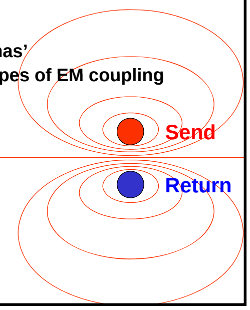
Understanding EMC Basics series
Webinar #2 of 3, May 29, 2013

Waveforms & Spectra, 4 types of EM coupling, Differential Mode and Common Mode, Overview of Emissions

EurIng Keith Armstrong
CEng, FIET, Senior MIEEE, ACGI

Presenter Contact Info
Email: keith.armstrong@cherryclough.com
Website: www.cherryclough.com

Contents of Webinar #2



Understanding EMC Basics

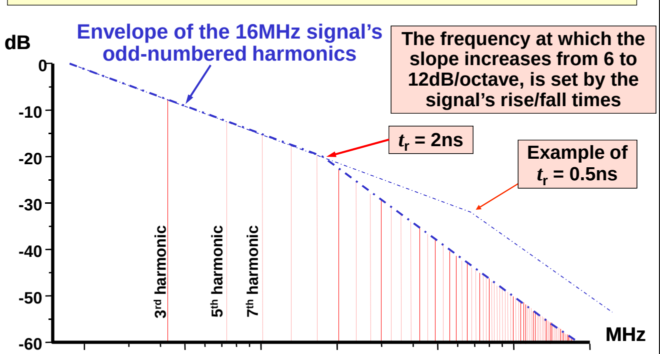
5

Waveforms, spectra, and "accidental antennas"

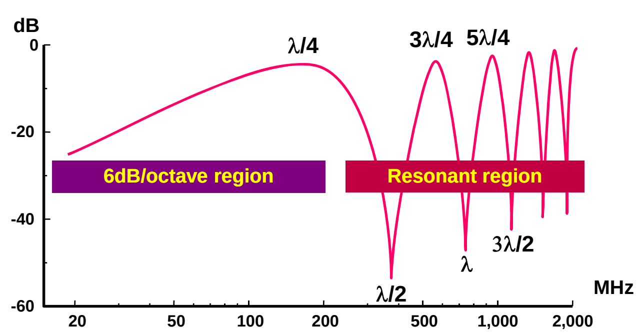
Waveforms and Spectra

- 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
- *So please don't use voltages or currents that change faster than they really need to !*

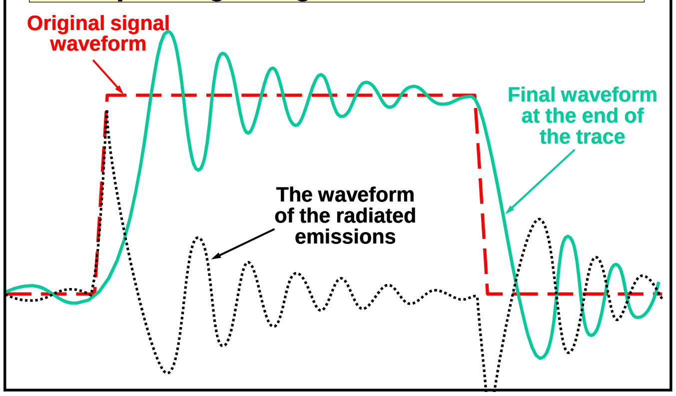
The spectrum of a 16 MHz squarewave with 2ns rise/falltimes (idealised analysis)



"Antenna efficiency" of a 200 mm PCB trace
(on FR4, no 0V plane, low-Z drive, high-Z load, idealised analysis)



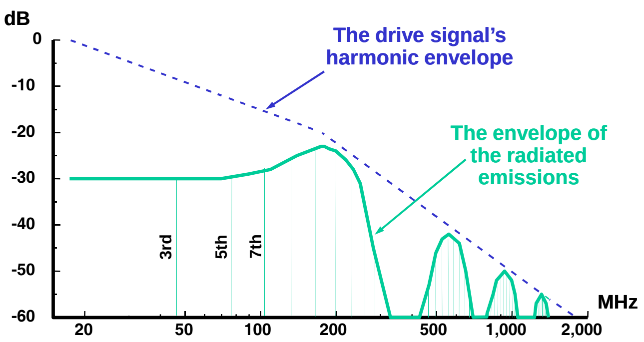
The resulting waveforms after passing along the 200 mm PCB trace



The close relationship between EMC and Signal Integrity (SI)

- Rectangular waveforms with overshoot and ringing are losing some of their energy into the air…
  - at the frequencies at which their traces/wires behave as efficient "accidental antennas"…
    - we can easily determine the worst emitted noise frequencies from the frequency of the ringing seen on the oscilloscope
- A circuit that has excellent SI (low, or no, overshoot or ringing on all signals) has good EMC…
  - and using good EMC design techniques from the start of a project achieves excellent SI…
    - because EMC is harder to achieve than SI

