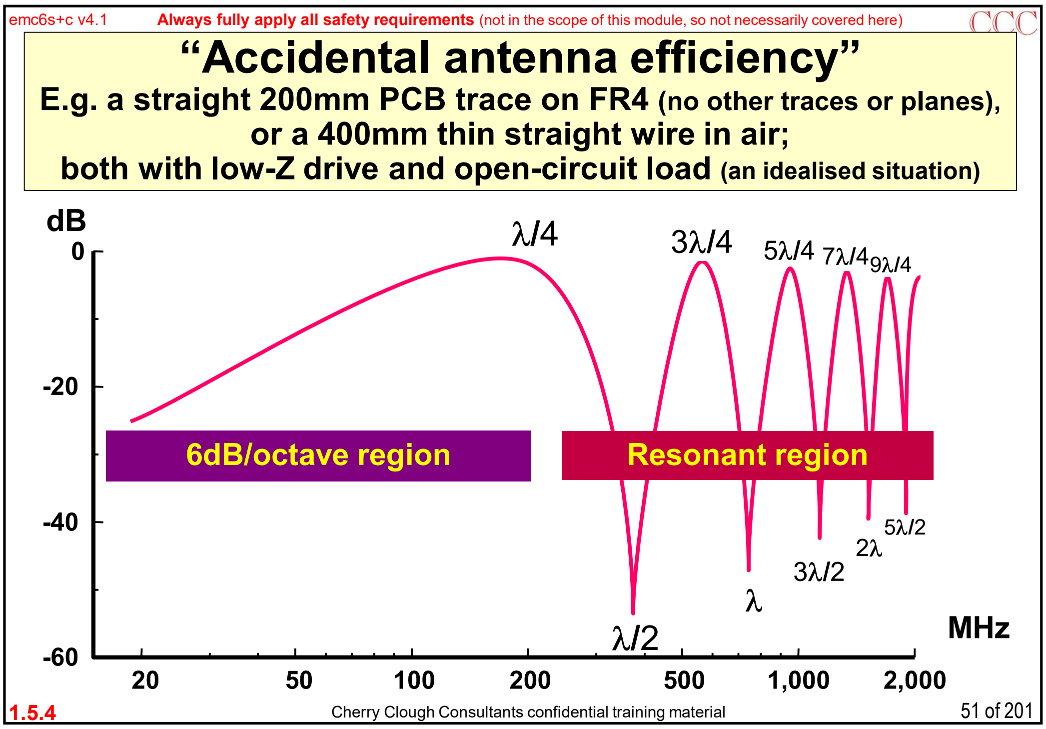
Waveforms, spectra, and "accidental antennas"

Waveforms and Spectra

- **On/off and discontinuous waveforms (e.g. digital, PWM, switch-mode, etc.) are rich in harmonics**
  - **it is not unusual for a 50kHz switch-mode power converter to cause high levels of emissions at 50MHz**
  - **or for 50MHz digital clocks to cause 900MHz emissions**
- **When resonant frequencies happen to lie at the same frequencies as these harmonics…**
  - **– they can 'amplify' the common-impedance, E, H and EM coupling effects (see later)…**
- ***So for good SI, PI or EMC we don't change voltages or currents more quickly than is necessary !***

The spectrum of a 16 MHz squarewave with 2ns rise/falltimes (idealised analysis)




emc6s+c v4.1
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CCC
"Accidental antenna efficiency"
E.g. a straight 200mm PCB trace on FR4 (no other traces or planes),
or a 400mm thin straight wire in air;
both with low-Z drive and open-circuit load (an idealised situation)
dB
0
-20
-40
-60
λ/4
3λ/4
5λ/4
7λ/4
9λ/4
6dB/octave region
Resonant region
5λ/2
2λ
3λ/2
λ
λ/2
MHz
20
50
100
200
500
1,000
2,000
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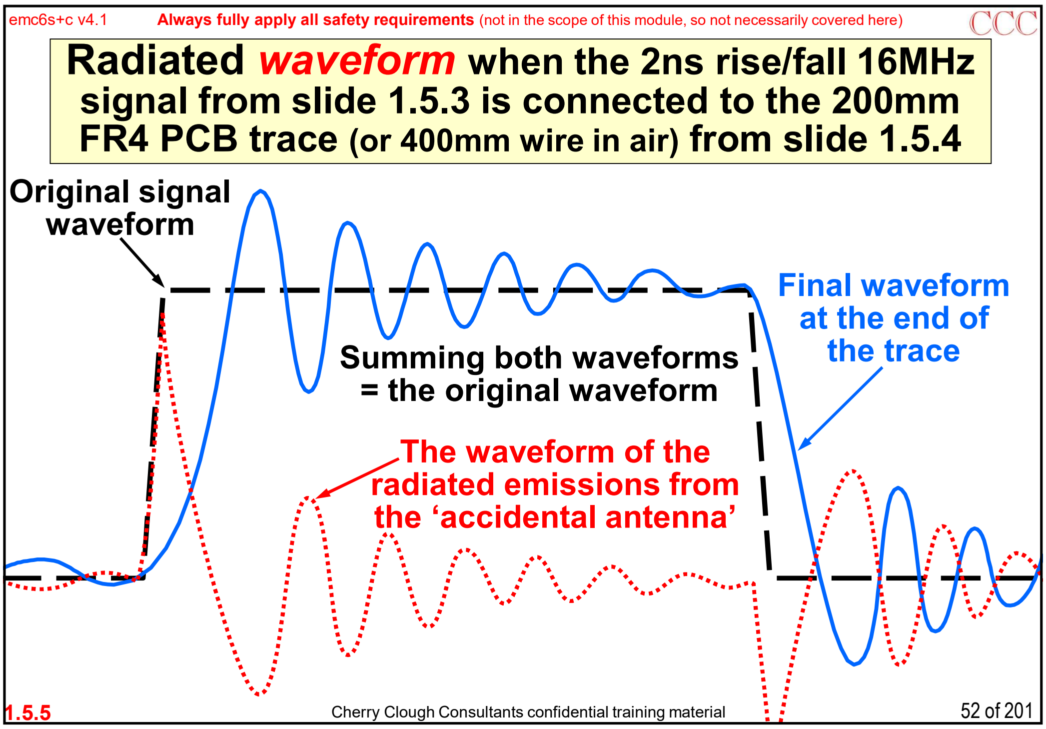
emc6s+c v4.1
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CCC
Radiated waveform when the 2ns rise/fall 16MHz signal from slide 1.5.3 is connected to the 200mm FR4 PCB trace (or 400mm wire in air) from slide 1.5.4
Original signal waveform
Final waveform at the end of the trace
Summing both waveforms = the original waveform
The waveform of the radiated emissions from the 'accidental antenna'
1.5.5
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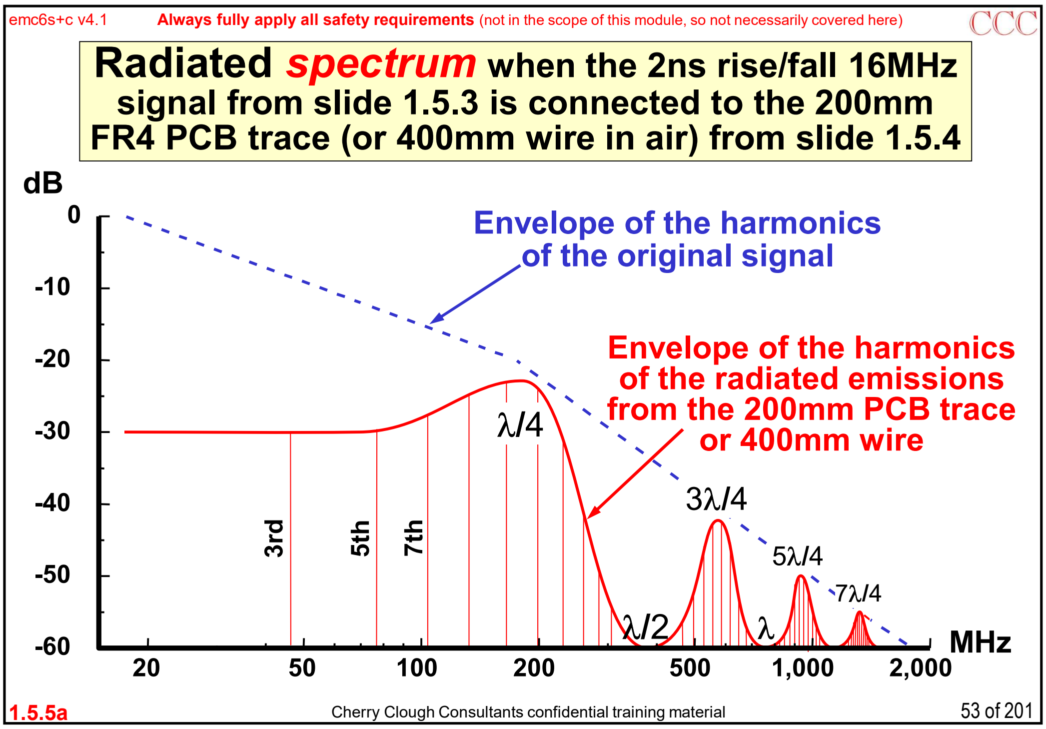
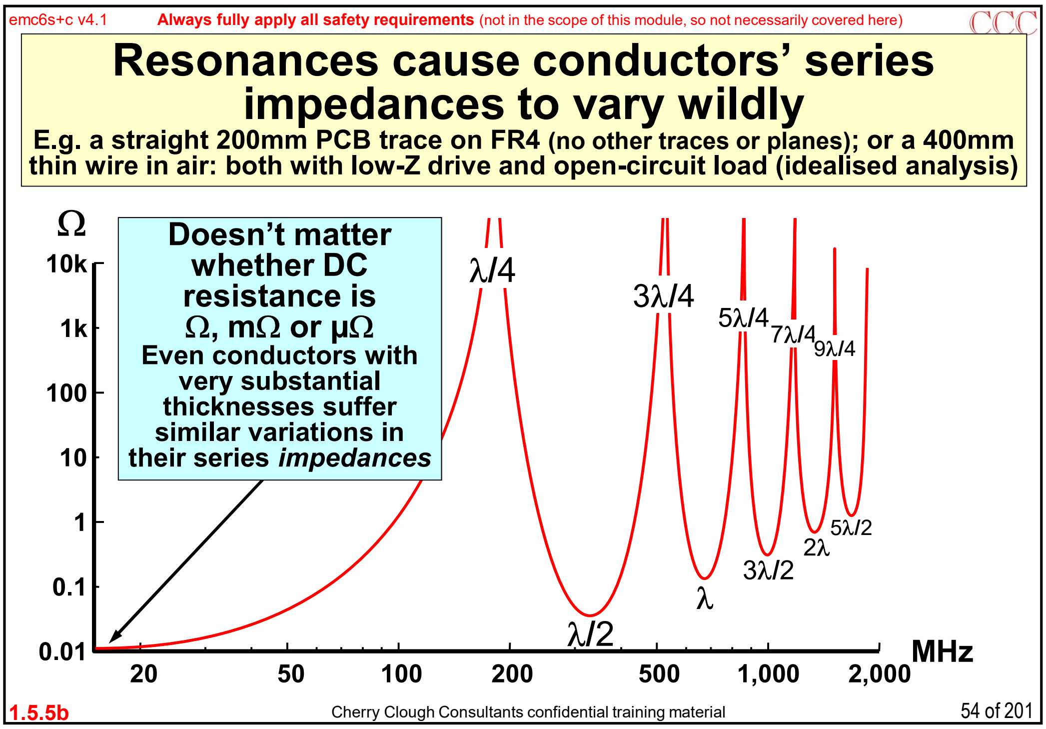
By Keith Armstrong





Structural resonances also create 'accidental antennas'

- **Similar figures can be drawn showing how the E and H fields associated with conductors can suffer resonances due to:**
  - **2-dimensional structures (e.g. printed-circuit boards) 3-dimensional structures (e.g. metal boxes)**
  - **resulting in higher levels of emissions (and worse immunity) at those resonant frequencies**

see [3] on slide 1.19.3 for more details

- **And how the series impedances of the metal structures vary, too**

The strong relationship between EMC, SI and PI

- **Conductors whose voltage or current waveforms have overshoot and/or ringing are losing some of their energy into the air…**
  - **by radiating E and/or H fields at the frequencies at which their conductors are efficient "accidental antennas"…**
    - **we can determine the worst emitted noise frequencies from the ringing frequencies seen on an oscilloscope**
- **A circuit with excellent SI & PI (i.e. very low overshoot and very little ringing on all signals, data, and power waveforms) has good EMC…**
  - **and using good EMC design techniques from the start of a project achieves *excellent* SI and PI, because cost-effective EMC design is harder than SI or PI**

Ever-increasing signal, data, and noise frequencies make accidental antennas increasingly important

- **This is why many of the EMC techniques that have been used for decades, e.g…**
  - **terminating cable shields/screens at one end only…**
  - **single-point or 'star' earthing or grounding…**
  - **splitting ground planes on PCBs (e.g. analogue/digital)…**

  – now create more problems than they (*used to*) solve…
  - **the accidental antennas they create now resonate at the signal / data frequencies we use (and the noise frequencies we suffer)…**
  - **making them very efficient indeed at radiating / picking-up EM noises that cause emissions or susceptibility**

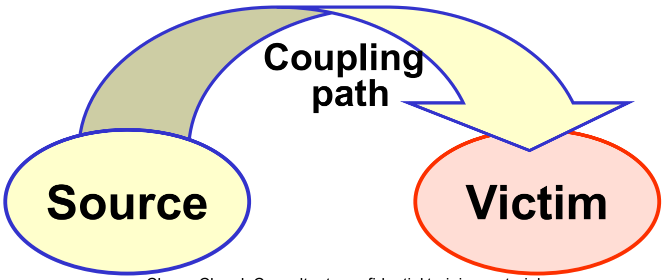
1. The Physical Basis of SI, PI, and EMC

1.6

Three parts to every EMC issue, and four types of EM coupling

The three parts to *every* EMC issue

- **A source of electromagnetic disturbances**
  i.e. a possible EM threat, a possible cause of EMI
- **An electrical or electronic circuit**
  i.e. a potential ‘victim’, susceptible to those EM disturbances
- **And *at least one* electromagnetic coupling path between them** **(out of the four *possible* paths)**



The four types of EM coupling...

1. **Common impedances**
2. **Electric (E) fields**
3. **Magnetic (H) fields**
4. **Electromagnetic (EM) fields**

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Common-impedance coupling

- **Every conductor has intrinsic R, L, and C**
  - so there is always an impedance in a shared conductor
  - e.g. AC or DC supply conductors, grounds, earths, 0Vs, cable shields, enclosure shields, connectors, etc.
- **The impedance is generally worse at higher frequencies**
  - because the skin effect increases the resistance R
  - and because of increasing inductive impedance ($2\pi f L$)

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Common-impedance coupling continued…

- **Currents flowing in the impedance of a shared conductor generate a "Common-Mode" (CM) voltage noise**
  - it is called CM because it is common to all of the circuits that share the conductor
- **So the common impedance of the shared conductor causes the currents of one circuit to couple CM voltage into other circuits**

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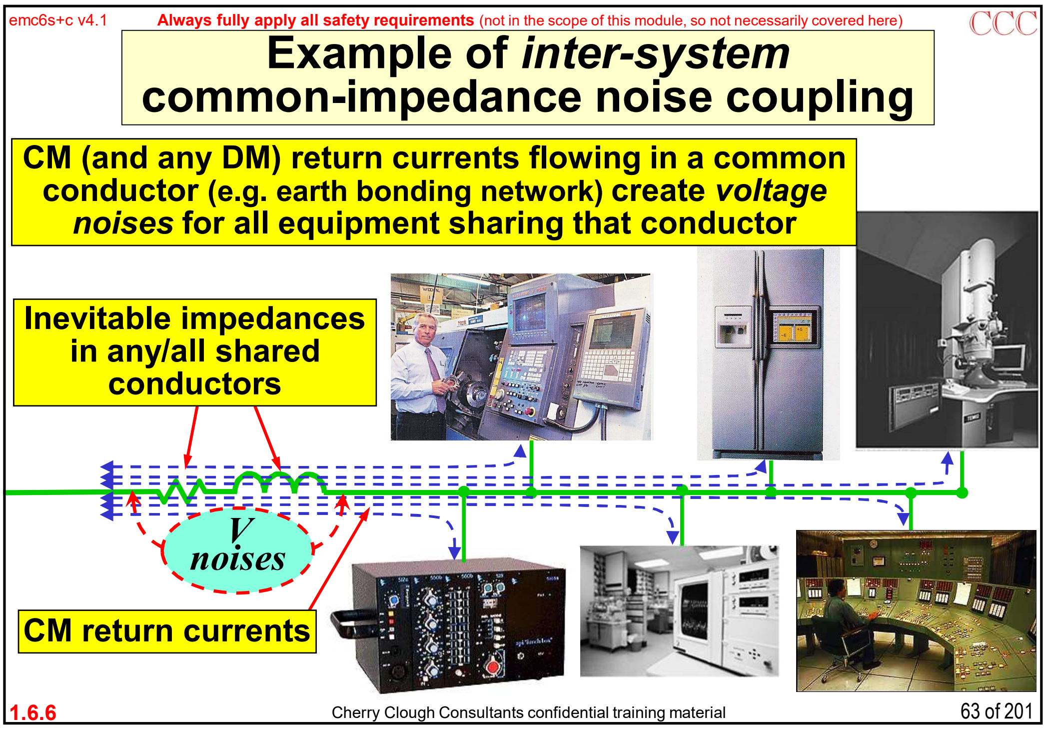
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Example of *inter-system* common-impedance noise coupling
CM (and any DM) return currents flowing in a common conductor (e.g. earth bonding network) create *voltage noises* for all equipment sharing that conductor
Inevitable impedances in any/all shared conductors
V noises
CM return currents
1.6.6
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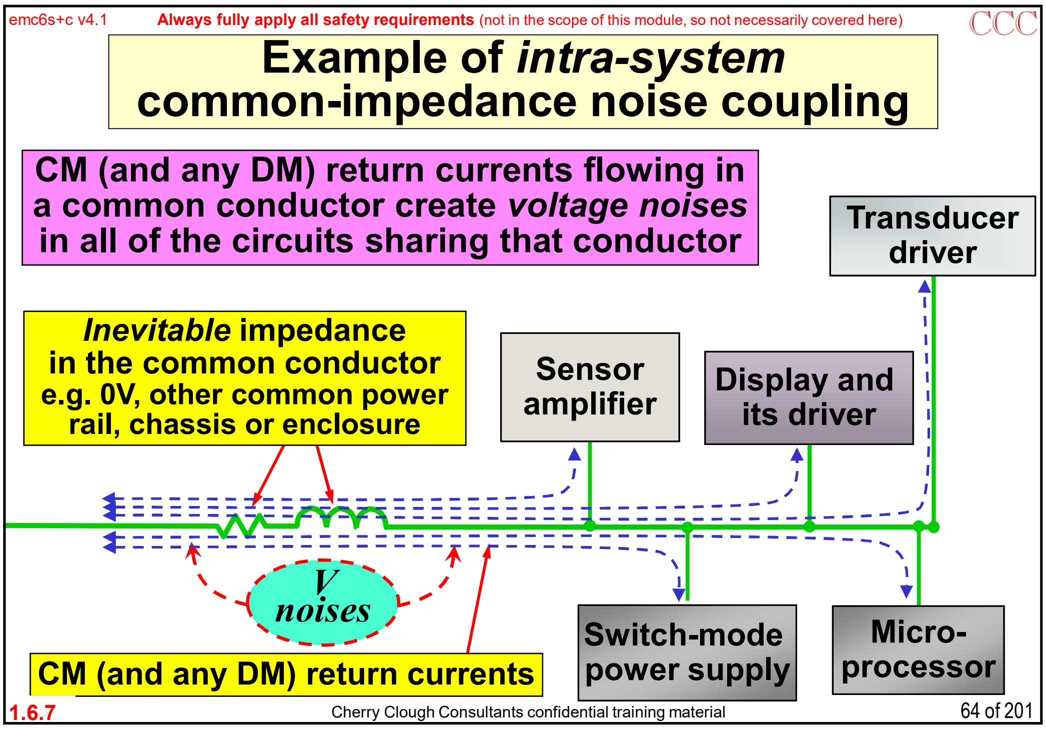
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Example of *intra-system* common-impedance noise coupling
CM (and any DM) return currents flowing in a common conductor create *voltage noises* in all of the circuits sharing that conductor
Transducer driver
Inevitable impedance in the common conductor e.g. 0V, other common power rail, chassis or enclosure
Sensor amplifier
Display and its driver
V noises
CM (and any DM) return currents
Switch-mode power supply
Micro-processor
1.6.7
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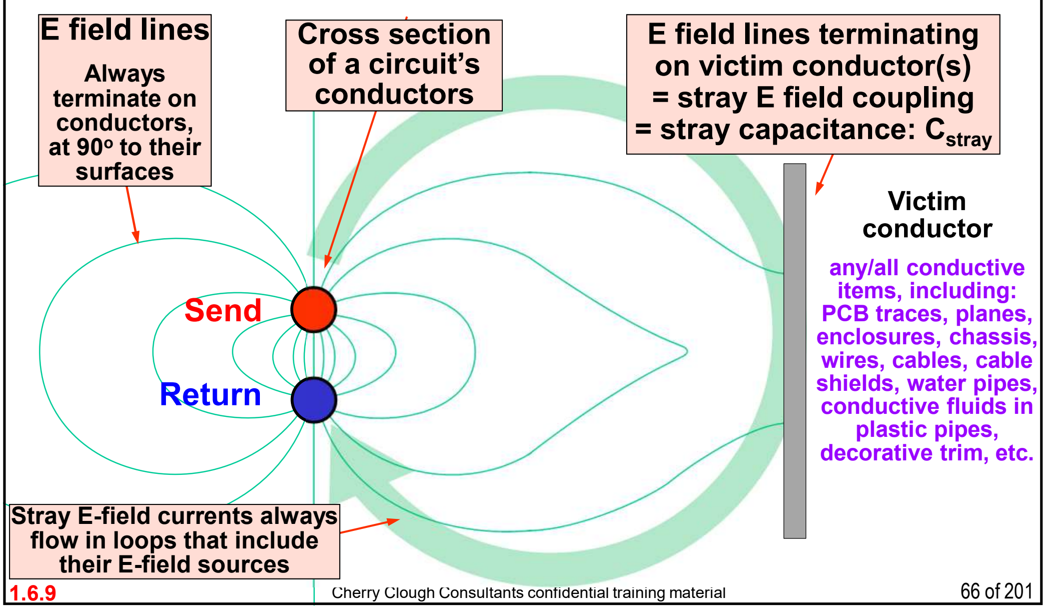
Circuit design is taught as if power rails and 0V returns have zero impedance

– so they are not drawn on the schematic

- This approach ***guarantees*** that circuits will ***not*** work correctly in real life…
  - because the real world is now full of noise frequencies that are so high that the common impedances of power rails and 0V 'grounds' are very important indeed
  - for the emissions/immunity of digital circuits
  - and for the immunity of analogue circuits
    - even DC and low-frequency instrumentation/audio circuits

Stray electric (E) field coupling



E-field coupling causes stray noise *currents*

- **Basically:** $I_{STRAY} = C_{STRAY} (dV/dt)$
  - this assumes: i) the victim's impedance is << $1/(2\pi f C_{STRAY})$ and, ii) the size of the victim circuit is << λ/6
- **All stray E-field coupled noise currents always flow in closed loops that include their E-field sources…**
  - these are properly known as stray *Displacement Currents*…
  - and a stray capacitance of just 0.1pF between a victim conductor and a 100MHz 3V squarewave signal, would couple 186μA of noise current into the victim conductor at the 100MHz fundamental frequency…
    - and just 2.5μA of Common Mode noise current *(see later)* coupled into a long cable is enough to fail Class B emissions!

E-field coupling continued...

- **The impedance of C_{STRAY} reduces as frequency increases:**

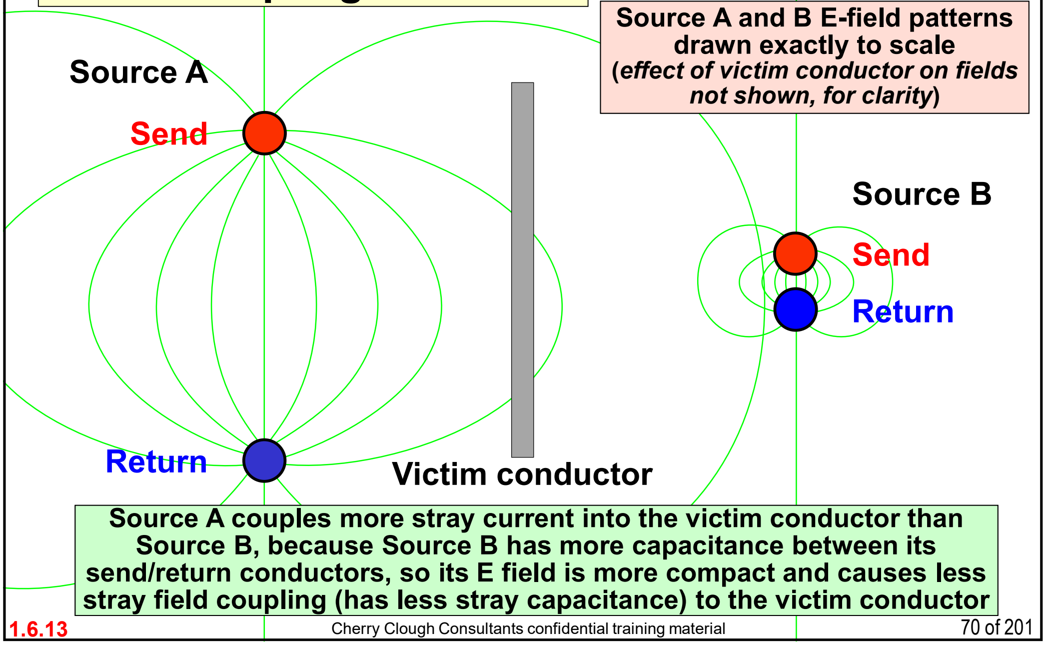
$$Z_C = 1/(2 \pi f C)$$

- **Reducing the rate of change of a voltage (it's dV/dt) reduces its high frequency content** *(Fourier transform)…*
  - whether it is a signal, data or power voltage
  - and therefore reduces its E-field emissions, and the noise current that it injects (couples) into victim conductors

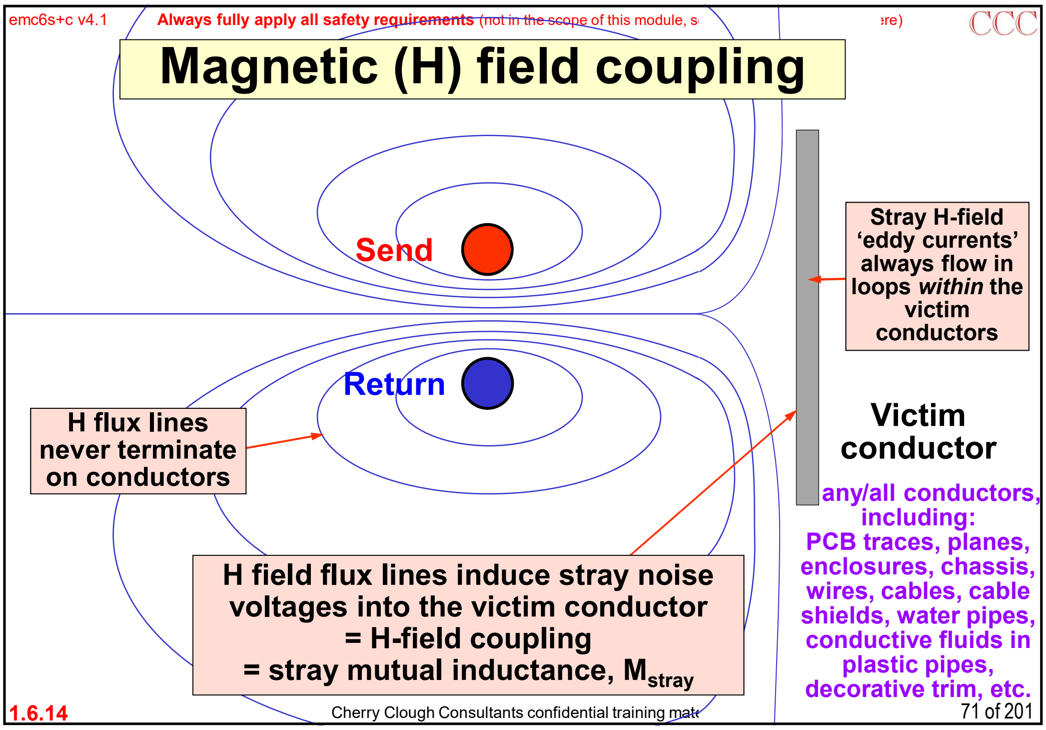
E-field coupling continued...

- **We want low stray capacitance (E-field coupling) between the source and victim conductors…**
  - **to reduce their noise coupling (interference)**
- **But for a signal/data communication, or power delivery…**
  - **we generally want a *high capacitance* between its designated send and return conductors…**
  - **because this makes its E-fields more compact…**
    - **which reduces its stray capacitance to 'victim' conductors…**
    - **thereby reducing the amount of stray noise coupling into those conductors: reducing noise emissions**

E-field coupling continued...



Source A couples more stray current into the victim conductor than Source B, because Source B has more capacitance between its send/return conductors, so its E field is more compact and causes less stray field coupling (has less stray capacitance) to the victim conductor



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H-field coupling causes noise <u>voltages</u> to be injected into victim conductors

- **Basically:** $V_{STRAY} = -M_{STRAY}\,(dI/dt)$…
  - this assumes: i) victim conductor's impedance >> $2\pi f M_{STRAY}$ and, ii) the size of the victim conductor is << $\lambda/6$
- **All stray H-field coupled noise voltages cause stray currents to flow *in closed loops entirely within the victim conductors*…**
  - these are properly known as stray *Eddy Currents*…
  - – e.g. a stray mutual inductance of only 10nH between a victim conductor and a circuit carrying a 100MHz squarewave at 100mA, would couple 63mV of noise into the victim at 100MHz, also 63mV at 300MHz, 63mV at 500MHz, 700MHz, etc.

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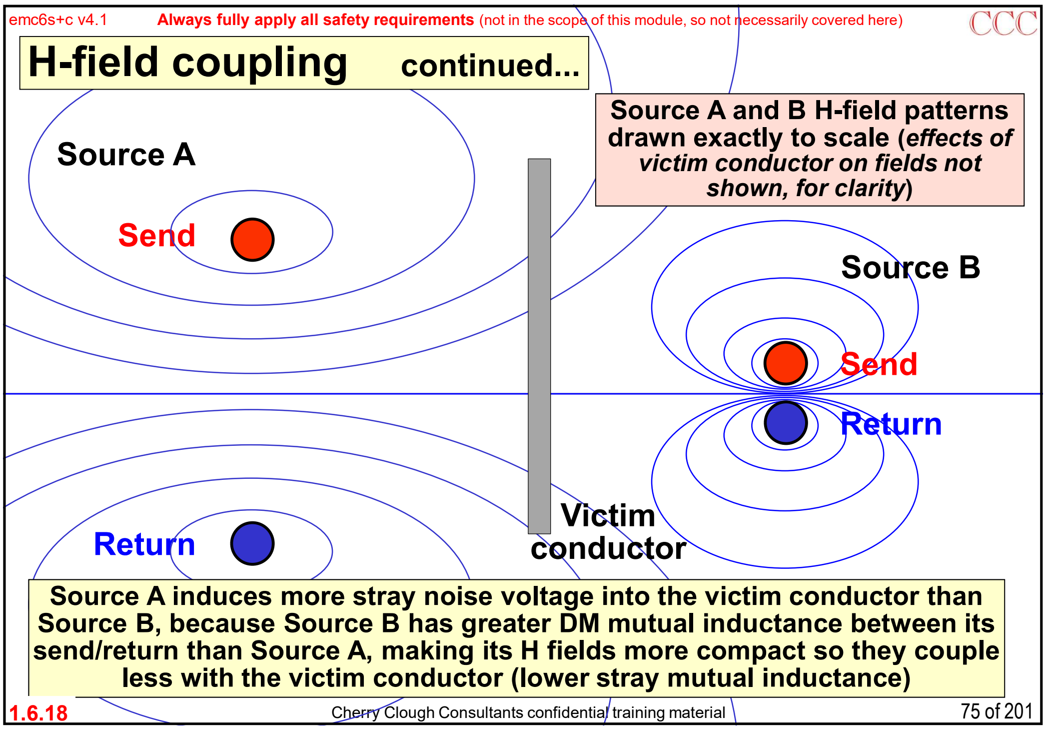
H-field coupling continued...

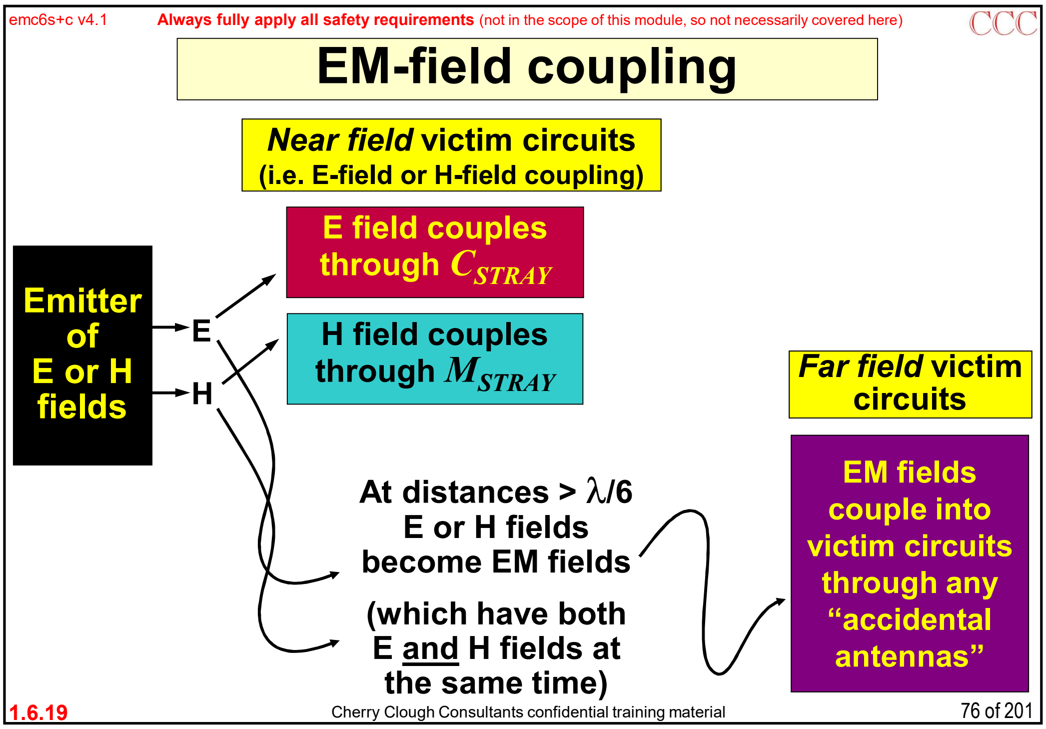
- Impedance of M_{STRAY} increases with increasing f : $Z_M = 2\pi f M$…
  - so, for a given dI/dt, the coupled noise voltage increases proportionally with frequency,
- Reducing the rate of change of a current (it's dI/dt) reduces its high frequency content *(Fourier transform)*…
  - and therefore reduces its H-field emissions, and the stray noise voltages that they induce (couple) into victim conductors

H-field coupling continued...

- We want to have low mutual inductance (M_{STRAY}) coupling between *different* circuits…
  - to reduce their noise coupling (interference)
- But for a signal/data communication, or power delivery...
  - we generally want a *high* mutual inductance between its designated send and return conductors, because this makes its H-fields more compact…
    - which reduces its stray mutual inductance with 'victim' conductors…
    - thereby reducing the amount of stray noise coupling into those conductors: reducing noise emissions

By Keith Armstrong





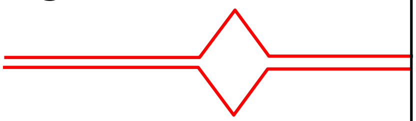
1. The Physical Basis of SI, PI, and EMC

1.7

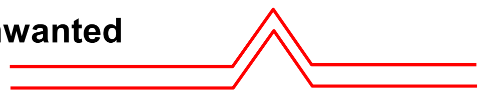
Differential Mode (DM), and Common Mode (CM)

Differential Mode and Common Mode

- **Differential Mode (DM) is where the send and return conductors carry opposing voltages or currents**
  - – **wanted signals, data and power are always DM**



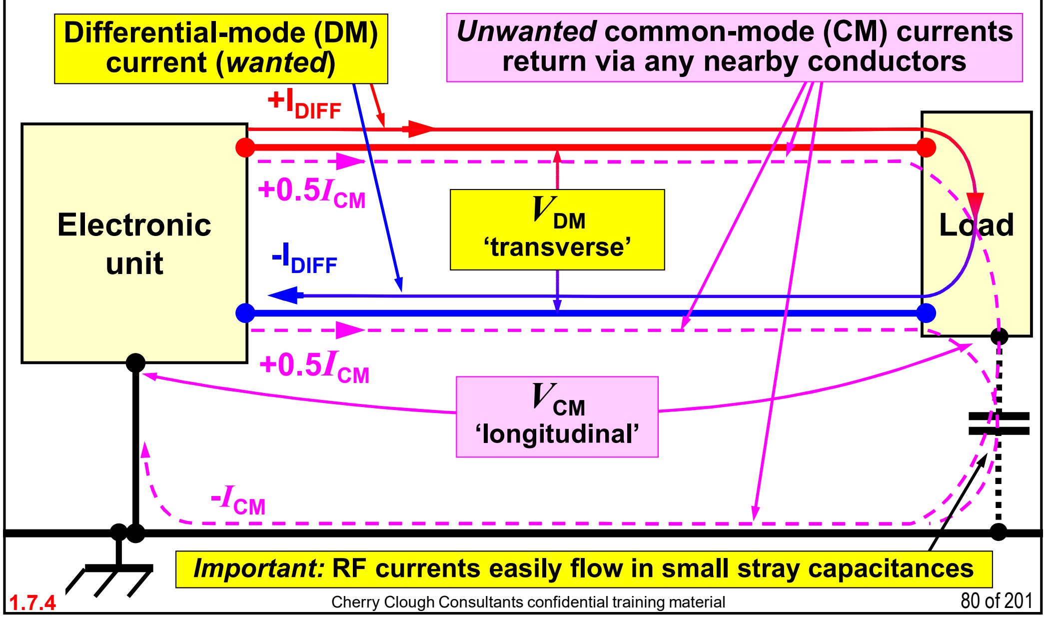
- **Common Mode (CM) is where the voltages or currents are the same on both send and return conductors**
    - **measured with respect to a remote 'earth' reference**
  - – **CM is accidental, and is unwanted**



Common Mode

- We *intentionally* create DM when we create our *wanted* signals, data or power…
  - DM is sometimes called 'transverse', because its voltages and currents exist *between* the specified send and return conductors
- But unbalanced 'stray' coupling converts some DM signal, data or power into *unwanted* CM current and voltage noise…
  - and these accidental CM currents and voltages also have 'stray' couplings into victim circuits…
    - CM is sometimes called 'longitudinal' when it appears along the length of a cable

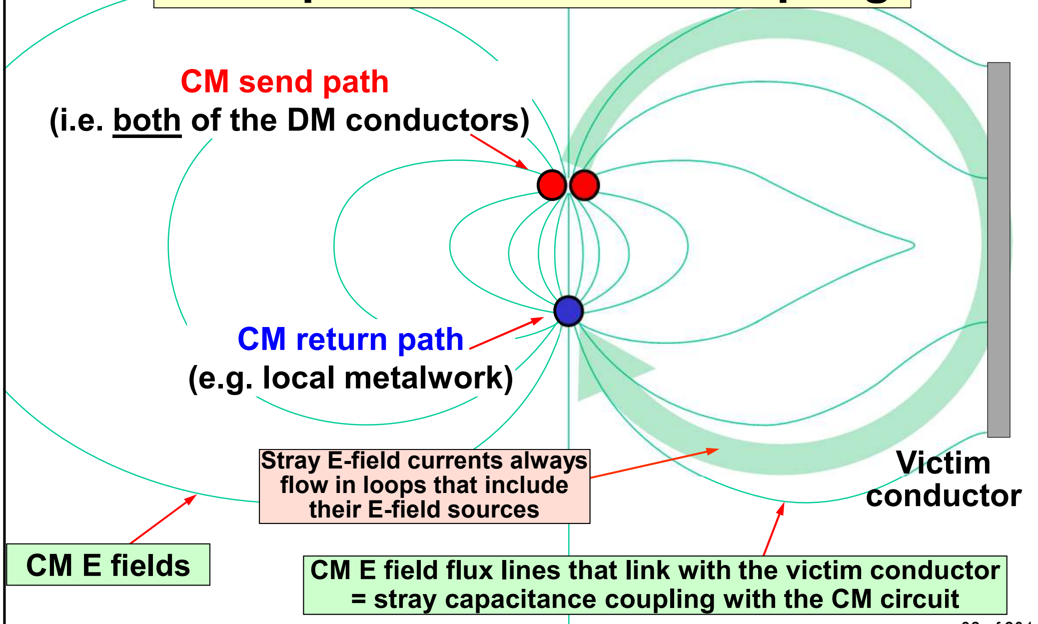
Sketch of DM signals, data or power causing CM noises, for a 'floating' load



Common Mode continued…

- Remember, the four causes of 'stray' coupling are…
  - Common-impedance
  - E-field
  - H-field
  - EM-field
  - – and they <u>all</u> couple stray CM current and voltage noises just as well as they couple stray DM currents and voltages as described earlier

Example of CM E-field coupling



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The very great importance of controlling CM

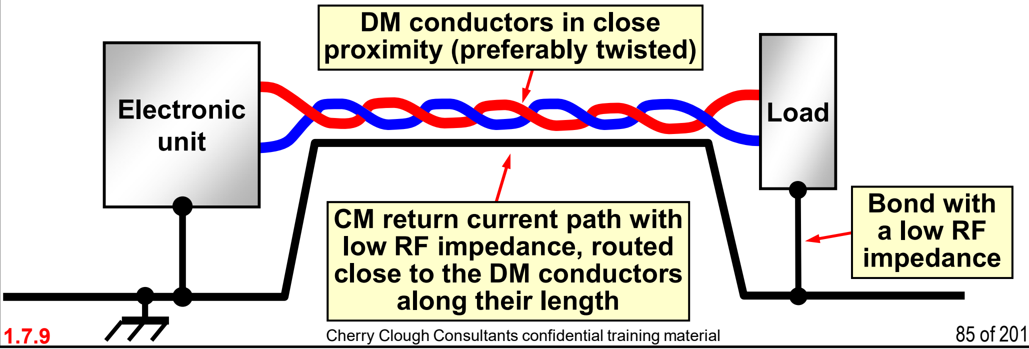
- **Because CM currents tend to flow in large loops…**
  - **and because CM voltages tend to appear across large areas and CM currents flow in large loops…**
  - **the 'accidental' conversion of (wanted) DM voltages and currents into CM noise, is generally the main cause of emissions from 1 - 1000MHz**
  - **and the corresponding conversion of CM noise into noise in DM signals, data or power is the main cause of poor immunity from 1 - 1000MHz**

Controlling CM return currents is *very important indeed* !