The spectrum of the radiated emissions from the 200mm PCB track (an idealised analysis)



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 high levels of emissions (or poorer immunity) at those frequencies

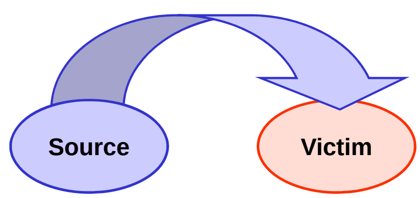
Understanding EMC Basics

6

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

The three parts to *every* EMC issue

- A circuit (a source of EM fields, a possible threat)
- Another circuit (a potential victim)
- And at least one EM coupling path between them



There are four types of EM coupling...

1 Common impedances

2 Electric (E) fields

3 Magnetic (H) fields

4 Electromagnetic (EM) fields

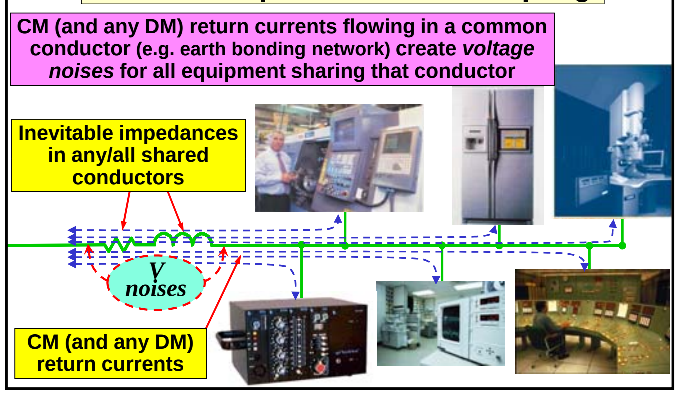
Common-impedance coupling

- 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)

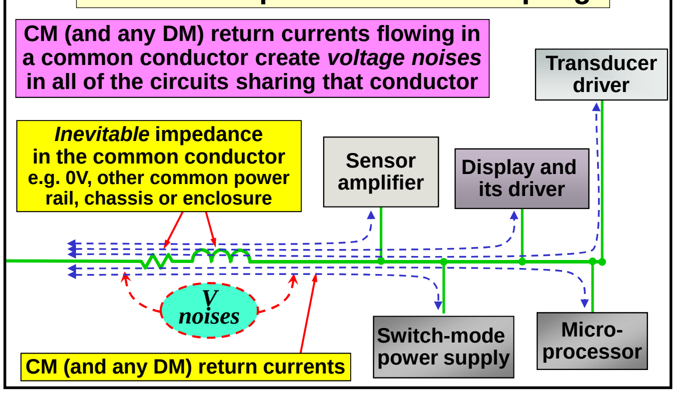
Common-impedance coupling continued...

- 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

Example of *inter-system* common-impedance noise coupling



Example of *intra-system* common-impedance noise coupling



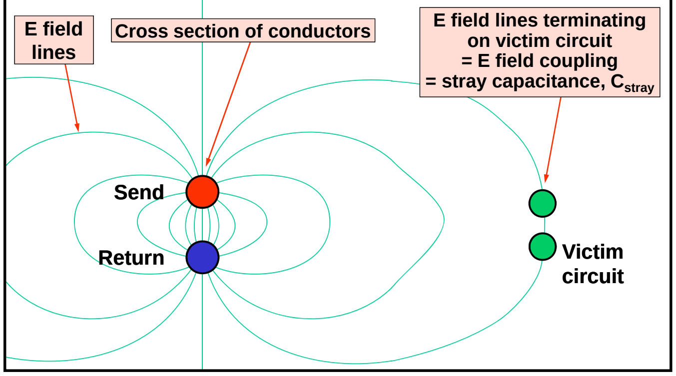
Circuit design is taught as if power rails and 0V returns have zero impedance

- 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

Electric (E) field coupling

(E field lines always terminate on conductors, at 90º to their surfaces)



E-field coupling causes noise *currents* to be injected into victim circuits

- Basically: $I_{COUPLED} = C_{STRAY} (dV_{SIGNAL}/dt)$
  - this assumes that the victim's impedance is << $1/(2\pi f C_{STRAY})$ and that the size of the victim circuit is << $\lambda/6$
  - and all stray currents flow in closed loops
- A stray capacitance of just 0.1pF between a victim circuit and a 100MHz 5V squarewave signal
  - would couple 310μA of noise current into the victim's circuit at the 100MHz fundamental frequency

E-field coupling continued...

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

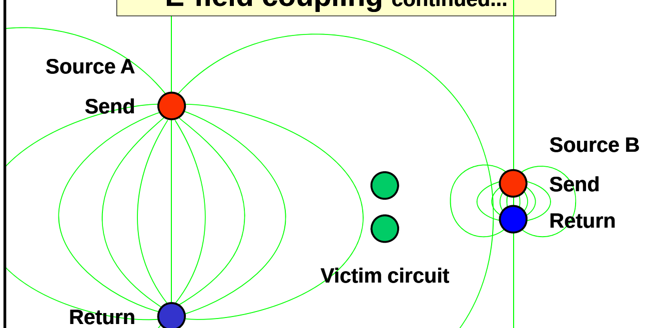
$$Z_C = 1/(2 \pi f C)$$

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

E-field coupling continued...

- We want to have a low stray capacitance (E-field coupling) between the source and victim circuits
  - to reduce their noise coupling (interference)
- But for a single signal's <u>own</u> send/return paths…
  - we generally want a *high capacitance* between its send and return current paths, because this makes its E-fields more compact
    - which reduces its stray capacitance to other circuits, thereby reducing the amount of noise coupling (interference)

E-field coupling continued...

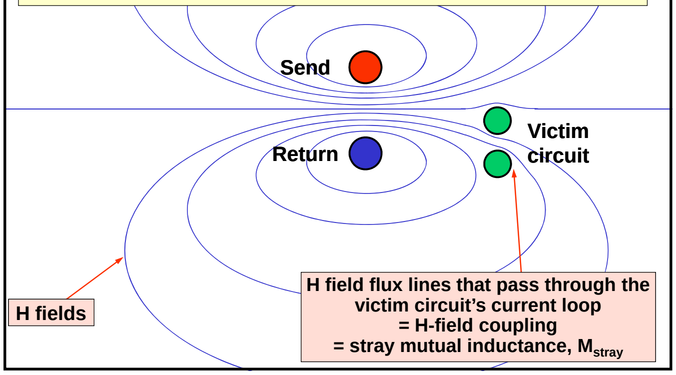


Source A couples to the Victim circuit more strongly than Source B, because Source B has more capacitance between its send/return conductors, so its E field is more compact and causes less stray field coupling (less stray capacitance) to the victim circuit

POLL QUESTIONS

Magnetic (H) field coupling

(H flux lines never terminate on conductors)



H-field coupling causes noise voltages to be injected into victim circuits

- Basically: $V_{COUPLED} = -M_{STRAY}\,(dI_{SIGNAL}/dt)$
  - this assumes victim circuit impedance >> $1/(2\pi f M_{STRAY})$ and that the size of the circuit is << $\lambda/6$
  - and all stray currents flow in closed loops
- A mutual inductance of only 10nH between a victim circuit and a circuit carrying a 100MHz squarewave at 100mA…
  - would couple 630mV of noise into the victim at the 100MHz fundamental frequency

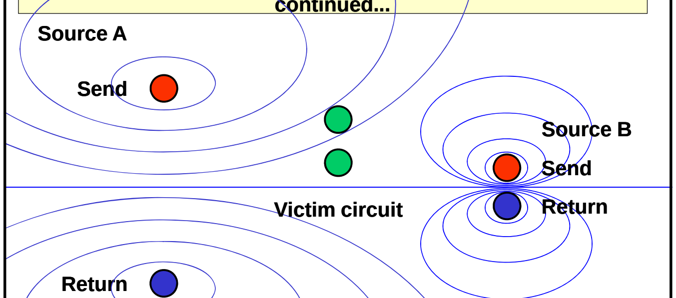
H-field coupling continued...

- Impedance of M_{STRAY} decreases with increasing f : $Z_M = 1/(2\pi f M)$
- Reducing a signal's rate of change of current (dI/dt) reduces its high frequency content *(Fourier transform)*
  - and therefore reduces its H-field emissions, and the noise voltage that it injects (couples) into victim circuits

H-field coupling continued...

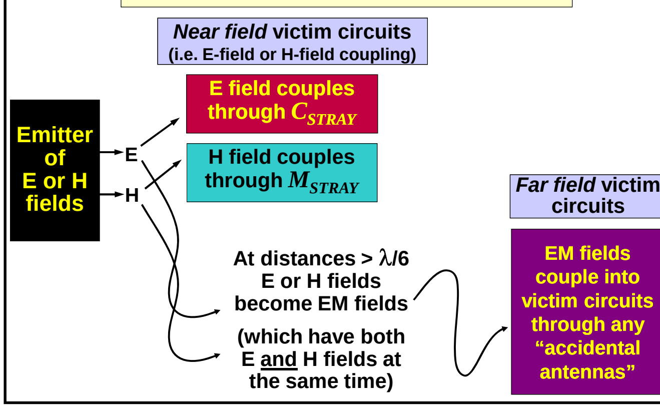
- We want to have low mutual inductance (M_{STRAY}) coupling between *different* circuits
  - to reduce their noise coupling (interference)
- But for a single signal's own send/return paths...
  - we generally want a *high* mutual inductance, because it makes its H-fields more compact
    - reducing its stray mutual inductance with other circuits, thereby reducing the amount of noise coupling (interference)

H-field coupling continued...