- ***1st :* reduce CM generation by…**
  - **reducing the RF impedance in shared conductors…**
  - **providing DM send/return paths in close proximity for both signals, data and power (e.g. twisted-pair conductors) to reduce CM field emissions**
- ***2nd :* where practical, provide a CM current return path in very close proximity *to each DM circuit…***
  - ***could be the shield of a screened cable…***
  - **currents always take the path of the least energy…**
  - **which is the path that emits the least E or H fields, and therefore causes the least CM stray coupling**

Controlling CM return currents is very important indeed continued…

- *3rd* **: where practical, reduce CM voltages by bonding 'floating' circuits to CM return current path**
  - **designing the bond to have the lowest practical impedance at the frequencies concerned**



Controlling CM return currents is very important indeed continued…

- *4th* **: where providing a CM path is impractical…**
  - **e.g. units not fixed to a metal structure, and not interconnected by screened cables…**
  - **increase the impedance of the CM path, for example by using CM chokes…**
    - **this can also be helpful when a CM path exists and is used**
- ***Note:* at < 1MHz and > 1GHz, DM currents can create as much *or more* emissions than CM…**
  - **so do not assume that all emissions are caused by CM**

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1. The Physical Basis of SI, PI, and EMC

1.8

The SI, PI and EMC benefits of metal planes

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Metal planes bring many benefits

- **Planes have very much lower RF impedance than conductors such as wires, cables or PCB traces…**
  - **so when used in a shared circuit they cause much lower common-impedance coupling**
- **Waves incident on a plane are partially cancelled out by their anti-phase reflections from the plane…**
  - **so when a source or victim circuit is very close to a large area of metal plane…**
  - **this 'image plane' effect reduces its coupling with E, H and EM fields**

More benefits from planes

- Nearby metal planes make ideal low-impedance return paths for both DM and CM currents… *see later*
  - closer planes means better DM and CM return paths, and lower E, H and EM field coupling
- So, metal planes are a powerful tool for SI, PI and EMC, and used in some ICs and most PCBs…
  - large systems sometimes use meshes instead…
    - their highest useful frequency depends on the diagonal size (D) of the mesh's elements: f_{MAX} = 30/D MHz (D in metres) but f_{MAX} = 3/D MHz gives better performance

1. The Physical Basis of SI, PI, and EMC

1.9

Overview of RF emissions

An overview of emissions

- **For emissions, all electronics can be thought of as many tens of thousands (maybe millions) of noise sources**
  - **i.e. the transistors in their ICs, and power transistors**
- **All coupled to thousands of "accidental antennas"**
  - **i.e. PCB traces, wires and cables, metal structures, slots and gaps in shielded enclosures, etc....**
  - **all of which have resonant frequencies that depend on their dimensions, build conditions, terminations, routing, and proximity to other conductors and materials**

1. The Physical Basis of SI, PI, and EMC

1.10

External connections to 'earth', 'ground', 'chassis', etc.

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Explaining previous experience

- **People often find that 'earthing' or 'grounding' metal items/structures reduced EMI…**
  - **which gave rise to the myth that the 'earth', 'ground', 'chassis', 'deck', etc., was an infinite sink for RF noise, which is 100% impossible in *this* universe!**
  - **– what is *really* happening, is that this provides extra opportunities for stray / leaked / sneak currents to flow in shorter / lower-impedance loops – back to the semiconductors they came from…**
    - **making their stray field patterns smaller, more compact, so that they then interacted less with other conductors (such as the LISNs and antennas in EMC test labs)…**
    - **assuming they managed to avoid creating resonant structures that made EMC worse** *see [3] and [5]*
    - **some more explanations follow, in the next few slides...**

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'Earthing', 'grounding', etc., doesn't help (1)

- **It is often mistakenly assumed that large conductive structures…**
  - **e.g. called Earth, Ground, Chassis, Frame, Hull, Deck, etc…**
  - **– are infinite sinks for noise currents at any frequency**
- **But this is *impossible*, because *any/all* currents inc. stray, parasitic, sneak, leaked, noise, DM, or CM currents, *always* flow in *closed loops!***
- **So no earths, grounds, chassis, etc., can possibly ever be 'waste disposal' sinks for any currents!**
  - **– nothing ever can**

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'Earthing', 'grounding', etc., doesn't help (2)

- **As we have seen, *all* conductors have self-inductance and space-charge capacitance, so have self-impedances that vary with frequency…**
  - **all conductors (except superconductors) also have resistance, but above a few hundred Hz this is generally swamped by their self-inductance…**
  - **e.g. a 300mm long 20mm dia. solid copper rod has a Z of 16μΩ at DC; but at 1kHz it is ≈ 40μΩ, and at 1MHz ≈ 1.3mΩ**
- **All conductors also have mutual inductance and mutual capacitance to any/all other conductors…**
  - **which causes noise voltages and currents to couple between them: i.e. near-field stray noise coupling**

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emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

'Earthing', 'grounding', etc., doesn't help (3)

- **We have also seen that voltages and currents in all conductors interact with their local EM fields…**
  - **so *all* conductors behave as accidental transmitting and receiving radio antennas, e.g. a 300mm long 20mm dia. copper rod is a perfect E-field antenna around 225 MHz (monopole mode) or 450 MHz (dipole mode)**
- **So *even if* external structures such as 'earth', 'ground', 'chassis', 'frame', 'deck', etc., *were* 'waste disposal' sinks for noisy currents *(which they aren't)*…**
  - ***no* conductor that connects to them can avoid noise, even if they are wide tin-plated copper braid straps, huge copper busbars, or steel girders, and *even if their insulation is green or green/yellow stripes!***

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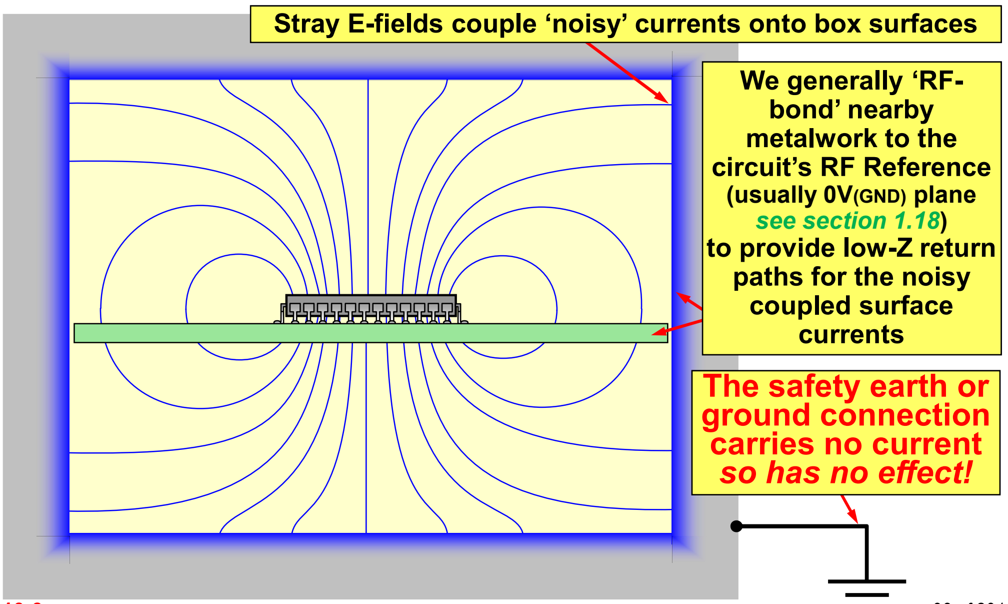
'Earthing', 'grounding', etc., doesn't help (4)

- ***Of course:*** circuits need conductors for their voltage references, and for carrying their return currents (whether wanted (DM); or leaked, stray', or 'sneak' (CM) noises)…
  see sections 1.17 and 1.18 for their requirements
  - and they might need to be connected to local earth, ground, chassis, etc., structures for safety reasons
- ***Of course:*** any large conductive structure near any circuit will couple with its 'leaked', 'stray' or 'sneak' near-fields (which ***should*** have been taken care of by good EMC design, *see section 1.18*)…
  – but connecting to the large structure itself, *whatever it is called,* is not ***necessary*** for good EMC, and can make EMC worse because such interconnections inevitably create resonant structures *see 1.4, also [3] and [5]*

E.g. a circuit in a *well-shielded* box



‘Earthing’, ‘grounding’, etc., doesn’t help (5)

- **Huge delays/costs often occur because designers *mistakenly assume* that large metal structures…**
  - **called: Earth, Ground, Chassis, Frame, Hull, Deck, etc.**
  - **– are necessary for EMC** ***(when they aren’t!)***
- **So:– we should only use words like Earth, Ground, Chassis, Frame, Hull, Fuselage, Deck, etc…**
  - **– and their relevant symbols…**
  - **– to mean the actual points of electrical connection to those large conductive structures…**
  - ***– and not for designing our electronic circuits themselves!***

But what about ‘Clean Earths’?

- **There’s no such thing as *(so-called)* ‘clean earths’ or ‘clean grounds’…**
  - **– for the reasons just discussed**
- **They were a 50/60Hz ‘fix’ for poorly-designed electronics…**
  - **– that has become outdated by developments since radio started to use VHF after the 1940s…**

Trying to use them these days, is like expecting Rainbow Unicorns to fix your EMC problems!

And 'clean earthing/grounding' encourages damage from transients and surges

- **Separated earth/ground conductors in a building can easily develop transient voltages of >10kV…**
  - with respect to the safety earthing/grounding structure
- **Such transients are induced by lightning (within a km or two), or by flyback or field-collapse when disconnecting a large inductive load…**
  - and when different parts of an equipment are connected to both safety earth/ground and to a *(so-called)* clean earth/ground…
  - such transients/surges can damage the electronics, (unless its insulation can cope with >10kV, *which it usually can't*) *see [5]*

What about *(so-called)* Earth Loops, Ground Loops, or Hum Loops?

- **These are all natural consequences of systems…**
  - stray/leaked noise currents that inevitably flow in their metal structures develop voltages in their impedances…
  - so items of equipment in different locations suffer different local CM noise voltages – in turn makes their interconnecting cables carry CM noise currents…
    - whether the metal structures are connected to a Protective Earth/Ground for safety reasons, or not (e.g. in a vehicle)
- **Attempting to solve this noise problem with *so-called* 'clean earthing/grounding' *just causes EMC problems…***
  - applying our course modules for product and system design should achieve good cost-effective EMC on the first iteration

1. The Physical Basis of SI, PI and EMC

1.11

Non-linearity, demodulation and intermodulation

All the previous slides are equally valid for emissions *and* immunity....

– because they are all concerned with controlling the propagation of E, H and EM fields...

- that we generally call electrical signals, data and power...

– and design techniques based on them are equally effective for controlling RF emissions and immunity at the same time

- However, the following slides cover some additional topics that we have to cover...

– that concern *RF immunity only*

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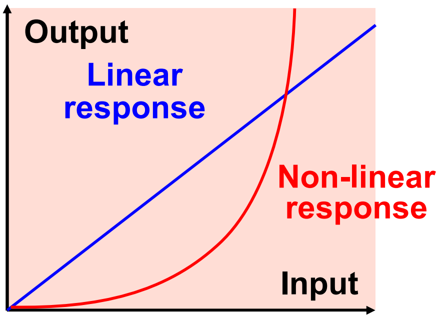
Non-linearity, demodulation and intermodulation

- **In a linear material or device the output is linearly proportional to the input**
- **But *all* semiconductors are non-linear**
  - **as are some oxidised electrical connections**
  - **– so they rectify AC**
    - **in a radio receiver this is called RF demodulation (or detection), and we want it**
    - **but in all the other PN junctions, *we don't want it***



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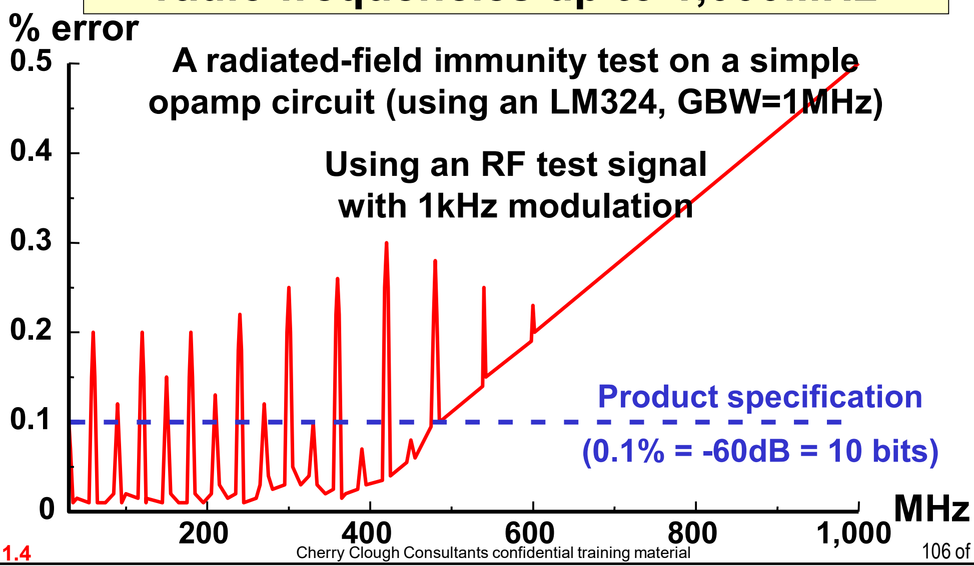
Example of a 'slow' opamp rectifying (demodulating) the 1kHz modulation of radio frequencies up to 1,000MHz



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Non-linearity, demodulation and intermodulation continued…

- **Where two or more frequencies are simultaneously present in a non-linear device…**
  - **new frequencies are created from their sums and differences…**
  - **and then from the sums and differences of these new frequencies (and so on)…**
    - **…it gets very complicated indeed when there are more than three frequencies present at the same time**

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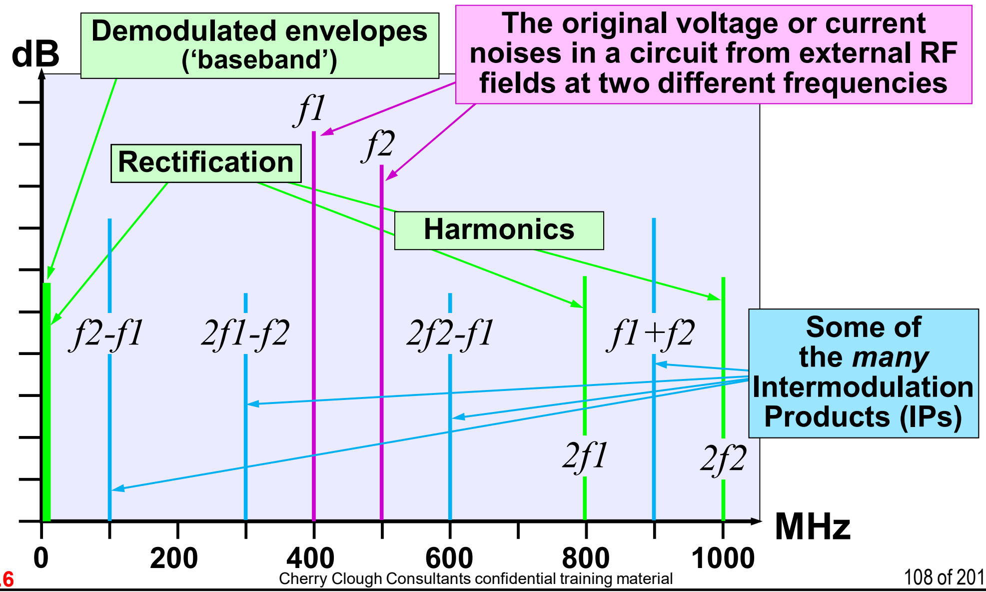
Demodulation and intermodulation create ***new*** frequencies ***inside circuits***



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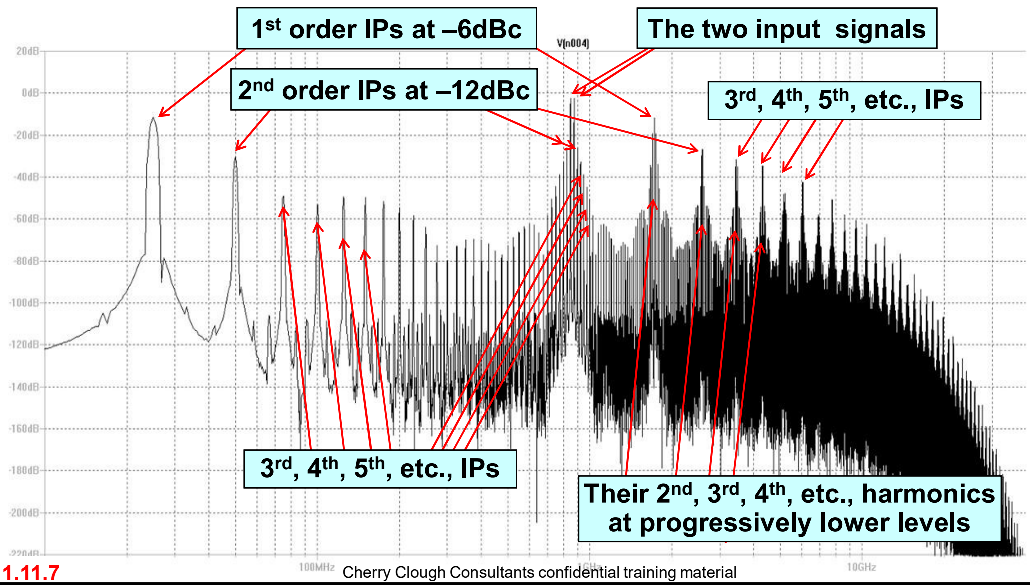
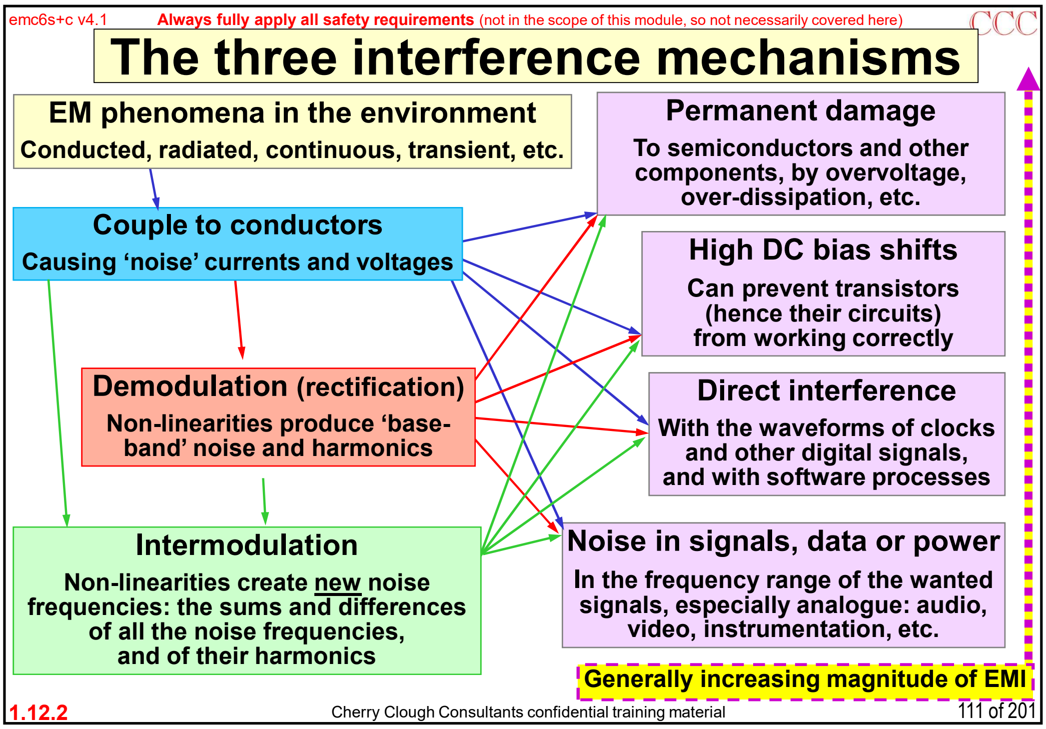
E.g. The spectrum of two RF signals: 850MHz and 875MHz, input to a perfect diode, simulated 10MHz to 35GHz, 20dB/division



1. The Physical Basis of SI, PI and EMC

1.12

The three interference mechanisms



An example of intermodulation

- **Conventional (single frequency) RF immunity testing over the range 150kHz - 1GHz reveals susceptibility over 50 - 200MHz…**
  - **shielding and filtering that is effective over 50 - 200MHz is added, and the equipment now passes that test**
- **But no protection was added from 200MHz - 1GHz…**
  - **allowing *simultaneous* frequencies in this range, in the real-life EM environment, to enter the equipment and intermodulate *inside its devices*...**
  - **creating internal noises within the susceptible range (50 - 200MHz), causing immunity problems**

1. The Physical Basis of SI, PI and EMC

1.13

Overview of RF immunity

All semiconductor circuits are really "accidental" radio tuners

- **For immunity, all electronics can be thought of as many tens of thousands (maybe millions) of 'accidental demodulators' (= rectifiers) *and* 'accidental superheterodynes' (= intermodulators)…**
  - **i.e. the diodes and transistors in ICs and power devices…**
  - **coupled to thousands of "accidental antennas"….**
    - **e.g. PCB traces, wires and cables, metal structures, slots and gaps in shields, etc....**
    - **all of which have resonant frequencies that depend on their dimensions, build conditions, terminations, routing, and proximity to other conductors and materials**

1. The Physical Basis of SI, PI and EMC

1.14

"Internal EMC" including crosstalk

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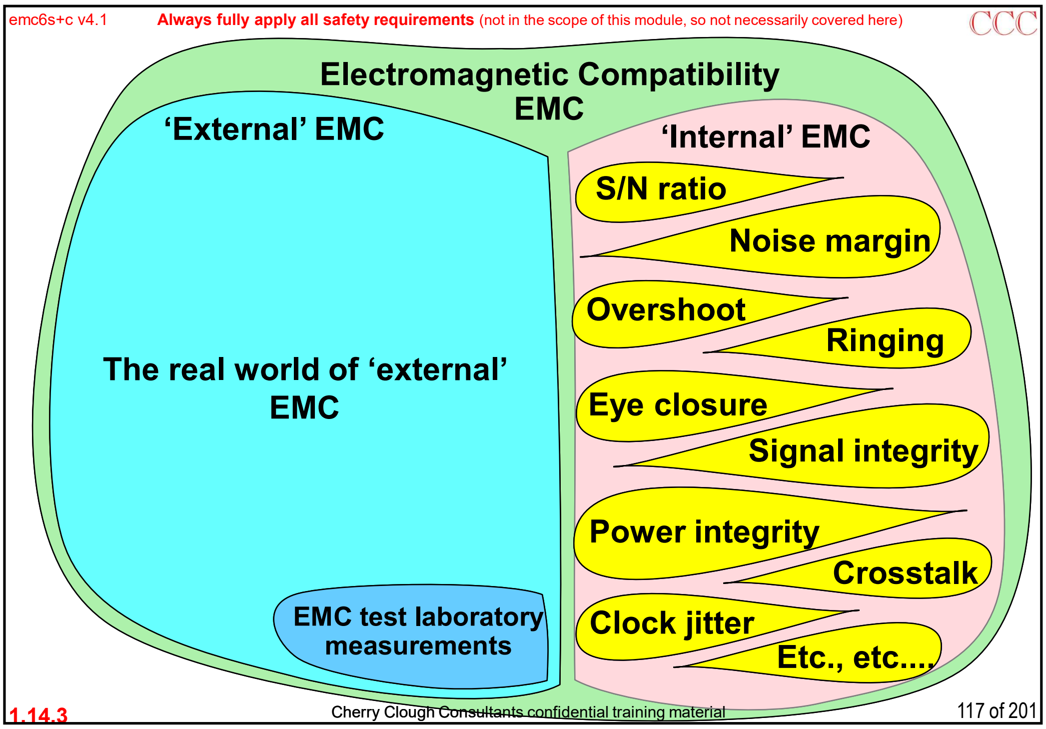
Crosstalk and other EM interactions *inside* equipment

- **For EMC compliance we are only concerned with the EM interactions between an item of equipment and its external environment**
- **But EM interactions also occur *between* devices, traces and wires *inside* an item of equipment…**
  - **and we care about these because they affect the number of design iterations and time-to-market…**
  - **and because they can also affect reliability and warranty costs…**
  - **we might call this issue "internal EMC"**



Crosstalk and other EM interactions *inside* equipment continued…

- **The material in this course module applies equally well whether the issue is "external EMC" or "internal EMC"**
- **Internal EM interactions are traditionally called crosstalk…**
  - **and analysed in terms of stray capacitance and stray mutual inductance…**
  - **i.e. a 'Lumped Analysis' approach…**
  - **which only works when the victim is in the near-field of the E of H field emissions from the noise source**

Crosstalk and other EM interactions *inside* equipment continued…

- **But traditional 'crosstalk' is often inadequate for modern designs…**
  - because the high frequencies we now employ (e.g. clock harmonics) have such short wavelengths that parts of the inside of the equipment are in their far field…
  - and the wires and cables inside an equipment; PCB traces; heatsinks and even devices themselves, can behave as resonant 'accidental antennas'…
  - and far-field EM interactions *cannot* be estimated by lumped analysis methods

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Most of the rest of the material in this course describes design-for-EMC techniques…

- for circuit design, interconnections, PCB layout, etc.
  - as well as shielding and filtering

- **These design techniques control both *internal* and *external* EM interactions, and aim to reduce…**
  - project costs and timescales
    - by reducing the number of design iterations required to achieve functional spec's, reliability and regulatory approval
  - reduce product cost of manufacture
    - by reducing the cost of the filtering and shielding required to achieve regulatory approvals

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1. The Physical Basis of SI, PI and EMC

1.15

Improving profitability while reducing financial risks

1.15.1 Cherry Clough Consultants confidential training material 121 of 201

emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

Improving profitability while reducing financial risks

- **Average for electronics industry:**
  - **6 months late to market = 33% loss of lifecycle profit…**
    - **but in some fast-moving industries, 6 months late to market means no market at all**
- **Many companies incorrectly fixate on controlling BOM (Bill Of Material) costs…**
    - **dates from when products were in production >10 years…**
  - **these days, the *time to market* usually has a *far greater* impact than BOM cost on the "total value generated over the product lifecycle"**

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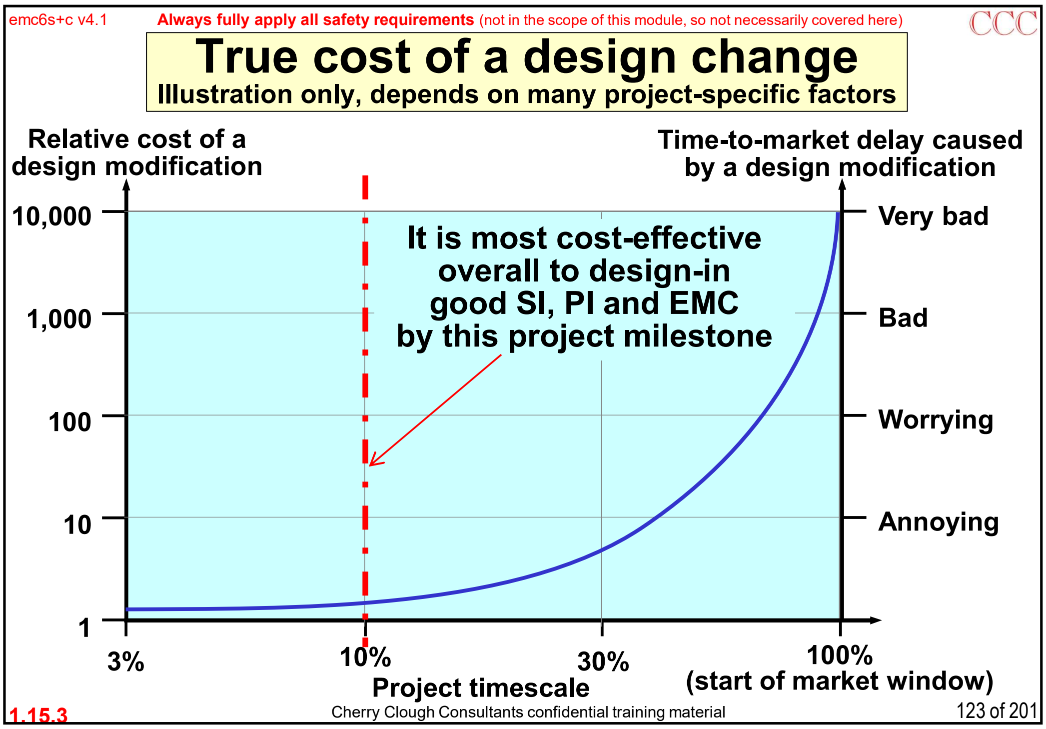
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
True cost of a design change
Illustration only, depends on many project-specific factors
Relative cost of a design modification
Time-to-market delay caused by a design modification
10,000
1,000
100
10
1
Very bad
Bad
Worrying
Annoying
It is most cost-effective overall to design-in good SI, PI and EMC by this project milestone
3%
10%
30%
100% (start of market window)
Project timescale
1.15.3
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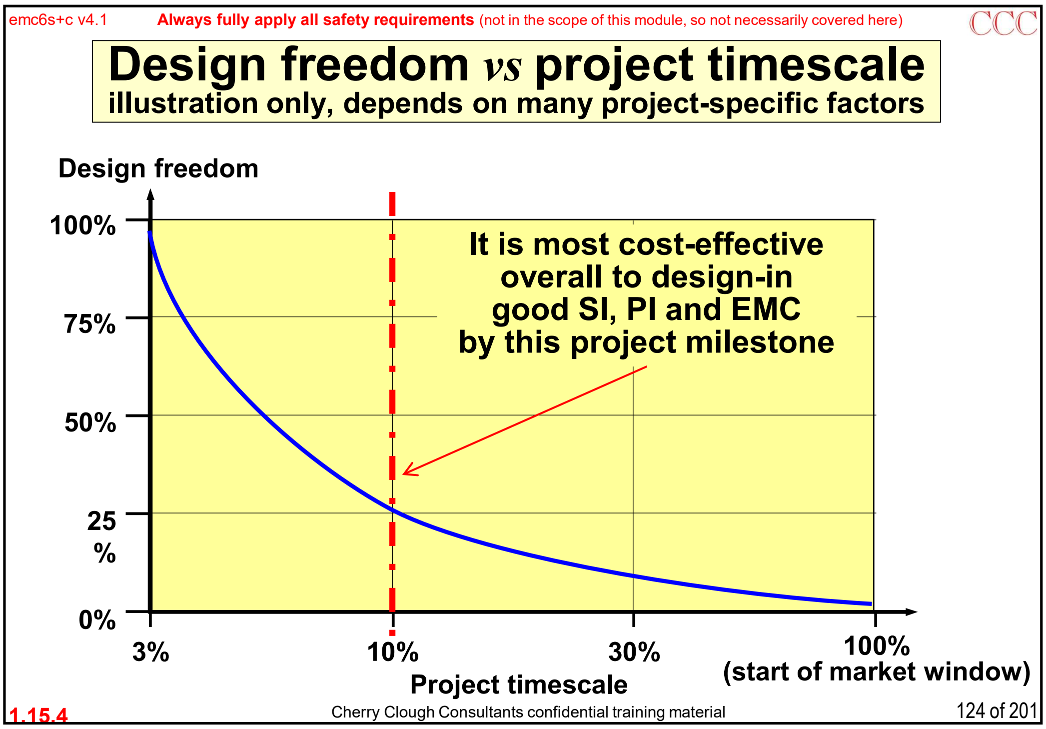
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Design freedom vs project timescale
illustration only, depends on many project-specific factors
Design freedom
100%
75%
50%
25 %
0%
It is most cost-effective overall to design-in good SI, PI and EMC by this project milestone
3%
10%
30%
100% (start of market window)
Project timescale
1.15.4
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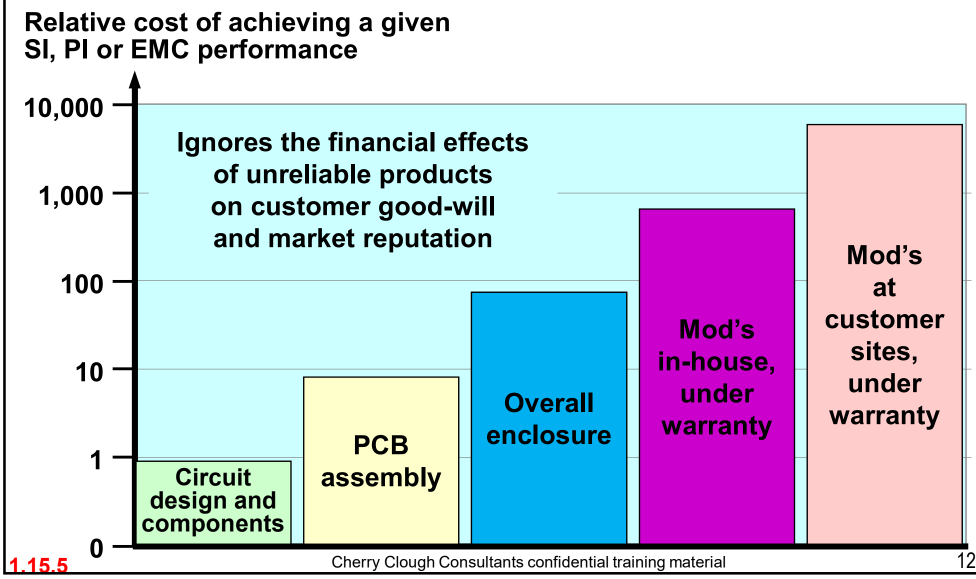
True cost of an SI, PI or EMC measure *versus* level of assembly (guide only)



Since 2000: time-to-market (*not BOM cost*) is most important for financial success

- **We can't have the *fastest possible* time-to-market (i.e. meet all SI, PI and EMC specifications for legal sales and low warranty costs) and the *lowest possible* BOM cost…**
  – ***without computer simulation tools***
- **Less computer simulation means more time in design experimentation and/or "development"...**
  - **to find out how to achieve the functional specifications (SI and PI) and EMC compliance, and also to reduce the BOM cost…**

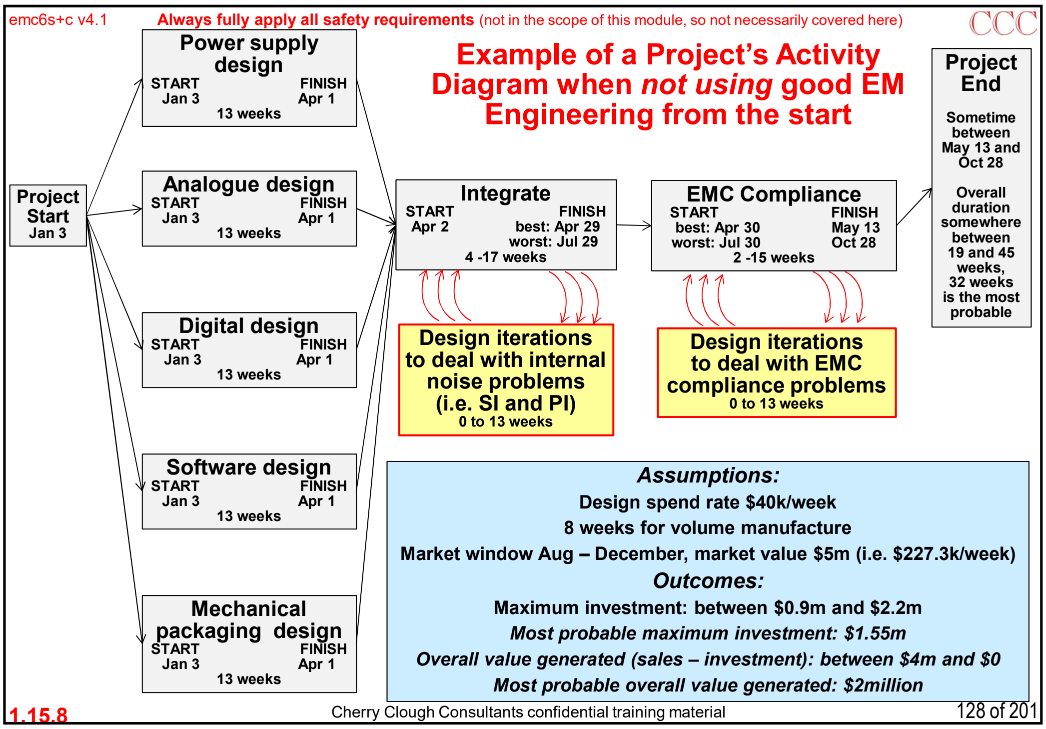
  – **but following these EM Engineering guidelines has been very well-proven for 30+ years to save time and cost overall, reducing financial risks and increasing success**

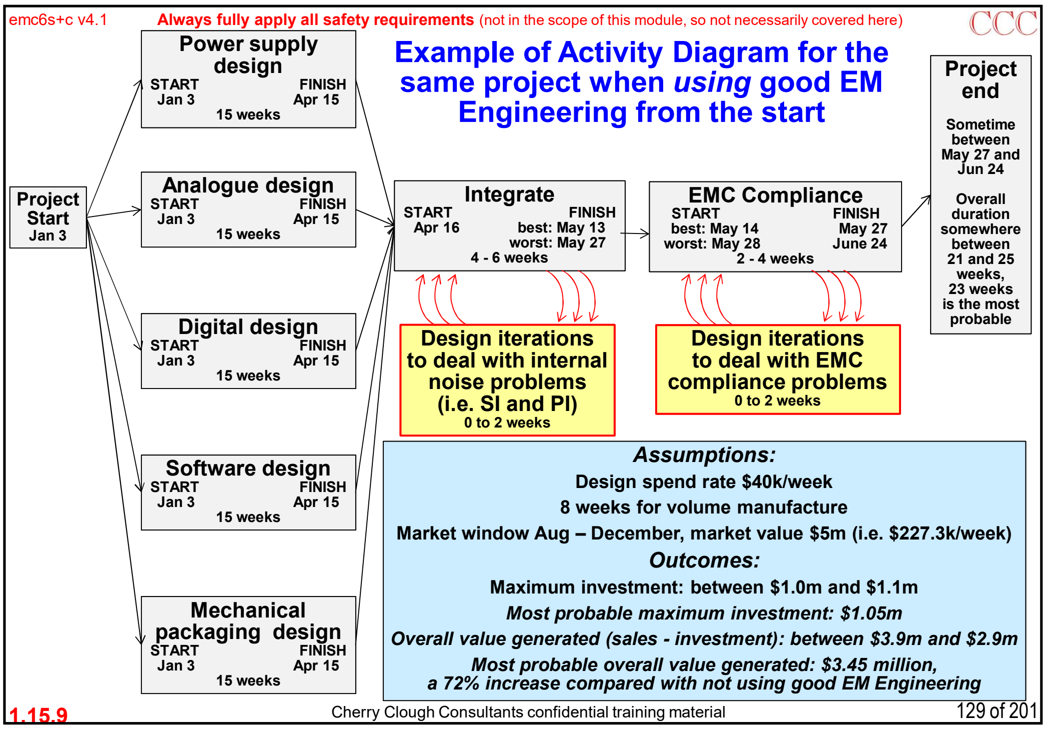
The required simulation tools include…

- Circuit simulators (e.g. SPICE, IBIS)
- Signal Integrity (SI) simulators
- Power Integrity (PI) simulators
- EMC simulators…
  - not *yet* able to predict the results of EMC tests, but valuable and important for optimising design details

■ **EMC simulators are more costly than SI and PI simulators…**

- but setting 5 or 10 times tighter design limits into SI *and* PI simulators generally helps achieve good EMC…
  - but no guarantees!




emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Example of Activity Diagram for the same project when using good EM Engineering from the start
Project Start Jan 3
Power supply design START Jan 3 FINISH Apr 15 15 weeks
Analogue design START Jan 3 FINISH Apr 15 15 weeks
Digital design START Jan 3 FINISH Apr 15 15 weeks
Software design START Jan 3 FINISH Apr 15 15 weeks
Mechanical packaging design START Jan 3 FINISH Apr 15 15 weeks
Integrate START Apr 16 FINISH best: May 13 worst: May 27 4 - 6 weeks
EMC Compliance START best: May 14 worst: May 28 FINISH May 27 June 24 2 - 4 weeks
Project end
Sometime between May 27 and Jun 24
Overall duration somewhere between 21 and 25 weeks, 23 weeks is the most probable
Design iterations to deal with internal noise problems (i.e. SI and PI) 0 to 2 weeks
Design iterations to deal with EMC compliance problems 0 to 2 weeks
Assumptions:
Design spend rate $40k/week
8 weeks for volume manufacture
Market window Aug – December, market value $5m (i.e. $227.3k/week)
Outcomes:
Maximum investment: between $1.0m and $1.1m
Most probable maximum investment: $1.05m
Overall value generated (sales - investment): between $3.9m and $2.9m
Most probable overall value generated: $3.45 million, a 72% increase compared with not using good EM Engineering
1.15.9
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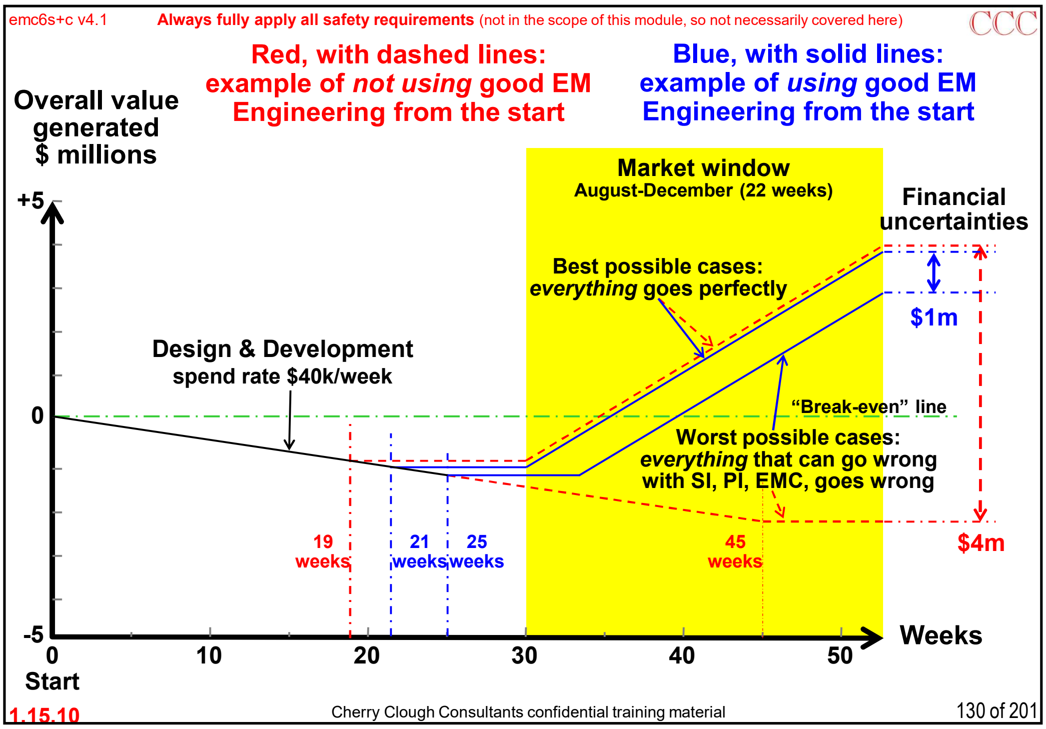
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Red, with dashed lines: example of not using good EM Engineering from the start
Blue, with solid lines: example of using good EM Engineering from the start
Overall value generated $ millions
+5
0
-5
Market window August-December (22 weeks)
Financial uncertainties
Best possible cases: everything goes perfectly
$1m
Design & Development spend rate $40k/week
"Break-even" line
Worst possible cases: everything that can go wrong with SI, PI, EMC, goes wrong
19 weeks
21 weeks
25 weeks
45 weeks
$4m
Weeks
0 Start
10
20
30
40
50
1.15.10
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EMC is an important financial risk issue
(it is not merely a Regulatory compliance issue)