Source A couples to the Victim circuit more strongly than Source B, because Source B has more DM mutual inductance between its send/return, so its H field is more compact and causes less stray field coupling (less stray mutual inductance) to the victim circuit

EM-field coupling



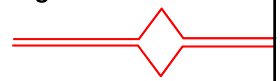
Understanding EMC Basics

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 and power are always DM

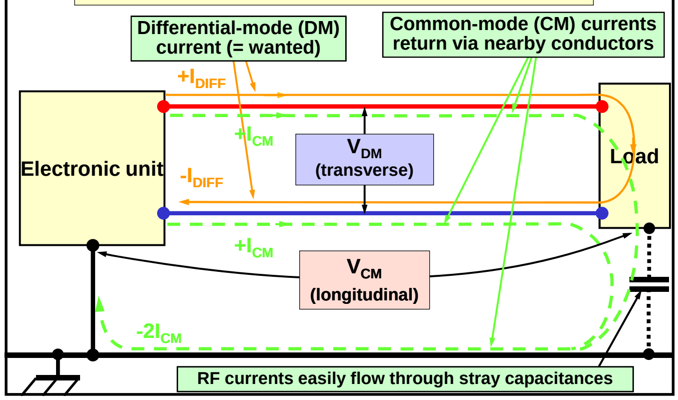


- Common Mode (CM) is where the voltages or currents are <u>the same</u> on both send *and return* conductors
  - measured with respect to a remote 'earth' reference
  - CM is accidental, and is unwanted

Common Mode

- We *intentionally* create DM signals and power…
  - these are our wanted signals and power, sometimes called 'transverse' (because they appear across two conductors)
- But unbalanced 'stray' coupling converts some DM signal 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…

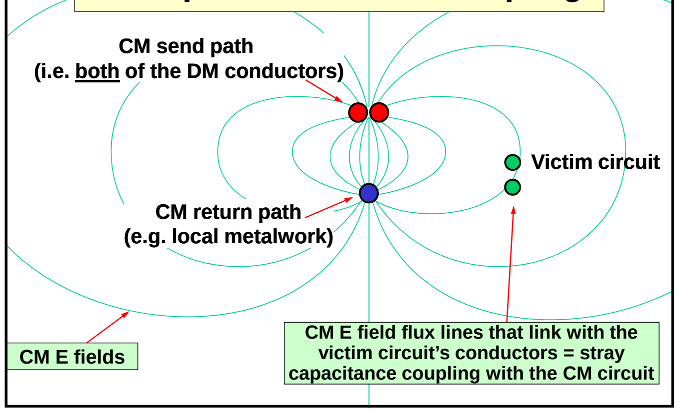
An example of DM (wanted) signals causing CM noises, for a 'floating' load



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



The very great importance of controlling CM

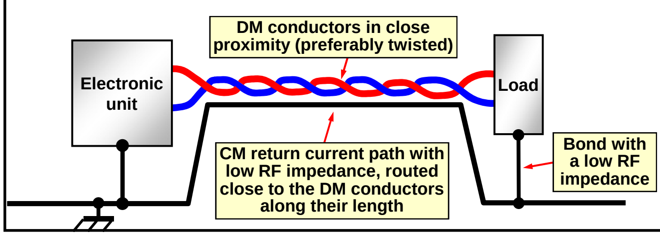
- Because CM currents tend to flow in large loops…
  - and because CM voltages tend to appear across large areas…
- The ‘accidental’ conversion of DM into CM is generally the main cause of emissions from 1 - 1000MHz
  - and the corresponding conversion of CM into DM noise signals is the main cause of poor immunity 1 - 1000MHz

Controlling CM return currents is very important indeed in EMC design

- *1st :* reduce CM generation by…
  - reducing the RF impedance in shared conductors
  - providing DM send/return paths in close proximity for both signals 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 that uses 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

Understanding EMC Basics

8

The EMC benefits of metal planes

Metal planes bring many EMC 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…
  - 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 EMC, and they are 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

Understanding EMC Basics

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 tuned antennas
  - i.e. PCB traces, wires and cables, metal structures, slots and gaps in shielded enclosure, etc....
  - all of which have resonant frequencies (that depend on their dimensions, build conditions, terminations, routing, and proximity to other conductors and materials)

POLL QUESTIONS

Understanding EMC Basics series

Webinar #2 of 3, May 29, 2013

Waveforms & Spectra, 4 types of EM coupling, Differential Mode and Common Mode, Overview of Emissions

the end

Presenter Contact Info
Email: keith.armstrong@cherryclough.com
Website: www.cherryclough.com