- **It is a mistake to treat EMC as a mere Regulatory issue** (to be just-about complied with, or avoided if possible)…
  - because in real life, products which don't comply with all relevant EMC emissions/immunity standards tend to have poor functional performance and be unreliable …
    - with high levels of warranty costs and poor customer perception: i.e. not good products if you want your company to be financially successful or have a good future
- **So, the *real reason* why we need EM Engineering is to achieve cost-effective SI, PI and EMC…**
  - *to help maximise profits whilst minimising risks*

1. The Physical Basis of SI, PI and EMC

1.16

Introduction to "EM Engineering"

Our Webinars and Training Courses describe *how* to do cost-effective SI, PI and EMC design

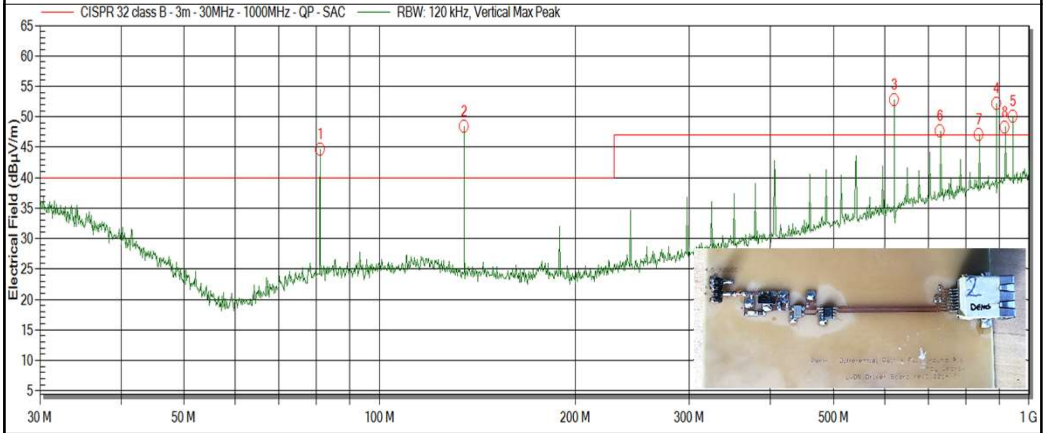
- ***Why*** **these techniques work well is only covered in depth in** ***this*** **course module…**
  - **and in our four Webinars 1a, 1b, 1c and 1d on "The Basics of EMC"…** ***(see the references at the end)***
  - **but all the design techniques described in our Webinars and training courses have been very well proven in practice, worldwide, for 30+ years, to at least 26GHz…**
  - **to save cost, time, reduce financial risks, and increase profitability in** ***all*** **electronic applications**

We could call this design approach: "good EM Engineering"

- **All electrical and electronic signals, data or power** ***are really*** **propagating EM waves…** ***see 1.1***
  - **so, using good EM Engineering throughout a project takes care of SI, PI and EMC issues** ***all at the same time***
- **To avoid repetition,** ***this*** **course module describes the good EM Engineering elements…**
  - **which are common to the design techniques described in our** ***other*** **training courses and Webinars…**
  - **most of which have been well-proven for 25+ years to give excellent results for saving time and cost**

emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

Emissions from an LVDS driver board after autorouting (with no shielding applied)



From the results of a laboratory exercise created for undergraduate students by Andy Degraeve, Research Assistant KU Leuven, Campus Bruges, M-Group (Mechatronics), Bruges, Belgium, in "*Teaching EMC using an EMC demonstration unit*", presented by him at APEMC/IEEE 2018, Singapore

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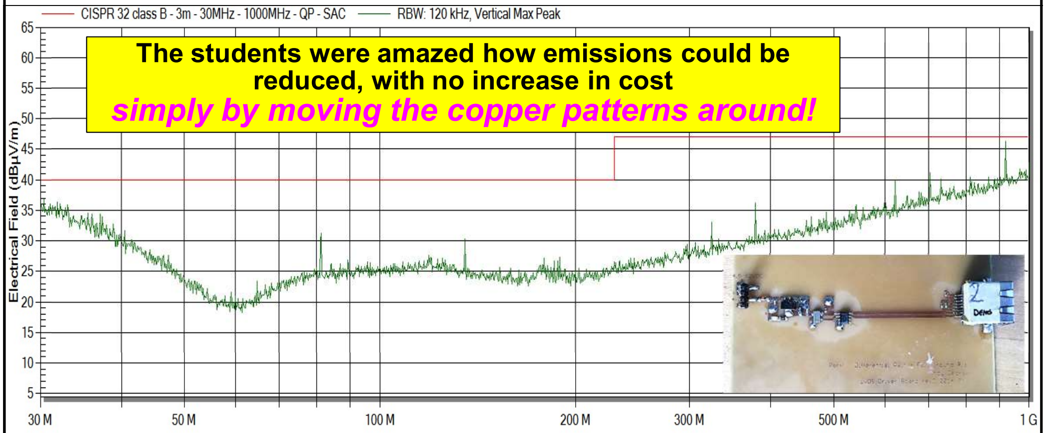
The same LVDS driver board after routing according to my 2010 EM Engineering guidelines



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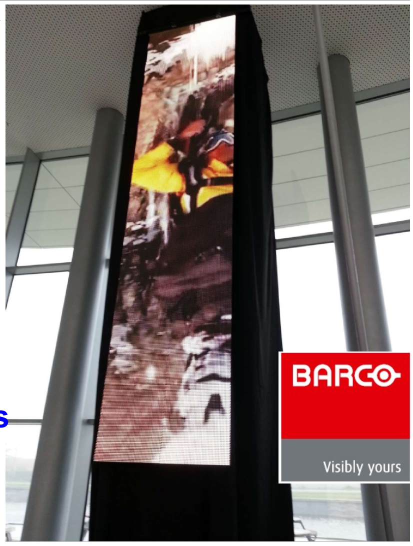
By Keith Armstrong

An example of customer feedback in 2016

- Barco R10: a 3.9m tall *flexible* outdoor video display, 1/4 the weight, 1/10th the thickness of earlier products
- SMD LEDs, 10mm pitch, on a 3-layer flexi-PCB *without a plane layer*
- 1000-BaseT Ethernet datacomm's
- 2.3kW of switching power conversion
- Powerful DSP image processing using FPGAs
- They aimed to meet Class A emissions by adding shielding (as was usual)
- But this was the first time they fully applied my EM Engineering, and their ***first prototype*** **functioned perfectly** ***and met Class B*** (≥10dB *below* Class A) ***without any shielding!***



Use our slides as design checklists

- **Just like a road trip: deviating from the optimum route will generally cause problems…**
  - in this case: delayed time-to-market; increased overall unit manufacturing cost; increased warranty costs, etc…
- – wherever one of our design guidelines can't be fully applied, it identifies a risky technical issue…
  - a very big help towards de-risking a project as early as possible – important for saving time/cost… *see Webinar 1c*
- – if any of the design techniques in our training courses or Webinars can't be fully applied, *do something else* that deals with the associated SI, PI, EMC issues…
  - or warn project/programme managers about the *likely* increases in financial and timescale risks

If you don't see your favourite design technique or guideline in our slides...

– then it probably isn't good any more for SI, PI or EMC !!
- especially 'single-point earthing/grounding' (i.e. 'star earthing/grounding') – even in low-frequency applications…

– because ***all*** applications are increasingly suffering more RF noise from worsening external EM environments…

– and semiconductor die-shrinking *search: 'Moore's Law'* is *continually* making devices both noisier *and* more sensitive, to *ever-higher* frequencies…

– so design for SI, PI and EMC has to keep evolving to keep pace – *whether we want to, or not!*

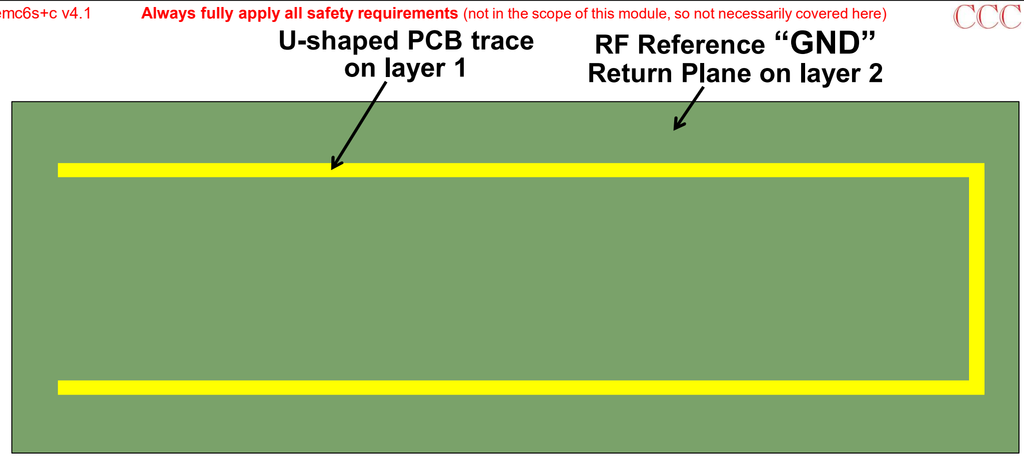
1. The Physical Basis of SI, PI and EMC

1.17

Controlling return currents with metal planes

Controlling return currents with metal planes

- ***All* currents *always* flow in loops…** *see 1.1*
  - **for DM** (Differential Mode: wanted signals, data or power) **and CM** (Common Mode: unwanted, stray) **currents…** *see 1.7*
    which is why circuits can work perfectly well with excellent EMC even without connections to metal rods in the soil…
  - – **naturally flowing in the loops with lowest impedances, giving the best SI, PI and EMC for any conductive structure**
- **Metal planes are ideal low-impedance current paths…** *see 1.8*
  - – **and the following slides show how our designs can use this to great advantage by "EM Zoning"** *see 1.18*



TRACE TOTAL LENGTH = 22" (i.e. 559 mm)
10 MILS WIDE, 1 MIL THICK, 10 MILS ABOVE GND PLANE
(i.e. 0.25 mm wide, 2.5 microns thick, 0.25 mm above Reference plane)

The Physical geometry for this example (drawing courtesy of Dr. Bruce Archambeault)

See Reference [1], at the end of this course module

The distribution of current for these higher frequencies is given by the following equation.[4]

$$J(x) = \frac{I}{w\pi}\left[\tan^{-1}\left(\frac{2x-w}{2h}\right) - \tan^{-1}\left(\frac{2x+w}{2h}\right)\right] \qquad \text{(Eq. 1)}$$

Where:

J(x) is the current density;

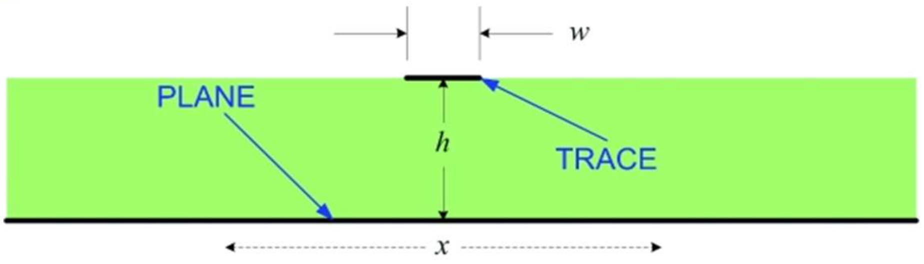
See Reference [1], at the end of this course module

I is the total current;

w is the trace width;

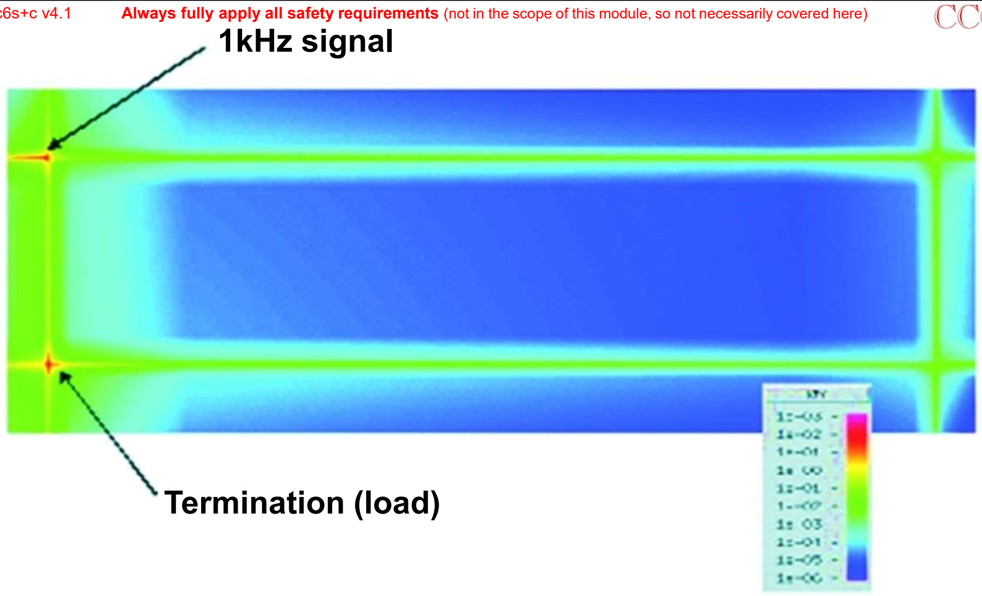
h is the board layer thickness (the height the trace is above the plane);

x is how far from directly under the trace we measure the current, as shown in **Figure 13**.



Cross section of board.

emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC



1kHz ground current flows from load to source in a straight line.
(Drawing: courtesy of Dr. Bruce Archambeault)

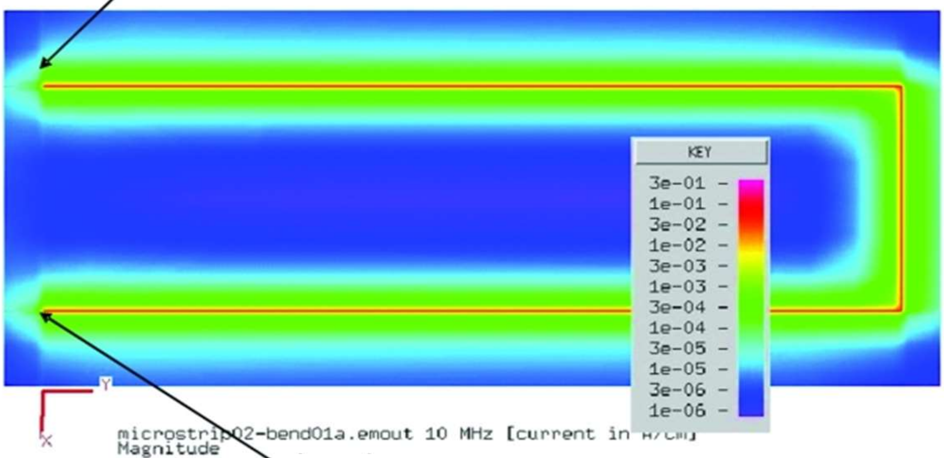
50kHz signal

Termination (load)

50kHz ground current flows everywhere.
(Drawing: courtesy of Dr. Bruce Archambeault)

10MHz signal

This simulation has been verified many times by different people, up to 100GHz, and validated on real PCBs with a surface current probe

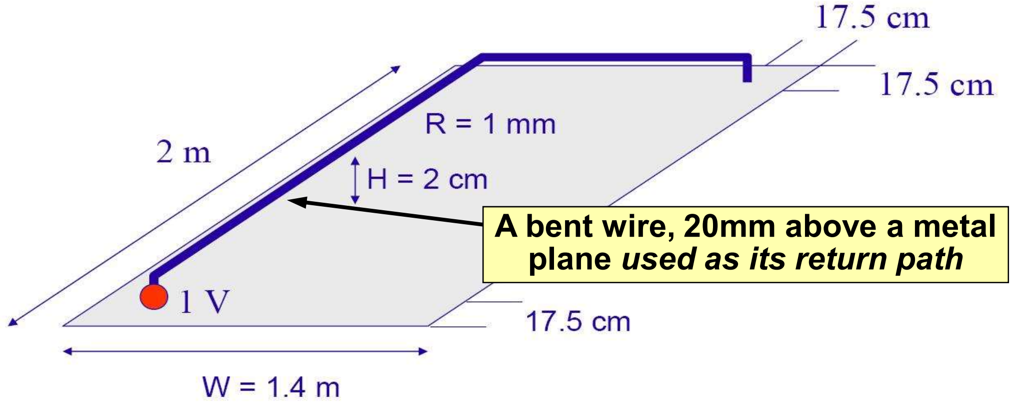


Termination (load)

10MHz ground current follows the signal trace.
(Drawing: courtesy of Dr. Bruce Archambeault)

Computer simulations of the return current path for a wire above a plane

(exactly the same for a PCB trace over a plane)

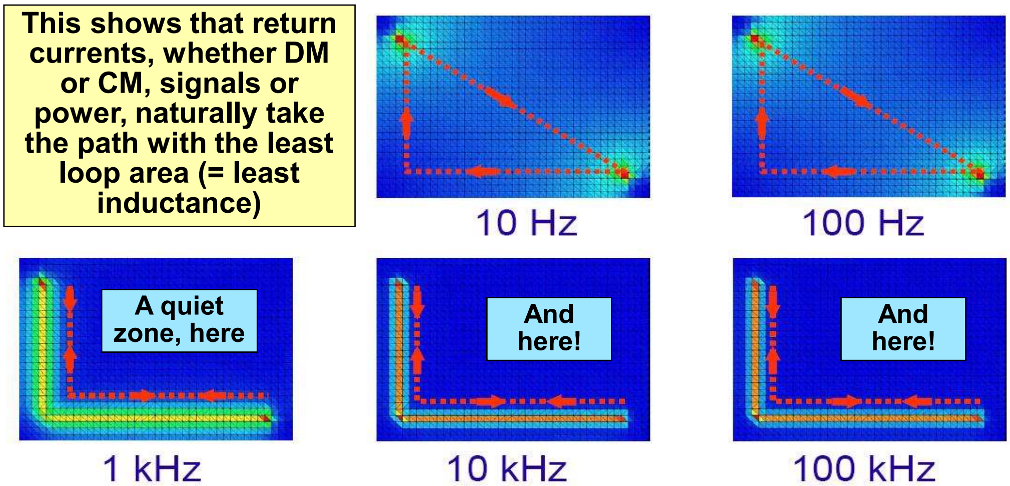


A bent wire, 20mm above a metal plane *used as its return path*

See Reference [2], at the end of this course module

Return current path for wire above plane continued... (red dotted lines drawn by hand)

This shows that return currents, whether DM or CM, signals or power, naturally take the path with the least loop area (= least inductance)



For conductors close to metal planes (at any voltage), **above some frequency the return currents closely follow the conductors' paths**

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Segregating circuits by area *into EM Zones, see 1.18* **close to a single common metal plane, means the return currents in one area do not affect other areas (not by very much anyway – nothing is perfect!)**

- In a PCB, best for SI, PI, & EMC is a common unbroken copper plane, with no splits or gaps, *underneath all* the board-mounted components and their traces, and very close to them… *see Module 6A*
  - – we call this the Reference Plane and it is usually (but not always) at the circuit's 0V potential…
    - it is often called GND, Ground, or Earth, which I don't recommend because of the risk of confusing it with safety grounding/earthing
  - – using this approach, I haven't split a Reference Plane since 1981 (except for Galvanic Isolation) on many hundreds of PCBs *which all achieved excellent SI, PI and EMC*

see section 1.18 for details of EM Zoning

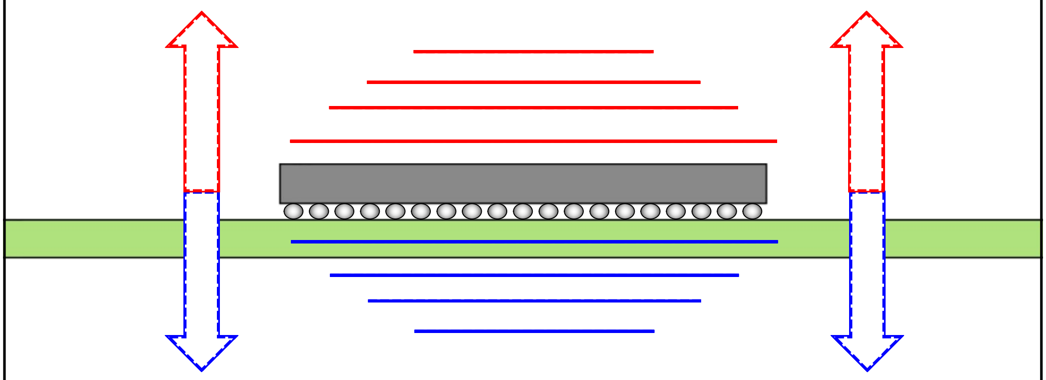
1. The Physical Basis of SI, PI and EMC

1.18

EM Zoning

using guidelines based on the wavelength, λ, at f_{MAX}, *plus* the use of Reference Planes and RF References (RF_{REF}s)

It is important to understand that *all* clocked digital devices suffer 'ground/power bounce' noise that <u>puts GHz noise *on all their pins*</u> (even inputs) *and therefore on <u>all of the</u> traces, test points, and planes connected to them*



Many EM Engineering guidelines could be said to be about "*anti-antenna*" and/or "*anti-resonance*" design

- **Whether conductors are electronic, electrical or mechanical** (including conductive liquids)…
  - they ***<u>all</u>*** couple EM noise energy by conduction, and/or by radiating fields (electric: E, magnetic: H, and electromagnetic: EM)… *see 1.6, also [3] and [5]*
    - especially at frequencies at which they behave as efficient "accidental antennas"… *see 1.5*
    - i.e. when they resonate, either due to circuit values e.g. $1/2\pi\sqrt{(LC)}$, or structural dimensions… *see 1.4*
  - so: good SI, PI, EMC design ("EM Engineering") avoids such *accidental antenna* and/or *resonant* behaviours

Preventing unwanted resonances due to circuit design and components

- All real components have stray Rs, Ls and Cs…
  - which severely change their impedance/behaviour above some frequency
  - unwanted resonances should be avoided by attending to the effects of these strays in design…
  - e.g. by using SPICE simulation *with the strays included,* using first-order, second-order, etc., models for the components, depending on f_{MAX}… *see later, and Module 8*
  - *better still:* simulate the circuit with added stray Rs, Ls, Cs, propagation times, couplings, etc., field-solver-extracted from 3-D drawings of PCB layout, shielding, cabling *see Module 10a*

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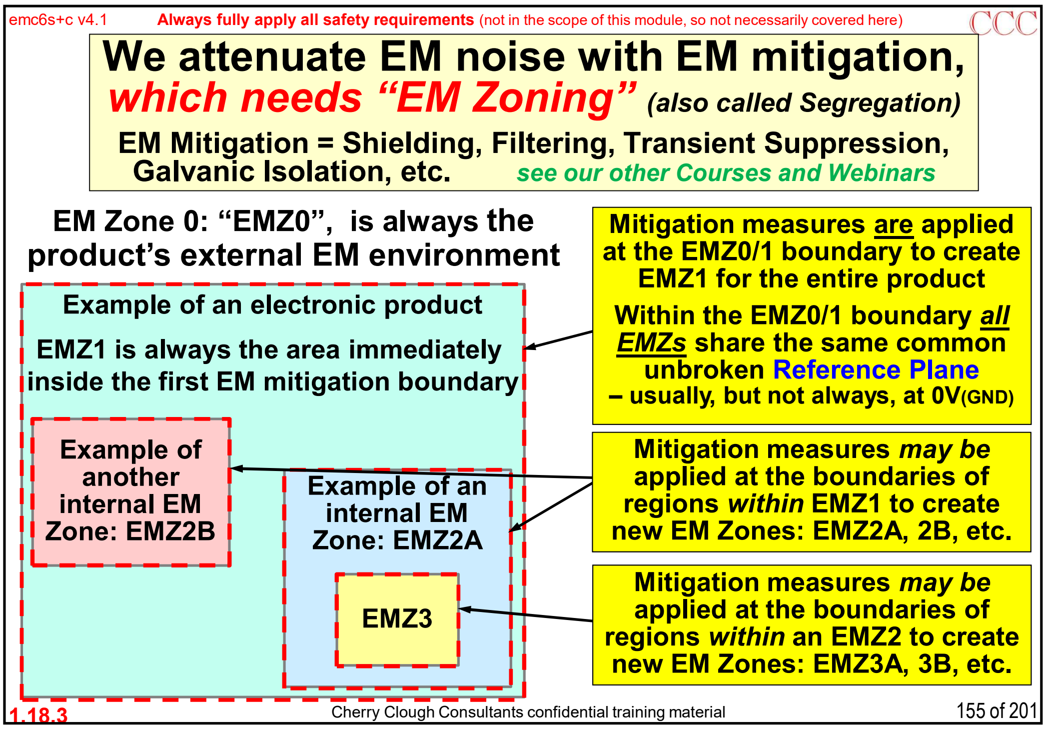
Preventing unwanted resonances due to the physical structure

- This is one reason why we use "EM Zoning" (sometimes called "Segregation") for circuits that share a single unbroken common metal plane (usually 0V or GND) that is very close by…
  - another reason is to prevent crosstalk and other types of coupling between different parts of a circuit…
    - e.g. between digital processing or DC/DC converters, and analogue circuits
- A great deal of EM Zoning design depends on the highest frequency of concern, f_{MAX} *see later*


emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
We attenuate EM noise with EM mitigation, which needs "EM Zoning" (also called Segregation)
EM Mitigation = Shielding, Filtering, Transient Suppression, Galvanic Isolation, etc.
see our other Courses and Webinars
EM Zone 0: "EMZ0", is always the product's external EM environment
Example of an electronic product
EMZ1 is always the area immediately inside the first EM mitigation boundary
Example of another internal EM Zone: EMZ2B
Example of an internal EM Zone: EMZ2A
EMZ3
Mitigation measures are applied at the EMZ0/1 boundary to create EMZ1 for the entire product
Within the EMZ0/1 boundary all EMZs share the same common unbroken Reference Plane – usually, but not always, at 0V(GND)
Mitigation measures may be applied at the boundaries of regions within EMZ1 to create new EM Zones: EMZ2A, 2B, etc.
Mitigation measures may be applied at the boundaries of regions within an EMZ2 to create new EM Zones: EMZ3A, 3B, etc.
1.18.3
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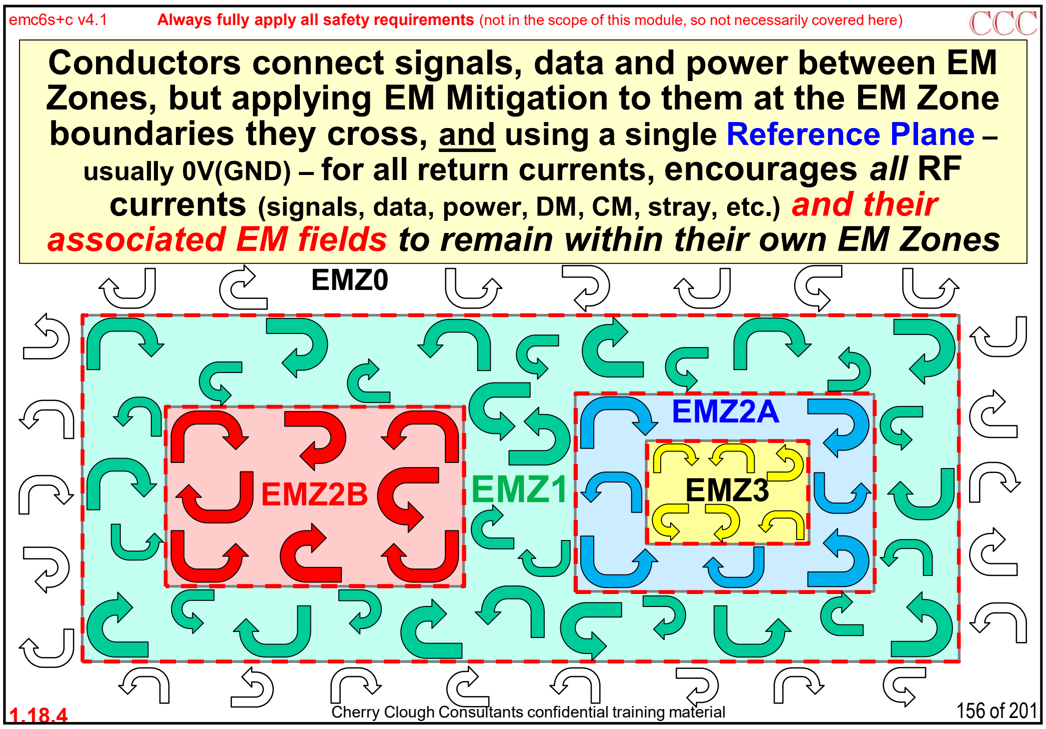
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Conductors connect signals, data and power between EM Zones, but applying EM Mitigation to them at the EM Zone boundaries they cross, and using a single Reference Plane – usually 0V(GND) – for all return currents, encourages all RF currents (signals, data, power, DM, CM, stray, etc.) and their associated EM fields to remain within their own EM Zones
EMZ0
EMZ2A
EMZ2B
EMZ1
EMZ3
1.18.4
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EM mitigation **must** **only** be applied at an EMZ boundary, *as follows…*

1st : Physical Separation: 'air gaps' around an EMZB reduce E, H and EM field couplings ('noise leakages') across it , *so it helps to make EMZBs rectangular!*
Remember: no splitting any common metal planes, usually 0V(GND)

2nd : Galvanic Isolation *and/or* **Overvoltage Protection** *and/or* **Filtering** *and/or* **RF Reference Bonding:** **must** be applied to **every** conductor that crosses *any* EMZB!...
…including: ***all*** PCB traces, wires, cables, etc., (including 'earthing' or 'grounding') – plus ***all*** *non-electrical conductors* such as fixings, supports, decorative trim; pipes, plastic tubes containing conductive liquids (blood, saline, etc.), etc., etc.

3rd : Shielding: when 'air gaps' can't be large enough to reduce 'noise leakages' across an EMZB by enough: *apply shielding all over that Zone's **entire** **volume***

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emc6s+c v4.1 Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here) CCC

Designing EM Zones and the EMZ boundaries between them

- For good SI, PI and EMC: design *within* an EMZ should *avoid* resonances, and only create *inefficient* accidental antennas…
  - and the *internal EMZ boundaries* themselves should sufficiently attenuate EM noises coupling across them…
    - which means that they should also *avoid* resonances and only have *inefficient* accidental antenna structures
- For good EMC: the EMZ0/1 boundary should sufficiently attenuate EM noises that could couple across it…
    - so, the boundary's design should *avoid* resonances, and only use *inefficient* accidental antenna structures

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Designing EMZs and the boundaries between them continued…

- To avoid resonances and to reduce the efficiency of accidental antenna structures…
  - we must base our design on the wavelength, λ, at the highest frequency of concern, f_{MAX}…
  - and take care with to keep series impedances low in all signals, data and power conductors…
    - and in all RF bonds…
    - and avoid resonances between lumped circuit elements, whether designed-in, or strays/parasitics

practical details are covered in our Modules: 2, 3, 4, 5, etc., etc.

Design guidelines based on the λ at f_{MAX}…

- are the most cost-effective…
  - because they help prevent over/under engineering…
- and are also future-proof…
  - these guidelines have been well-proven in practice, worldwide, at frequencies up to 26GHz

- But what is f_{MAX}?
  It is *the highest frequency of concern…*
  - i.e. the highest frequency that needs to be controlled to achieve acceptable SI, PI and EMC…
  - *for each individual EMZ and its boundaries*

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What f_{MAX} values should apply to internal EMZs and their boundaries?

- **Digital devices can emit noise at 10s of GHz as DM from signal / data / power pins…**
  - and/or as CM from any/all pins due to ground/power bounce noise
- **Low-frequency analogue devices can be susceptible to many GHz…**
  - due to the inevitable non-linearities in their semiconductors
- **Power switching devices can emit significant noises at >1000 times their switching frequency**

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emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

What f_{MAX} values should apply to internal EMZs and their boundaries? (2)

- **The f_{MAX} for an EMZ should be the highest f_{MAX} for the emissions & immunity of the devices within it…**
  - the f_{MAX} for an <u>internal zone boundary</u> should be the highest f_{MAX} for emissions/immunity of the EMZs on either/both sides of that boundary
- **Measure device f_{MAX} with IEC 61967** (for emissions) **and with IEC 62132** (for immunity)…
  - device manufacturers might provide this data,
    and our Webinars on near-field probing describe quick, low-cost, non-standardised methods for measuring device f_{MAX}

visit www.emcstandards.co.uk

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emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

Finding f_{MAX} values for device immunity / susceptibility

- Active digital devices *generally* have f_{MAX} values for their emissions = f_{MAX} values for their immunity
- Devices containing any non-digital technologies should be tested with frequencies that are…
  - either 80% amplitude-modulated, or pulse-modulated, with a modulation frequency that is 'in-band' for the intended circuit function, e.g…
    - 1kHz for an audio circuit…
    - 0.5Hz for a typical medical temperature sensor or typical industrial control loop

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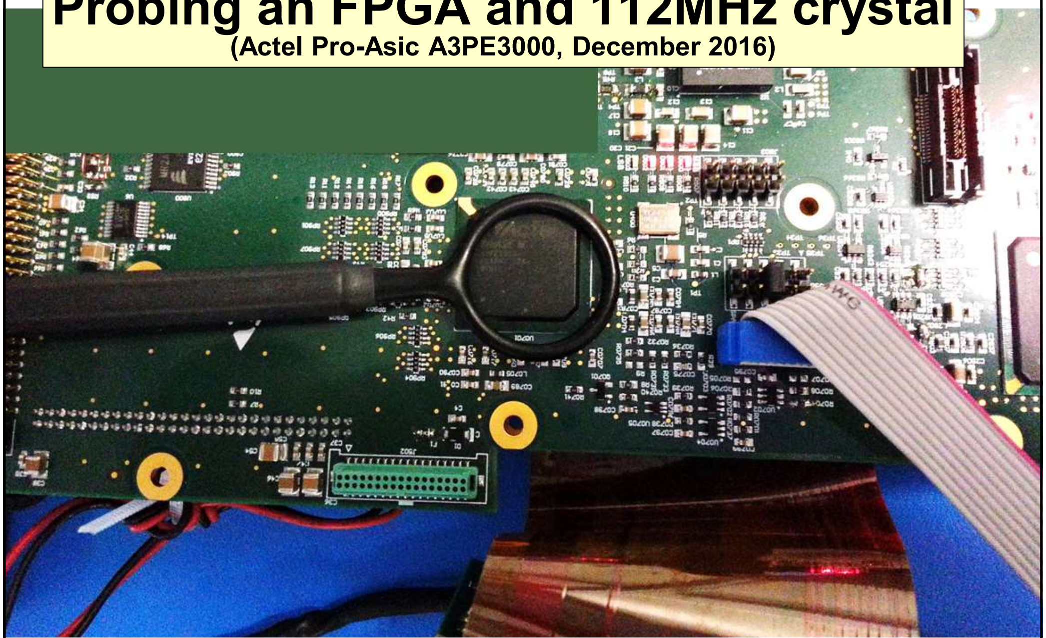
emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

Probing an FPGA and 112MHz crystal

(Actel Pro-Asic A3PE3000, December 2016)



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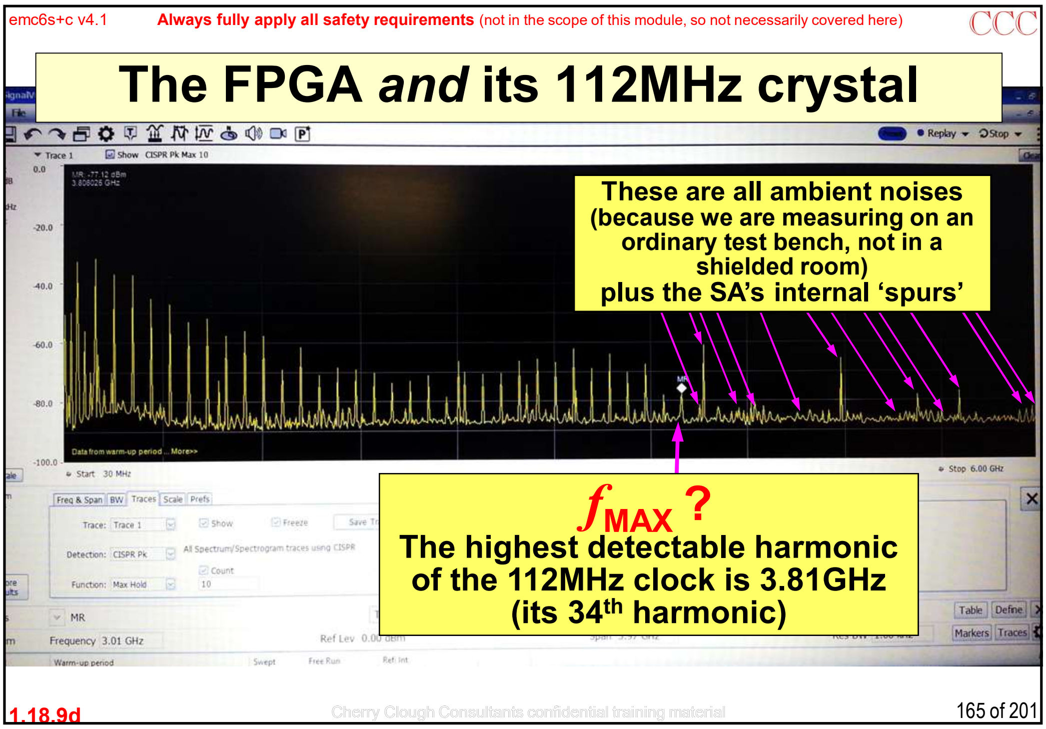
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
The FPGA *and* its 112MHz crystal
These are all ambient noises (because we are measuring on an ordinary test bench, not in a shielded room) plus the SA's internal 'spurs'
fMAX ?
The highest detectable harmonic of the 112MHz clock is 3.81GHz (its 34th harmonic)
1.18.9d
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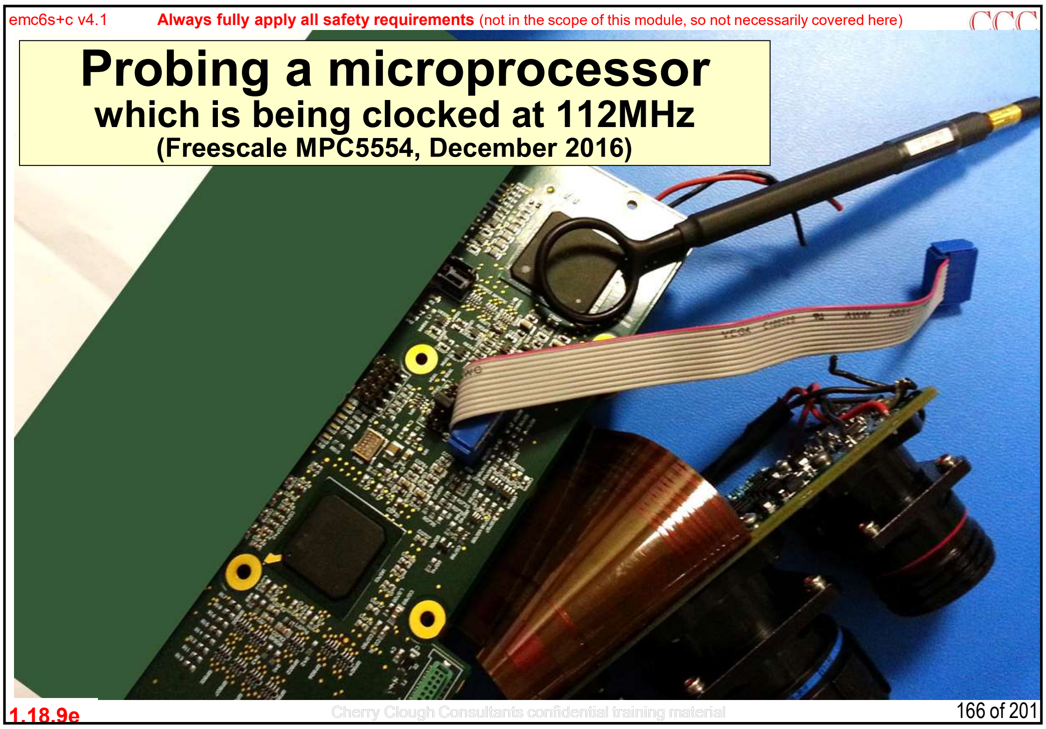
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
Probing a microprocessor
which is being clocked at 112MHz
(Freescale MPC5554, December 2016)
1.18.9e
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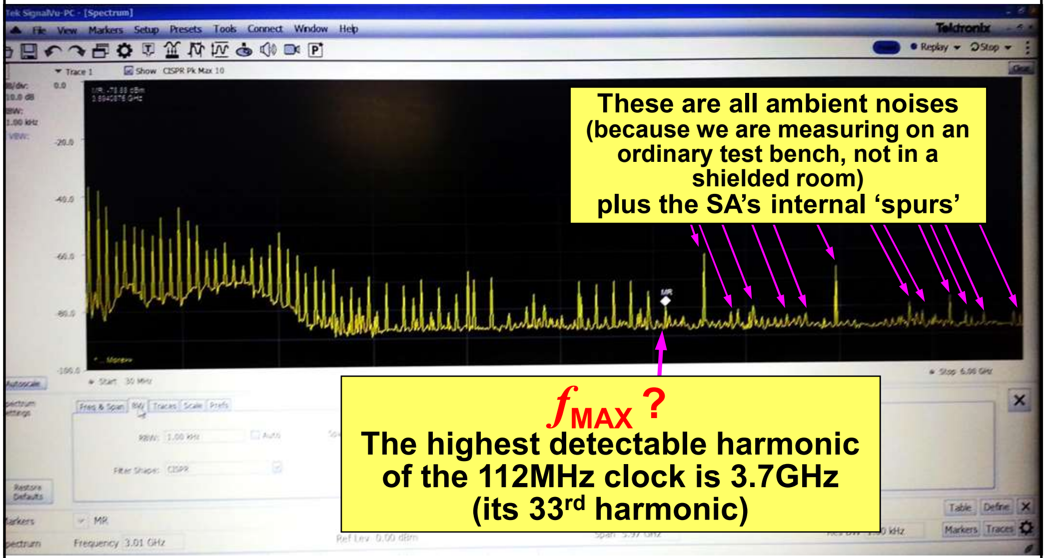
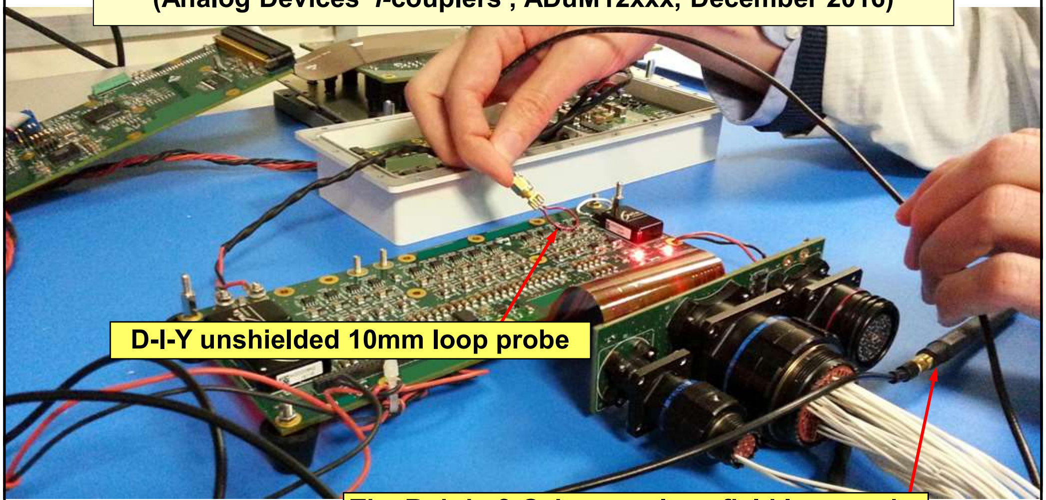
The Freescale microprocessor



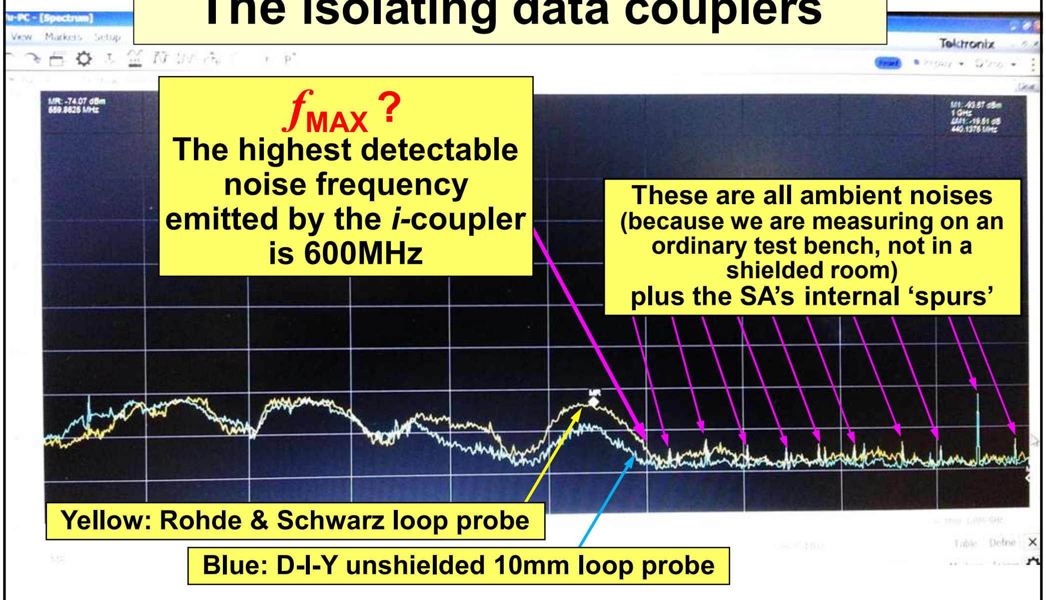
Probing isolating data couplers

(Analog Devices '*i*-couplers', ADuM12xxx, December 2016)



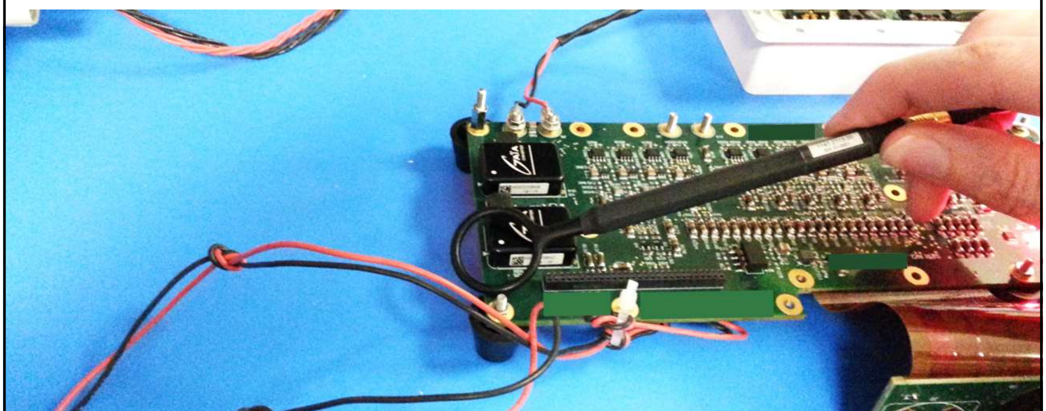
The Rohde & Schwarz close-field loop probe used for the other f_{MAX} measurements

The isolating data couplers



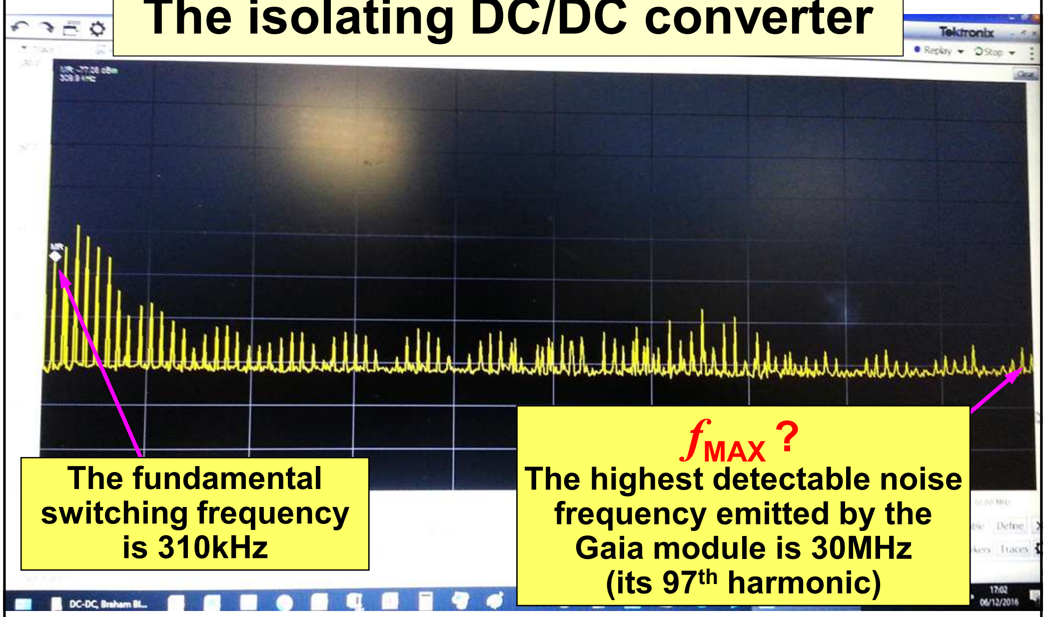
Probing an isolating DC/DC converter

(a Gaia MGDD series, 5V-output, December 2016)



emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

The isolating DC/DC converter



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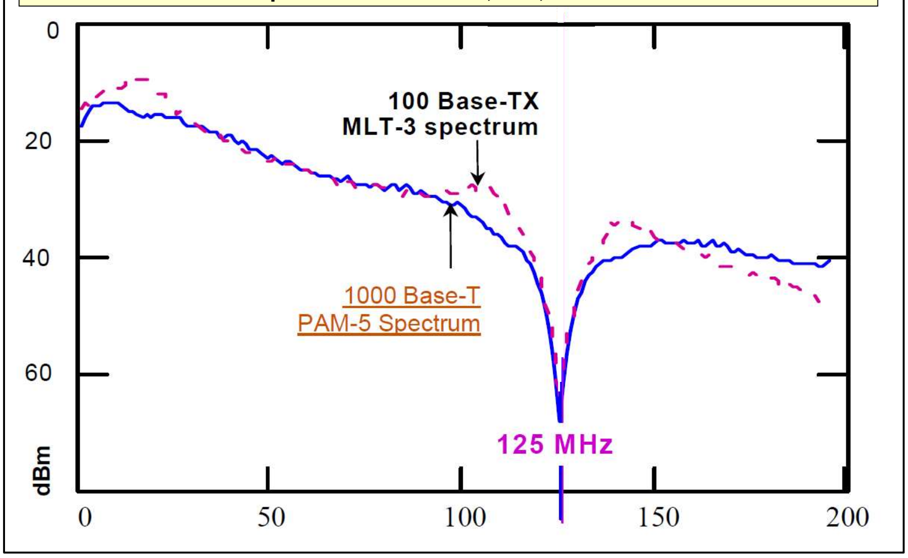
Spectra of 100 and 1000BASE-T Ethernet

From "Gigabit Ethernet over Category 5", Fanny Mlinarsky, Scope Communications, Inc., 6 Jun 1998



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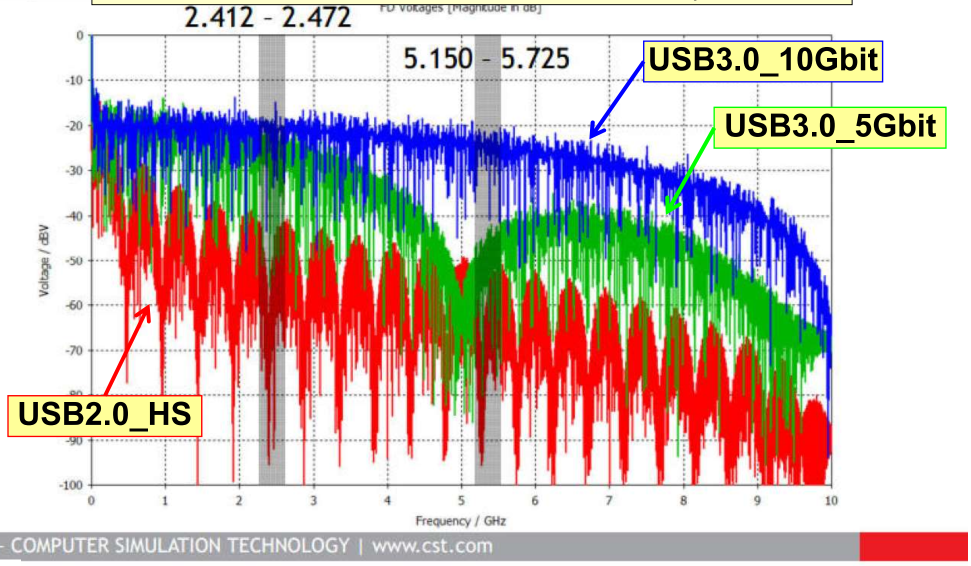
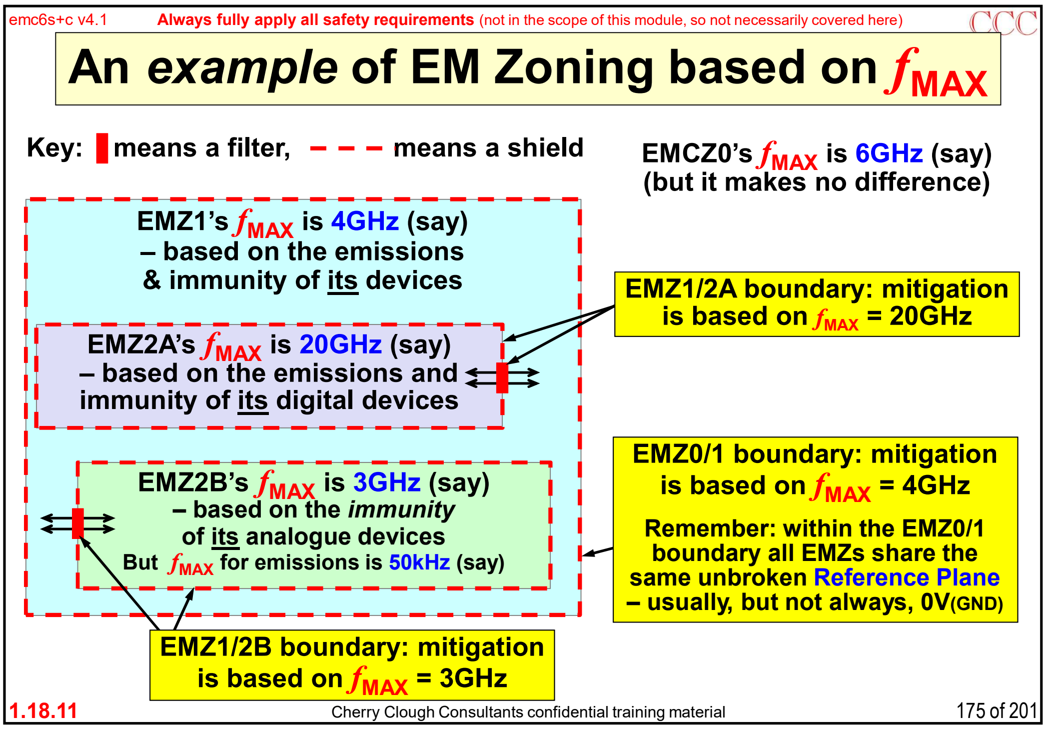
Noise spectra of some USBs

(from 'Simulation of RF Interference' by Andreas Barchanski, www.cst.com/events/webinars/archive#)



What f_{MAX} should we use for the external boundary: EMZ0/1 ?

- **The relevant EMC standards are based on <u>typical</u> EM environments – some will be worse…**
  - **also: all EM environments are getting worse; standards are *at least* 5 years out-of-date *<u>when published</u>*, and products need to achieve EMC for their whole lifetimes**
- **Because the EU's EMC and RE Directives' *legal requirements* are not to cause/suffer EMI *<u>at any frequency</u>* DC-300GHz, (which is also important for low warranty costs, customer satisfaction and future sales)…**
  - **we must ignore EMC standards, and base our EMZ0/1 boundary specification on our internal devices' maximum emissions / immunity frequencies**


emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
An example of EM Zoning based on fMAX
Key: means a filter, means a shield
EMCZ0's fMAX is 6GHz (say) (but it makes no difference)
EMZ1's fMAX is 4GHz (say) – based on the emissions & immunity of its devices
EMZ1/2A boundary: mitigation is based on fMAX = 20GHz
EMZ2A's fMAX is 20GHz (say) – based on the emissions and immunity of its digital devices
EMZ0/1 boundary: mitigation is based on fMAX = 4GHz
EMZ2B's fMAX is 3GHz (say) – based on the immunity of its analogue devices
But fMAX for emissions is 50kHz (say)
Remember: within the EMZ0/1 boundary all EMZs share the same unbroken Reference Plane – usually, but not always, 0V(GND)
EMZ1/2B boundary: mitigation is based on fMAX = 3GHz
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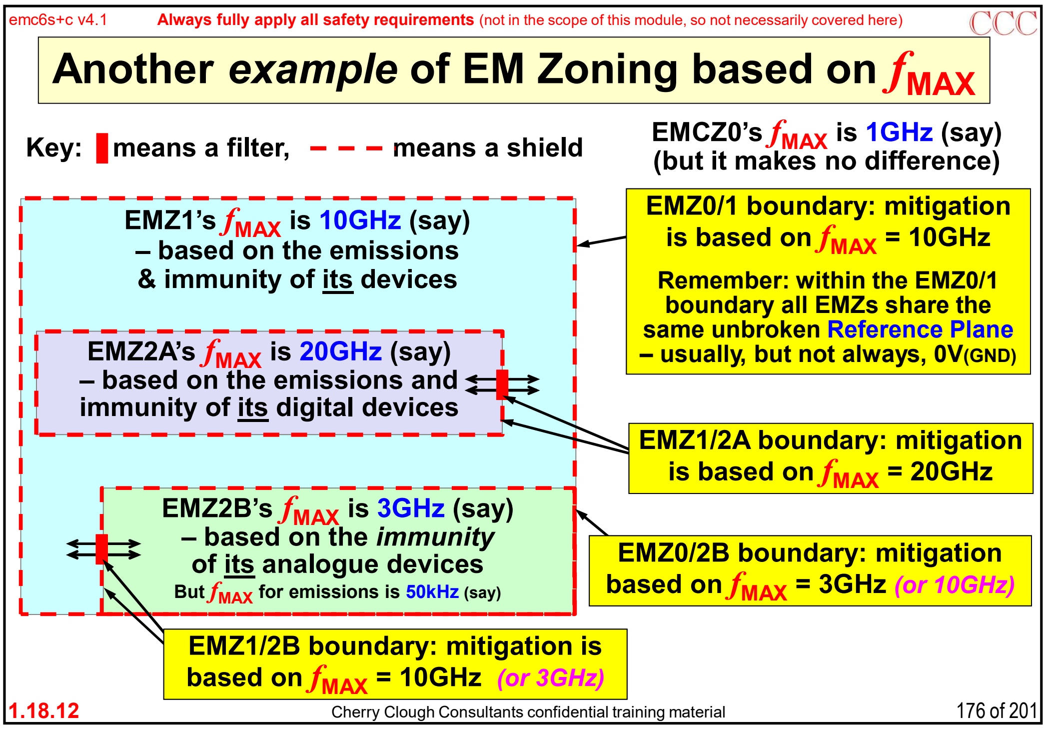
emc6s+c v4.1
Always fully apply all safety requirements (not in the scope of this module, so not necessarily covered here)
CCC
Another example of EM Zoning based on fMAX
Key: means a filter, means a shield
EMCZ0's fMAX is 1GHz (say) (but it makes no difference)
EMZ1's fMAX is 10GHz (say) – based on the emissions & immunity of its devices
EMZ0/1 boundary: mitigation is based on fMAX = 10GHz
Remember: within the EMZ0/1 boundary all EMZs share the same unbroken Reference Plane – usually, but not always, 0V(GND)
EMZ2A's fMAX is 20GHz (say) – based on the emissions and immunity of its digital devices
EMZ1/2A boundary: mitigation is based on fMAX = 20GHz
EMZ2B's fMAX is 3GHz (say) – based on the immunity of its analogue devices
But fMAX for emissions is 50kHz (say)
EMZ0/2B boundary: mitigation based on fMAX = 3GHz (or 10GHz)
EMZ1/2B boundary: mitigation is based on fMAX = 10GHz (or 3GHz)
1.18.12
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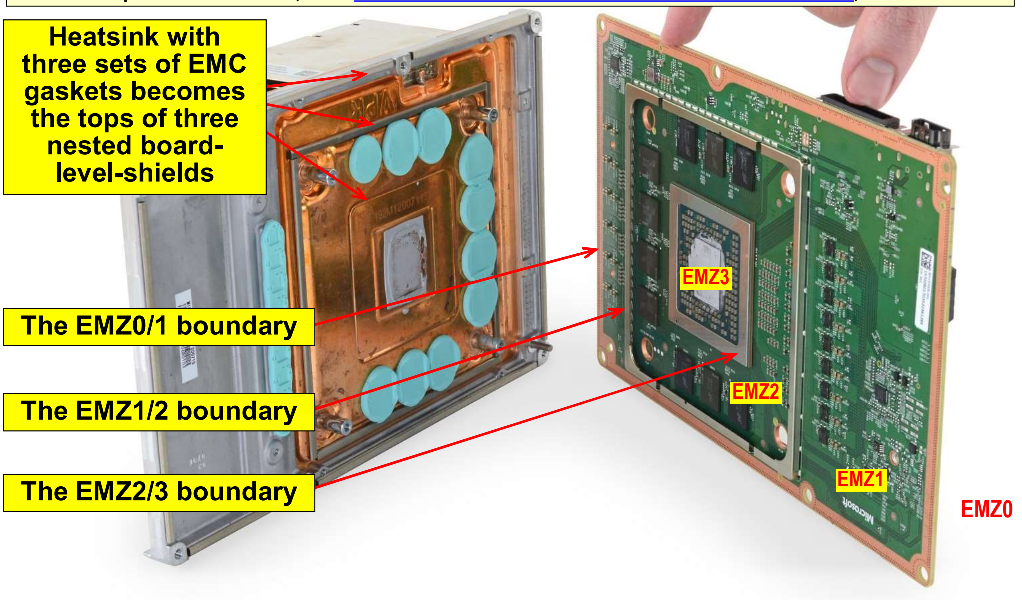
emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

An example of EM Zoning: X-Box Model X

iFixit WqvE5NOUO1ZrPwhS, from www.ifixit.com/Teardown/Xbox+Series+X+Teardown/138451, 29 Jan 2021



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emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

λ-based design guidelines for EMZs and Zone boundaries

- **So, having determined the different f_{MAX} values for all EMZs, and their boundaries…**
  - **we then apply wavelength (λ)-based design guidelines to prevent structural resonances** *see [3]* **and reduce accidental antenna efficiencies in *all* conductors…**
    - **whether electronic, electrical, mechanical or conductive liquids...**
  - **i.e. we measure SI, PI, and EMC in MHz (or GHz), and design anti-resonance and anti-antenna structures in metres (or millimetres)**
  - **our guidelines contain many λ/10 at f_{MAX} guidelines…**
  - **in some circumstances these might reduce to λ/20, λ/30, or even λ/50 at f_{MAX}**

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Calculating the λ at f_{MAX}

- Frequency (f), λ, and velocity of propagation (v) are related by: $v = f \cdot \lambda$
  - in vacuum or air: $v = 3.10^8$ metres/second, so $\lambda = 300/f$
    (f in MHz gives λ in metres; f in GHz gives λ in mm)
  - but in PCB traces $v = 3.10^8/\sqrt{\varepsilon_r}$ so: $\lambda_{PCB} = 300/f \cdot \sqrt{\varepsilon_r}$
    (ε_r is the relative dielectric constant of the PCB)
  - e.g: FR4 has $\varepsilon_r \approx 4$ (above 1MHz) making v and λ approximately half what they are in air…
  - so for FR4 PCBs we generally assume: $\lambda_{PCB} = 150/f$
    (f in MHz gives λ in metres; f in GHz gives λ in mm)

λ-based design guidelines are all about reducing accidental antenna efficiency, or increasing attenuation

- Conductor dimensions ≤ λ/10 at f_{MAX} cannot resonate, and are inefficient accidental antennas…
  - and reducing dimensions even more, i.e. << λ/10 at f_{MAX}, makes them even more inefficient as accidental antennas
- Conductors used in RF shields at EMZ boundaries, or as RF References *see later* within an EMZ…
  - make better shields or RF_{REF}s *see later* when any/all gaps or interconnections are reduced below λ/10 at f_{MAX}
- ***Never use anything > λ/10 at f_{MAX}!*** (e.g. λ/5) ✗

λ-based design of the EMZ0/1 boundary, and the influence of EMC standards

- **Our guidelines generally assume emissions limits and immunity test levels corresponding to IEC 61000-6-3 and IEC 61000-6-1…**

  i.e. residential, commercial, light industrial environments

  – **so if applying *lower emissions limits than IEC 61000-6-3*, reduce all λ-based guidances accordingly...**

    - **e.g. if 10dB lower emissions limit: reduce a $\lambda/10$ guideline associated with an EMZ0/1 boundary to $\lambda/30$...** (-10dB is about 1/3rd)

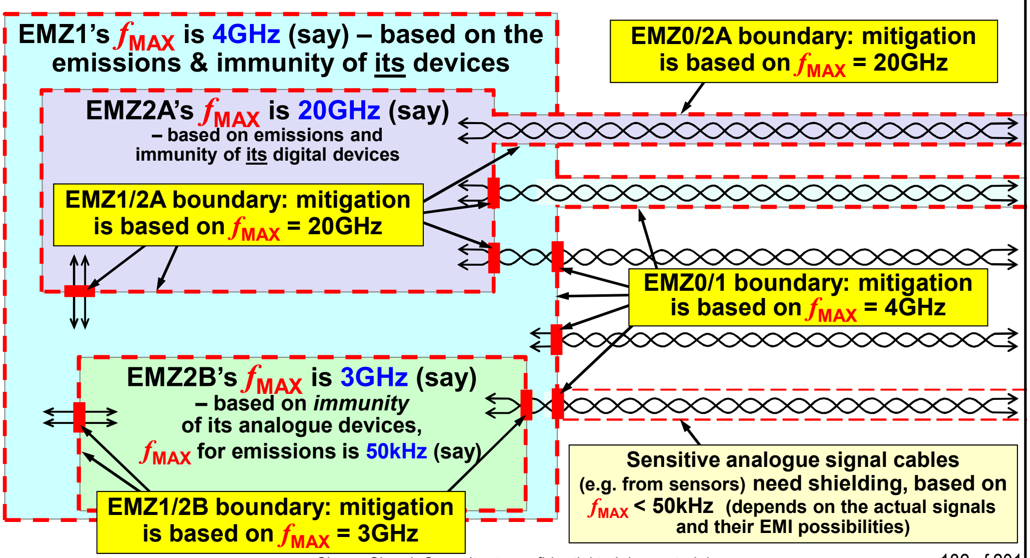
  – **and if applying *higher immunity levels than IEC 61000-6-1*, reduce all λ-based guidance accordingly...**

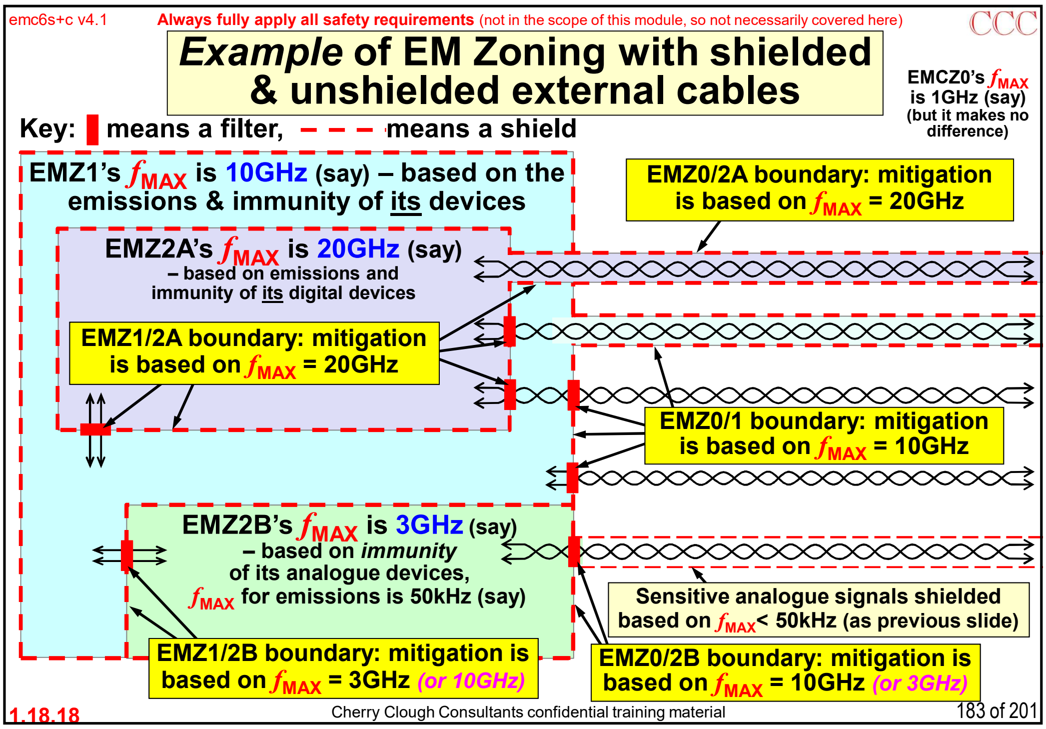
    - **e.g. if 10 times higher test level: reduce a $\lambda/20$ guideline associated with an EMZ0/1 boundary to $\lambda/200$**

Example of EM Zoning with shielded & unshielded external cables

EMCZ0's f_{MAX} is 6GHz (say) (but it makes no difference)

Key: ▌ means a filter, – – – means a shield





λ-based design and RF *transmitters*

- All the λ-based design guidelines have assumed that f_{MAX} is the highest significant frequency in a harmonic spectrum…
  - but RF transmitters are narrowband, and more powerful than a digital circuit's emissions…
    - so: f_{MAX} guidelines are *not appropriate for transmitters*
- Design using appropriate λ-based guidelines for the transmitted frequency (-ies) (*not* for f_{MAX})…
  - for the antenna's ***local*** field strengths: discovered by simulation or calibrated near-field measurements…
    - often a tougher requirement than guidelines based on f_{MAX}

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λ-based design and RF *receivers*

- Same sort of issues as for transmitters…
  - except the problem now is the product's near-field emissions at the location of the antenna(s)
- Design using appropriate λ-based guidelines for the maximum sensitivity (-ies) of the received frequency (-ies) (*not* for f_{MAX})…
  - for the product's ***local*** field strengths: discovered by comprehensive simulations or calibrated near-field measurements on experiments or first prototypes…
    - could use the actual radio/wireless antennas as near-field probes to find suitable antenna locations or improve design

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The Reference Plane, and RF_{REF}s

- Remember: within an EMZ0/1 boundary, all EMZs share the same common, unbroken, Reference Plane (usually, but not always, at 0V or GND potential) *see slides 1.17.10 and 1.18.3 - 4*
- Each individual component, device or point on a conductor (e.g. a PCB trace) has its own, unique, Radio Frequency Reference, RF_{REF}…
  - the region of Reference Plane within $\lambda/10$ at f_{MAX} distance from the component, device, or point being considered…
  - so: the Reference Plane provides all the different, unique, RF_{REF} areas for all of the different components, devices, and points on conductors…
    - note that a Reference Plane can only be considered to be a single RF_{REF} if its longest diagonal is less than $\lambda/10$ at f_{MAX}

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RF-bonding to an EMZ boundary (1)

- It is generally most cost-effective for an electronic circuit to use its Reference Plane as part of its EM Zones boundary structures…

  see Module 1, section 1.18

  - the Reference Plane is usually at 0V(GND) potential, although for a *few* types of devices (e.g. emitter-coupled logic (ECL); ICs for metering mains power, etc.) it might need to be at a different potential, e.g. +V, V_{CC}, V_{DD}…

  – but where a Reference Plane – usually 0V(GND) – must use a *different* physical structure from the EMZ boundary, the cavities inbetween them can resonate… *see Module 1, section 1.4*

  – which could increase the requirements for shielding and/or filtering at the EMZ0/1 boundary by up to 60dB !!

To help avoid the cavity resonances caused by separating a Reference Plane from an EMZ boundary's structure…

…fit RF-bonds between them…

1) as close as possible to any/all shielded and/or filtered external cable connections… *(see Modules 2 and 3)*

2) ***then either:*** totally shield the entire PCB structure… *(see Module 10A, Section 8)*

   or: fit extra RF-bonds to the Reference Plane to make the cavity resonant frequencies higher than f_{MAX} *(see the next two slides)*

- RF-bonds should use direct metal-to-metal contacts, or suitable types of EMC gasket *(see Module 4)*
  but if the Reference Plane has to be galvanically isolated from the EMZ boundary: use capacitors instead *(see 1.18.25)*
  (appropriate types and ratings to comply with the safety requirements)

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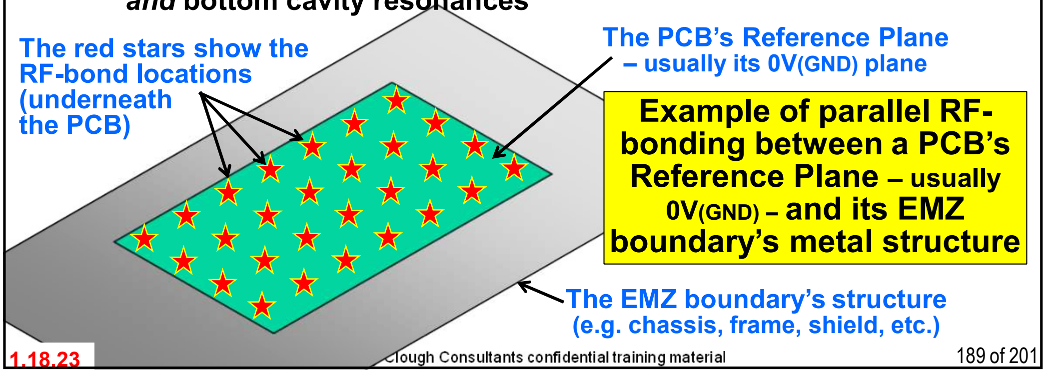
RF-bonding to an EMZ boundary (3)

- **E.g. where a PCB's Reference Plane (usually 0V(GND) plane) is <u>parallel</u> to its EMZ boundary…**
  - **fit extra RF-bonds (direct, gasket, capacitor) << λ/10 at f_{MAX} *apart <u>over the whole area of the Reference Plane</u>*…**
    - **it may be necessary to fit them to the EMZ boundary's structures *both above* and *below* the Reference Plane, to suppress *both* top *and* bottom cavity resonances**



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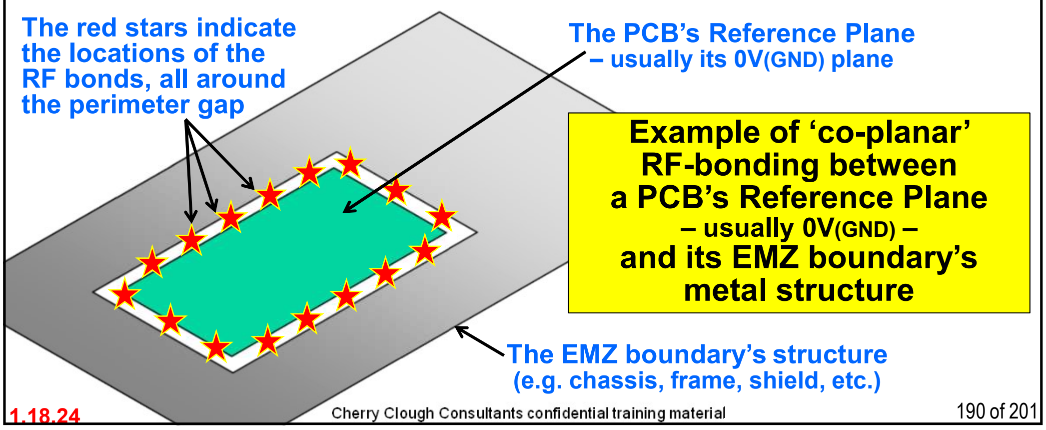
RF-bonding to an EMZ boundary (4)

- **E.g. where a PCB's Reference Plane (usually its 0V(GND) plane) fills a gap in an EMZ boundary structure…**
  - **fit extra RF-bonds (direct, gasketed, or capacitors) all around their perimeter gap, spaced apart << λ/10 at f_{MAX}**



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RF-bonding to an EMZ boundary (5)

- Good general guidance on RF-bonds is to keep them very short (<<1mm), to create very low series inductances…
  - and, for galvanic isolation, use all the same values of capacitors, usually in the range 1nF – 10nF, and all with the same *very short* connections...
    - resonances can arise due to connecting capacitors in parallel – all the detail on dealing with this is given in Section 7 on Power Supply Decoupling
      (and Sections 9, 10 in Module 10A describe damping techniques)
- ***BUT IF** the galvanic isolation is for **SAFETY** reasons:*
  the relevant safety standards will mandate specifications for the types, values, voltage ratings, safety approvals, etc., of any/all RF-bonding capacitors

1. The Physical Basis of SI, PI, and EMC

1.19

Some useful references

emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

Some useful references (numbered)

[1] *Successful PCB Grounding with Mixed-signal Chips - Part 1: Principles of Current Flow,* by Mark Fortunato of Maxim Integrated Products, in EDN Analogue Network, August 27, 2012: www.edn.com/design/analog/4394761/Successful-PCB-grounding-with-mixed-signal-chips---Part-1--Principles-of-current-flow

[2] *Modeling and Simulation of Powertrains for Electric and Hybrid Vehicles,* by Marco Klinger, Workshop FR-AM-4-1, IEEE 2009 Int'l Symp. on EMC, Austin, Aug 17-21, 2009, ISBN: 978-1-4244-4285-0

[3] *De-risking Resonances In Single Conductor Systems Such As Ground,* Keith Armstrong, Incompliance magazine October 2019:
https://incompliancemag.com/DigEd/icm1910/ **or** https://resources.incompliancemag.com/october-2019

[4] *How Interconnects Work: Modeling Conductor Loss and Dispersion*, Yuriy Shlepnev, Signal Integrity Journal, August 21, 2016,
www.signalintegrityjournal.com/articles/25-how-interconnects-work-modeling-conductor-loss-anddispersion

[5] EMC and Safety for Installations – Developments in Ground Bonding Networks, Part 1: Keith Armstrong, In Compliance magazine, Vol. 12, No. 10, October 2020,
https://digital.incompliancemag.com/issue/october-2020/sponsored/, https://resources.incompliancemag.com/october-2020
Part 2: Keith Armstrong, In Compliance magazine, Vol. 12, No. 11, November 2020,
https://digital.incompliancemag.com/issue/november-2020/, https://resources.incompliancemag.com/november-2020

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emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here) CCC

Some useful references (others)

- ***The Physical Basis of EMC***
  Keith Armstrong, Nutwood UK October 2010
  ISBN: 978-0-9555118-3-7, full colour graphics throughout
  – **Order from** www.emcstandards.co.uk/books4 ***(NOT available from Amazon!)***
  – **Provides an understanding of electromagnetic phenomena, in a way that can be easily understood by practising electronic engineers.**
  – **Chapter 2 of my book "EMC Design Techniques for electronic engineers" (below) is the complete text of this book, so don't purchase both of them!**

- ***EMC Design Techniques for electronic engineers, Chapter 2,*** **Keith Armstrong, Nutwood UK November 2010**
  ISBN: 978-0-9555118-4-4, full colour graphics throughout
  – **Order from** www.emcstandards.co.uk/books4 ***(NOT available from Amazon!)***
  – **Covers all electronic applications, with a practical approach to good EMC design practices proven over many years in real life to save time and cost, reduce time-to-market, and reduce warranty costs and financial risks**

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Some useful references (others, continued)

- *EMC for Product Designers 5th Edition*, Chapters 1, 11, 12 & Appendix D Tim Williams, Newnes 2016, ISBN 978-0-08-101016-7, order from https://www.emcstandards.co.uk/emc-for-product-designers
  or *4th Edition*, Newnes 2007, ISBN 0-7506-8170-5, Chapters 1, 10, 11 & Appendix D
  or *3rd Edition*, Newnes 2001, ISBN 0-7506-4930-5, Chapters 1, 5 & Appendix C
- **Clemson University Vehicular Electronics Laboratory** introduction to EMC, plus useful EMC tools: https://cecas.clemson.edu/cvel/emc/
- ***Skin Effect and Surface Currents – Visualizations that Help Simplify Good EM Engineering***, Keith Armstrong, In Compliance magazine, Jan 2019, https://incompliancemag.com/article/skin-effect-and-surface-currents
- **Skin Depth tools** (including the properties of numerous metals)…
  www.rfcafe.com/references/electrical/cond-high-freq.htm
  www.rfcafe.com/references/calculators/skin-depth-calculator.htm
- **Proximity Effect:**
  https://en.wikipedia.org/wiki/Proximity_effect_(electromagnetism)
  https://circuitglobe.com/proximity-effect.html

Some useful references (others, continued)

- ***All About Circuits, Vol II – Alternating Current, Chapter 14 - Transmission Lines: Standing Waves and Resonance***
  – www.allaboutcircuits.com/textbook/alternating-current/chpt-14/standing-waves-and-resonance/
- ***Electromagnetic compatibility (EMC) - Part 5-6: Installation and mitigation guidelines – Mitigation of external EM influences***
  – IEC/TR 61000-5-6
  – this Technical Report addresses installations, but its reasoning regarding EM Zoning is valid at every level of assembly, from Integrated Circuits up

Webinars and Training Course Notes

- **All our training courses are (or will soon be) available as both Webinars and Coursenotes from www.emcstandards.co.uk**
- **And the following webinars are available from other sites:**

a) 'Cost-effective EMC Design by Working with the Laws of Physics'
b) 'Understanding EMC Basics' (3-part series)
c) 'Cost Effective Use of Close Field Probing' (2-part series)
– all from: www.interferencetechnology.com/webinar-series/
or www.youtube.com/user/InterferenceTech1

d) 'Simulators for SI, PI, EMC can minimise / eliminate design iterations, and justifying their high cost is easy'
– from: https://emc.live/2015/simulators-for-si-pi-emc-can-minimizeeliminate-design-iterations-justifying-their-high-cost-is-easy/

Very simplified formulae for emissions

DM. **For a small loop (max dimension <λ/6) the maximum *possible* far-field E-field emission (maximised by varying antenna height over a groundplane as per the normal CISPR22 OATS emissions-testing method) is:**

$$E = \frac{131.6 \cdot 10^{-16} (f^2 \cdot A \cdot I)}{R} \text{ V/m}$$

E = electric field in Volts/metre
f = frequency in Hz
A = loop area in square metres
I = loop's differential-mode (DM) current, Amps
R = measurement distance from loop in metres

CM. **For a short monopole (wire perpendicular to large 0V plane, max dimension < λ/6) the maximum *possible* E-field emission (maximised by varying antenna height over a groundplane as per the normal CISPR22 OATS emissions-testing method) is:**

$$E = \frac{1.26 \cdot 10^{-6} (f \cdot L \cdot I)}{R} \text{ V/m}$$

E = electric field in Volts/metre
f = frequency in Hz
L = length of wire in metres
I = wire's common-mode (CM) current, Amps
R = measurement distance from wire in metres

Simplified formulae for DM voltage noise 'pick-up' from external E and H fields

For a small loop (max dimension < λ/2) the maximum *possible* DM (differential-mode) voltage induced in it by an external H field is:

$$V_{DM} = 8 \cdot 10^{-6} (f \cdot H \cdot A) \quad \text{Volts}$$

- V_{DM} = the loop's induced DM voltage
- f = frequency in Hz
- H = the external magnetic field in Amps/metre
- A = the loop's area in square metres

$A=\lambda^2/4\pi$ gives the highest voltage possible in <u>any size</u> of loop, hence $V_{DM(max)} = 600 \cdot H \cdot \lambda/\pi$

For a small loop (max dimension < λ/2) the maximum *possible* DM voltage induced in it by an external E field is same as the above equation divided by 120π (approx. 377), the impedance of free space, in ohms:

$$V_{DM} = 2.1 \cdot 10^{-8} (f \cdot E \cdot A) \quad \text{Volts}$$

- V_{DM} = the loop's induced DM voltage
- f = frequency in Hz
- E = the external electric field in Volts/metre
- A = the loop's area in square metres

$A=\lambda^2/4\pi$ gives the highest voltage possible in <u>any size</u> of loop, hence $V_{DM(max)} = E \cdot \lambda/2$

For the induced DM current in the loop, divide the induced voltage by the circuit loop's (complex) impedance (vector calculation finds the phase angle between the induced current and voltage)

Simplified formulae for CM voltage noise 'pick-up' from external E fields

For a short monopole (wire perpendicular to reference plane, maximum length λ/4) the maximum *possible* CM (common-mode) voltage induced by an external E field is:

$$V_{CM} = E \cdot L \quad \text{Volts}$$

- V = the induced common-mode voltage in Volts
- E = the external electric field in Volts/metre
- L = the length of the wire in metres

$L = \lambda/4$ gives the highest voltage possible in <u>any length</u> of wire, hence $V_{CM(max)} = E \cdot \lambda/4$

For a small loop (max dimension < λ/4) the maximum *possible* CM voltage induced in it by an external E field is:

$$V_{CM} = \frac{E \cdot 2\pi \cdot A}{\lambda} \quad \text{Volts}$$

- V = the induced common-mode voltage in Volts
- E = the external electric field in Volts/metre
- A = loop area in square metres
- λ = the wavelength of the external electric field

For a given loop, this gives the same V_{CM} (in V) as I_{DM} (in A)

$A=\lambda^2/4\pi$ gives the highest voltage possible in <u>any size</u> of loop, hence $V_{CM(max)} = E \cdot \lambda/2$

For the induced CM current, divide the CM voltage by the (complex) CM impedance of the affected circuit (vector calculation finds the phase angle between the induced current and the induced voltage) emc6s+c v4.1 **Always fully apply all safety requirements** (not in the scope of this module, so not necessarily covered here)

Module 1: The Physical Basis of SI, PI, and EMC

Part of the background material provided free with our EMC courses

the end

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